# CANAL SYSTEMS AUTOMATION MANUAL

## A Bureau of Reclamation Technical Publication

## Volume 2

United States Department of the Interior
Bureau of Reclamation

## MISSION STATEMENTS

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. Administration.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

# PREFACE

Canal automation is a proven method of providing cost-effective solutions to improve canal operations and conserve water. This manual has been prepared as a technical reference to provide specific tools for the design of an automated canal. Since the publication of volume 1 of the *Canal Systems Automation Manual* in 1991, the Bureau of Reclamation has received numerous requests for volume 2. Reorganization, retirements of key personnel, and budget, personnel, and program cutbacks have resulted in delays in the completion of volume 2 until 1995.

Volume 1 of the *Canal Systems Automation Manual* discusses the fundamentals of canal operation and automation. Volume 2 gives the reader more specific information for designing an automated canal or to retrofit automation to an existing canal. Chapter 5 deals with canal design and automation requirements. In chapter 6, the reader is provided with a brief review of canal hydraulics and a discussion of numerical solutions to the hydraulic equations used in canal applications. Chapter 7 is a discussion of control theory and application. Chapter 8 examines communication systems and their application to data telemetry and control. In chapter 9, the reader can learn about various types of measurement instrumentation. Chapter 10 discusses the mechanical features of an automated canal system. The last chapter, chapter 11, deals with the electronic components used to control a canal, either onsite or remotely.

The Bureau of Reclamation's canal automation team is a multidisciplinary team that has been actively involved in practical application of canal automation technology. The manual is an attempt to bring together the various technologies into a single resource for the canal operator, manager, and designer. A single gate structure could be automated by an individual using this manual and off-the-shelf components. However, the complexities of a centralized control system would require a team with varied technical expertise. The manual provides important considerations to aid in the technical design of an automated canal. In volume 2, the authors have documented institutional knowledge that should help canal operators and designers with practical applications of canal automation.

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# CANAL SYSTEMS AUTOMATION MANUAL

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## Volume 2

***A guide to the use of engineering technology pertaining to selecting automatic control schemes for canals conveying water to irrigable lands***

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# CHAPTER 5

# DESIGN OF AUTOMATED CANAL SYSTEMS

## COMBINING CANAL AND CONTROL DESIGN

### 5-1. New Canal Design

Selection of control methods to upgrade the operation of an *existing* canal was discussed in chapter 4, which also included a process for designing an automatic control system. However, modifications to infrastructure and operations are limited for existing canals; more choices are available when designing a new canal. Chapter 5 discusses the design of new automated canals.

Included in this chapter is the design of canal and control system components. The process of designing a new automated canal system must coordinate design of the civil works, mechanical equipment, electrical equipment, and control logic. Therefore, chapter 5 includes additional steps in the design process which were not discussed in chapter 4.

In theory, designing a new canal system has the advantage over modification of an existing canal because the designer can choose from all possibilities to yield the optimum system design. Structural features and control system design can be tailored to each other to produce the best and most economical overall system. Coordinating the structural and control system design allows greater optimization, but designing a new automated canal can be much more difficult than upgrading an existing canal because the design choices appear to be infinite. A designer can never be sure when the best design has been achieved.

Chapter 5 begins with a description of the process to follow when designing an automated canal system. An important order dependency exists, starting with canal operations and finishing with automatic control equipment and software. Often, the process is iterative because designers must start over as new alternatives arise. Computer models have become valuable design tools, providing data to help designers make decisions; however, computer programs do not replace engineering. Design alternatives must be proposed, studied, and economically evaluated.

The design process starts with project definition. This step includes establishing project objectives, laying out the canal network, determining patterns of expected water use and delivery, and establishing project operating criteria. Canal operation is the first item to be designed; the designer must work within operational constraints to select a concept and method of operation for the system.

Armed with a preliminary operation scheme, an engineer can design the canal system's structural components. This step involves civil engineering design in a more traditional sense, specifying conveyance channel properties, check structure location and details, turnout structures, storage facilities, siphons, drops, wasteways, and any other structural details. Structural design details can be found in other texts such as the Bureau of Reclamation's (Reclamation) *Design of Small Canal Structures* [1].[1] Chapter 5 does not provide a thorough discussion of canal design.

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[1] Numbers in brackets refer to bibliography.

Here, design considerations specifically associated with automated canals are emphasized.

Finally, control system components can be designed, beginning with the selection of a control concept and control method. Control logic must be developed and coded into software. Then, specifications can be written for mechanical, electrical, and communication equipment. The discussion of control system design in this chapter concerns important considerations in the design process. Control equipment details are provided in chapters 8 through 11.

Modern canal design must thoroughly consider operation and control. Unfortunately, designing an automated canal system is not a "cookbook" process—no design code exists. However, this chapter presents procedures and criteria that should help designers make good engineering decisions.

## DESIGN PLANNING

### 5-2. Operation, Control, and Automation

Historically, canal operation and control has been an afterthought to canal design. The physical features of a canal system were designed for the maximum steady-state flow, incorporating freeboard and wasteways to prevent damage during emergency conditions. Although operating criteria were provided, operation was the responsibility of operators, not designers. Conventional operation evolved as a practical method of satisfying irrigation needs within traditional canal system limitations. Local manual control was the only control method available.

Design of automated canals should follow a nontraditional approach to optimize the potential advantages of automatic control. The realm of possibilities for operating canals has been greatly expanded by recent advancements in monitoring and control systems. Designers must now consider many more operation alternatives before designing the structural features of a canal system. If a canal is designed based on steady-state assumptions and conventional operations, the best operation alternatives may be eliminated by structural constraints. Canal design should be based on realistic operations that include the types of flow changes and delivery flexibility that are feasible in a modern canal.

Operation, control, and automation are interrelated and order dependent. New canal design should start with a thorough study of unsteady-flow scenarios and evaluation of various operational alternatives. After the method of operation is known, specific control methods can be studied and selected. Then, automatic control logic and equipment can be designed.

When determining control system complexity, the objective is to serve the needs of water users efficiently and economically. Underdesign will lead to inefficiencies and problems with operation and maintenance; overdesign can yield an overly expensive or complex system. Using automation does not necessarily result in a "gold plated" project. On the other hand, the best design may not incorporate a large, complex control system. A simpler system often works better. The minimum system which satisfies users' requirements is preferable to an overdesigned system.

### 5-3. Design Process

Automated canal system design is a relatively new science and, consequently, the best procedure is not yet defined clearly. A natural starting point is to organize the design process so that a designer can step through the process in a logical and efficient order. The axiom "first things first" applies to the design process. The wrong order of design will result in a poor design which, in turn, will lead to poor canal operations.

In the early stages of project design, the choices appear to be unlimited. A process of elimination is needed to reduce alternatives to a workable number. Elimination is easier in the beginning, when some alternatives are obviously better than others. One of the designer's first jobs is to identify known or "given" parameters. Design parameters that are not subject to variation can be separated from variables to limit the number of choices as early in the process as possible.

Successive elimination of alternatives should proceed as far as possible based on experience and judgment. Decisions will require a more detailed level of study as the process of elimination proceeds. Selection of the best alternative will be based on engineering and economic factors. To evaluate these factors, studies and preliminary designs must be prepared. A workable number of alternatives should be proposed for detailed analysis.

Typically, designing a new automated canal is an iterative process; a designer may need to repeatedly loop back to earlier steps to evaluate design alternatives or changes. For example, a preliminary canal design must be proposed before canal operations can be studied. Results of operation studies may suggest changes to canal layout, capacity, freeboard, or control structures. Designers must then loop back to create a new design before proceeding. The design process includes successive stages of trial and evaluation before selection of a final design.

Various tasks required to design an automated canal system are listed below in a suggested chronological order:

1. Establish overall project goals and objectives
2. Lay out conveyance network alternatives
3. Select or predict water use patterns
4. Choose a delivery concept
5. Perform preliminary sizing of canal
6. Establish operating criteria and constraints
7. Select a canal operation concept
8. Choose a method of operation
9. Design structural components
10. Evaluate economic feasibility
11. Select a canal control concept
12. Select a control method
13. Develop control procedures, logic, and algorithms
14. Specify control equipment
15. Implement control system
16. Operate and maintain
17. Continue to develop and upgrade

Design tasks need not always be accomplished in this suggested order, but the above list provides a guide that should approximate the design process. Designers should evaluate alternatives at various stages in the process, looping back to previous steps whenever the evaluation leads to design changes. For example, evaluation of economic feasibility at step 10 should yield the cost of different alternatives and influence the choice of delivery concept, constraints, and method of operation. Designers may have to recycle successive alternatives through steps 4 through 10 until the best design is found.

An automatic control system is designed near the end of the process even though approximate capabilities of the control system must be anticipated earlier. Control software often remains uncompleted until after the canal is put into service; only then will operators know the exact project needs and water use patterns. The most successful existing automated canal projects have control details that were developed dynamically (over a period of time) based on actual project operations.

The following pages discuss the design process, including all of the various design tasks in the recommended order of completion.

## 5-4. Design Alternatives

Canal system design involves evaluating structural alternatives to select a final design. Information concerning expected operations will limit the possible design choices. When delivery concept and method of operation are known, structural needs can be identified more clearly. Knowing the delivery concept will help define the maximum flow and expected flow variations. Designers must know the method of operation to establish design water surface profiles.

Accommodating expected flow changes presents a major challenge for canal designers. One possible solution involves preventing canal flow changes by insulating the canal from the causes of these changes. Reservoirs and wasteways can be used to keep canal flow relatively steady while delivery and/or supply flows fluctuate. Another alternative manages flow changes within the canal rather than preventing them. In this case, the conveyance channel, control structures, and control system must all be designed for anticipated flow fluctuations.

A brief discussion of design alternatives follows. More detailed information is provided later in this chapter under the heading "Design of Structural Components."

**a. Conveyance channel design.**—A canal prism's conveyance capacity determines the range of possible operations. Channel size and slope limit the maximum achievable flow rate, thus establishing the canal system's steady-state delivery capacity. Additionally, canal capacity greatly affects operational flexibility; increasing canal cross-sectional area increases capability to make flow changes.

When a flow change occurs, acceleration of the water causes depth fluctuations. The larger the canal, the smaller these fluctuations will be. A larger canal will also provide additional volume in which to store extra water. This in-channel storage provides a buffer for absorbing flow changes because flow imbalances can be accommodated by adding or draining water from storage.

To illustrate the effects of channel size on water level fluctuations, consider the following example canal:

Bottom width = 6 meters (m) (20 feet [ft])
Side slope = 2:1 (horizontal to vertical)
Manning's $n$ = 0.013
Bottom slope = 0.0001
Pool length = 2,500 m (8,200 ft)
Initial flow = 18.4 cubic meters per second ($m^3/s$) (650 cubic feet per second [$ft^3/s$])
Normal depth = 2 m (6.5 ft)
Initial depth = 2 m (6.5 ft)

If the flow at the downstream end of this canal pool is suddenly reduced by 2.8 $m^3/s$ (100 $ft^3/s$), the accompanying sudden depth increase will equal about 70 millimeters (mm) (0.23 ft). If pool inflow remains at the initial flow for 1 hour after this outflow reduction, the average pool water level will rise 320 mm (1.05 ft).

If the bottom width is doubled to 12 m (40 ft), keeping all other dimensions the same, the same flow reduction would cause a sudden depth increase of about 40 mm (0.13 ft), and the 2.8-$m^3/s$ (100-$ft^3/s$) flow mismatch for 1 hour would cause the average pool level to rise 200 mm (0.66 ft). Therefore, increasing channel size reduces both the short-term and long-term effects of a flow change. Furthermore, normal depth in the widened channel is only 1.4 m (4.7 ft) for the initial flow rate in this example. Pool water level could be raised and lowered between this normal depth and higher operating levels, as needed, to use in-channel operational storage.

Canal automation facilitates the use of in-channel storage. Supervisory control systems in particular allow a canal operation to take advantage of extra storage within the canal prism.

**b. Control structures.**—The location and type of control structures in a canal system have a major impact on operations. The distance between control structures such as check structures and pumping plants affects the canal system's response to flow changes. Large distances require slow flow changes to avoid rapid depth fluctuations. With some methods of operation, structure spacing has a significant effect on the volume of water required to change to a new water surface profile, and, therefore, on the time required to achieve a new flow rate (see chapter 2).

Pumps create additional operational problems which must be accommodated during design. Without variable-speed motor controllers, pumps can be controlled only in large steps of flow change. In canal systems with pumps, supply will seldom match demand exactly. Some type of regulatory storage is needed to absorb the flow mismatches. Additionally, pump power failures and limitations on the pump on-off cycling frequency can have a major impact on canal operations. Advanced control system capabilities are more important where pumps are involved.

**c. Regulatory storage.**—Storage capacity outside of the conveyance channel can create a buffer which insulates canal operations on one side of the storage facility from the other side. Storage facilities can be in line with the canal or off-channel. Commonly, reservoirs, ponds, and tanks are used to provide this storage. These facilities allow a mismatch in the flow to exist without wasting water or changing the depth in the canal. Flow changes which occur upstream from the storage facility do not have to be matched on the downstream side, and vice versa. For example, a change in turnout demands can be fed from storage without changing inflow to the canal at the headworks.

**d. Spill flows.**—Canal flow fluctuations can also be reduced by spilling, or wasting, water from the canal. When canal flow rate exceeds demand for that water, the excess supply can be spilled through wasteways. This excess may be caused by an inflow increase such as storm runoff entering the canal or by outflow changes such as turnout flow reductions, power failures, pump shutoff, gate closings, or flow obstruction.

Building a canal with wasteways generally is less expensive than providing supplemental storage, but wasteways offer fewer advantages. Unlike storage, wasteways will not supply flow shortages caused by inflow decreases or outflow increases. Usually, spilled water is not recoverable like stored water. In some canals, wasteways may be designed for use only during emergency conditions.

An automated control system will significantly reduce spills in most cases. Canals without wasteways need a dependable control system.

## 5-5. Technical Studies

To evaluate alternatives accurately, a canal designer must perform studies. Studies vary from brief investigations using simple deductions to detailed and highly technical analyses. Regardless of scope or level of sophistication, study results should provide the designer with specific information for making design decisions. Typically, studies are required at various stages in the design process.

**a. Preliminary studies.**—Planning studies determine the water requirements to predict required flow capacities and delivery point locations. Studies may begin during canal system layout, helping the engineer locate main features such as reservoirs, pumping plants, branch canals, check structures, tunnels, siphons, and wasteways. Preliminary design studies also may be required to produce initial designs for structural features such as canal prism size and shape, lining material, bank height, and control structure type and location.

Preliminary design studies can be quite simple, using experience and deduction to choose between alternatives. Preliminary decisions may require only simple calculations and cost estimates—just enough detail to eliminate obviously inferior alternatives. Designers should not lose sight of the purpose, information needed, or decision to be made. Analysis results are only as good as the assumptions on which they are based. A study's complexity and accuracy should match the accuracy of the input data and the accuracy of the answers required.

Good data collection is essential. Conventional design data may include information such as topography and required delivery capacities. Data on flow changes are of particular importance for automated canals. To develop operating strategies and design a control system, designers must know the magnitude and rate of flow changes expected for the canal. Therefore, design data should include expected delivery flow patterns.

Final design requires more comprehensive and detailed studies. When decisions become difficult, more sophisticated analyses must be used to determine the best alternatives. Automated canal system design studies are rooted in hydraulic analysis, ranging from simple steady-state hydraulic computations to complete unsteady-state analysis. Hydraulic analysis can begin as soon as a preliminary design of the physical system is available. Canal layout, dimensions, hydraulic properties, and control structure data are needed as input to hydraulic studies. Study results may show a need to change preliminary physical properties to improve system performance or decrease project cost.

**b. Steady-state hydraulic studies.**—Hydraulic analysis should begin with steady-state hydraulics. Steady, gradually varied flow water surface profiles—or backwater curves—will yield important design information. Ignoring transient effects, a designer can estimate changes in storage volumes and water levels for different methods of pool operation. This estimate, in turn, leads to approximate times required to perform various operations, assuming accurate control.

Generally, steady-state hydraulic analysis will suffice for selecting a method of operation. For a particular method of operation, steady-state flow profiles should be calculated to produce data relating to water volume changes, depth variations, freeboard requirements, delivery water levels, and preliminary design of wasteways and check structures.

Costs of different methods of operation can be estimated by looking at full-flow and zero-flow steady-state water surface profiles. As shown on figure 5-1, these profiles show required bank height and maximum depth variations.

By predicting maximum possible flow changes for a specified time span and comparing water surface profiles, designers can estimate short-term depth variations and select preliminary check structure spacing. Section 5-16a discusses check structure spacing.

**c. Unsteady-state hydraulic studies.**—Unsteady-state hydraulic studies should be performed as canal system design progresses. System response

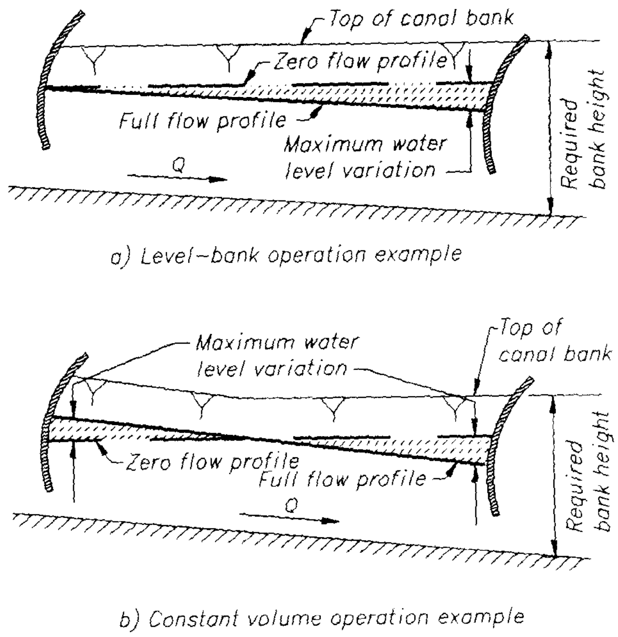


Figure 5-1.—Steady-state water levels and fluctuations.

will vary considerably with different methods of pool operation, so unsteady-flow analysis should be used to confirm that the selected method of operation responds to flow changes as expected. Alternate methods should be studied if any questions remain as to the best method of operation.

Unsteady-flow analysis is required to refine the structural design and to study control system behavior. Canal lining, bank, and control structures must be designed to accommodate transient waves caused by flow changes. Transient waves are of particular concern in canal systems with pumping plants that can produce sudden, large flow changes. Wave heights can be estimated assuming instantaneous flow change. Books by Chow [2] and Chaudhry [3] contain equations for calculating open channel wave heights. Maximum wave height plus the steady-state profiles provide a good estimate of depth fluctuation ranges as shown on figure 5-2.

Control method selection requires analysis of response to various anticipated operating scenarios. To study the performance of different control methods, designers should estimate the response of each method. Then, based on estimated control responses, an unsteady-flow model can be used to analyze conveyance system behavior.

For example, supervisory control should respond quickly to a specific operating condition. Designers might assume a maximum control response delay of 15 minutes for a canal with supervisory control. However, a delay of several hours may be more realistic for a canal with local manual control. A flow mismatch may exist for several hours followin an unexpected delivery change. Designers should study the effects of these delays on canal water levels.

Unsteady-flow analysis is required to develop, test and calibrate canal control logic. Developing control procedures and automatic control algorithn requires both experience and numerical analysis. With experience, performance of different control algorithms can be estimated. However, true verification of controller performance and development of specific control parameters requir detailed analyses.

A control system designer must analyze automati control logic using the selected physical system a

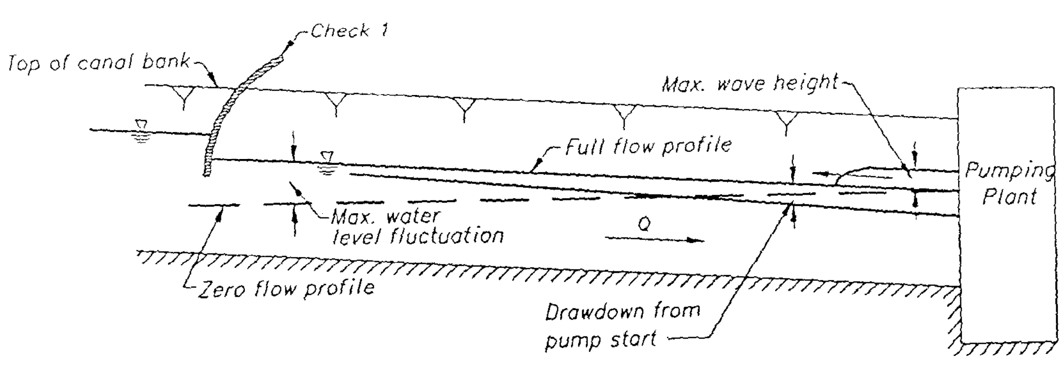


Figure 5-2.—Initial depth fluctuation estimates.

projected operations. Studies should test stability during daily operations and quick response to severe operations. For a fair evaluation of a particular control algorithm's potential and comparison to other algorithms, studies should use reasonable values for control parameters. As discussed in chapter 7, either frequency domain analysis or time domain analysis can be used to determine control parameters.

**d. Continuing studies.**—Studies will continue to be useful after a canal is put into operation. Computer simulations can be used to try different control techniques instead of experimenting with the real canal system. Input data can be based on actual delivery patterns, canal properties, and known constraints. Real operations will indicate problem areas and needs for improvement, and water users will be quick to point out any shortcomings with deliveries. Canal operators can learn how to improve operations and make their own jobs easier by studying new control strategies and developing new control software.

Numerical analysis and its use in performing design and operation studies are discussed further in chapter 6.

## 5-6. Economic Feasibility

Design studies help the engineer evaluate economic feasibility in addition to evaluating the technical feasibility of alternatives. Usually, design studies conclude with cost analysis and cost comparison of different schemes. Chapter 4 includes a section on the feasibility of upgrading existing canals. Generally, the information in that section applies to new canals as well. The information below summarizes costs and benefits for automating new canals.

**a. Costs.**—When estimating project cost for automated canals, control system costs must be considered in addition to the cost of civil works. Some of the items that might contribute to control system costs are listed below:

- Initial capital expenses:
  - Data collection equipment
  - Communication system
  - Interface equipment
  - Control equipment
  - Software development
  - Additional design costs
  - Control system installation and testing
  - Additional mechanical components (e.g., gate motors)
  - Power systems
  - Structures to house control equipment (e.g., master station)

- Long-term operation and maintenance costs:
  - Control system equipment maintenance
  - Equipment upgrades and replacement
  - Software maintenance and upgrades
  - Skilled labor
  - Power costs

**b. Benefits.**—The benefits attained through enhanced control capabilities usually justify the extra expense. Some of these benefits may show definitive money savings. For example, better control through automation can replace more expensive structural alternatives such as regulating reservoirs. However, many benefits are intangible. Improved service to water users, in the form of increased delivery flexibility and dependability, will create significant benefits, but placing an accurate monetary value on intangible benefits can be extremely difficult.

Potential benefits from canal automation might include:

- Tangible benefits:
  - Civil works prevented (e.g., storage facilities, wasteways)
  - Canal maintenance and repair savings
  - Reduced labor costs
  - Decreased power consumption
  - Water savings
  - Prevention of damage from spills

- Intangible benefits:
  - Increased crop production
  - Delivery flexibility
  - Canal operation flexibility
  - Rapid response to abnormal operations and emergencies
  - Improved client relations
  - Fish and wildlife enhancements
  - Salinity reduction

## PROJECT DEFINITION

### 5-7. Project Objectives

The design process should begin with establishment of overall project goals or objectives. The primary objective on most Reclamation canal systems is to deliver water for irrigation, municipal, and industrial use. Other project objectives include power generation, ground-water collection, water quality enhancement, wetlands management, streamflow maintenance, recreation, and drainage.

Objectives should be clearly understood and prioritized so design decisions can be based on the stated objectives. Generally, a project's objectives are developed by aggregating needs. Satisfying water users' needs is the top priority for most delivery canals. Planners must identify these needs early in the design process. Customer requirements that must be defined might include:

- Quantity, rate, and duration of delivery flows
- Delivery water pressure or head
- Types of turnouts (e.g., gravity, pipe, or pumped)
- Delivery flexibility requirements
- Level of dependability

Other factors influencing the formulation of objectives may include economic, social, political, and environmental factors. The relative importance of each factor must be weighed to prioritize all project objectives.

Project objectives will affect design decisions concerning operation, control, and automation. Operational concept and method of operation will be chosen by balancing project requirements with economic constraints. For example, extra expense to design the canal and control system for on-demand operation may be warranted in a project where delivery flexibility is extremely important. However, a minimum-cost canal design may be a better alternative if canal water can be spilled easily with little negative consequence.

Future needs of both water users and canal operators must be thoroughly considered before making design decisions. Communication is the key to establishing project objectives. The client must be informed of the consequences and costs of different alternatives. Water users will want to know their costs before choosing an alternative. For example, a farmer may be willing to pay a 10-percent premium to obtain water on demand instead of having to order it a day in advance. But, if on-demand delivery will cost 50 percent more, one may prefer to accept the restrictions of scheduled delivery.

Planners and designers must know and prioritize project objectives to produce the best design. Designers can match project capabilities to customer needs when they have good information.

### 5-8. Layout

Designers should produce a preliminary layout of principal project features after formulating project objectives. Project layout should include main structural features such as canal reaches, tunnels, check structures, reservoirs, river crossings, turnouts, pumping plants, powerplants, wasteways, and other significant structures. First, the general location of these features should be established. Then, if known, approximate dimensions and flow capacities can be added.

The initial layout of structural features provides a starting point from which to pursue design details, even if these details change several times during the design process. Sometimes, alternative layouts can be formally prepared, and parallel studies can be carried out on each alternative. Alternative layouts should be kept to a workable number, usually a maximum of two or three.

**a. Service areas.**—Land areas to be irrigated should be mapped, showing location and size of each area. Then, irrigated lands can be grouped into service areas that each represent a single delivery point from the canal. Other major delivery points, such as municipal turnouts, should be included. A map of proposed service areas will serve as a guide for selecting the canal alignment. The canal should follow an efficient path from the supply source(s) to the service areas.

**b. Topography.**—The canal network alignment depends on existing topography, especially natural features that prevent the canal from following constant elevation contours. Rivers, lakes, steep slopes, and cross-drainage channels can present obstacles to the canal alignment. Designers must estimate the economic and operating consequences of crossing or avoiding topographical features. Land acquisition (right-of-way), environmental concerns, and proximity to populated areas may also influence canal alignment.

**c. Delivery capacity.**—Initially, a delivery canal's size can be estimated from the accumulated water needs of service areas. Once individual users' water allotments have been determined, the total of all allotments will yield a total quantity of water that the project must deliver over the course of a season. Project seasonal storage must be adequate to supply the total quantity. However, the maximum water delivery rate during the peak water use period is more important for predicting delivery capacity.

For a given service area, the types of crops to be grown and the anticipated application efficiency of water to crops will provide input to the calculation of required delivery capacity [4,5]. Records of actual water use under similar conditions will help estimate water requirements per hectare (or acre) for a project.

Capacity requirements for collector or connector canals will be based on supply flow estimates.

**d. Turnouts.**—Many canals deliver water through a limited number of major turnouts into secondary canal or pipeline systems. A single turnout may supply an entire service area or even multiple service areas. Location, type, and capacity of major turnouts will help define conveyance channel requirements. Minor turnouts should be estimated or lumped together to produce approximate location and capacity information for use in designing the canal.

**e. Canal hydraulic design.**—Minimum canal size will be determined from the required maximum conveyance capacity. For delivery systems, a first estimate of channel conveyance capacity—or *design flow rate*—is the aggregate of all turnout flows. Inflow requirements will determine the design flow for collector and connector canals. Canal design flow also should consider hydraulic efficiency, accounting for evaporation and seepage losses.

Using steady flow at the design flow rate, initial hydraulic design of the canal prism will yield canal hydraulic properties such as channel slope, bottom width, side slope, and depth. Numerous factors must be weighed to select the most economical design because the proper flow capacity can be achieved with many different combinations of hydraulic properties. Lining type, head losses, available head, and cut/fill balance will influence the design choice (section 5-15 presents more details on designing the conveyance channel).

**f. Conveyance structures.**—A canal system may include numerous structures to convey water over, under, around, or through topographical features or existing infrastructure. Tunnels, bridges, inverted siphons, drop structures, pumping plants, cross-drainage structures, fish screens and ladders, energy dissipation structures, and elevated flumes are examples of expensive structures sometimes required in canal systems. Usually, minimizing the need for and cost of these structures will influence canal alignment and design.

**g. Control structures.**—Preliminary control structure locations should be based on terrain, turnout or branch canal locations, and location of conveyance structures that require flow or depth control. Generally, these factors will override operational considerations. Additional check gate structures should be designed and located to fulfill operational requirements, as described later in this chapter. Initial check structure spacing can be estimated from experience or rules of thumb. For example, checks might be spaced so that the elevation drop between checks equals the allowable water level fluctuation from expected flow changes.

## 5-9. Water Delivery

When designing a structure, engineers work with maximum load combinations to ensure that the structure is strong enough to hold all *design loads*. In designing a canal, the design loads consist of the maximum anticipated flow changes. The canal should have the capability to handle all flow changes without exceeding operating criteria. Therefore, designers must establish the most severe flow changes that can occur early in the design process.

The term *delivery* refers to release of water through turnouts from the canal system to water users. Canal system design depends on water delivery characteristics because delivery flows create flow changes in the canal. Water use patterns and delivery flexibility help define the flow changes for which a canal system must be designed. The rate and amount of delivery flow change must be predicted to predict flow changes in the canal system.

**a. Water use patterns.**—Water users, project personnel, and designers should predict the frequency, rate, and duration of water use throughout the project area. Usually, municipal and industrial water use patterns are predictable from historical records, which contain daily, weekly, and seasonal water use data. Agricultural water use is more difficult to predict.

Maximum agricultural water use during the peak of the irrigation season defines the canal's maximum delivery requirement, but delivery flow frequency and duration will depend on crop patterns, water application methods, soil conditions, weather, and water users' habits. The canal will not experience many short-term flow changes if most turnouts maintain constant delivery flow. For example, larger farms may take a constant flow from the canal and rotate irrigation among different land areas within the farm boundaries. Conversely, canal flow may change drastically twice a day if many water users begin taking water at daybreak and quit taking water at dark. Another cause of large flow change might be many irrigators growing the same crop; they may all take water at the same times during peak crop demand periods and stop irrigating at the same time to harvest.

**b. Delivery flexibility.**—As discussed in chapter 2, delivery flexibility depends largely on the canal system's delivery concept, i.e., rotation, schedule, or demand. Delivery flow changes—and, therefore, canal flow changes—vary dramatically among the different delivery concepts.

The level of delivery flexibility should be established, either project-wide or for individual turnouts. Usually, delivery flexibility depends on convenience and economics. Water users benefit from unrestricted delivery. Studies have shown that increased delivery flexibility can greatly increase the value of water to irrigators [6]. In addition to growing more crops with less water, farmers can enjoy the convenience of irrigating when they want to instead of when the water arrives. However, the price of flexible delivery is increased canal flow variation. Water users' desires for fewer delivery restrictions must be weighed against the system-wide costs and required capabilities.

For some types of turnouts, delivery flexibility is a requirement. The canal design may have to accommodate uncontrolled situations. For example, pumped turnouts may shut down upon power failure. Drain inlets, which can produce uncontrolled inflow to the canal, may also cause problems.

## 5-10. Operating Criteria

As stated previously (section 5-9), a canal must be designed to accommodate expected flow changes without exceeding operating criteria. Therefore, the next logical step is to establish these criteria. Some important operating criteria are discussed in the following subsections.

**a. Depth fluctuations.**—Water surface fluctuations should be limited to prevent canal lining damage and undesirable turnout flow changes. General fluctuation limits can be used for design purposes, although acceptable rate and amount of water level variation should be determined for each particular canal through operating experience.

Water surface *rise* usually is limited to 0.15 m (6 inches [in]) in any 1 hour to prevent undesirable changes in turnout discharge. A faster rate of rise may be acceptable for canals without gravity turnouts (e.g., all turnout flow goes through canal-side pumping plants). Experience has shown that the rate of water surface rise during canal filling should not exceed 0.45 m (18 in) in any 24-hour period.

Water surface *drawdown* limitations prevent undesirable changes in turnout flows, protect concrete and membrane lining from damage by external hydrostatic pressures, and prevent earth-lined sections from sloughing. The acceptable rate of depth reduction varies with the strength and weight of the lining material, drainage behind the lining, and shape of the canal prism. For design purposes, drawdown should not exceed 0.15 m (6 in) in any 1-hour period, 0.30 m (12 in) in any 2-hour period, and 0.45 m (18 in) in any 24-hour period. Exceptions to these drawdown rates, either increases or decreases, should be based on specific design conditions for each particular canal. Impervious or poorly drained soil may require slower drawdown rates. Conversely, reinforced canal lining or good drainage behind the lining may allow faster drawdown.

**b. Spills.**—Most canals have wasteways for spilling excess water. (The terms **spill** and **waste** are interchangeable.) Criteria for spilling water can vary widely. Spills may have few negative consequences in some canals, so criteria for spilling water can be quite liberal. Other canal systems may not tolerate spilling.

Many canals that are supplied by gravity from a river follow a path more or less parallel to the river, but at a higher elevation. Excess water in the canal can be returned to the river by way of gravity wasteways. Spilling canal water through wasteways may be an acceptable and routine procedure during normal canal operation. Operators of these canals prefer the term **spill** to **waste** because little water is actually lost. Excess flow is sometimes intentionally diverted through canal headworks to assure an adequate supply to all users. Reasonable criteria in this type of operation might involve limiting spill flows to 10 percent of total canal flow.

Spills are highly undesirable in most new canals. Water availability, cost, or environmental concerns have resulted in canal systems that are designed for minimal waste. Usually, spills are unacceptable when spilled water cannot be recovered and reused or when the water has been pumped. Spilling pumped water wastes the energy that was used for pumping. Sometimes, acceptable wasteway locations and drainage channels are not available. Therefore, modern spill criteria may be prohibitive.

Canal and control system design must be based on appropriate spill criteria. Examples of criteria to be established prior to design include:

- Quantity of water that can be spilled from the canal (percent of total delivery quantity)
- Wasteway locations
- Maximum spill flow rate at each location
- Threshold canal water levels and/or flows that trigger spills
- Allowable spill frequency
- Operating conditions during which spills are allowed

**c. Power limitations.**—Power requirements and restrictions influence the design of control structures and equipment. A first criterion is power availability for gate motors, pump motors, monitoring, communication, and control hardware. Maximum power demand will establish transmission and onsite electrical equipment design capacities. The power required for motor startup usually constitutes the maximum power requirement.

Power cost can vary between peak use and off-peak use time periods. Therefore, criteria should be established for on-peak and off-peak pumping. These criteria may influence the design of major structural features such as regulating reservoirs. Designers need to scrutinize the consequences of power outages, which can cause extreme disruptions to operations. Pump shutdown criteria should address valve closures, check gate closures, and wasteway operation. Criteria are also required for unexpected power loss at motorized check gates. That is, should gates automatically close or maintain their position following a power outage?

The need for and cost of backup power for monitoring and control equipment should be considered, and criteria should be established to itemize which monitoring and control functions are to remain operational through loss of primary power. Generally, data collection and communication equipment should be backed up with battery power to allow continuous system monitoring through power outages. Usually, backup power for gate motors and pump motors is not feasible for canal systems.

**d. Pump operation.**—Criteria for pump operation include minimum run and rest times, number of pump starts per day, size of flow change increments, and requirements for distribution of run time among pump units. Minimum run times and rest times ensure proper cooling of pump motors before successive motor starts. Table 5-1 shows minimum run times for pumps of different sizes (horsepower[hp]) and speeds (revolutions per minute [r/min]).

A pump motor that has been on for the minimum run time can be restarted if stopped for at least 5 minutes. If the pump is shut off before the minimum run time, an off time equal to three times the minimum run time is required before restarting the motor. Motors rated 200 hp and larger should not average more than eight starts per day.

Sequencing and rotation of pump unit operation may be important to avoid uneven wear of different pumps within a pumping plant. Pump operation may be scheduled to intentionally promote uneven wear so that all pumps will not need maintenance at the same time. Example criteria might include:

Table 5-1.—Minimum pump motor run times

| Minimum run time (minutes) | 1,800 r/min (horsepower) | 1,200 r/min (horsepower) | 900 r/min (horsepower) | 720 r/min (horsepower) |
|---|---|---|---|---|
| 5 | 0–50 | 0–25 | – | – |
| 10 | 50–300 | 25–125 | 0–75 | 0–50 |
| 20 | 300–1000 | 125–700 | 75–400 | 50–250 |
| 30 | – | 700–1000 | 400–1000 | 250–700 |

- First on, first off—whichever unit has been running longest is the first unit to shut off, and the unit that has been off longest is turned on first.
- Small units cycle before large units—smaller pumps are always turned on and off before larger pumps to minimize starts of large motors.
- Scheduled rotation of unit designation—unit designations (No. 1, No. 2, No. 3, etc.) are periodically changed among the pumps; No. 1 is always first on and first off, No. 2 is second, etc.

Criteria for the maximum size of flow change increments will influence pumping plant design. Large, fixed-speed pumps may be unacceptable because of the large flow mismatches they cause in the canal system. Smaller, fixed- or variable-speed pumps may be required if a small flow change increment is needed.

**e. Response time.**—System response time criteria will influence structural component design and control system capabilities. Severity of emergency conditions and consequences of slow response will determine the length of delay that can be tolerated in responding to emergencies. Quick response may be unnecessary in a gravity system with wasteways but essential for a canal with in-line pumping plants and no wasteways. Some examples of design decisions based on response time criteria are:

- Whether local manual control can be used as a backup to automatic control during power outage or if backup power is needed
- Whether operations staff are required on duty 24 hours a day
- Whether automatic control response to emergencies should be programmed or if manual override is sufficient
- Extent of the alarm system

The response time used for canal design will depend on control method. When local manual control is the only method available to move gates during power outages, a delay of several hours may exist before ditchriders can reach every control structure. However, the delay may last only a few minutes if backup power is available. The appropriate delay should be used to predict depth and flow changes during critical operations and to design canal sections, check structures, and wasteways accordingly.

**f. Hazards.**—Operating criteria definition also must take hazards into account. A finite level of risk always will exist, so the risk and consequences of failure must be evaluated to establish acceptable criteria.

Statistical information can help predict severe natural conditions such as floods. The designs of drain inlets, cross-drainage structures, canal embankment, bypass weirs, and wasteways depend on predicted floodflows. Similarly, control system design should be based on naturally occurring severe conditions. Designers must weigh frequency of occurrence versus cost to prevent damage from such events.

For example, canal structures might be designed for a 25-year flood if the consequences of failure are not too severe. Repairing damage every 25 years may be cheaper than preventing the damage. In cities or environmentally sensitive areas, design might be based on a 100-year flood. Similarly, a canal control system might be designed to prevent overtopping the canal lining or exceeding drawdown criteria for an event that occurs several times per year but not for events that occur once every 5 years. Capability should be provided to ensure that a 25-year event does not overtop the canal bank.

**g. Miscellaneous criteria.**—Additional operating criteria are listed below:

- Gate movement, e.g., maximum number of gate adjustments per hour, minimum increment of movement, gate movement speed, total number of gate movements per week, etc. These criteria influence the selection of gate motors and gearing. Automatically controlled gates typically move much more frequently than manually controlled gates, requiring more expensive gate motors. In addition, canal flow can only be controlled within the limits established by gate setting accuracy and minimum increment of gate movement.
- Free versus submerged flow at check structures. Free flow or flow in the transition between free and submerged flow may interfere with stability of automatic gate controllers. Structure and control system designs depend on these criteria.
- Maximum flow velocity in the canal and through structures. High velocities may cause erosion damage.

# OPERATIONS

## 5-11. Designing for Operations

Chapter 2 describes canal operation as the transfer of water from source to diversion points. Rooted in open channel hydraulics, canal operation is mostly a matter of flow change management. In the design of a new canal, operation is not a given, but rather, an unknown quantity to be designed and optimized. Therefore, engineers should design canal system operations before designing structural components.

Automation has made more operational choices available to canal designers today than in the past. Having more alternatives from which to choose makes the design process more difficult but should result in a better canal system. Consequently, following an organized evaluation and selection process becomes increasingly important.

Primarily, designing canal operations involves studying and selecting an operational concept and a method of operation (see chapter 2). Normal, abnormal, and emergency operating conditions must be considered, including procedures for filling and draining canals, early and late season operations, and, in some cases, winter operations.

## 5-12. Operational Concept

The first step in designing canal operations is selecting an operational concept. Operational concepts deal with the location of control priorities. Usually, a canal will have either supply oriented operation (upstream concept) or demand oriented operation (downstream concept).

Supply oriented operation is used when upstream conditions dictate system operation. An example of supply oriented operation is a system which collects water from multiple sources into a single conveyance channel with the purpose of conveying whatever is collected to the downstream end.

Demand oriented operation bases operations on downstream conditions. Most irrigation systems should use this downstream concept. The canal system should be operated to satisfy downstream needs, responding to what is taken out of the system rather than to what is put into the system.

Ideally, a canal should be designed with a single, clearly defined operational concept. The canal system's method of operation, structural components, and control system should be based on the concept selected. Mixing upstream and downstream concepts within a canal system is both difficult and inefficient in most cases.

At low flows, many existing canals can operate based on demand because of ample storage in the canal prism. But at high flows, they cannot keep up with demand changes, so canal operators must convert to an upstream operational concept. Generally, this conversion results in inefficiencies and fewer benefits to water users. New canals should be designed to overcome these operational shortcomings by ensuring that the full range of operations can be accommodated using a single operational concept.

Some mixing of operational concepts may be unavoidable in a multiple-purpose project.

Abnormal or emergency operations may necessitate temporary changes in the primary concept. For example, an irrigation canal that normally operates with a downstream concept may need to convert to the upstream concept to pass flood inflows during a rainstorm. In this case, temporary inefficient operations are acceptable. Some canals change operational concept seasonally to accommodate different summer and winter needs. For example, a canal which makes irrigation deliveries during the summer may switch to an upstream concept to deliver water to a reservoir in winter.

## 5-13. Method of Operation

Canal designers must choose a method of operation before designing structural components. Structure height, freeboard, and pool length all depend on the method chosen because different methods of operation result in different water surface profiles. Method of operation should be compatible with operational concept and should have appropriate response and recovery characteristics. Four methods of pool operation are described in chapter 2 and depicted on figure 2-14:

1. Constant downstream depth
2. Constant upstream depth
3. Constant volume
4. Controlled volume

The **constant downstream depth** method is compatible with the upstream (supply oriented) operational concept. When flow changes originate at a canal's upstream end, the canal responds quickly and recovers smoothly to a new steady state (figure 2–16). Recovery may be slow for a large flow change—as pool storage volumes adjust to new steady-state flow profiles—but canal pools should recover easily. The constant downstream depth method is less compatible with demand oriented operation. Downstream flow changes cause unfavorable depth changes in canal pools. Response and recovery characteristics are poor because of the overcompensation required. Flow changes which originate downstream must be relatively small and gradual to avoid excessive depth fluctuations. Therefore, the constant downstream depth method of operation should be paired with the upstream operational concept.

The **constant upstream depth** method should be used with the downstream (demand oriented) operational concept. This combination yields good response and recovery characteristics because downstream flow changes cause favorable depth changes in canal pools (figure 2–19). Recovery is smooth, but slow, for large flow changes because pool volume change is needed to achieve new steady-state profiles. The constant upstream depth method should never be used with supply oriented operation because an overly expensive canal with poor response and recovery characteristics would result.

The main disadvantage to the constant upstream depth method of operation is construction of a level bank canal. With concrete-lined canals, level bank construction cost may be prohibitive in some cases. Unlined or earth-lined canals may minimize the additional cost of a level bank.

Depending on the lining height, pool length, channel slope, and maximum flow rate, constant upstream depth operation sometimes can be used within a conventional prismatic channel. Usually, additional freeboard is available at low flows, so a level bank operation could be used even though the canal bank is parallel to the invert. A canal can be designed for constant upstream depth operation at low flows, allowing on-demand delivery, and for conventional operation with scheduled delivery at high flows.

The **constant volume** method can be applied with either upstream or downstream operational concepts (figure 2–20). Rapid response and recovery can be achieved using a simultaneous check gate operating technique. Flow in the entire canal system can be changed quickly with excellent recovery characteristics. Unlike the previous methods, in-channel storage volume need not change significantly to achieve a new steady-state flow. Additionally, the constant volume method can adapt easily to changes in operational concept.

For constant volume operation, canal design must provide a raised canal bank at the downstream end of each pool to accommodate the level water surface at zero flow. Although less expensive than a level bank canal, a canal designed for constant volume operation will be more expensive than a conventional canal. (Additional bank and lining is about 25 percent of that required for level bank operation.) Cost depends on lining type, pool length, and channel slope.

Simultaneous adjustment at all control structures requires a supervisory control system. Data monitoring should include water levels at both ends of each canal pool. Although complex supervisory control software is used on some projects, constant volume operation can be implemented effectively with supervisory manual control. Designers should account for control system cost when choosing a method of operation. If supervisory control is planned regardless of the method of operation selected, additional cost to implement constant volume operation may be minor.

The **controlled volume** method can be combined effectively with either operational concept. The volume of water in each canal pool can be managed to satisfy priorities from either upstream or downstream, although only one operational concept should be used at a time (figure 2–21).

Potentially, controlled volume operation has all the advantages of the other methods of operation. Designers should consider using the controlled volume method to store or spill excess water for canals having limited capacity that are prone to sudden flow changes or large flow mismatches. This method is most applicable for canals with complex operational needs such as:

- Large daily fluctuations in delivery flows
- Demand delivery concept
- Large canal-side pumping plants
- In-line (relift) pumping plants
- Pumping schedule restraints (e.g., off-peak pumping)
- Storm runoff inflows
- No wasteways
- No off-channel storage

Controlled volume operation is the most difficult method to implement. Its complexity makes local manual control infeasible; a supervisory control system and complex software (customized) is required. Consequently, control system cost will be expensive.

The controlled volume method of operation can be accomplished in a number of ways. Pool volume can be used as the controlled quantity by comparing the calculated volume of water in each pool to a target volume. Then, a control algorithm adjusts inflows and/or outflows to correct pool volume errors. Target volumes are established at the master station to satisfy system-wide water needs, and actual pool volumes are calculated from measured data such as water level, gate position, or flow velocity. Although pool volume change can be calculated from pool inflow and outflow totals, water level must always be monitored to keep depths and drawdown rates within limits.

Another means of accomplishing controlled volume operation involves directly controlling water level and varying the target water level to create the desired pool volume changes. Different target water levels are prescribed at different flow rates. Local controllers can be used if supervisory setpoint variation or some other form of supervisory override is provided.

The possibilities for implementing controlled volume operation are practically limitless. Potentially, canal operation can be extremely flexible and responsive. Presently, however, details must be worked out for each canal system individually; no "cookbook" solution exists. Producing comprehensive control software to accommodate all situations is a substantial design task. The California Aqueduct [7], Canal de Provence [8], and Central Arizona Project [9,10] have implemented controlled volume operation successfully using supervisory control. Another controlled volume scheme that uses variable setpoint local controllers was developed for the Canal de Cartagena, Spain [11].

## DESIGN OF STRUCTURAL COMPONENTS

### 5-14. Structural Considerations

An automated canal's structural design differs little from that of a conventional canal. The bulk of the civil engineering work to design canals and related structures remains virtually unchanged. However, designing structural components for an automated canal system requires decisions based on knowledge of operations. A designer should anticipate different operating conditions—normal, abnormal, and emergency—for the method of pool operation chosen. Many assumptions and rules of thumb used to design conventionally operated canals are not valid or prudent in an automated canal design. Results of design studies—uniquely determined for each canal—should be used to make design decisions.

Without attempting to provide structural design details, the following sections address design considerations which are especially important for automated canals. Structural components discussed include:

- Conveyance channel
- Check structures
- Turnouts
- Wasteways
- Siphons and drops
- Regulating reservoirs
- Pumping plants
- Cross drainage
- Water measurement structures

## 5-15. Conveyance Channel

Usually, conveyance channel design begins with selection of a channel cross-section shape and lining type. Most canals are trapezoidal, although semicircular and rectangular channels are used in some instances. Typical lining materials include compacted earth, concrete, masonry, and plastic membranes. Trapezoidal canal side slope varies with lining type and canal size. Typical side slopes are 1½:1 (horizontal:vertical) for concrete lining, 2:1 for earth lining, and 2½:1 or 3:1 for membrane lining. Side slopes may be steeper in small canals and less steep in very large canals.

Canal lining material and method of operation are interrelated. Constant upstream depth or controlled volume operation may be more feasible for earth-lined canals than for concrete- or membrane-lined canals. Therefore, lining material and method of operation should be selected concurrently, based on the economics of both.

Lining thickness, strength, and underdrains should be designed using predicted canal depth fluctuations and ground-water conditions. Recommended minimum lining thicknesses for compacted earth lining and for concrete lining are shown on figure 5-3. Anticipated rapid depth drawdown or high ground water will require stronger lining or underdrainage. Concrete lining can be thickened or reinforced to provide additional strength against hydraulic back pressures. Underdrains may be required to reduce ground water and may also allow more rapid drawdown in the canal for all lining types.

Initially, canal hydraulic properties should be calculated based on steady, uniform flow assumptions. Maximum flow capacity should be known from projected delivery flows and water use patterns predicted during project definition. Channel slope, size, shape, and friction interrelate to produce the desired flow capacity, as calculated using the Manning equation or another uniform flow equation [2].

A canal's longitudinal slope is influenced by the canal alignment, existing ground surface, available head, elevation of delivery points, allowable flow velocities, and lining type. Minimal available head may require a large canal with a mild slope. Conversely, a smaller canal with a steeper slope may be preferable when elevation head is available. Allowable flow velocities will limit channel slope. Design velocity should remain within 0.3 to 1 meter per second (m/s) (1 to 3.5 feet per second [ft/s]) for earth- and membrane-lined canals and within 0.6 to 1.5 m/s (2 to 5 ft/s) for concrete-lined canals. Higher velocities may be acceptable in concrete canals with special design considerations.

Designing the size and shape of a canal section combines hydraulic and construction considerations. The channel should provide the required flow capacity and minimize frictional losses yet be practical and economical to construct and maintain. For trapezoidal canals, bottom width can be estimated using the curves shown on figure 5-4.

To maximize hydraulic efficiency, the channel width to depth ratio should result in a maximum hydraulic radius (area divided by wetted perimeter). The bottom width to depth ( *b/d*) ratio for trapezoidal canals typically is between 1 and 3 for concrete lining and between 2 and 8 for earth and membrane lining. Figure 5-5 shows minimum recommended *b/d* ratio versus flow for trapezoidal canals.

The graphs on figures 5-4 and 5-5 provide initial design estimates, not strict rules to follow. Designers should consider site-specific conditions and canal operations before finalizing canal dimensions. For example, a deeper, narrower channel may be cheaper where canal right-of-way is expensive to purchase or where the canal is to be cut below existing ground surface. Conversely, wide, shallow canals can have operational advantages. For a given depth change, a wide canal section will have more storage than a narrow section. A wider canal will experience less depth fluctuation during a flow change.

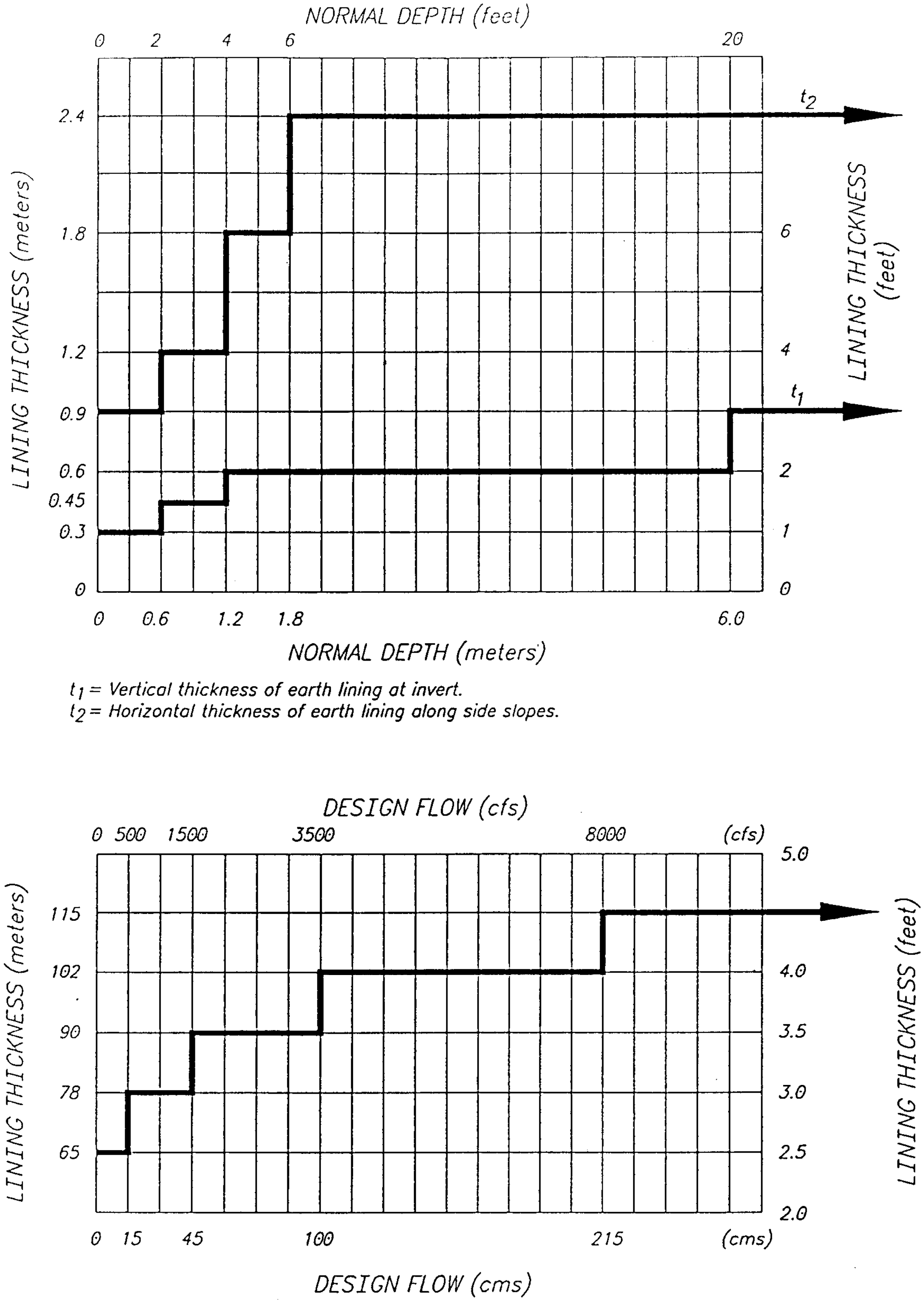


Figure 5-3.—Recommended minimum canal lining thicknesses.

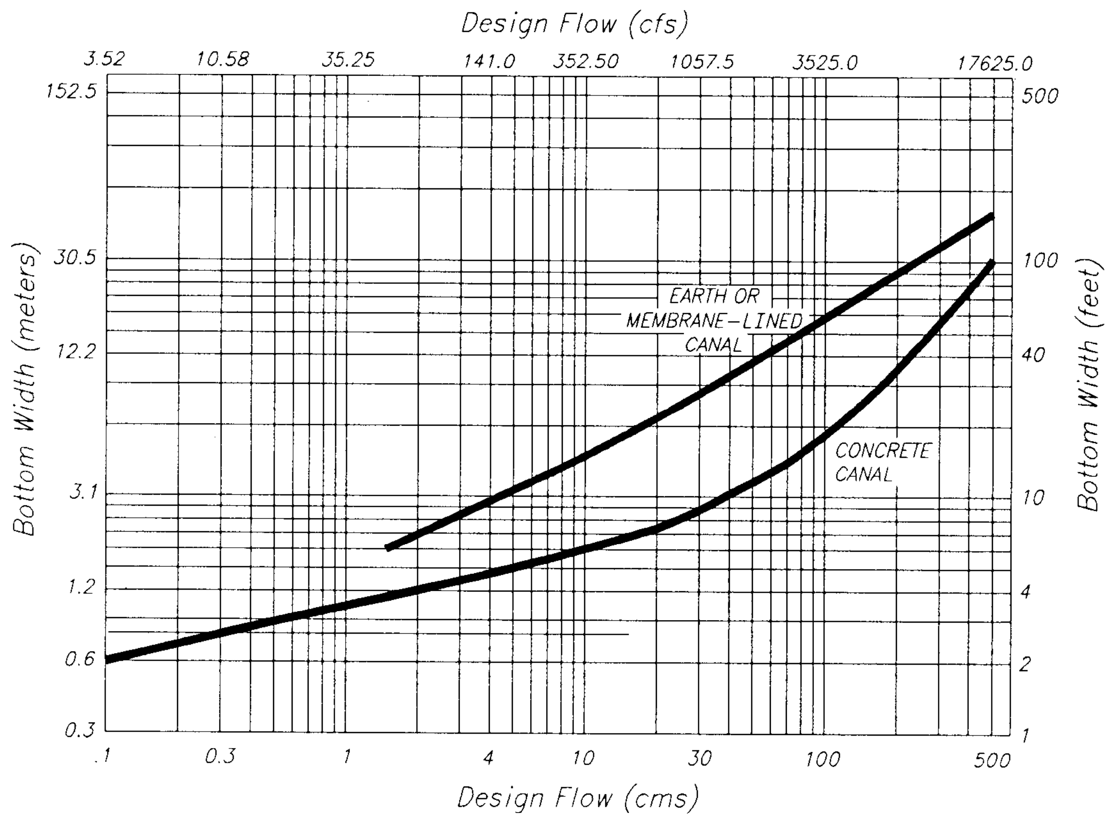


Figure 5-4.—Canal bottom width versus design flow rate.

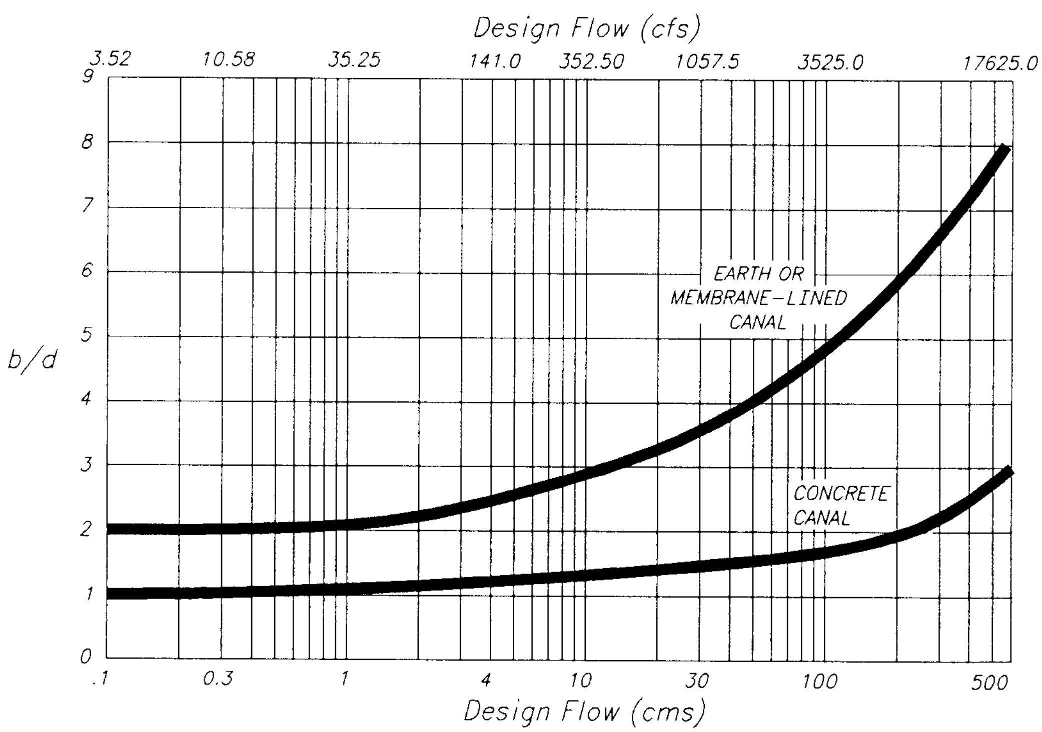


Figure 5-5.—Minimum bottom width to depth ratio.

Initial estimates for canal lining and bank height using steady flow profiles must take into account the selected method of pool operation. Constant upstream depth and constant volume methods require additional lining and canal bank to contain the horizontal water surface at zero flow. During controlled volume operation, lining and bank height depends on maximum pool volumes planned.

After determining maximum steady-state water levels for the given method of operation, the designer should add freeboard to increase canal lining and embankment height. Freeboard allows for wind waves, flow change surges, excess friction, storm runoff entering the canal, sedimentation, and operation errors. Generally, canal lining freeboard ranges from 150 mm (6 in) for small canals to 1 m (3 ft) or more for large canals. Canal bank freeboard ranges from 0.35 m (1.2 ft) to more than 2 m (6 ft). Suggested freeboard for conventionally operated canals is shown on figure 5-6.

Although the curves on figure 5-6 are valuable as an initial freeboard estimate, canal lining and bank heights in the final design should be based on method of operation and anticipated rate of flow change. For example, with constant upstream depth (level bank) operation, freeboard can be minimized. Freeboard may need only accommodate wind waves because maximum steady-state depths occur at zero flow. Conversely, canals with storm drain inlets or in-line pumping may require a large amount of freeboard. Waves from sudden flow changes should remain within the lining, so freeboard design requires unsteady-flow analysis.

*Design of Small Canal Structures* [1] contains additional information on channel design, lining materials, drainage, and other design details.

## 5-16. Check Structures

Canal system operation depends on check structures for depth and flow management. Designers should select check structure type and location to satisfy system-wide operational needs. Traditionally, check structures have been used to regulate the canal water surface upstream from the structure to maintain the water surface elevation required for upstream deliveries. For a new canal,

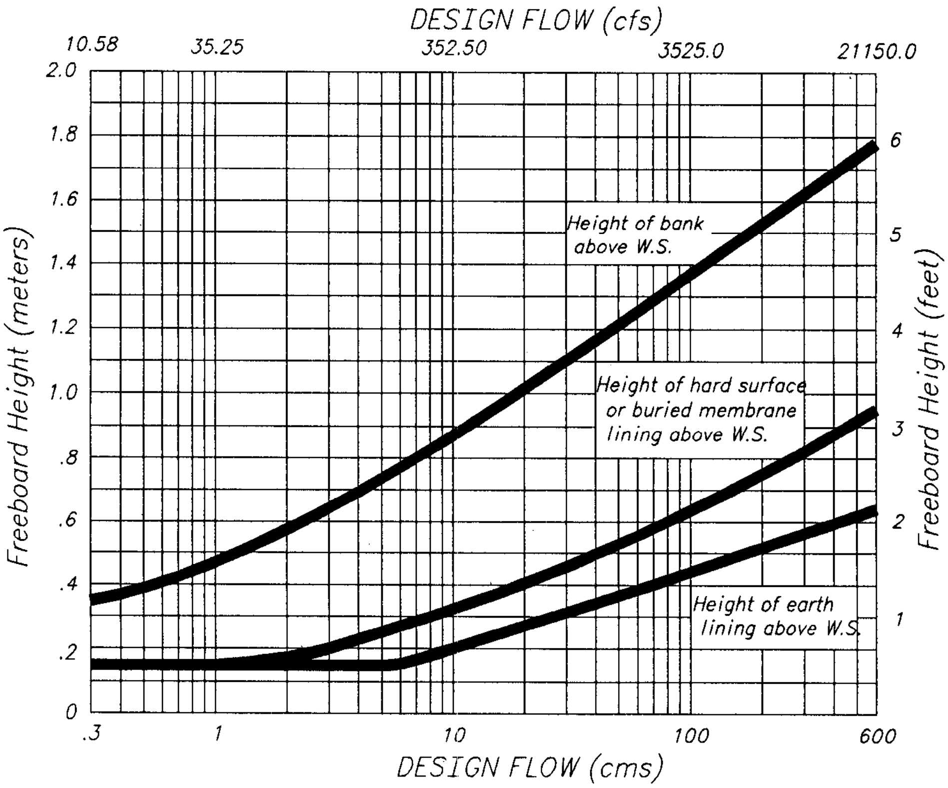


Figure 5-6.—Freeboard and bank height for canal sections.

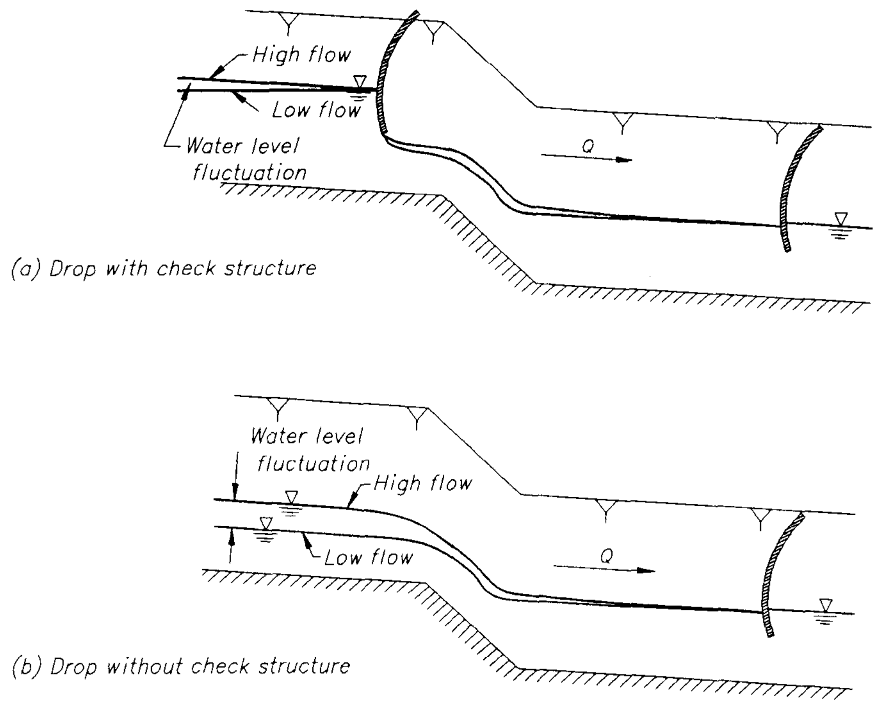


Figure 5-7.—Water level fluctuation upstream from a drop with and without a check structure.

checks should be designed to enable operation of the chosen scheme. Check structures may be used to regulate depths, to measure and control flow, and to increase and regulate in-channel storage volumes. Chapter 2 discusses the need for check structures and their importance to canal operations.

**a. Check structure spacing.**—Deciding the number and location of check structures is difficult, but the decision impacts canal operations significantly. Minimally, check structures should be located at critical places such as bifurcations, siphons, drops, changes in channel capacity, major turnouts, and wasteways. In any canal that will experience significant flow changes, checks are essential upstream from siphons and drops to prevent excessive drawdown during reduced flow. Figure 5-7 shows the difference in water level fluctuation upstream from a drop with and without a check structure.

After critical check structure sites have been designated, more checks should be added to create appropriate pool lengths. The distance between check structures has a large impact on the ability to control canal flow. If this distance is large, changing flow without causing large depth fluctuations will be difficult. Depth fluctuation between the full flow profile and the zero flow profile will be proportional to the invert elevation drop from one check to the next, as shown on figure 5-8.

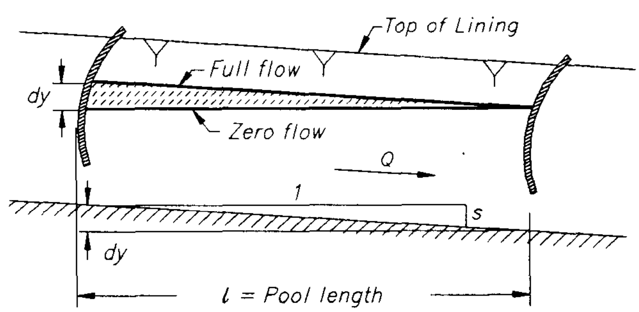


Figure 5-8.—Influence of check structure spacing on water level fluctuation.

Water level fluctuations will vary with the method of operation being used. The example on figure 5-8 shows constant downstream depth operation, so maximum fluctuation occurs at the upstream pool end. With level bank operation, maximum water level fluctuation would occur at the downstream end. Absolute criteria do not exist for check structure spacing, but an initial estimate might be achieved by spacing check structures so the vertical drop between them equals the maximum allowable water level fluctuation:

$$l = \frac{dy}{s} \qquad 5.1$$

where:

$l$ = pool length (distance between checks)
$dy$ = maximum allowable water level fluctuation
$s$ = pool invert slope

The above spacing permits flow change from maximum to zero, or vice versa, without exceeding the allowable water level fluctuation. This criterion may be overly conservative for many canals where such a severe flow change never occurs. Therefore, the designer should evaluate the largest realistic flow change for the time period to which water level fluctuation limits apply and increase check structure spacing accordingly.

For example, steady-state profiles for 100 percent and 75 percent of design flow can be calculated if the canal shown on figure 5-9 will never experience a flow change greater than 25 percent of design flow in any 12-hour period. Check spacing is acceptable for steady-state conditions when the maximum water level difference between these two profiles is less than the allowable fluctuation for a 12-hour period. This logic can be applied using any time period for which flow change and water level fluctuation data are known.

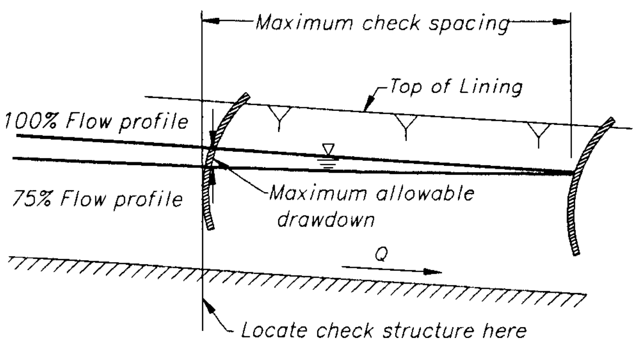


Figure 5-9.—Influence of check structure spacing on water level fluctuation.

As discussed in chapter 2, check structure spacing influences canal system response because of storage considerations. In most canals, check spacing has a significant effect on the volume of water required to change to a new water surface profile. Increasing the number of check structures will reduce the volume change needed to establish a new steady-state flow. Therefore, flow changes can be accomplished more quickly when check structure spacing is reduced.

Unsteady-flow considerations and automatic control response may also affect check spacing. Most automatic control schemes will work better when check spacing is reduced, and many schemes will not work with too few check structures in the canal.

Naturally, designers must consider economics when deciding on check structure spacing. Increasing the number of checks in a canal increases initial costs and forces canal operators to manage more control structures. However, additional check structures usually improve canal operations and reduce long-term maintenance costs. Canals with too few check structures usually experience operating problems.

**b. Automated checks.**—Gates must be motorized in most automated canal check structures. (An exception is float- and counterweight-driven gates such as the NEYRTEC automatic gates [12].) Either radial gates or vertical slide gates may be used, but radial gates are preferable for automated structures. Slide gates are less expensive initially but have more operation and maintenance problems. Radial gates are more durable, pass trash better, can be adjusted more accurately, and perform better in applications that require frequent gate movements. Reclamation designs generally use radial gates when the design flow exceeds 6 $m^3/s$ (200 $ft^3/s$), or for gates wider than 1.8 m (6 ft). Designers should also consider radial gates for the smaller automated checks to attain long-term dependability and cost savings.

Gate hoists and motors for automated gates should be designed for frequent and accurate gate adjustment. To permit accurate gate positioning and measurement, the gate hoist mechanism should have a minimum amount of play. Gate motor, gearing, and hoist should be designed for a gate setting accuracy of about 6 to 15 mm (0.02 to 0.05 ft). Typical gate movement speeds for automated check gates are 0.3 to 0.6 meters per minute (1 to 2 feet per minute). Gate motors should have a high duty cycle to accommodate a large number of gate movements per day. Mechanical equipment is discussed in more detail in chapter 10.

In designing automated canal systems, engineers should consider alternatives for gate operation during abnormal and emergency conditions.

- What should the gates do if communication or power to the check structure is lost?
- Is backup power required?
- During a power failure, should gates close automatically or remain stationary?

The answers depend on site-specific conditions; anticipated frequency, duration, and severity of abnormal conditions; and manual backup capability.

For most canals, local manual control of structures during abnormal operating conditions is the most feasible backup method. During communication, power, or equipment failures, operation and maintenance personnel have to travel to check sites and manually adjust gates. Although canal operations may suffer during local manual control, the canal system usually can be protected from damage until normal operation resumes. Design provisions should allow manual gate adjustment at check structures, either with handwheels or portable generators to power gate motors. Check gates should be designed to maintain position upon power or communication loss to minimize canal flow disturbance.

Local manual control cannot always provide satisfactory backup to automatic gate control. More extensive backup systems should be designed when travel time to check sites is too long or when severe consequences can develop rapidly during a failure of the primary control system. For example, in a canal with a headworks pumping plant, the upstream pools can dewater rapidly following power failure if check gates remain open after the supply pumps shut off. Automatic gate closure should be specified if an operator cannot reach these check sites quickly. Backup power to close gates can come from batteries or from pressure stored in a hydraulic accumulator. Automatic closure should be delayed 5 or 10 minutes after primary power is lost to prevent unnecessary canal flow disturbance during short-term outages. A motor generator set with automatic start may be desirable at check structures that require continuous gate operation through loss of primary power.

Check structures often include a combination of gates and weirs. Bypass weirs (overflow walls) are constructed on either side of the gates to pass excess flow in emergencies and to prevent excessive canal depths. Bypass weir capacity equals the canal maximum flow rate in case gates accidentally close when the canal is flowing full. Designers may choose to allow water to overtop the canal lining in this case but should ensure that the canal bank is not overtopped.

In conventionally operated canals, bypass weir crest elevation usually is about 60 mm (0.2 ft) above the normal water surface elevation on the upstream side of the check. However, if an alternate method of operation is to be used, bypass weirs must be raised or eliminated so the canal water surface upstream from the check can be raised above normal depth. Bypass weirs must be higher than the zero-flow depth at the downstream end of the pool when using the constant upstream depth (level bank) and constant volume methods of operation.

As discussed in chapter 2, a check gate can operate under either free or submerged conditions on the downstream face of the gate. Flow will be free when downstream water level is low and submerged when downstream water level is high. In the transition zone between free and submerged flow levels, flow through the gate may be either free or submerged. Operating a gate in the transition zone can have unpredictable results. Avoiding transitional gate flow is particularly important under automatic control. Control instability may develop if flow in the transition zone oscillates between free and submerged flow. Check structures should be designed so that gate flow is either always submerged or always free during normal operation.

## 5-17. Turnouts

The type and location of canal-side turnouts must be compatible with canal system operations. Turnout locations should be identified early in the design process to establish check structure locations and method of pool operation.

Gravity turnouts require a relatively constant canal water level so turnout flow is steady. Canal flow change will cause water level fluctuations that disturb turnout service, especially if turnouts are located throughout canal pools. Therefore, most canals with gravity turnouts must maintain a steady flow to provide good service to water users. This constraint severely limits delivery flexibility, so a designer may wish to change the type, number, or location of turnouts. For example, delivery flows can be lumped together at a single turnout instead of at many individual turnouts from the main canal. The single turnout—to serve a secondary distribution system (lateral)—should be located where pool water level remains fairly constant.

Pipeline distribution systems provide superior delivery flexibility for water users. Either gravity flow or canal-side pumps can supply pipe laterals, and delivery flow can be controlled at each water user's valve. Canal water level fluctuations may have little or no effect on delivery flows. Therefore, pipe delivery can tolerate head variation in the main canal without affecting service. Pipe turnouts can be located anywhere along the canal as long as a minimum canal water level is maintained to supply the turnout.

The best turnout locations depend on the method of pool operation. With the constant downstream depth method of operation, gravity turnouts should be located near the downstream end of canal pools—where water depth is maximum and relatively constant—to avoid water delivery problems caused by low or fluctuating canal water depths. With the constant upstream depth method, turnouts can be located anywhere within a pool because the canal water depth should always at least equal the design flow normal depth. However, turnouts should be located near the upstream ends of canal pools if a constant head is required.

Constant flow turnout structures—developed in France—are gravity turnouts that maintain relatively constant delivery flow through a limited range of upstream head variation [12].

## 5-18. Wasteways

In conventional canal design, wasteways provide important protection from disasters and sometimes are useful to release normal excess flows. Wasteways can be quite practical in canals where waste flows can easily return to a river through natural drainage channels. These canal systems can be simple to operate by supplying a large steady flow through the canal headworks and spilling any excess back to the river. Wasteways are particularly important if uncontrolled inflow such as rainfall runoff enters the canal by way of drain inlets.

**a. Determining need.**—Wasteways may not always be needed or desirable in new canals. Wasteways can be eliminated from the design through good control over water in a canal and effective use of in-channel storage. As with most engineering design, the designer should weigh safety and economics. The water's value will have a direct impact on the decision to either spill or store excess water. In systems which pump water from a source to higher elevations, the cost of the power used to pump water will be sacrificed whenever water is wasted. A good location to spill water cannot always be found.

The need for wasteways depends on canal size and cross-drainage design. Wasteways may not be needed if cross-drainage structures are provided to prevent storm runoff from entering the canal or if the canal prism is enlarged to contain all inflows. Alternative methods to prevent damage from storm runoff should be studied for economic feasibility. When designing an automated canal, one should explore operation and control alternatives before deciding on wasteways. The type, size, and location of wasteways depend on canal operations.

**b. Selecting wasteway type.**—Wasteways often include a gravity overflow structure. Typically, the overflow crest is slightly above the maximum normal operating water level, so water will be spilled automatically whenever the canal water level exceeds the overflow crest level. When properly designed, overflow wasteways provide excellent protection against excessive water depths in the canal. However, they may prevent using the upper portion of the canal prism for storage. Uncontrolled overflow wasteways should be avoided when the canal is being designed for a method of operation that intentionally creates greater than normal water levels.

Gated wasteways impose less operational constraint because outflow from the canal is controllable. Spilling through gates is less depth dependent than spilling through uncontrolled overflow wasteways. Wasteway gates can remain closed to allow intentionally high water levels and open to pass high flows when spilling is necessary.

Wasteway gates also can be used to sluice sediment and other submerged debris from the canal if the gate sill is low enough. However, gated wasteways do not provide the level of protection provided by overflow wasteways because a gate must open to protect the canal. Designers must evaluate risk of failure and assure the wasteway can always do its job when needed. Redundant control equipment, backup power, and alarms can provide additional safety. Local manual control may be necessary during emergencies.

**c. Size.**—To determine wasteway size, designers must predict the maximum spill flow required. In some cases, a wasteway should be sized to convey 100 percent of the canal flow. In other cases, a smaller wasteway is adequate. Emergency canal operations must be analyzed to find the combination of events that causes maximum spill flow requirement. Power failure, equipment malfunction, and rainstorms are typical causes of worst case scenarios. Rainfall runoff into the canal through drain inlets often will influence wasteway size, so hydrologic studies will be needed to predict canal inflows.

**d. Location.**—Wasteway location depends on:

- Natural terrain
- Canal structures
- Method of pool operation
- Availability of right-of-way

Wasteways must be located where spills cause minimal environmental impact. Wasteways typically empty into natural drainage channels or streams. With many canals, spill flows return to the river that supplied the canal headworks.

A canal's structural features may influence wasteway location. Wasteways often are located just upstream from transitions to a smaller canal size to prevent exceeding the capacity of the smaller channel downstream. Wasteways also might be placed just upstream from pumping plants or powerplants where a power failure or load rejection can suddenly decrease flow.

Method of pool operation will determine the best wasteway location within a canal pool. Generally, wasteways should be located at the water surface pivot point for best operation. Wasteways should be located at the downstream ends of pools when using the constant downstream depth method of operation. Wasteway location within a pool is less critical when using other methods of pool operation. The combination of location and crest elevation must be designed to protect the canal without spilling water during normal operations.

A designer should combine the above priorities to find optimum wasteway locations throughout a canal system. The canal may need to be enlarged to carry excess flow to a suitable wasteway location when canal features do not coincide with natural terrain.

## 5-19. Siphons and Drops

Sudden changes in elevation across a canal's path may require inverted siphons and drop structures. The natural terrain almost always dictates the location of these structures, so adjacent canal features must be designed to accommodate hydraulic conditions that can result. The depth upstream from a siphon or drop structure frequently is independent of the depth downstream. Flow through the structure depends on upstream conditions in these cases; backwater effect from a control structure downstream is lost.

In most cases, siphons and drop structures should have a check inlet; otherwise, excessive upstream depth fluctuations may occur in the canal. Flow change will move the water level to the corresponding normal depth in the canal. If flow is stopped, the canal upstream from the siphon or drop can drain completely. Operational flexibility will need to be severely restricted to prevent depth fluctuations. Figure 2-31 in volume 1 illustrates possible depth fluctuation upstream from an uncontrolled siphon.

One design alternative involves reinforcing the canal lining upstream from siphons or drops so the canal can withstand large depth fluctuations. This option may be feasible for a short pool.

Siphons with check inlets may present control complications because the check's downstream water level can be unpredictable. Water level between the check gate(s) and siphon entrance will fluctuate more than usual and may not maintain submerged gate flow. Siphons are designed to convey full flow with a prescribed head loss. Usually, the siphon entrance will be submerged at full flow, resulting in submerged gate flow. However, smaller head loss through the siphon at low flows may create free gate flow and supercritical flow entering the siphon, preventing accurate prediction of siphon head loss, water level on the downstream side of gates, and check structure flow. Control at the check structure will be erratic when gate flow fluctuates between free and submerged conditions. Potential problems include excessive gate movements and instability.

Designers should analyze hydraulics at various flow rates when designing a check inlet structure. Changes to structure design should be considered if control problems are envisioned. For example, the check invert and siphon inlet can be lowered to increase submergence.

## 5-20. Regulating Reservoirs

The benefits of automation will be limited in a canal that lacks operational storage. Regulating reservoirs provide additional water storage in canal systems to improve operations. Reservoir storage can supply water to points downstream or provide a place to put excess water from upstream. The term **reregulating reservoir** sometimes is used to describe a reservoir located in the middle of a canal system because it regulates canal flow for a second time (after primary regulation at the headworks).

Dictionaries define **regulate** as:

> to bring order, method, or uniformity to; to fix or adjust the time, amount, degree, or rate of.

Consistent with these definitions, a regulating reservoir brings order and uniformity to canal operations. Reservoirs simplify and stabilize operations by adjusting the time, amount, and rate of flow changes in the canal. The main purpose of a regulating reservoir is to provide hydraulic separation between two parts of a system. Reservoir storage is used to accommodate flow mismatches between the canal segment upstream from the reservoir and the canal downstream from the reservoir.

Several reasons exist for flow mismatches. The following are specific applications of reservoirs in canal systems:

1. Supplemental storage where downstream demand may exceed upstream supply capacity
2. Separation of two canal system parts with different operating periods
3. Separation by operation priority (supply oriented or demand oriented)
4. Buffer between steady flow on one side and unsteady flow on the other
5. Separation between a gravity system and a pumped system
6. Automatic control regulation

The operating period for a canal's source of supply sometimes will differ from the operating period for deliveries. For example, many pumping plants in Brazil must shut down for 4 hours in the evening during peak power demand. Canal systems supplied by pumps have a 20-hour supply period and a 24-hour delivery period, so an intermediate reservoir is required to supply deliveries while the pumps are off.

As another example, farmers may want to irrigate only during daylight—perhaps 16 hours a day—but supply flow is constant 24 hours a day. With an intermediate reservoir, as shown on figure 5-10, maximum supply flow will be only two-thirds of the maximum delivery flow rate, allowing smaller, less expensive conveyance structures upstream from the reservoir.

Irrigation canals are usually demand oriented; i.e., operated to satisfy downstream delivery needs. However, controlling a long canal based on downstream conditions is difficult, requires a flexible flow source, and may create undesirable depth and flow fluctuations throughout the canal length. Supply oriented canals are much easier to operate because excess flows can be passed downstream. Combining a supply oriented segment with a demand oriented segment requires a regulating reservoir to separate the two segments. Canal inflow can be passed through the upstream segment to the reservoir using supply oriented operation, and outflow from the reservoir can be based on downstream demand, as shown on figure 5-11. Reservoir storage will absorb flow mismatches between the two segments.

The preceding examples involve situations where flow is relatively steady on one side of a regulating reservoir and unsteady on the other side. The reservoir insulates one segment from flow changes in the other segment. Canals having fluctuating flow require complex control methods, but simple

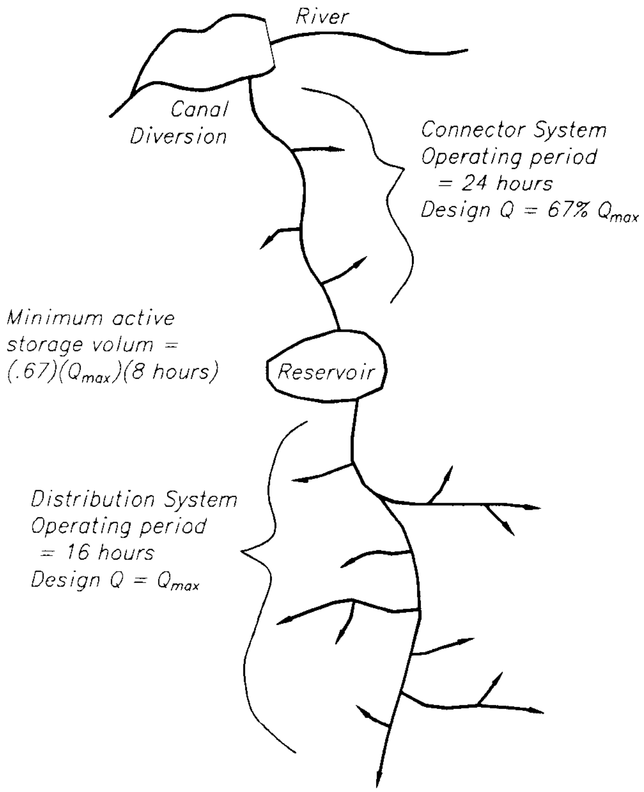


Figure 5-10.—Regulating reservoir allowing different operating periods.

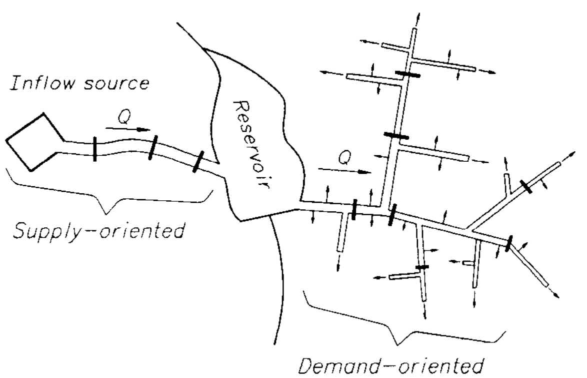


Figure 5-11.—Upstream supply oriented segment, reservoir, and downstream demand oriented segment.

methods will suffice in a canal with relatively steady flow. Therefore, the reservoir simplifies and reduces the cost of controlling the segment with steady flow.

Pumping commonly causes flow changes and system flow mismatches. Pumping plants with fixed speed pumps can only produce flow changes in increments equal to pump unit capacity, so a balanced flow condition (inflow = outflow) rarely exists. Regulating reservoirs often are used adjacent to pumping plants to offset flow mismatches. In addition, a reservoir provides a convenient and effective location to measure water level for automatic pumping plant control. Pumps are turned on and off to automatically maintain the reservoir level within a prescribed range.

Regulating reservoir design should be based on site conditions and anticipated canal system operations. Reservoir type, size, and structural design will vary with different applications.

**a. Types of regulating reservoirs.**—Most regulating reservoirs are constructed, although existing ponds or lakes occasionally can be used. Usually, reservoirs are constructed using a combination of earth embankments and natural terrain. To minimize leakage, embankment reservoirs may be lined with concrete, plastic membrane, or compacted earth. Embankments must be designed to withstand depth fluctuations anticipated during reservoir operations.

Concrete or steel tanks can be used when a relatively small amount of storage is required. Tanks are applicable in situations requiring less surface area, more water level fluctuation, and locations unsuitable for embankment reservoirs. Regulating tanks are often used adjacent to pumping plants and powerplants.

Regulating reservoirs can be located in-line with the canal or off-line. Canal water flows through in-line reservoirs, entering at the upstream end and exiting at the downstream end, as shown on figure 5-12. Constructing a reservoir in-line with the canal requires a suitable location and enough hydraulic head to control flow between the reservoir and the canal. In-line reservoirs regulate canal flow continuously because all canal flow must go through the reservoir.

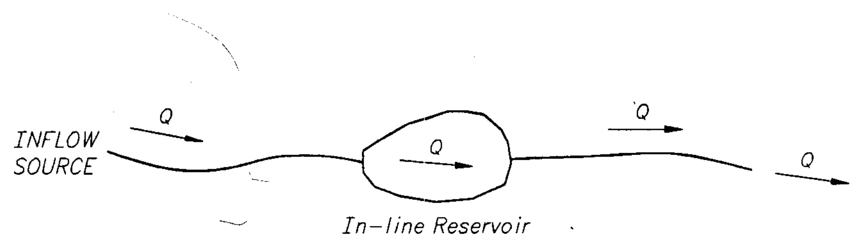


Figure 5-12.—In-line reservoir.

Off-line reservoirs are located alongside the canal so that water can be turned out from the canal into the reservoir, or from the reservoir back into the canal, as shown on figure 5-13. Water usually flows by gravity in one direction and is pumped in the other direction. An off-line reservoir can be used for pumped storage with sufficient flow and when enough elevation difference exists between the reservoir and the canal. Pump-turbine units pump water in one direction and generate power (usually to meet peak power demands) when water flows in the opposite direction.

To store excess canal flow during emergencies, an off-line reservoir should be lower than the canal so the canal can spill into the reservoir by gravity. Pumping power may be unavailable during emergencies, thus disabling a reservoir above the canal. Finding a suitable location for off-line reservoirs is easier than for in-line reservoirs.

Individual reservoirs can be located at turnouts to regulate delivery flows from the canal. Canal-side turnout reservoirs permit water users to use water according to a different schedule than the delivery schedule from the main canal. For example, farmers may irrigate for short periods of time at a high flow rate while the canal turnout supplies their individual reservoir with a constant small flow. The main canal capacity could not satisfy these high demands without the individual reservoir. Another example is a forebay reservoir for a canal-side pumping plant. The forebay reservoir can be supplied from a canal turnout with less disruption to canal operations from pump starts and stops.

**b. Sizing.**—The required size of a regulating reservoir is based on storage volume and depth fluctuation limits. The active or working storage volume in the reservoir should equal or exceed the maximum canal flow mismatch times the duration of the mismatch:

$$V \geq \Delta Q \times t \qquad 5.2$$

where:

$V$ = minimum active storage volume
$\Delta Q$ = maximum flow mismatch (inflow minus outflow)
$t$ = length of time for flow mismatch

Dead storage, below the active storage, also is required in many cases.

Storage volume is a product of surface area and vertical height. Depth fluctuation limits may determine the surface area required in embankment reservoirs. Surface area must be large enough to prevent excessive depth changes

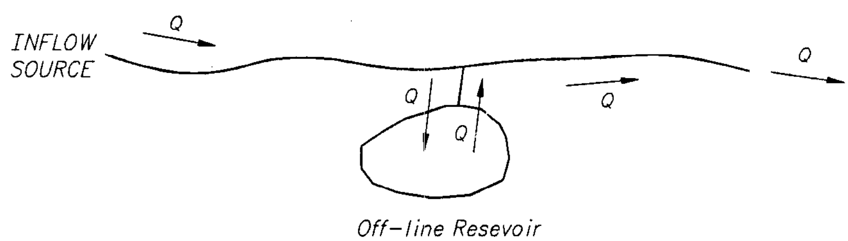


Figure 5-13.—Off-line reservoir.

or drawdown that exceeds the maximum allowable drawdown rate. Unless space is limited, larger surface area usually is more economical than high embankments. Additionally, hydraulic head may not be available for a large range of water levels.

When designing a storage reservoir or tank, surface area versus height decisions may affect the pumping head required, power consumption, and pump efficiency. Also, the range of water level fluctuations will influence the design of gravity turnouts, wasteways, and the pumping plant structure.

Reservoirs in which different water levels are used to control pumps, turbines, or gates require a minimum elevation difference between control levels. The minimum vertical distance between control levels should be about 0.15 to 0.3 m (0.5 to 1.0 ft).

Minimum distance between control levels is affected by depth measurement precision, control deadbands, wind wave action, and transient waves. Control points must be at least twice as far apart as the depth measurement accuracy. Wind waves will be important in large reservoirs; control levels must be spaced far enough apart to prevent wind waves from causing false pump starts and stops. Hydraulic transients will be more important in small reservoirs or tanks. If control levels are too close together, transient waves from a pump starting or stopping may trigger an immediate and undesirable operation of another pump. This problem can be avoided with built-in time delays or control deadbands. Hydraulic transient analysis may be necessary to determine reservoir size and control levels.

Storage volume between successive control points is also important. Volume between control levels should be a function of reservoir surface area and the elevation between levels:

$$\Delta V \geq \Delta Y \times A \qquad 5.3$$

where:

$\Delta V$ = storage volume between successive control levels
$\Delta Y$ = elevation difference between levels
$A$ = reservoir surface area

Operations may be unstable if the volume between control points is too small; the water level may "hunt" up and down while pumps cycle on and off. Large pumps require minimum run and rest times to prevent motor overheating. Therefore, sufficient reservoir volume must be provided between on and off control levels to satisfy minimum pump operating times. Regulating reservoirs must be sized to meet these criteria.

## 5-21. Pumping Plants

Many canal systems include pumping plants, as shown on figure 5-14. Pumping plants can be located in-line with the canal (figure 5–14a) or can function as a turnout from the canal (figure 5–14b). In either case, pumping plants usually will create the largest sudden flow changes in a canal system. Some pumps have variable speed motors, which allow gradual flow change, but most pumps start and stop flow in discrete increments. Therefore, even normal pump operations cause sudden flow changes. Flow mismatches are typical because canal supply and demand flows seldom match pump flows exactly. Power failures are a major concern in canal systems that include pumps. Sudden flow rejection from power failure is the most severe operating condition.

Canal design must accommodate all of the operating conditions caused by pumps. Hydraulic transient analysis should be used to predict maximum wave heights, and lining and embankment freeboard should be designed accordingly. Increased lining height, an enlarged canal section, or a forebay reservoir may be warranted upstream from a pumping plant.

Canal dewatering may be a concern downstream from an in-line pumping plant. Whether through structural features or control system capabilities, the design should include methods to prevent or withstand channel dewatering. In an automated canal, check structures downstream from a pumping plant should be able to close gates quickly following power failure. Backup power, pressure accumulators, and clutch mechanisms can be designed to close gates after loss of primary power, but local manual control may be adequate backup if operations personnel can reach the site quickly.

Limits on the frequency of pump starts and stops—because of minimum run time and rest time criteria—may impact the design of a canal system's a.

b.

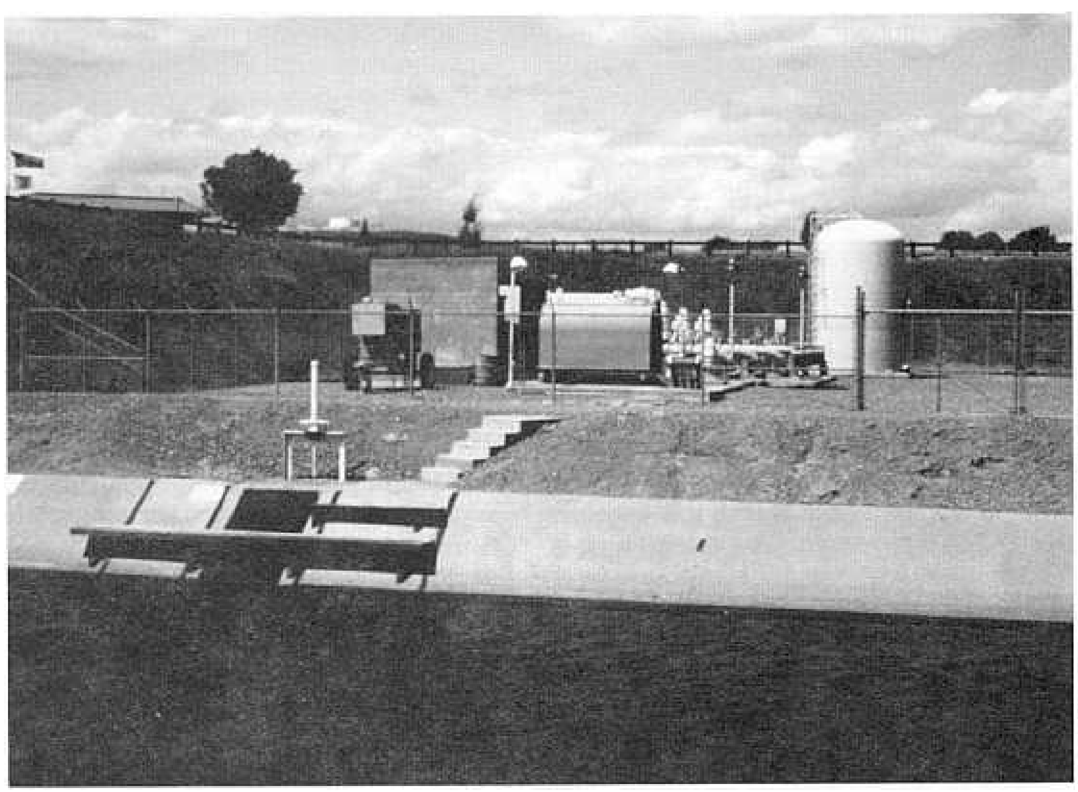

Figure 5-14.—Canal pumping plants.

storage capacity and control logic. Pump motors require a minimum time to cool off between successive pump starts, especially with large pumps. Sufficient storage must exist for flow imbalances that can result. Automatic control logic should be designed to comply with pump start and stop criteria.

Most modern canal pumping plants are automatically controlled. Pump starts and stops may be based on pressure in an enclosed hydropneumatic tank, flow measured at a flow meter, or water level in a tank, reservoir, or canal. Control of a large pumping plant is complex. Plant control includes pump and valve startup and shutdown sequencing, unit rotation to balance unit wear and meet minimum run/rest time requirements, and monitoring of numerous mechanical and electrical conditions.

Frequently, automatic pumping plant control uses water level sensed in a forebay or afterbay reservoir to start and stop pumps. Pump control is based on maintaining one or more target levels in the reservoir. Designing this type of automatic pumping plant control should include the following steps:

1. Select mode of control
2. Determine number of control levels (number of pumps) and order
3. Establish minimum vertical distance between levels
4. Calculate storage volume between levels
5. Evaluate surface area versus increased height considerations
6. Perform preliminary design
7. Perform hydraulic analysis
8. Complete final design

The most common control mode is called **on-off control**. Distinct water levels in the reservoir turn each pump on and off, with as many pairs of water levels as there are pumps. On-off control levels are set in the reservoir as shown on figure 5-15. The example on figure 5-15 shows a pumping plant afterbay reservoir with control levels for four pumps. The target level in the middle represents the optimum reservoir level, with a deadband on either side of the target. When the reservoir level is within the deadband, control action will not be initiated. As the water level decreases, pumps will be turned on to refill the reservoir. When the depth increases above the deadband, pumps will be turned off.

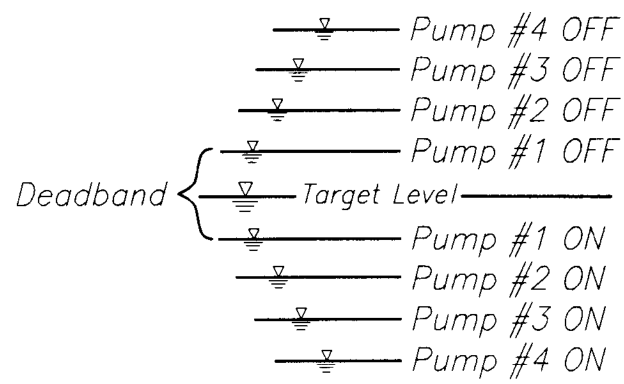


Figure 5-15.—On-off pumping plant control.

On figure 5-15, pump No. 1 will always start and stop first, and pump No. 4 will always start and stop last. Whenever a mismatch between reservoir inflow and outflow exists, the lowest numbered pumps will cycle on and off to keep the reservoir level near the target. This scheme is convenient with different-sized pumps. The lower numbered pumps should be small units, and the higher numbered pumps should be large units. Smaller pumps cycle to keep the flow and reservoir level near target. Figure 5-16 shows an example in which the pump shutoff order is opposite from the order of pump starts. This order has more vertical distance—and, therefore, more reservoir storage volume—between the on and off control point for any one pump. A longer time will pass before the reservoir storage changes enough for a pump to cycle on and off, so the elevation between control levels can be reduced without violating minimum pump run and rest time criteria. Additionally, different pumps will cycle at different flows, not always pump No. 1. This scheme has advantages with several pumps of the same size.

The advantages of the above two schemes can be combined to control a pumping plant with different-sized pumps, as shown on figure 5-17. Pumps No. 1 and 2 are small, and pumps No. 3 and 4 are large. Both small pumps will cycle as required, but their run and rest times will be maximized.
Total operating time will be shared evenly between all pumps.

Reservoirs or tanks with pump start/stop controls should also have control levels for alarms, emergency pump shutdown, overflow, and top of

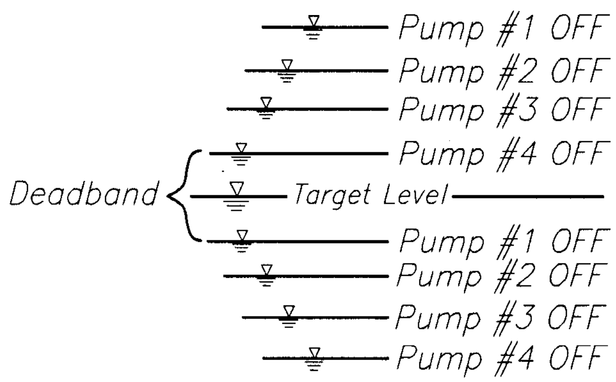


Figure 5-16.—Control levels for reduced pump cycling.

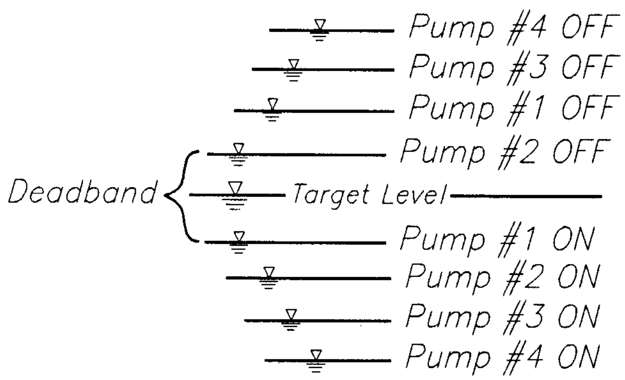


Figure 5-17.—Control levels for different-sized pumps.

embankment. Alarms warn operators that the reservoir level is out of normal range. If the water surface reaches the emergency off level, the entire pumping plant will be automatically shut down. The overflow level should be set to pass maximum overflow with sufficient embankment freeboard above the water level. Figure 5-18 shows an example layout of all levels in pumping plant forebay and afterbay reservoirs.

## 5-22. Cross Drainage

Most canals traverse natural drainage channels, presenting the canal designer with three options:

1. Convey drainage flows under the canal
2. Convey drainage flows over the canal
3. Allow drainage flows to enter the canal

Options No. 1 and 2 can be accomplished with siphons, elevated flumes, overshoot structures, or culverts. When properly designed, these structures should have a minimum effect on canal operations. Option No. 3 is accomplished using drain inlets. Flow into the canal through drain inlets will affect canal operations, sometimes significantly, and canal structures must be designed to pass extra flow. Drainage inflow should be considered when designing the conveyance channel, wasteways, and check structure bypass weirs.

Control system design should account for drainage inflow also. An irrigation canal's operational priorities may shift from the downstream operation concept to the upstream operation concept during periods of drainage inflow. Local automatic control impedes this shift. To avoid control problems, local automatic controllers cannot include provisions for both upstream and downstream control concepts at the same time. If operational priorities must change to accommodate flood inflows, manual intervention should be used to disable automatic downstream control or switch all controllers to the upstream control concept.

The effect of drainage inflow should be evaluated much the same as the effect of turnout flow changes. Maximum drainage inflow will often happen concurrently with outflow reductions because the same storm that causes drainage inflow may result in power failure and turnout flow reductions. The combined effect of more inflow and less outflow may result in a worst case design scenario.

## 5-23. Water Measurement Structures

**a. Water level measurement.**—Automatically controlled canal operation depends on water level data collection. In most automated canals, accurate and dependable water level information is critical. Problems with water level data can cripple a monitoring and control system.

Stilling wells—also known as float wells or probe wells—usually are constructed adjacent to the canal to allow dependable water level measurement. A small pipe connects the stilling well with the canal, as shown on figure 5-19. The well's water level equals that in the canal, except less wave-induced water surface fluctuation occurs in the well. Floats, probes, pressure transducers, or staff gages can be installed in the well to measure water level.

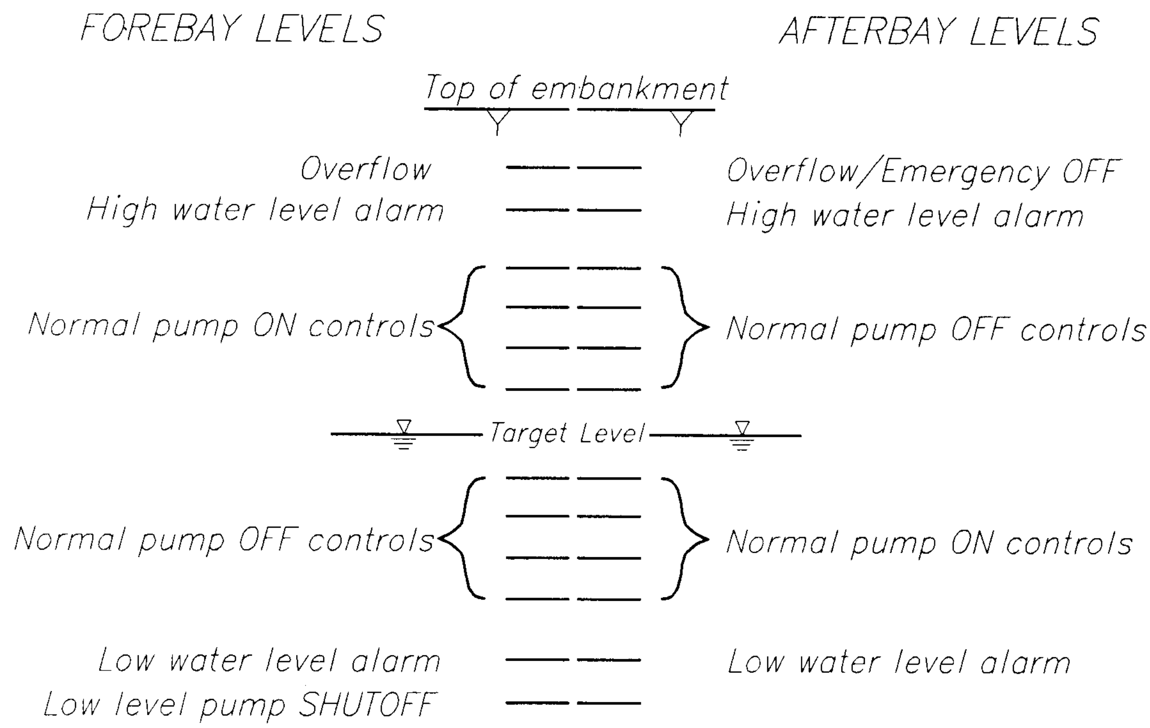


Figure 5-18.—Forebay and afterbay reservoir levels.

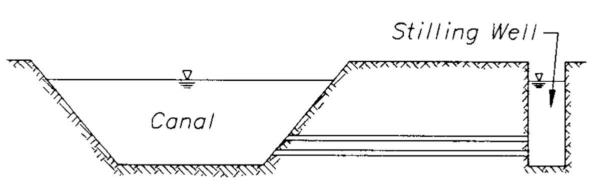


Figure 5-19.—Stilling well for water level measurement.

Measurement equipment is discussed in chapter 9, and stilling well structural design details are provided in *Design of Small Canal Structures* [1].

Stilling wells should be located wherever water level data are required. Frequently, wells are located a short distance upstream and downstream from check structures. Wells should be located far enough away from structures to avoid nonuniform flow that can disturb the water surface.

Stilling wells should be located at least 15 to 30 m (50 to 100 ft) upstream and 30 to 60 m (100 to 200 ft) downstream from check gates. Sometimes, another structure—such as a siphon, drop, or tunnel—is located immediately downstream from the check structure. In most of these cases, the stilling well should be located in the canal pool downstream from the structure.

Water level can be measured without stilling wells by installing probes, pressure transducers, bubbler pipes, and staff gages directly in the canal prism, but accuracy and dependability may be reduced. Wind waves on the canal surface will adversely affect water level readings, and canal debris may damage sensors.

**b. Flow measurement.**—Technically, flow is not actually measured but is calculated from water level and/or velocity measurements and known physical dimensions. Flow appears to be measured because these calculations may be transparent to the person using the flow data.

Several devices to "measure" canal flow are discussed briefly in the following paragraphs. More detailed information can be found in references 1, 13, 14, 15, and 16.

**Weirs** are simple and reliable flow measurement structures consisting of an overflow crest or notch. Weirs can have rectangular, trapezoidal, or triangular openings. Preferably, weirs should be used where sufficient head is available for free flow over the weir crest. Then, weir flow can be computed as a function of upstream water level and weir structure dimensions. The basic equation for free weir flow is:

$$Q = C\,L\,H^{3/2} \qquad 5.4$$

where:

- $Q$ = discharge
- $C$ = a weir flow coefficient (dependent on type of weir)
- $L$ = weir crest length (sometimes adjusted for end contraction)
- $H$ = head on weir crest (upstream water level minus crest level)

For example, a Cipolletti weir has a trapezoidal opening such that the sloping sides of the opening negate flow area contraction from the weir sides. The equation to calculate flow through a Cipolletti weir is:

$$Q = 3.367\,L\,H^{3/2} \qquad 5.5$$

where:

- $Q$ = discharge
- $L$ = weir crest length
- $H$ = head on weir crest

If downstream water level is higher than the weir crest, weir flow is submerged. To compute submerged weir flow, the flow coefficient and head terms are modified [13]. Generally, submerged weir flow calculation is less accurate than free flow.

Advantages to using weirs for flow measurement include ease of construction, low cost, simple flow calculation, and minimal input data required. For automatic flow monitoring, data from a water level sensor can be entered into the above formula to calculate a value for weir discharge. Disadvantages include high head loss and potential problems with trash.

The **Parshall flume** is a specially shaped open channel structure designed to measure flow, as shown on figure 5-20. Water enters the flume through a converging section into a narrow, downward-sloping throat and then exits through an upward-sloping diverging section. The flume's constricted throat produces a differential head that can be related to flow rate.

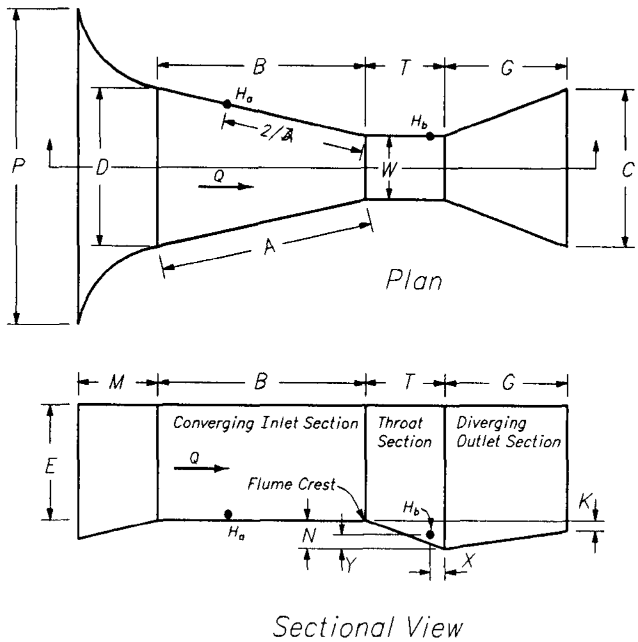


Figure 5-20.—Parshall flume.

A Parshall flume will operate in either free or submerged conditions. Free flow exists when the downstream water level is not high enough to affect flume flow. For free flow, discharge rate can be calculated from a single depth measurement in the flume ($H_a$). Submerged flow—when the downstream water level is high enough to reduce flume flow—requires water level measurement at two points in the flume ($H_a$, $H_b$).

Advantages of Parshall flumes include the following:

- Accurate and reliable flow measurement (typically within 2 to 5 percent accuracy for free flow, less accurate for submerged flow)

- Small head loss
- Operating range from free flow to a high degree of submergence
- Self-cleaning
- Unaffected by velocity of approach, which is often a problem with weirs and orifices
- Easy maintenance
- Tamper-proof
- Commercial availability and easy installation of prefabricated flumes

Disadvantages include:

- Expensive construction of large flumes
- Field calibration required for large flumes
- High degree of precision required for construction
- Cannot be located close to other structures that can disturb uniform inflow to the Parshall flume
- Settling of flumes over time, which requires recalibration

Calculating Parshall flume flow is a little more complicated than weir flow but easily programmed into an automated system. For example, free flow through flumes with throats from 0.3 to 2.4 m (1 to 8 ft) wide follows the equation:

$$Q = 4\ W\ H_a^{1.522W^{0.026}} \qquad 5.6$$

where:

$Q$ = discharge
$W$ = throat width (ft)
$H_a$ = head (water depth) at upstream gage

For submerged flow, head at the downstream gage is used to calculate a correction to the free flow discharge.

A modification of the Parshall flume with a flat bottom is called the **cutthroat flume**. Cutthroat flumes are useful for delivery turnouts and are commercially available.

**The ramp flume**, also called the long-throated flume**,** is an effective flow measurement structure that has advantages over Parshall flumes and weirs. As shown on figure 5-21, the ramp flume is constructed in the canal prism and consists of a 3:1 approach ramp to a horizontal broad crest, followed by a vertical drop to the canal invert. Discharge rate is calculated from a single water level measured just upstream from the approach ramp.

Ramp flumes can predict discharge rate accurately through a wide range of submergence. Depending on calibration and depth measurement accuracy, flow can be calculated within 1 to 5 percent accuracy [17]. Ramp flumes with a vertical drop at the end of the crest have a submergence depth limit of 85 percent. (Submergence is $H_s$ on figure 5–21.) Submergence as high as 92 percent is acceptable with a 6:1 downward-sloping ramp at the end of the crest. These high submergence limits allow ramp flumes to operate with low head loss.

Unlike Parshall flumes, ramp flumes do not require precise construction for accurate flow measurement. Ramp flumes can be computer calibrated using dimensions measured after construction. A computer program has been developed to calibrate ramp flumes and, after calibration, generate rating curve data (head versus flow) [14]. Another advantage to ramp flumes is the relative ease with which they can be installed in existing canals. One disadvantage is the potential for problems with sediment buildup.

**Submerged orifices** can be used to calculate flow when water level on either side of the orifice is known. In a canal, check gates or turnout gates can serve as flow measurement devices. Flow prediction accuracy depends on water level measurement, gate position measurement, and structure calibration.

The major advantage to using submerged orifice flow calculation is that gate structures required for regulation can also be used for flow measurement. Therefore, additional cost is minimal, and additional head loss is not created. Disadvantages include problems with trash plugging the orifice and flow measurement inaccuracy from inaccurate gate position measurement or calibration.

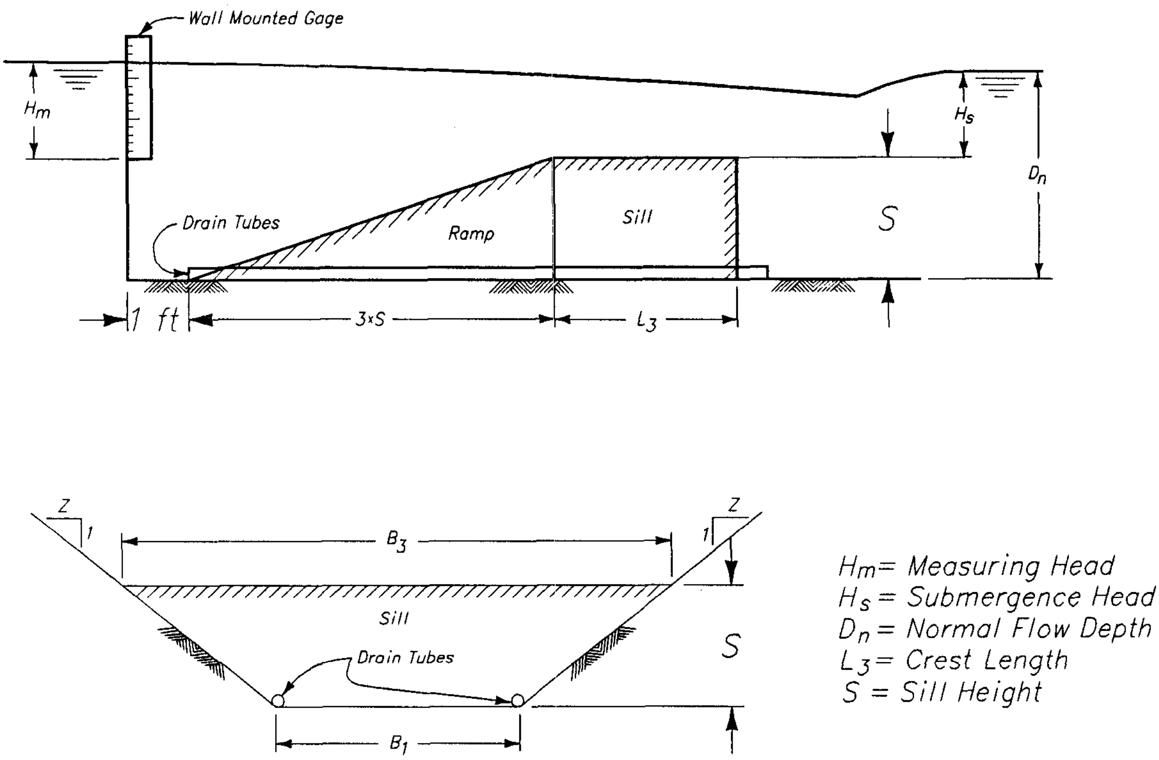


Figure 5-21.—Ramp flume.

The general form of the orifice equation is:

$$Q = C_d \, G_o \, B \, \sqrt{2gh} \qquad 5.7$$

where:

$Q$ = discharge
$C_d$ = coefficient of discharge
$G_o$ = gate opening height
$B$ = orifice (gate) width
$g$ = gravitational constant
$h$ = differential head across the orifice (upstream water level minus downstream water level)

For a square-edged orifice, approximate results may be obtained using $C_d$ equals 0.6. However, $C_d$ must be calibrated as a function of water levels and gate opening to improve accuracy. Also, the definition of the head term, *h*, often is modified to avoid problems when differential head is very small. The orifice equation can be applied to check structures or turnouts with vertical slide gates with moderate calibration.

The constant-head orifice (CHO) structure uses submerged orifice flow calculation to both regulate and measure flow. Usually used for turnout structures, CHO's use two gates in series. The first gate regulates or measures flow, and the second gate is used to maintain a constant head across the first gate [1].

Canal **radial gate check structures** can be calibrated to estimate flow within 2 to 5 percent accuracy. Discharge algorithms were developed for radial gates through an extensive Reclamation research program [18]. A computer program uses these algorithms to generate rating tables or calculate gate flow for combinations of upstream and downstream depths and gate positions. Additionally, flow or gate position can be calculated in a real-time mode as a flow (*Q*) controller.

Using check structures to measure and control discharge has many advantages. Control already requires check structures, so using them to measure flow saves the additional expense and head losses of separate flow measurement structures. Frequently, depth and gate position monitoring is required for other reasons, so using these data to calculate flow makes sense.

Local flow control can be a powerful addition to supervisory control systems, simplifying centralized decisions and calculation. Operators can think in terms of flow, which facilitates balancing and adjusting of system flows to match total turnout demands. Supervisory control software can adjust canal pool volumes by incrementing structure flows, leaving individual gate adjustment to the local flow controllers.

The radial gate flow algorithms' complexity is the main disadvantage of check structure flow measurement. The logic is much more complicated than most local control algorithms. Despite this complexity, real-time application is quite feasible using computers.

Flow rate in canals and pipes can be calculated using **current meters** and **acoustic velocity meters**. Current meters have a propeller or a cup wheel that rotates to indicate flow velocity at a single point. Different types of current meters and their use are described in the *Water Measurement Manual* [13]. Acoustic velocity meters (AVM's) yield average flow velocity through a section by measuring travel time of a sonic signal, which travels faster downstream than upstream [19,20]. When combined with a stage-area relationship, measured velocities are used to determine a discharge. AVM's also can be used to measure depth.

Current meters and AVM's should be located in cross sections of stable flow and uniform velocity distribution. Velocity measurement should take place far away from checks, turnouts, or other structures that can disturb the uniform flow pattern. Both types of meters operate without head loss, and current meters can be used as a portable flow measurement tool.

In canal application, velocity measurement is only valuable if velocity can be converted to flow accurately. Flow calculations require accurate knowledge of flow, water level, and channel cross-section dimensions. Water level measurement accuracy and changing channel dimensions (e.g., caused by sediment deposition) will affect flow calculation accuracy. Therefore, flow measurement accuracy may be significantly less than velocity measurement accuracy.

Accurate velocity measurement requires initial calibration and periodic adjustment. Velocity measurement errors are difficult to detect because velocity cannot be checked with observations of physical parameters such as water level and gate positions.

AVM accuracy depends on equipment limitations, acoustic-path length and angle measurements, water quality, and the stability of the mean velocity to acoustic path velocity relationship. Typical velocity error in AVM systems ranges from about ±1 millimeter per second (±0.003 ft/s) for a 200-m (700-ft) path length to ±10 millimeters per second (±0.03 ft/s) for a 20-m (70-ft) path length.

Designers must evaluate system-wide flow measurement requirements—considering the total control scheme—to design the type of measurement structures, number and location of measurement sites, and accuracy required. Nontechnical considerations may impact decisions. For example, some States require the use of Parshall flumes for water rights accounting even though other methods of flow measurement may have technical and economic advantages.

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# CHAPTER 6

# SIMULATION AND ANALYSIS

## SIMULATION

### 6-1. Simulation

Investigating the response characteristics of a water system is essential to integrate canal design with the control method. Both steady and unsteady flow conditions require careful examination. For existing canal systems, response characteristics can be determined in the field. However, field investigation of response characteristics is time consuming and expensive. Because the design depends upon the control method, response characteristics should be known before a system is constructed. Therefore, methods have been developed to study canal response characteristics using simulation techniques. Simulation techniques are based upon the use of analogs.

Anything that corresponds in some respects to something else, especially in its function, but is different in other respects, is called an *analog*. Many analogs exist in engineering. For instance, analytic description of water motion in a canal is a mathematical analog. In mathematical analogs, water motion is simulated by differential equations. The solutions of equations result in numbers representing velocities or discharges and flow depths within the canal. Fluctuations in the actual flow depths and discharges can be analyzed by studying variations of the values of mathematical solutions. The principal analogs used to simulate canal systems are:

- physical
- electrical
- mathematical

In the following sections, these analogs will be described in detail; the specific function being simulated will be discussed. Each type of analog has inherent advantages and limitations, and none of the analogs will completely simulate conditions existing in nature. The problem for the engineer or designer is to recognize the limitations and advantages of the different types and to select the analog that best fits the needs of the analysis.

The last section in this chapter describes types of analyses that should be considered in the design of canal system automation. Too often, only normal operational characteristics are analyzed. However, in considering a period of abnormal operation, or if an emergency or unusual event should occur, a knowledge of the best course of action to take can significantly reduce or even eliminate damage to structures. The "Analysis" section in this chapter illustrates two examples.

### 6-2. Physical Analog

Physical analogs usually resemble the actual canal system in every respect except size. Normally, a physical model of the entire canal system is not used because of construction costs. Instead, parts of the canal system are simulated to explore specific problems [1, 2]. For example, the physical model shown on figure 6-1 was used to develop algorithms for estimating discharge characteristics of radial gates in a canal check structure [3].

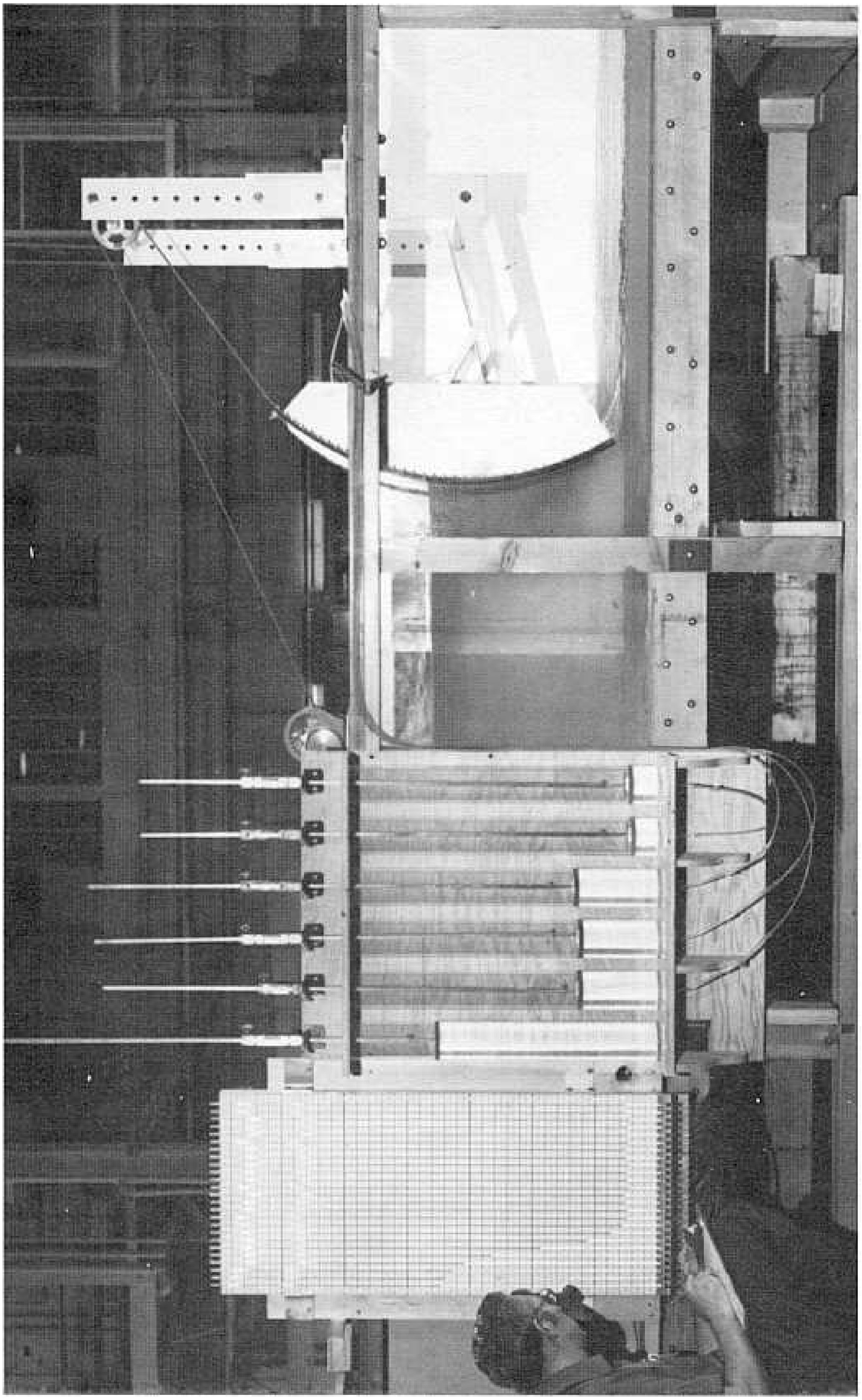


Figure 6-1.—View of hydraulic laboratory canal radial gate model showing manometer and stilling well boards used to measure water pressure at selected points.

Physical analogs have been used to develop control schemes and to obtain data to verify mathematical analogs. For example, one analog of this type was constructed in the Bureau of Reclamation's (Reclamation) Hydraulics Laboratory as shown on figures 6-2 and 6-3 [4]. This model consisted of three pools having a total length of 335 meters (m) (1,100 feet [ft]). The canal prism was rectangular in cross section with a bottom width of 360 millimeters (mm) (14 inches [in]) and a maximum flow depth of 360 mm (14 in). The maximum flow rate in the facility was 0.03 cubic meter per second ($m^3$/s) (1 cubic foot per second [$ft^3$/s]). Four motorized radial gates were installed to control water levels within the pools. Numerous types of controllers could be investigated by routing all electrical leads into one control console (figure 6-3). This type of facility has the advantage that surges in the canal and interaction between pools could be simulated.

Water motion in a canal prism also has been simulated by flow into and out of a tank as shown on figure 6-4 [5]. The purpose of this study was to simulate water level fluctuations in a canal that had been predicted using a numerical analog. In essence, this procedure simulates full-scale operation. Usually, operation of this type of analog is termed hybrid operation because the input variables to the physical analog are determined from a numerical analog.

The main limitation of physical analogs is the difficulty encountered in modeling an entire canal system. And because each canal system is unique, a new physical model is required for each canal system.

## 6-3. Electrical Analog

An electrical analog uses components such as resistors, capacitors, inductors, transformers, etc., to simulate appropriate features in a canal system. By choosing appropriate values for the components and connecting them systematically, a canal system can be simulated. Usually, assembly of electrical components is performed on a device known as an analog computer. The analog computer incorporates switches, contacts, meters, and various types of signal sources into one console. Analog computers integrate instantaneously but can only integrate linearized differential equations.

Electrical to hydraulic analogs can be formulated in several ways. One method was proposed by Braunagel [6], in which hydraulic quantities in the equation of motion are simulated by electrical quantities. These quantities are shown in the following table.

*Electrical analog quantities*

| Hydraulic quantity | Electrical quantity |
|---|---|
| Force acting on the cross-sectional area of the canal prism | Voltage |
| Water velocity | Current |
| Mass of the water prism | Inductance |
| Water storage capacity of the canal pool | Capacitance |
| Force due to wall shear per unit of average velocity (equivalent to energy loss) | Resistance |
| Acceleration | Time rate of change of current |
| Total volume of water displaced | Electrical charge |

Figure 6-5 is an example electrical analog for a canal reach consisting of:

- A reservoir
- Three pools
- A gated turnout
- A pumped turnout
- A downstream weir

Electrical analogs can be used to investigate the effect of variations in one or more parameters about a steady-state condition. Initial conditions of the electrical analog represent known steady-state hydraulic conditions. A perturbation is input into the analog computer, and effects of the perturbation are observed. For instance, the effect of a sinusoidal variation in depth is simulated by replacing the appropriate constant-voltage source at the equivalent location in the electrical analog with a varying sinusoidal source. In this manner, the propagation of disturbances through a canal system caused by fluctuation at a specific location can be investigated.

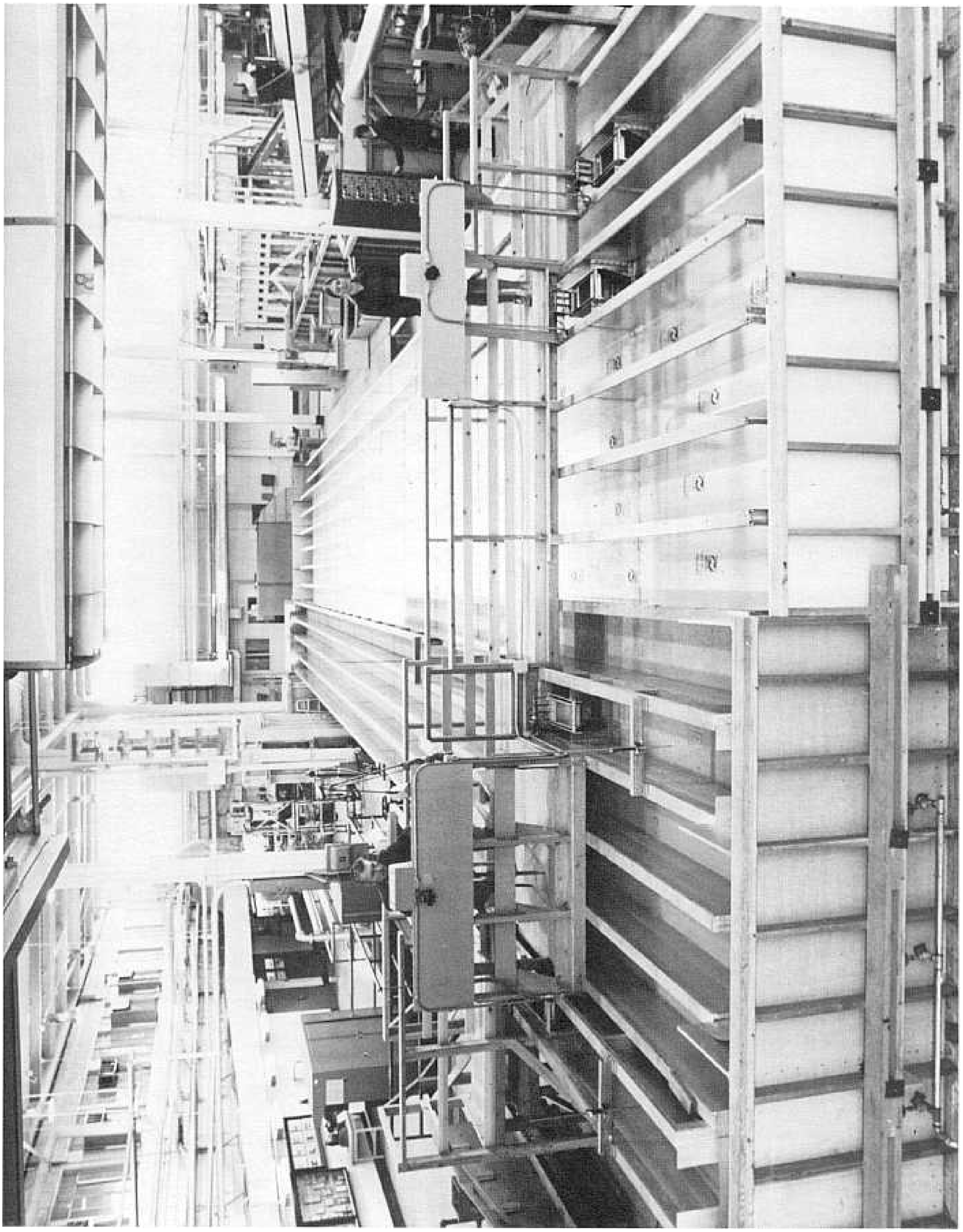


Figure 6-2.—Canal model.

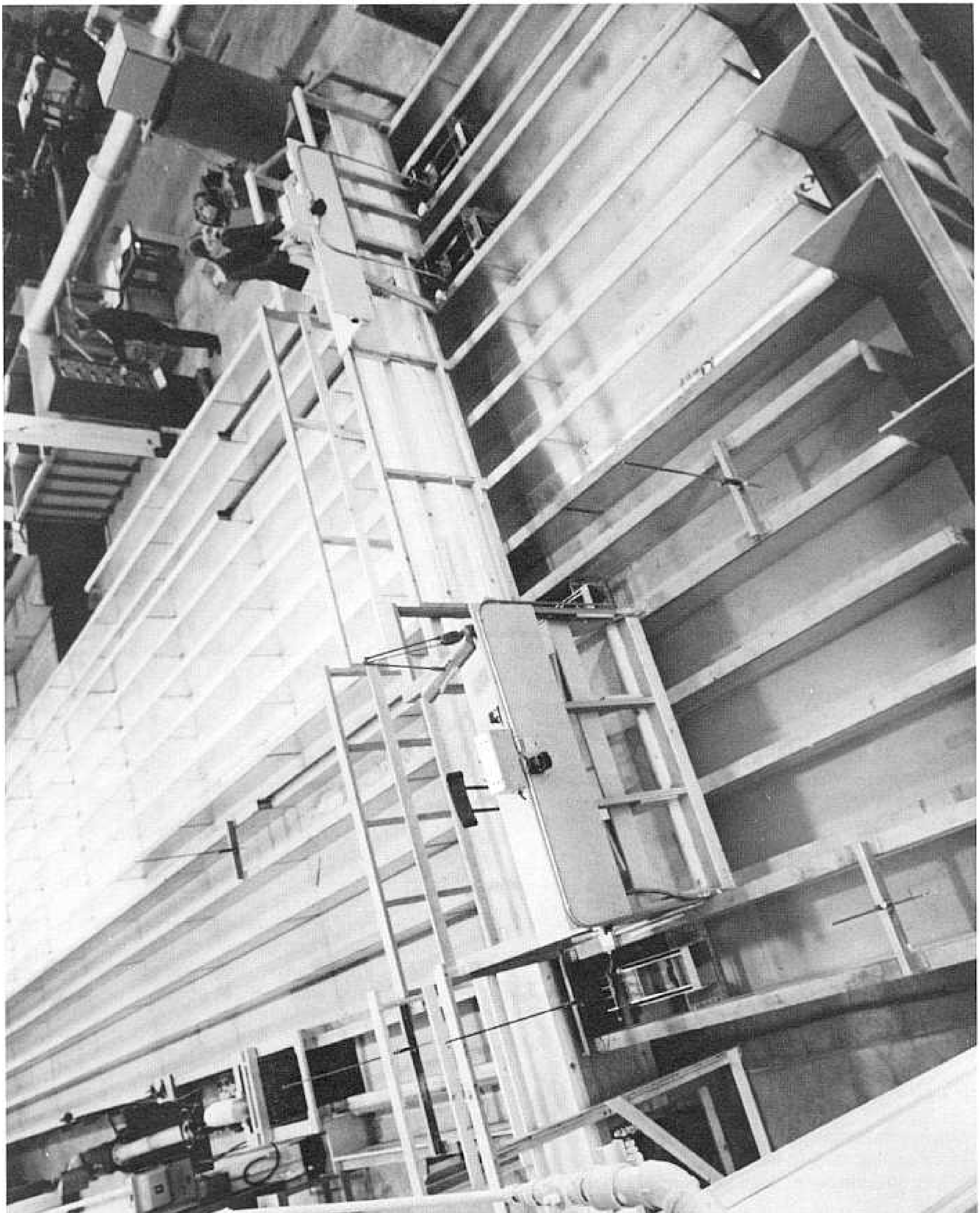


Figure 6-3.—Control panels, flumes, and side-spill weirs of canal model.

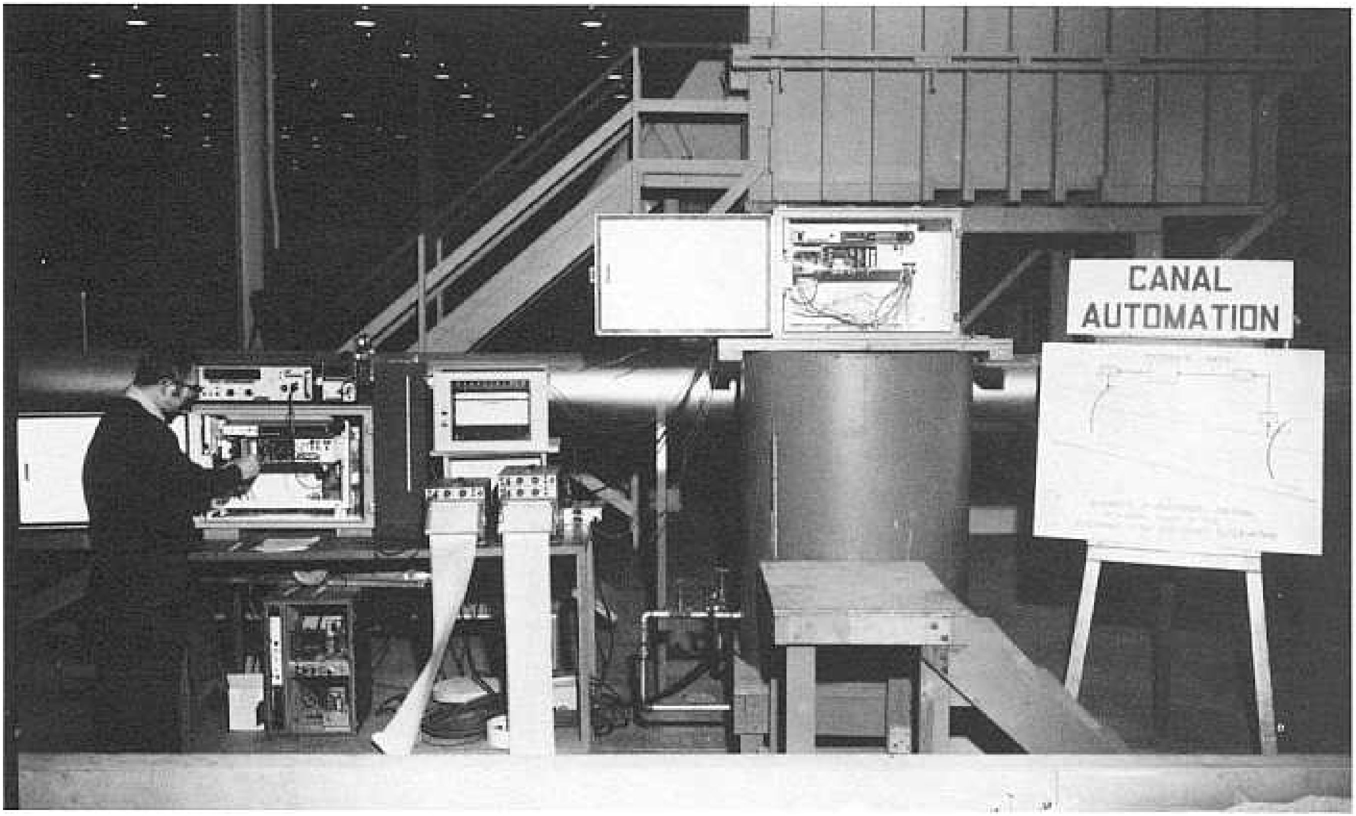



Figure 6-4.—Laboratory test facility used for the ELFLO plus RESET controller.

Electrical analogs are especially useful to simulate canal-system stability. Studies of feedback controllers have shown that some canal designs are easily automated; other designs are almost impossible. For those problem cases, small disturbances tend to amplify rather than decay. By input of sinusoidal disturbances at various locations in an electrical analog, engineers can investigate a canal's sensitivity and identify the elements causing problems.

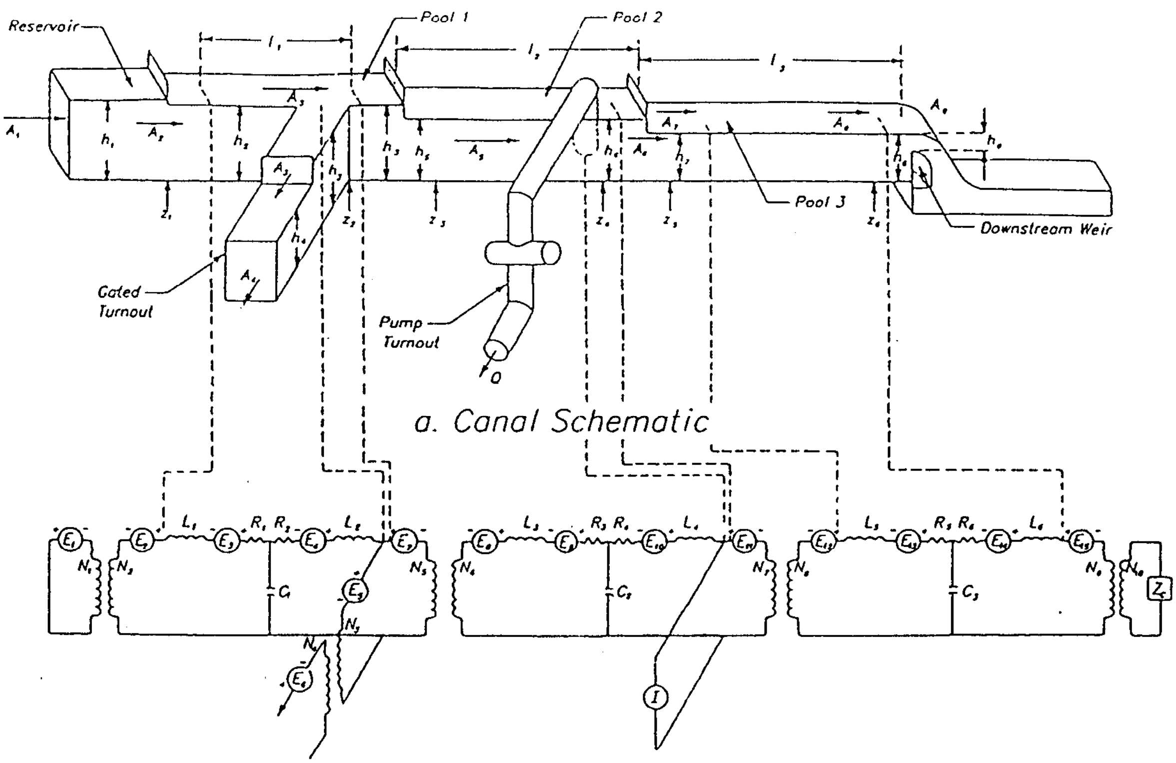
Analog computers have been used primarily for flood routing, ground-water, and estuarine simulations. Although electrical analog techniques can be applied to studies of canal systems, digital computers are much easier to use and are now fast enough to eliminate the advantage once held by analog computers.

## 6-4. Numerical Analog

A numerical analog of a canal system consists of a set of equations that describes significant hydraulic relationships in each canal pool and in their connecting control structures. Solutions to the equations result in an approximation of the canal's water surface level and flow as a function of time and space.

The set of equations is an approximation of the physical conditions. The equations can accurately simulate natural conditions if enough mathematical terms are included in the equations and if the coefficients of these terms are properly selected. In some cases, essential hydraulic behavior can be simulated using only a few terms. However, as the complexity of flow increases, more terms must be included in the equations. For example, the simulation of steady-state flow in one pool of a trapezoidal channel can be achieved using a simple equation having only two terms. However, satisfactory simulation of unsteady flow may require up to five terms in the equations.

Equations that describe flow in canal systems are nonlinear; therefore, a closed form solution of the equations cannot be obtained. Instead, approximate solutions are obtained using numerical integration techniques. Various solution methods




b. Electrical Schematic

$$\left(\frac{N_1}{N_2}\right)^2 = \left(\frac{h_1}{h_2}\right)^3 \qquad E_1 = \frac{Pg\,A_1}{2}(h_1 - h_2) \qquad E_2 = \frac{Pg\,A_2}{2}(h_1 - h_2)$$

$$L_1 = L_2 = P\,\frac{(A_2 + A_3)}{2}\,l_1 \qquad C_1 = \frac{l_1}{Pg\dfrac{(A_2+A_3)}{2}\dfrac{(h_2 + h_3)}{2}} \qquad \frac{R_1}{R_2} = \left(\frac{h_2}{h_3}\right)^{\frac{3}{2}}$$

$$E_3 = E_4 = \left(\frac{Pg}{2}\right)\frac{(A_2+A_3)}{2}(z_1 - z_2) \qquad \left(\frac{N_3}{N_4}\right)^2 = \left(\frac{h_3}{h_4}\right)^2 \qquad E_5 = \left(\frac{Pg\,A_3}{2}\right)(h_3 - h_4)$$

$$E_6 = \frac{Pg\,A_4}{2}(h_3 - h_4) \qquad \left(\frac{N_5}{N_6}\right)^2 = \left(\frac{h_3}{h_5}\right)^3 \qquad E_7 = \frac{Pg\,A_3}{2}(h_3 - h_5)$$

$$E_8 = \frac{Pg\,A_3}{2}(h_3 - h_5) \qquad L_3 = L_4 = P\frac{(A_5 + A_6)}{2}(l_2) \qquad E_9 = E_{10} = \frac{(Pg)}{2}\frac{(A_5 + A_6)}{2}(z_3 - z_4)$$

$$C_2 = \frac{l_2}{Pg\dfrac{(A_5 + A_6)}{2}\dfrac{(h_5 + h_6)}{2}} \qquad \frac{R_3}{R_4} = \left(\frac{h_5}{h_6}\right)^{\frac{3}{2}} \qquad I = \frac{Q}{\dfrac{(A_5 + A_6)}{2}}$$

$$\left(\frac{N_7}{N_6}\right)^2 = \left(\frac{h_6}{h_7}\right)^3 \qquad E_{11} = \frac{Pg\,A_6}{2}(h_6 - h_7) \qquad E_{12} = \frac{Pg\,A_7}{2}(h_6 - h_7)$$

$$L_5 = L_6 = \frac{Pg(A_7 + A_8)}{2}\,l_3 \qquad C_3 = \frac{l_3}{Pg\dfrac{(A_7 + A_8)}{2}\dfrac{(h_7 + h_8)}{2}} \qquad R_5 = R_6 = \left(\frac{h_7}{h_8}\right)^{\frac{3}{2}}$$

$$E_{13} = E_{14} = \left(\frac{Pg}{2}\right)\frac{(A_7 + A_8)}{2}(z_5 - z_6) \qquad E_{15} = \frac{Pg\,A_8\,h_8}{2} \qquad \left(\frac{N_6}{N_{10}}\right)^2 = \left(\frac{h_8}{h_9}\right)^3$$

$$Z_C = PA_9\sqrt{gh_9}$$

Figure 6-5.—Electrical analog of a canal.

have been developed because the equations can be integrated numerically in several different ways. As the number of terms in the equations increases, the solution techniques become more and more complicated. The art of numerical simulation is in knowing different solution techniques and being able to select the method that produces the best solution with a minimum of computational effort.

Chapter 2 included a brief discussion of basic canal hydraulics. The following examines numerical techniques used to simulate different types of canal flow and to delineate some of the preferred methods used in solving the applicable mathematical equations.

**a. Basic equations.**—Unsteady flow in open channels is governed by the principles of *conservation of mass and momentum*. The equation of water continuity expresses conservation of mass, and the equation of motion (dynamic equilibrium) describes the momentum balance. Commonly, these two unsteady-flow equations are called the *Saint-Venant equations*. The Saint-Venant equations assume the following [7]:

- Flow is one-dimensional, and velocity is uniform over the cross section.
- Streamline curvature is small.
- Effects of boundary friction and turbulence can be accounted for by the resistance laws of steady-state flow.
- Channel slope is small enough so that the cosine of the angle between the invert and horizontal can be replaced with unity.

Notice that these assumptions introduce approximations into a simulation. That is, velocity is not truly uniform throughout the cross section of a constructed canal. The assumption of small streamline curvatures means no sudden expansions of the flow and no vertical accelerations exist. The first condition is violated at control structures, and the second condition is violated at sudden changes of invert slope.

Two formulations of the Saint-Venant equations are possible: (1) an integral form and (2) a differential form [7]. The integral form is more general, and from it the differential form can be derived. The integral form does not require the functions to be continuous. Therefore, it can be used to simulate problems where water surface variation is discontinuous—as with a hydraulic jump or bore wave. However, in practice, differential equations are used most frequently for numerical analog formulation.

By making simplifications to the complete differential equations, equations having application to a specific type of flow can be generated. Each flow type is denoted by a unique name. Delineation of the flow types can be understood by referring to the dimensionless form of the full differential equations of conservation for momentum and mass. The differential equations are defined in dimensionless terms, respectively, as:

Term: I II III IV V

$$\underbrace{\frac{\partial Y'}{\partial X'}}_{\mathrm{I}} + \underbrace{F_0^2 V' \left(\frac{\partial V'}{\partial X'}\right)}_{\mathrm{II}} + \underbrace{F_0^2 \left(\frac{\partial V'}{\partial t'}\right)}_{\mathrm{III}} + \underbrace{\frac{F_0^2}{S_0}\left(\frac{V'q'}{A'}\right)}_{\mathrm{IV}} = \underbrace{(1 - S')}_{\mathrm{V}} \qquad 6.1$$

and

$$V' \frac{\partial Y'}{\partial X'} + \frac{\partial Y'}{\partial t'} + \frac{A'}{T'} \frac{\partial V'}{\partial X'} = \frac{1}{S_0} q' \qquad 6.2$$

*where:*

$A$ = cross-sectional area
$V$ = flow velocity
$V_0$ = flow velocity at normal depth
$A_0$ = cross-sectional area at normal depth
$A'$ = $A_0 / Y_0^2$, dimensionless area
$F_0$ = $V_0 / (gA_0 / T_0)^{½}$, Froude number
$g$ = gravitational acceleration
$L_0$ = distance for change in elevation of energy grade line to equal flow depth at normal depth
$q$ = lateral inflow
$q'$ = $q / (V_0 Y_0)$, dimensionless lateral inflow
$S$ = slope of energy grade line
$S_0$ = sine of bottom slope of channel
$S'$ = $S/S_0$, dimensionless slope
$T$ = top width of water surface
$T_0$ = top width of water surface at normal depth
$T'$ = $T / T_0$, dimensionless top width
$t$ = time
$t'$ = $tV_0 / L_0$, dimensionless time
$V'$ = $V / V_0$, dimensionless velocity
$X$ = horizontal distance along canal
$X'$ = $X / L_0$, dimensionless distance
$Y$ = depth of flow
$Y'$ = $Y / Y_0$, dimensionless flow depth

Equations 6.1 and 6.2 are referred to as the *dimensionless, one-dimensional shallow-water* wave equations, or as the *dynamic* wave model. Equation 6.1 is frequently simplified as follows:

- For furrow irrigation, water enters at the upstream end of a furrow and advances down a dry channel. The Froude number is small in comparison to the other terms. Therefore, only terms IV and V are significant in equation 6.1. Solutions using only term V or terms IV and V are called *kinematic* approximations. Flood routing problems also are frequently solved using the kinematic approximation.
- For rapidly varying flow in power and pumping canals, frictional and lateral inflow or outflow effects are minimal. In this case, terms I, II, and III are the only ones used. Solutions using these terms are referred to as *gravity* wave approximations.
- Other combinations of terms are possible. For instance, the inclusion of pressure and frictional effects (terms I and V)—ignoring inertial and inflow effects (terms II, III, and IV)—results in the *diffusion* wave model.
- The *steady dynamic* wave model adds the convective acceleration effect (term II) to the diffusion wave model.

**b. Numerical methods of solution.**—In general, several numerical techniques are available to solve each of the simplified equations previously discussed. The goal of each technique is to obtain solutions quickly and accurately. Solutions must be stable from a computational point of view. Consequently, understanding the advantages and limitations of each technique is imperative.

Numerical methods have been developed to solve both steady and unsteady flow problems. A numerical method determines an approximation to the true solution of the differential and integral equations at discrete locations or points in time. For specific types of problems, several popular techniques encountered in water systems automation are discussed below.

**c. Steady-state analysis.**—Steady state means that only spatial variations in the water surface exist; conditions remain constant with respect to time. In this case, equations 6.1 and 6.2 can be combined into one total differential equation given by:

$$\frac{dY'}{dX'} = \frac{1 - (S / S_0)}{1 - F} - \frac{(F_0^2 / S_0)\,(V'q' / A')\,(1 + T')}{1 - F} \qquad 6.3$$

where:

F = $V / (gA / T)^{½}$ = local Froude number

Equation 6.3 can be solved using any of the numerical methods developed for solving first order nonlinear differential equations. Two traditional methods are the step method and the standard-step method [8].

**(1) Step method.**—In the step method, equation 6.3 is written as:

$$\Delta X = \frac{Y_2 - Y_1 + V_2^2 / 2g\ V_1^2 / 2g}{S_o - S} \qquad 6.4$$

where:

subscripts 1 and 2 refer to upstream and downstream conditions, respectively

The solution of the equation, $\triangle X$, is the distance between locations 1 and 2 (from the point where depth equals $Y_1$ to the point where depth equals $Y_2$).

To solve the equation, a value of $Y_2$ slightly different from $Y_1$ is assumed. Values of velocity head and energy slope are calculated for the depth $Y_2$. The energy gradient is calculated from:

$$V = \frac{C_f R_1}{2\sqrt{S}} \qquad 6.5$$

where:

$C_f$ = Chezy coefficient
$R_1$ = hydraulic radius at point 1
$S$ = energy gradient

The hydraulic radius is defined as the cross-sectional area divided by the wetted perimeter. The Chezy coefficient is defined as:

$$C_f = \left(\frac{8g}{f}\right)^{1/2} \qquad 6.6$$

where:

$f$ = the Darcy-Weisbach friction factor

In equation 6.4, the energy gradient is the arithmetic average of the values at $Y_1$ and $Y_2$. Studies by Laurenson [9] show that the arithmetic average is the single best method of averaging. Computations progress upstream if the flow depth is greater than critical depth and downstream if the flow depth is less than critical. Because the solution is asymptotic to normal depth, this procedure minimizes error growth in the computations. When computations progress away from normal depth, the solution may be incorrect because the starting depth is imprecise.

**(2) Standard-step method.**—This method uses a prescribed distance increment rather than a prescribed depth. Equation 6.3 is solved for a constant value of $\triangle X$. Because the incremental distance is fixed, the $Y_2$ depth and the corresponding velocity head and energy slope must be determined by trial and error. Equation 6.3 can be programmed for solution on a computer using Newton's method of finding roots of an equation. To use Newton's method, equation 6.3 is rewritten as:

$$f(Y) = Y_2 - Y_1 + \frac{V_2^2}{2g} - \frac{V_1^2}{2g} - (S_o - S)(X_2 - X_1) \qquad 6.7$$

where:

$f(Y)$ = a function whose value should equal zero

The derivative of equation 6.7 is written as:

$$\frac{df(Y)}{dY} = \frac{Q^2}{gA_1^3}\frac{dA}{dY} + (X_2 - X_1)\frac{dS}{dY} + 1 \qquad 6.8$$

The next trial value of $Y_2$ is obtained from:

$$Y_{2_{(new)}} = Y_{s_{(old)}} - \frac{f(Y)}{df(Y)\,/\,dY} \qquad 6.9$$

Equations 6.7 through 6.9 are iterated until the new depth, $Y_2$, is within some predetermined tolerance of the old depth.

**(3) Direct integration.**—Equation 6.3 can be integrated directly if the following simplified assumptions are made [10]:

- Friction slope at depth $Y$ and discharge $Q$ is the same in nonuniform flow as in uniform flow
- Chezy coefficient is constant
- Channel is rectangular
- Hydraulic radius is equal to the flow depth (infinitely wide canal)

The solution of equation 6.3 is:

$$X = \frac{Y}{S_0} - Y_o\frac{1}{S_o} - \Phi\frac{C_f^2}{g} \qquad 6.10$$

The function $\Phi$ is defined as:

$$\Phi = \frac{1}{6} \ln\left(\frac{Z^2 + Z + 1}{(Z - 1)^2}\right) - \frac{1}{3} \tan^{-1}\left(\frac{3}{2Z + 1}\right) + C_1 \qquad 6.11$$

where:

$C_1$ = constant of integration to make $X = X_o$ at $Y = Y_o$
$Z$ = $Y / Y_o$
ln = natural logarithm

This method is used infrequently because of restrictive assumptions.

Two other numerical integration methods are more stable numerically than either the step method or the standard-step method: the trapezoidal method [11] and the Runge-Kutta method [12].

(4) **Trapezoidal method.**—For the trapezoidal rule, water depth is given by:

$$Y_2 = Y_1 + \Delta Y = Y_1 + \frac{dY}{dX} \Delta X \qquad 6.12$$

Assuming that the derivative varies linearly, the following expression is derived for the water depth:

$$Y_2 = Y_1 + \frac{(dY/dX)_1 + (dY/dX)_2}{2} \Delta X \qquad 6.13$$

The trapezoidal method requires an iterative solution similar to the standard-step method. However, in this case, the function to be solved is:

$$F = Y_2 - Y_1 - \frac{(dY/dX)_1 + (dY/dX)_2}{2} \Delta X \qquad 6.14$$

The value of the derivatives in the numerator of equation 6.14 can be determined by substitution into equation 6.3. Therefore, the trapezoidal method can easily deal with the effects of lateral inflow or outflow.

The trapezoidal method is less conducive to propagation of numerical errors than the standard-step method. Additionally, convergence seems to occur faster because rate of depth change is iterated rather than energy.

(5) **Runge–Kutta method.**—The preceding method assumes a linear change in the derivative over the integration interval. The Runge–Kutta method accounts for the variation of the derivative at the midpoint and at both ends of the interval. The Runge–Kutta method extrapolates depth based upon previously known derivative values. Therefore, an iterative procedure is not required. The fourth order scheme is given by:

$$Y_2 = Y_1 + \frac{K_1 + 2K_2 + 2K_3 + K_4}{6} \qquad 6.15$$

where:

$K_1$ = $\Delta X\,(dY/dX)\ Y_1$
$K_2$ = $\Delta X\,(dY/dX)\ Y_1 + K_1/2$
$K_3$ = $\Delta X\,(dY/dX)\ Y_1 + K_2/2$
$K_4$ = $\Delta X\,(dY/dX)\ Y_1 + K_3$

The Runge–Kutta method is unconditionally stable. This stability may be a disadvantage if the water depth is near critical depth or if the integration interval chosen is too large. In either case, the method can produce erroneous results.

Considering speed, accuracy, and numeric stability of the various methods for computing steady-state profiles, the trapezoidal method appears to offer the most advantages.

**d. Unsteady-state analysis.**—Generally, unsteady-state or hydraulic transient analysis of automated canals requires retention of all terms in the unsteady-state flow equations. Two approaches have been used. One is to solve the partial differential equations by the method of characteristics or by finite differences [13]. The second approach is to solve the integral form of the equations. As noted earlier, the latter approach can be used to simulate the formation of hydraulic jumps and bore waves. A brief description of these methods follows. Each of the methods are complex, and only the essential elements of the methods are discussed. Implementation of the methods will require additional reference to the literature cited.

(1) **Method of characteristics.**—This method converts the two partial differential equations into

four total differential equations called *characteristic* equations. The four characteristic equations are given as follows:

*Positive characteristic*:

$$\frac{g}{C}\frac{dY}{dt} + \frac{dV}{dt} + g(S - S_o) + \frac{q}{A}(V - C) = 0 \qquad 6.16$$

and

$$\frac{dX}{dt} = V + C \qquad 6.17$$

*Negative characteristic*:

$$-\frac{g}{C}\frac{dY}{dt} + \frac{dV}{dt} + g(S - S_o) + \frac{q}{A}(V + C) = 0 \qquad 6.18$$

and

$$\frac{dX}{dt} = V - C \qquad 6.19$$

where:

the wave celerity $C = (gT/A)^{½}$

Equations 6.17 and 6.19 are referred to as characteristic lines because they can be plotted in the $X$–$t$ (distance–time) plane. Their geometric representation is shown on figure 6-6. Equations 6.16 and 6.18 are the *constitutive* equations. The constitutive equations convey depth and velocity information along the characteristic lines. Each constitutive equation is valid only on the appropriate characteristic line.

On figure 6-6, the intersection point, $P$, represents a location at which the solution of the variables $X$, $Y$, $Q$, and $t$ is theoretically possible. If conditions are known simultaneously at any other point on each of the characteristic lines (at either of the $R$ points or either of the $S$ points), then numerical integration of the four total differential equations will yield a solution for the variables at the intersection of the characteristic lines (point $P$). The four characteristic equations can be integrated as follows:

$$\int_{X_0}^{X_n} Y\,dx = \frac{h}{2}(Y_0 + 2Y_1 + 2Y_2 + \ldots + 2Y_{n-1} + Y_n) \qquad 6.20$$

where:

$h = dx = X_1 - X_0$

For the trapezoidal rule, $n$=1.

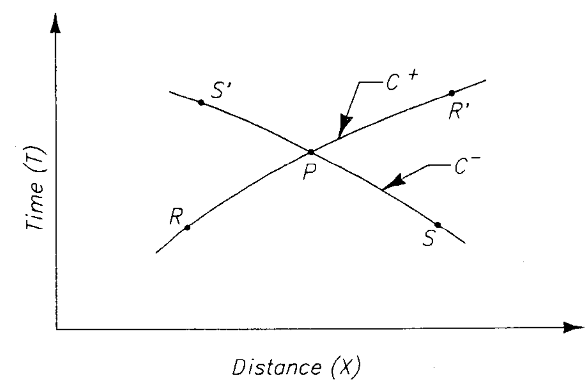
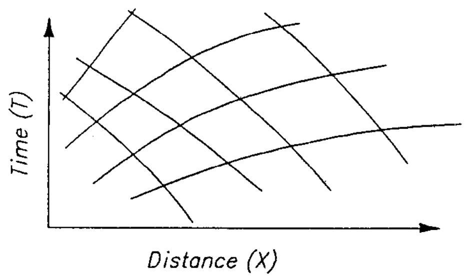



Figure 6-6.—Characteristic lines.

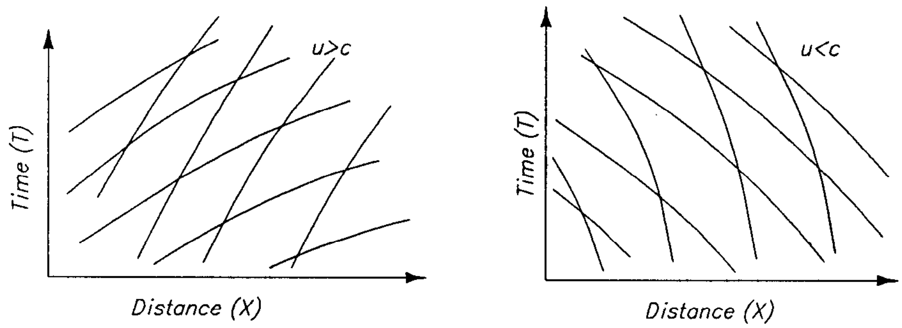
In the constitutive equations, the energy gradient, $S_p$, is a function of $V_p$ and $Y_p$. Because of the nonlinearity introduced by the energy gradient term, an iterative solution procedure is needed.

The solution results in unequal spacing of intersection points in the $X$–$t$ plane, as shown on figure 6-7. Although the unequal spacing requires interpolation at the boundaries, the grid has one distinct advantage: it is adaptive. Adaptive grid spacing changes to a fine mesh where flow changes rapidly and to a coarse mesh where flow changes slowly. This adaptation to flow conditions produces an accurate solution to the Saint-Venant equations. The adaptive grid is known as the *grid of characteristics.*

A fixed grid is used frequently to solve the characteristic equations as shown on figure 6-8. This grid is known as the *specified time interval grid.*

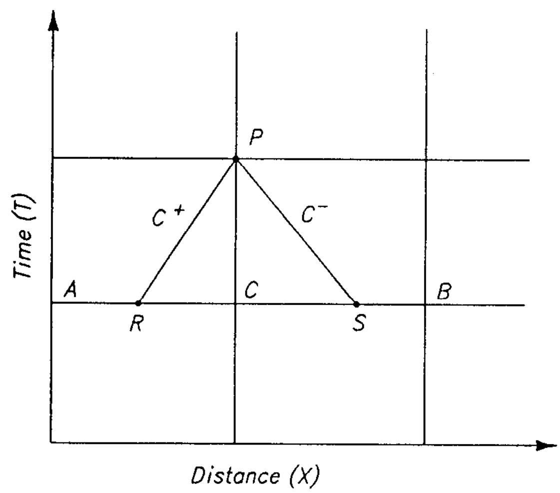



*a. Subcritical flow*

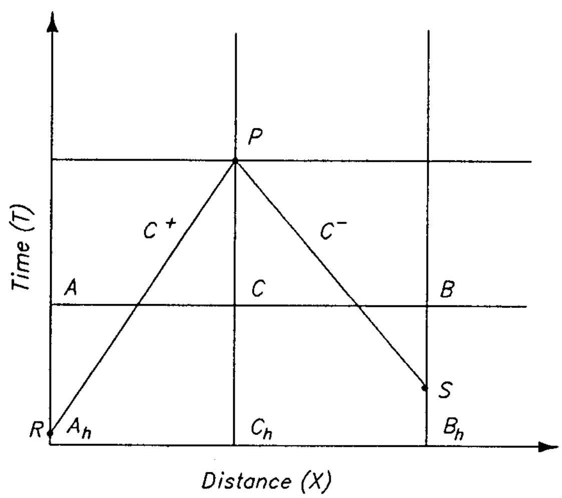



*b. Supercritical flow*

Figure 6-7.—Grid of characteristics.




*a. Interpolation with distance.*




*b. Interpolation with time.*

Figure 6-8.—Specified time interval grid.

To ensure accuracy of specified time interval computations, the relationship between time increment and distance increment must obey the *Courant* condition. This condition is:

$$\frac{\Delta t}{\Delta X} \leq \frac{1}{|V| + C} \qquad 6.21$$

At every computational point of the grid of characteristics, two interpolations for the solution of the characteristic equations are required. Two methods of interpolation are possible. The conventional method is to interpolate along distance (figure 6-8a). The problem with this method of interpolation is that the solution will not approach the steady-state condition. In fact, if started at steady state, the solution will gradually drift until the canal overflows or becomes empty. This trait has led some to think that the method of characteristics does not conserve mass [14]; but, the true fault lies in the method of interpolation.

To achieve a steady-state solution using a specified time interval grid, interpolation along the time line must be performed (figure 6-8b). Although this method converges to the steady state—and thus conserves mass—it does have disadvantages. First, the amplitudes of the transient will not be accurately represented because, during unsteady flow, variations in velocity, celerity, and depth are not linear along the time lines. Second, historical values of depth and velocity must be saved, which adds to computer memory requirements.

In summary, the method of characteristics is probably the most accurate of the numerical methods for solving the Saint-Venant equations. Implementation using the grid of characteristics provides the best solution from a numerical accuracy standpoint. However, matching the solutions in adjacent pools requires interpolation at the boundaries. The method of characteristics works well for either subcritical or supercritical flow but is difficult to apply if a bore wave exists.

(2) **Finite difference methods.**—The finite difference method uses a rectangular grid in the *X–t* plane as depicted on figure 6-9. The derivatives in the Saint-Venant equations are approximated by finite differences to yield two algebraic equations. For example, the partial derivative of velocity with distance might be approximated for a constant value of time by:

$$\frac{\partial V}{\partial X} = \frac{V_{j+1} - V_{j-1}}{2\Delta X} \qquad 6.22$$

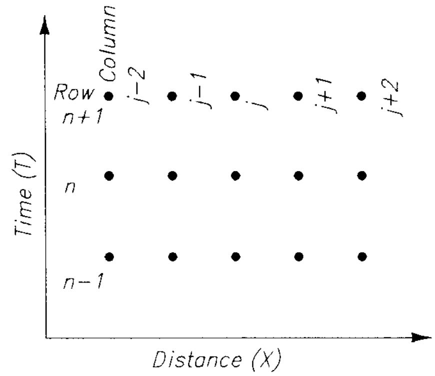



Figure 6-9.—Finite difference grid.

The partial derivative of velocity with time can be approximated for a constant value of distance by:

$$\frac{\partial V}{\partial t} = \frac{V_{n+1} - V_n}{\Delta t} \qquad 6.23$$

The centered difference approximation of equation 6.22 yields satisfactory results. However, the forward difference approximation of equation 6.23 is unstable. Therefore, one should exercise care in making approximations.

The resulting finite difference equations can be solved using either an explicit or implicit scheme. With the *explicit* scheme, unknown variables are expressed explicitly in terms of known quantities. The two algebraic equations are solved directly using information from the previous time step. Known values on the previous time line are used to determine unknowns for the present time step, one computational node at a time. Once all present values have been determined, the solution then progresses through all points for the next time step. The time step that can be used with the explicit method is limited by the Courant condition, as it was in the method of characteristics using a fixed time-step grid.

With the *implicit* scheme, finite difference approximations are expressed in terms of unknown variables. A set of algebraic equations is written for the entire system using present time values. All of the equations are solved simultaneously to evaluate every point at a single time step, and the unknowns appear implicitly. The implicit scheme is not limited by the Courant condition; it is unconditionally stable for all time steps. However, using a time step that is too large may produce unsatisfactory results.

The time step used with the implicit scheme should be short relative to the time required for a significant flow change. If flow can change rapidly, a short time step should be used; if flow changes are gradual, a long time step is adequate. One measure of the time-step size is the *wave number.* The wave number, σ, is defined as:

$$\sigma = \left(\frac{2\pi}{\Gamma}\right) L_0 \qquad 6.24$$

where:

- $L_0$ = horizontal length in which change in invert elevation equals the normal flow depth
- $\Gamma$ = wave length
- $\pi$ = 3.14159 . . .

Small wave numbers correspond to slow variations in the water surface or discharge. Large time steps can be used for small wave numbers. The flood wave is an example of a shallow water wave that can be simulated with large time steps. Usually, normal canal operating conditions can be accurately simulated with large time steps, offering great improvements in computational speed.

Large wave numbers correspond to rapid fluctuations in water level and flow. If the problem has large wave numbers, then the Courant condition should be observed. Emergency conditions in a canal must be simulated with small time steps. Generally, simulations of flows associated with water systems automation should be studied with methods that obey the Courant criterion.

**(3) Integral method.**—Although the integral method has not been used extensively in engineering computations, it is the best formulation for the solution of problems in which bore waves form. The integral form of the conservation equations can be written as shown in equations 6.25 and 6.26 below [7]:

$$\int_{X_1}^{X_2} [\,(VA)_{t_2} - (VA)_{t_1}\,]\, dX = \int_{t_1}^{t_2} [\,(V^2A)_{X_1} - (V^2A)_{X_2}\,]\, dt$$

$$+\, g \int_{t_1}^{t_2} [\,(I1)_{X_1} - (I_1)_{X_2}\,]\, dt + g \int_{t_1}^{t_2}\int_{X_1}^{X_2} I2\, dX\, dt + g \int_{t_1}^{t_2}\int_{X_1}^{X_2} A\,(S_o - S_f)\, dX\, dt \qquad 6.25$$

and

$$\int_{X_1}^{X_2} [A_{t_2} - A_{t_1}]\, dX + \int_{t_1}^{t_2} [Q_{X_2} - Q_{X_1}]\, dt = 0 \qquad 6.26$$

where:

$$I_1 = \int_0^{Y(X)} [Y(X) - h]\, s(X,h)\, dh$$

$$I_2 = \int_0^{Y(X)} (Y(X) - h) \left(\frac{\partial s}{\partial X}\right)_{Y=Y_o} dh$$

where:

$h$ = height of area increment above bottom
$s$ = width of area increment
$Y(X)$ = water depth at location $X$

For prismatic canals having a constant cross section, the value of $I_2$ is zero. The integral $I_1$ is the first moment of the wetted area with respect to the water surface, as shown on figure 6-10.

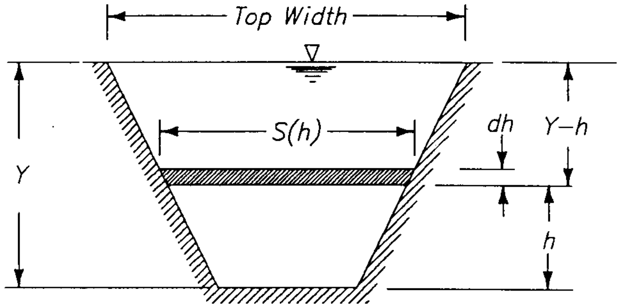



Figure 6-10.—Cross section of canal.

The discretization of these integral equations is given as follows [7]:

$$\frac{\Delta X}{2}\left[\,(Q_{j+1})^{n+1} + (Q_j)^{n+1} - (Q_{j+1})^{n} + (Q_j)^{n}\,\right]$$

$$+\ \Delta t \left[\!\left[\ \theta\left[\left(\frac{Q^2}{A} + g\,I\right)_{j+1}^{n+1} \left(\frac{Q^2}{A} + g\,I_1\right)_j^{n+1}\right] + (1-\theta)\left[\left(\frac{Q^2}{A} + g\,I_1\right)_{j+1}^{n} - \left(\frac{Q^2}{A} + g\,I_1\right)_j^{n}\right]\right]\!\right]$$

$$+\ \frac{g\,\Delta t\,\Delta X}{2}\left[\!\left[\ \theta\left[\,(-I_2 + AS_f - AS_o)_j^{n+1} + (-I_2 + AS_f - AS_o)_{j+1}^{n+1}\,\right]\right.\right.$$

$$\left.\left. + (1-\theta)\left[\,(-I_2 + AS_f - AS_o)_j^{n} + (-I_2 + AS_f - AS_o)_{j+1}^{n}\,\right]\right]\!\right] = 0 \qquad 6.27$$

and

$$\frac{\Delta X}{2}\left(A_j^{n+1} + A_{j+1}^{n+1}\right) - \frac{\Delta X}{2}\left(A_j^{n} + A_j^{n+1}\right)$$

$$+\ \Delta t\left[\ \theta\left(Q_{j+1}^{n+1} - Q_j^{n+1}\right) + (1-\theta)\left(Q_j^{n+1} - Q_j^{n}\right)\right] = 0 \qquad 6.28$$

where:

$\theta$ = equals a weight factor that has a value of 0.5 to 1.0.

The magnitude of the factor determines the amount of numerical dispersion in the solution. For $\theta > 0.6$, numerical oscillations probably will not occur.

Because $I_1$, $I_2$, and $S_f$ are functions of $Q$ and $A$, equations 6.27 and 6.28 are nonlinear. Generally, the discretization given by equations 6.27 and 6.28 is not used in computer programs because of the increased computational effort required with this formulation. However, if the purpose of the simulation is to reproduce the steep wave fronts found with bore waves, this formulation is the correct one to use.

**e. Software.**—Generally, numerical analogs are applied through computer programs. Hydraulic analysis computer programs have been developed and used by government agencies, universities, and industry. Several computer programs have been developed and tested by the Bureau of Reclamation. Some of these programs are summarized below.

**(1) Steady-state analysis.**—Numerous steady-state drawdown and backwater programs are available. One of the most comprehensive programs available in the public domain is WS77 [15]. The program is available on diskettes and will run on IBM PC compatible computers.

Program WS77 uses the standard-step method and can compute:

- Supercritical or subcritical flow in open channels
- Supercritical or subcritical in free-flowing closed conduits

The program has capability to calculate:

- Air entrainment
- Cavitation potential
- Turbulence characteristics

Open-channel cross sections may be:

- Triangular
- Rectangular
- Trapezoidal

Closed-conduit cross sections may be:

- Rectangular
- Circular
- Horseshoe
- Formed of rectangles and arcs
- Circular to rectangular transitions

Input data may be entered interactively or from a file in either International System of Units or inch-pound units.

Output data can be sent to a printer or displayed graphically on the terminal screen, a printer, or a plotter.

Either Manning's *n* or rugosity may be specified to describe conduit friction.

**(2) Unsteady-state analysis.**—Reclamation has developed and used several unsteady-state analysis programs. Programs AQMAIN, CORNING, and CBACCH are different versions of a program that were developed under contract. Each program is a modification for a specific purpose. These programs are based upon the method of characteristics, using a specified time interval with interpolation along the distance line. Program coding includes logic for upstream Proportional Plus Reset (P+PR), ELFLO, ELFLO plus RESET, and Colvin controllers (vol. 1, chapter 3). The programs gave good results [6] when verified with field results. However, using these programs is discouraged because each program's source code must be modified to make it compatible with the specific canal and controller being analyzed. Also, flow parameters must be artificially adjusted to compensate for interpolation errors that cause the canal to appear to be "leaky" near steady state.

For unsteady-state analysis, USM [16,17] is the most general program developed by Reclamation. This program uses the method of characteristics, either with specified time intervals or with the grid of characteristics. The specified time interval solution executes more quickly, but the grid of characteristics significantly improves conservation of mass. A large number of typical boundary conditions can be simulated, including:

- Gates
- Siphons
- Gates with siphons
- Weirs
- Gates with weirs
- Transitions
- Turnouts
- Pumps

Gates may be controlled with either upstream or downstream local controllers. These controller types include:

- Little-Man
- P+PR
- ELFLO plus RESET
- Colvin

The canal sections that can be simulated include:

- Rectangular
- Trapezoidal
- Triangular
- Circular
- Horseshoe

Program USM has a modular format which facilitates the addition of other canal cross sections or controllers into the computer code. USM is available for IBM PC compatible computers.

For gate stroking, the Gate Stroking Model (GSM) [18,19] is used. GSM will determine a series of continuous or discontinuous gate motions that produce a desired water surface profile in a canal. GSM uses the grid of characteristics solution method. Available pool cross-section shapes and structure types (boundary conditions) are the same as in USM. User-entered depth and flow schedules are employed to calculate gate movements and pump discharges. GSM is available for IBM PC compatible computers.

**f. Practical considerations.**—The choice of a numerical analog must always satisfy several requirements. First, the solution should conserve mass. Within reasonable limits, the solution should not gain or lose water. Mass conservation can be tested by observing the solution's behavior at steady state. As mentioned above, some of the interpolation techniques will cause a solution to gradually depart from the steady-state solution.

Second, the numerical solution obtained with large time intervals and incremental distances should converge to the solution obtained if the time and incremental distance was allowed to approach zero. Errors always will be introduced when using finite increments rather than exact integrals. The errors may be large where the solution varies rapidly. Third, the numerical solution should be stable. Some methods used to approximate differentials have the characteristic that small errors amplify with time. It is difficult to distinguish between instabilities that arise from the flow conditions and those that are caused by improper approximations. Fortunately, most of the typical errors caused by poor approximations have been studied. However, a novice programmer may generate poorly formed discretizations.

Fourth, the analog should closely represent the simulated field conditions. One of the most difficult conditions to simulate properly is the boundary friction characteristic. Often, Manning's equation is used as the analog. Manning's equation is a poor choice because the coefficient is a function of depth and discharge. The Colebrook–White equation overcomes some of the weaknesses of the Manning equation, but even the Colebrook–White equation does not represent channel friction perfectly. Rouse [20] showed that a Froude number must be included in the resistance equation for unsteady flow.

Numerical analysis is a new field, and many computer programs are becoming available. Users are often unaware of programming techniques and inherent limitations of the programs. Therefore, users frequently lose track of the approximate nature of the numerical solution. The tendency to resolutely accept the computer output as being the true solution must be resisted. The results of even the most sophisticated and user-friendly computer program should be treated with skepticism and thoroughly checked for correctness. If possible, results should be verified with field data or, at least, with carefully formulated test problems.

## ANALYSIS

### 6-5. Analysis

The purpose of the analogs discussed in this chapter is to simulate canal system behavior given certain design and operational parameters. The goal of the simulation is to develop improved designs and operational methods. This goal can be realized only if the proper analog is chosen and the proper analysis is performed.

Before the analysis can begin, *preliminary studies* must be completed. The primary purpose of these studies is to establish both the operation concept and the method of operation. Additionally, a preliminary canal system design should be developed, including the following items:

- Establish the plan and profile
- Estimate inflow and delivery requirements
- Identify inflow and outflow locations along the canal system
- Detail environmental, political and operational constraints

The importance of carefully conducting preliminary studies is emphasized. Too often, analytic studies commence with little or no consideration of the appropriate operation concept that should be applied to the system. Neglecting to perform preliminary studies can lead to systems that are difficult or impossible to operate.

Analysis requires using analogs that simulate unsteady flow. Often, unsteady-flow simulation is referred to as hydraulic transient studies. Transient studies consist of two broad classifications: design and operational. Design studies are used to determine how to build a canal system. Operational studies are used to determine how to operate the system. Although separated into these two classifications, the investigation is often one interrelated process.

**a. Design studies.**—Design studies are intended to finalize the selection of structural, mechanical, and electrical components of the canal system. The studies are performed for a given operation concept and method of operation. For example, the operation concept might be downstream control, and the method of operation could be the maintenance of a constant water level upstream from each gate. During the design studies, the effects of the operation concept and method on the design of the canal system are investigated. Distinct features of a system, such as the canal cross-section geometry, longitudinal slope, and the type and location of check structures are established. Additionally, the most appropriate control concept and control method required for automating the canal are investigated.

Frequently, canal systems are designed using only steady-flow assumptions. The technique is to size the canal and all the flow regulating structures to convey the maximum design discharge. The design is checked for the no-flow condition to ensure against canal dewatering and structure overtopping, but unsteady flow is not analyzed. This technique may lead to designs that are difficult or impossible to operate.

To investigate the effect of canal geometry and operations, both normal and emergency conditions need to be investigated.

**(1) Normal condition studies.**—Normal conditions are situations expected to occur frequently during project operation. A canal should be designed to accommodate normal operating conditions without causing any damage or exceeding design criteria. Studies of normal conditions include investigations using appropriate discharge variations in canal inflow and turnout deliveries (within design flow criteria). These studies begin with a pre-established method of operation.

For instance, with a constant volume method of operation, typical water-surface fluctuation rate is studied and compared with drawdown criteria. Additionally, the magnitude of water-surface fluctuation is checked against freeboard allowance. If either drawdown or freeboard criteria are exceeded, the canal system design or the method of operation will be revised until water-surface fluctuation is within allowable limits.

**(2) Emergency condition studies.**—Emergency conditions are the most severe events anticipated during the lifetime of a project. Although infrequent, emergencies should be accommodated in the design. Of course, all emergencies cannot be foreseen. However, events such as loss of power, equipment failure, and flood inflows into the canal should be studied. Usually, normal drawdown and freeboard criteria are relaxed for emergency operating conditions. The anticipated frequency of an emergency and resulting physical damage to the system are important factors requiring analysis. As a result of studies—at emergency conditions—methods of operation and designs are developed that minimize economic, environmental, and political consequences of the emergency.

**b. Design studies example.**—A numerical analog was used to simulate the Narmada Main Canal in India. The reach of canal between the diversion structure at station 0+000 and the Mahi River crossing at station 139+987 (meters) was simulated using computer program USM.

The Narmada Main Canal reach:

- Cross section is trapezoidal with side slopes of 2:1 (horizontal:vertical).
- Canal bottom width varies from 73 m (240 ft) at the diversion structure to 60 m (196 ft) at the Mahi Crossing.
- Normal depth is 7.60 m (24.9 ft).
- Bottom slope is 0.00008 with a Manning's *n* of 0.018.
- Check gate structures total 9.
- Gate structure includes a 0.5-m (1.6-ft) rise in invert from the upstream canal to the gate section and a 0.59-m (1.9-ft) drop on the downstream side of the gate.
- Average pool length is 18.6 kilometers (km) (11.5 miles [mi]), with the exception of the first pool.
- First pool has a length of about 9.3 km (5.8 mi).
- Design discharge is 1150 $m^3/s$ (40,000 $ft^3/s$).

The purpose of the simulations was to verify that the canal can operate satisfactorily at its design discharge. A downstream operation concept (demand oriented) was to be used for this section of the canal with a constant water surface elevation upstream from every check gate. This method of operation provides a predictable flow rate into the major secondary canals that branch off the main canal.

(1) **Normal operation (increasing discharge).**—The flow was increased from 54 percent of design discharge to the design discharge at the Mahi crossing in 19 hours. The flow was increased by 90 $m^3/s$ (3,160 $ft^3/s$) every 5 hours for the first 15 hours and by 76.1 $m^3/s$ (2,670 $ft^3/s$) during the last 4 hours. This discharge schedule caused the water surface upstream from the third check gate structure to overtop the canal lining. Therefore, this operating schedule could not be used without redesigning the canal. Two design changes were considered. First, the drop across the second and third gate structures could be increased. The second possibility would be to change the normal depth in the first and second pools; however, this change would require changes to the bottom width or side slopes in these two pools.

As an alternative, when flow increases, a decreasing discharge increment operating schedule could be adopted. To minimize disturbances, an exponentially decreasing rate of change could be used. For instance, the changes in flow rate could progress as: 240, 100, 50, 30, and 6 $m^3/s$ (8,500, 3,500, 1,750, 1,050, 200 $ft^3/s$) at 5-hour intervals.

The exponentially decreasing flow increment schedule would establish design flow in a satisfactory manner without exceeding drawdown or canal freeboard design limitations.

(2) **Normal operation (decreasing discharge).**—To decrease the discharge from the design flow, a constant increment of 90 $m^3/s$ (3,160 $ft^3/s$) every 5 hours was investigated. This schedule did not produce any adverse flow conditions.

(3) **Emergency flow stoppage.**—Preliminary investigations using the gate stroking algorithm yielded a procedure to stop the canal flow as quickly as possible. While keeping the water level upstream from each gate at a depth of 7.6 m (24.9 ft), flow was shut down from maximum to zero without generating waves that exceeded the freeboard. Flow in the entire canal could be stopped in 15 hours using a complicated sequence of gate opening and closing movements.

If a uniform gate closure was used instead of the complex gate adjustment pattern dictated by gate stroking, flow could be stopped in 13.5 hours. However, water level would exceed the freeboard in the most downstream pool.

Computer simulations showed that adding three check gate structures would permit a total shutdown from maximum flow in only 8 hours without overtopping the lining in any pools. Additionally, maximum flow at the Mahi crossing could be stopped in only 1 hour if upstream diversions were not turned off. Because of these significant reductions in shutdown time, the decision was made to add the three additional check gate structures.

The preceding example points out that the method of operation and the design are interrelated. Physical properties impose constraints on the capability to operate a canal at the design discharge. The example shows how a change in the number of check-gate structures or in the gate(s) operating sequence may significantly improve response to emergencies. Successful canal system design requires analysis of unsteady-flow conditions using analogs to simulate the important physical properties and flow schedule.

**c. Operational studies.**—Operational studies are conducted to determine how the canal system will be operated during its development from startup to full capacity. Historically, canal system operations have not been addressed until the canal is built and ready to use. This procedure has been particularly true with conventional canals controlled by ditchriders. Operations must be thoroughly analyzed in advance with automated canals. Operational studies are concerned with ensuring acceptable operations under a wide range of conditions. The primary goals are to:

- Determine the control concept and control method—if this determination was not made during the design studies
- Select algorithms for automatic controllers
- Determine parameters for the automatic controllers
- Specify operational strategies that allow continued operation during periods of minor equipment failure
- Specify operational procedures to be followed during emergencies

Three types of conditions need to be investigated:

- Normal
- Abnormal
- Emergency

**(1) Normal operation studies.**—A control system must perform smoothly during typical daily canal operation. Normal operation studies are used to select the most appropriate type of controller. The studies determine controller parameters that will result in stable and responsive control action over both the design and low flow rates. Low flow rates may occur during the irrigation off-season or during the irrigation system's initial development period. Normal operation studies permit quantitative evaluation of tradeoffs. Tradeoffs may include:

- Flexibility in deliveries
- Allowable canal level fluctuations
- Maintenance of delivery flow rates
- Operational costs

**(2) Abnormal operation studies.**—Abnormal studies are performed to determine how flow will be delivered when an abnormal or unusual event occurs. Abnormal events include:

- Minor equipment failure
- Draining the canal
- Filling the canal system
- Taking parts of the system out of service for testing or maintenance

These studies define the best control response for each of the anticipated abnormal operating situations.

**(3) Emergency operation studies.**—Emergency studies are used to predict the optimum response to the most severe operating conditions conceivable. Emergencies are defined as conditions that would cause severe damage to the system if specific actions are not undertaken to mitigate the situation. Usually, damage is the result of excessive water levels or the effect of rapid variation in the water level. Simulation results will indicate the best operating strategy for different emergencies. These strategies can be performed by the watermaster at the time of the emergency or preprogrammed into a supervisory control system.

**d. Operational studies example.**—Studies were made of Reclamation's Garrison Diversion Unit in North Dakota. The unit consists of three conveyance canals connected in series (McClusky, Sykeston, and New Rockford Canals).

- The combined length of canals is 230 km (140 mi).
- The maximum discharge ranges from 45.3 $m^3/s$ (1,600 $ft^3/s$) at the upstream end to 24.8 $m^3/s$ (870 $ft^3/s$) at the downstream end.
- The canal bottom width ranges from 7.6 to 13.4 m (25 to 44 ft).
- The average flow depth is 3.2 m (10.5 ft).

Originally, McClusky and New Rockford Canals were to be connected by a regulating reservoir. For environmental reasons, the reservoir was eliminated, and Sykeston Canal was needed to connect the other two canals. Before producing the final design of Sykeston Canal, designers needed an operation plan for the entire canal system. Preliminary operational studies were required to develop methods of operation and control which would satisfy delivery, environmental, and design constraints.

Delivery to water users was to be unscheduled. Therefore, a demand oriented operation concept was established. Because the canal is a combination delivery and connector system, water level was allowed to fluctuate within narrow limits.

The constant volume method of operation, in which the water level in each pool pivots about a point near its mid-pool, was selected. This method requires simultaneous operation of all check gates; therefore, a supervisory control method is required.

To study normal operations, typical day-to-day conditions in the aqueduct system were predicted. Depths and flow variations in the canal system and typical turnout flow changes were used as program input to the numerical analog. The simulation showed that water level fluctuations in the entire canal system did not exceed the drawdown criteria. Therefore, for normal operation, the supervisory control system is satisfactory.

Emergency operation studies were deemed to be critical because of environmental constraints. International requirements dictated that water could not be wasted from the Missouri River watershed into the Red River watershed that passes into Canada. The extreme emergency condition was assumed to be a large, sudden rainstorm over a majority of the irrigation area, causing most of the turnout deliveries to be turned off in a short period of time. This emergency event was simulated by totally shutting down the system from design flow to zero flow in 2 hours.

Simulation results showed that simultaneous operation of the gates would create unacceptably large fluctuations in the water levels. Additional analysis indicated large fluctuations could be controlled by using a sequential check gate operation technique and by allowing pool storage to increase during the shutdown period.

The Sykeston Canal study illustrates that different methods of operation may be needed for normal versus emergency operations to accommodate design constraints. In this case, two methods were necessary, but both could be implemented with supervisory control.

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# CHAPTER 7

# CONTROL THEORY AND APPLICATION

## CONTROL SYSTEM FUNDAMENTALS

### 7-1. Definitions

A *control system* is an arrangement of electronic, electrical, and mechanical components that commands or directs the regulation of a system. Many types of control systems exist. An electrical switch that controls the flow of electricity to a light bulb is a simple control system. A more complicated control system is a thermostat, which regulates the supply of heat to a room. Heat is supplied to the room if the temperature drops below the set value. A more complicated example is a combined heating and cooling system. In this case, if room temperature is greater than a set value, air is cooled; if temperature goes below a selected value, air is heated. Between the two limits (also called setpoint or target), action does not occur.

One characteristic of control systems is that they have an input and an output. *Input* is the stimulus applied to a control system to produce a response from the system. *Output* is the response produced by the control system. In the light bulb example, activating the electrical switch is the input, and the output is the flow or nonflow of electricity. In the thermostat examples, the thermostat setting is the input, and the affected room temperature is the output. *Error* is the difference between the actual output and the desired output.

As discussed in volume 1 (section 3-2, page 57), control systems can be classified as either *open loop* or *closed loop*. In an open-loop system, the control action is independent of actual or desired conditions (output). The electrical switch example is an open-loop system. The action of pressing the switch is completely independent of whether or not electricity flows to the light bulb. In a closed-loop system, the control action depends on the actual or desired conditions (output). Both air temperature control examples are closed-loop systems. Their control actions depend upon the temperature of the air in the room.

All closed-loop systems have a characteristic called *feedback*. Feedback is that property of a system in which the controlled quantity (output) is measured and compared to the target or setpoint. The relative values of the input and output determine the control action. In the room air example, air temperature is compared to the thermostat setting. If a difference (an error) exists between the air temperature and the thermostat setting, the room is heated or cooled to increase or decrease the room temperature.

In a canal situation, local-manual control of a canal is an example of an open-loop system. The input is a change in position of a check gate, and the output is the change in either the upstream or downstream water levels at the check structure. The water level does not directly determine the setting of the check gate. Likewise, manual-supervisory control is also an example of an open-loop system. The input and output variables are the same as for local-manual control. Both of these examples represent the most elementary types of control systems.

Local-automatic and supervisory-automatic control are examples of closed-loop systems which employ feedback. The simplest control action is a three-position mode of control; that is, the correction has three discrete values: no correction, increase in correction, and decrease in correction. The Little-Man controller is a simple, closed-loop control system that uses a three-position mode of control. Other types of closed-loop controllers use more complicated control modes, which include proportional, integral, and derivative functions. Modes of control were introduced in volume 1 (section 3-6, page 60). A detailed discussion of the logic used in these modes is described in section 7-6, *Controller Components*.

The control action affects the response and stability characteristics of the system. Responsiveness is the time in which the control system corrects errors. Stability is the ability to return to equilibrium after initiating a change [14]. In a *stable* system, disturbances decay with time. If the disturbances oscillate or fluctuate at a constant amplitude or if they increase in amplitude, the system is *unstable*. As noted in volume 1 (section 3-5, page 59), the designer has to balance responsiveness and stability.

The advantages of a *properly* designed feedback control action:

- Provides stability to the system being controlled
- Minimizes variations in the output
- Reduces the effects of nonlinearities
- Increases range of frequencies over which the system will function properly
- Provides responsiveness

The disadvantage of feedback is an increase in the tendency for the system to oscillate and become unstable.

In analyzing a system for stability, a time history analysis of the disturbances is often unnecessary. Predicting the behavior of the oscillations with time may be sufficient. This prediction can be done by analyzing the characteristics of the Laplace transform of the system [15]. The analysis is simplified by representing the system as a block diagram.

A *block diagram* is the pictorial representation of the relation between the input and output of elements of a control system as shown on figure 7-1. Block diagrams show the logic of the interrelations between various elements of a control system. Each block represents a transfer function of an element of the system. A *transfer function* is the ratio of the Laplace transform of the input to the Laplace transform of the output of a block. Transfer functions are written with the assumption that all initial conditions are equal to zero. In block diagrams, the operation of addition and subtraction is a *summing point*. The output of the summing point is equal to the algebraic sum of the inputs to the point.

In the following sections, elements in the feed forward path are noted by a $G_x$ and those in the feedback path by an $H_x$. The *feed forward* path is the transmission path from the actuating or error signal to the controlled output. The *feedback* path is the transmission path from the output to the primary feedback signal. The *primary feedback* signal is the signal that is summed with the reference signal or input to obtain the actuating signal. The subscript $x$ is a function identifier.

## 7-2. Input and Output Variables

In canals, discharge is normally the parameter that is to be controlled, although discharge is not a quantity which can readily be determined. Instead, some other quantity must be measured; then, discharge is related to that quantity through algorithms. In canals, the parameter most frequently used is water surface elevation or the difference in water surface elevation between two points. Unless otherwise noted, water surface elevation is the controlled parameter (input) in the following discussion.

The location and number of sensors used as output depend on the objectives of the conveyance system (see volume 1, section 4-2, page 84). Only one water level sensor per reach is used if the canal is a delivery system consisting of gravity turnouts. Usually, the location of the sensor is near the downstream end of a canal reach near the turnouts. Thus, the water level at the turnout is relatively constant as the flow rate in the main canal varies. Similarly, a pumping plant is usually controlled with only one water level sensor. If the pumping plant is used in a collector system, the sensor is located on the suction side of the pumping plant. With a delivery system, the sensor is located on the delivery side of the pumping plant.

Multiple sensors in a canal pool are used to implement various control methods. Figure 7-2 shows the use of two sensors in a canal to control the location of the pivot point [14, 15]. In this case, the sensors are located at each end of the pool. They are connected to a proportional controller which prorates the contribution of each sensor.

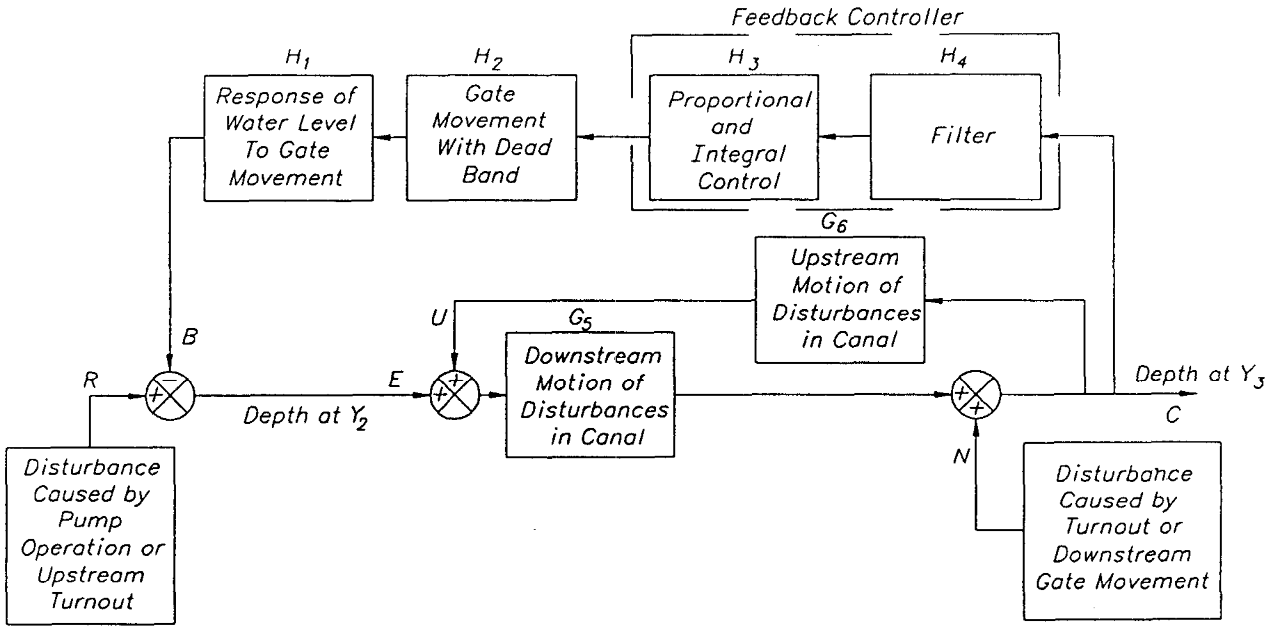



Figure 7-1.—Block diagram.

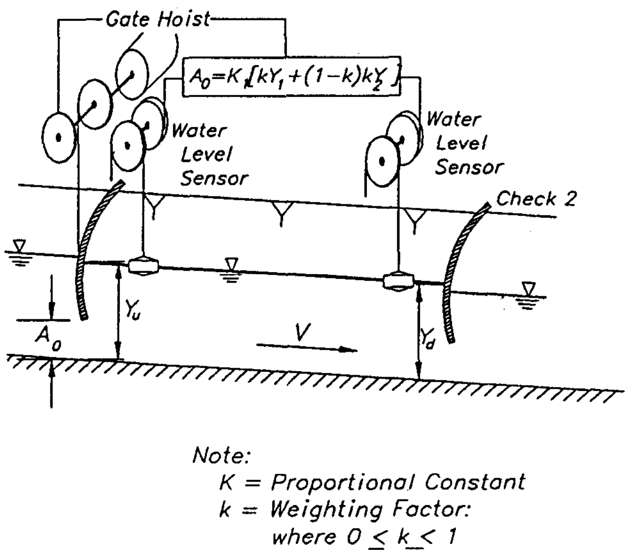



Figure 7-2.—Multiple sensors in a pool.

The relative weight given to the input of each sensor determines the location of the pivot point within the pool. Several sensors can detect the amount of water existing in the pool during unsteady operation of the canal [3]. The West Oakes Test Area [2] is an example where three sensors per pool have been used on a Bureau of Reclamation (Reclamation) canal.

To use an output based upon discharge, the flow rate is determined from flow measurement devices such as Parshall flumes, venturi meters, and weirs. The differential head produced across radial (tainter) gates can also be used to determine discharge if a flow calibration curve for the gates is available. Buyalski [9] developed calibration curves for a variety of conventional radial gate configurations used in canal operations. Using a discharge-based input requires some type of flow meter which limits the application of a discharge-based output.

## 7-3. Control Action

Control of a variable requires mechanical equipment such as gates, valves, and pumps. Electrical signals from an input sensor control the setting of the gate position(s) or pump discharge(s). The interdependence of the input and output variables, how they are implemented by a control action, and their representation by block diagrams can better be understood by using an example.

Figure 7-3 shows a downstream controller designed for the downstream operating concept. This controller is known as the ELFLO plus RESET. The controlled system is the canal water prism between check gates. The input is the setpoint water level, and the output is the water level at the pool's

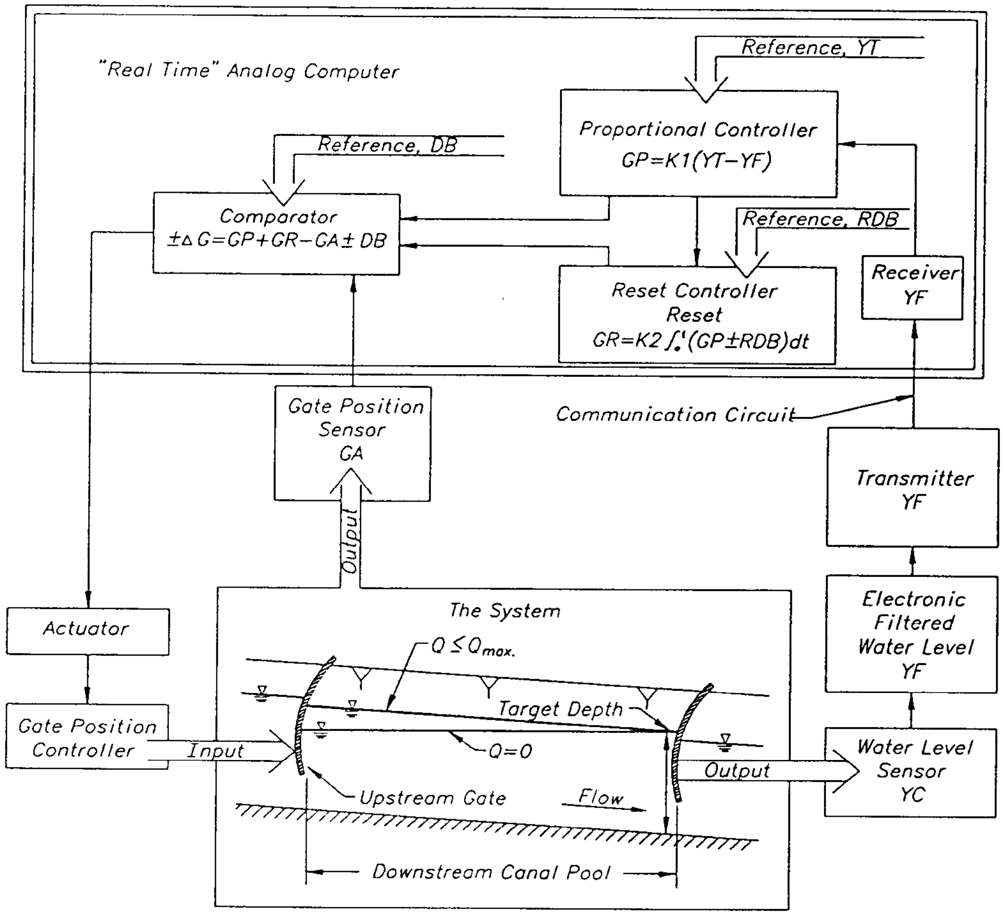



Figure 7-3.—ELFLO plus RESET controller.

downstream end. The mechanical equipment that implements the control action is the gate at the pool's upstream end. The controller includes all of the electrical and electronic equipment between the input sensor and the gate, including:

- Control element
- Comparator
- Gate movement actuator
- Gate position indicator

The following items will affect water levels throughout the prism:

- Variation of flow rate in pools upstream from the upstream gate
- Movements of the upstream gate
- Turnouts within the prism
- Movement of the downstream gate
- Changes in discharge in the downstream pools

The components of an ELFLO plus RESET controller are shown on figure 7-4. As noted earlier, all transforms noted with a **G** are located on the feed forward path. All transforms noted with an **H** are located on the feedback path. This controller uses two feedback paths. One is located in the gate-position loop, and the other consists of the sensor transform. Also, the diagram has three summing points. At these points, signals are either added or subtracted to initiate a primary feedback signal. A block diagram reduces the complicated interrelations of the canal and feedback components to a "black box" describing the system and its feedback path.

The goal of the controller in this example is to maintain the downstream-pool water level as constant as possible by controlling the motion of the upstream gate. A rapid response to disturbances is desirable (responsiveness). However, the gate motion must not be too large or fast because an overreaction to the disturbance can

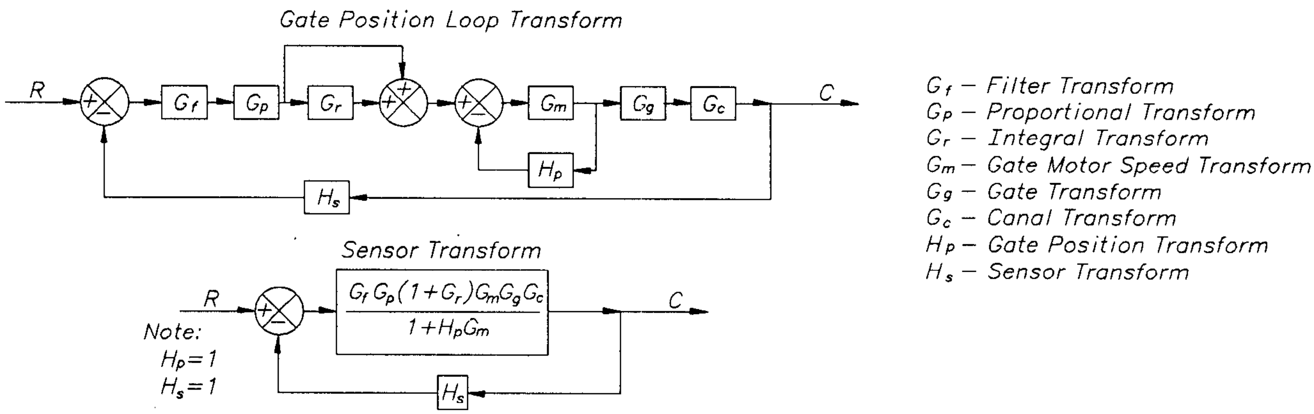



Figure 7-4.—Control components of ELFLO plus RESET.

lead to instability. Thus, the selection of components for the feedback controller requires careful consideration. The selection of controller components, other than for gain, to create desirable system characteristics is called *providing compensation.*

# RESPONSE CHARACTERISTICS OF CONTROL AND CANAL COMPONENTS

## 7-4. Description of Response Characteristics

To construct an analytical model of a canal system, the response characteristics of each component (block) of the system must be expressed in mathematical terms. The mathematical terms can be written either as functions of time (*time domain*) or as Laplace transforms (*complex domain*). The time-domain description is used to develop an analytical model that behaves much like the actual canal. All of the nonlinear effects can be simulated with the time-domain responses. The Laplace transform description is used to develop an analytical model for investigating the stability of the canal system and can aid in determining control parameters. The complex-domain description is a simplification of the real system using linear versions of the response characteristics. Each of the components given in the following sections describes the response characteristics in both the time and complex domains. In addition to describing the response characteristics of the controller, the response of the water in the pool to control actions is considered.

## 7-5. Hydraulic Components

**a. Canal prism.**—The hydraulic characteristics of the canal prism are described by the Saint-Venant equations, which are the nonlinear partial differential equations presented in chapter 6 (equations 6.1 and 6.2).

These equations were solved by Hâncu et al. [15] to give the nondimensional form in the time domain as:

$$\frac{\partial^2 Y}{\partial \tau^2} = 2F \frac{\partial^2 Y}{\partial X \partial \tau} - R^2 \frac{\partial^2 Y}{\partial X^2} + \beta \frac{\partial Y}{\partial \tau} + \Gamma \frac{\partial Y}{\partial X} = 0 \qquad 7.1$$

where:

$C$ = wave celerity
$L$ = length of pool
$R^2$ = $1 - F^2$
$F$ = $V / C$ = Froude number
$V$ = velocity
$X$ = $x / L$ = dimensionless distance
$x$ = distance along canal invert
$Y$ = $y / Y_n$ = dimensionless depth
$Y_n$ = normal depth
$y$ = flow depth

Equation 7.1 neglects the effect of lateral inflow. The dimensionless variables are defined as:

$$\beta = \frac{2gS_0L}{V_n} \qquad 7.2$$

$$\Gamma = \frac{kS_0L}{Y_n} \tag{7.3}$$

$$\tau = \frac{tC}{L} \tag{7.4}$$

where:

- $g$ = gravitational acceleration
- $k$ = hydraulic exponent
- $S_0$ = bottom slope
- $t$ = time
- $V_n$ = average velocity at normal depth

For the complex domain, the Saint-Venant equation is linearized and written in terms of small deviations [14]. The transform of the linearized partial differential equation, written in nondimensional units, leads to the following ordinary differential equation:

$$R^2 \frac{d^2Y(S)}{dX^2} - (2FS + \Gamma)\frac{dY(S)}{dX} - S(S + \beta)\, Y(S) = 0 \tag{7.5}$$

This equation has the following initial conditions:

$$\tau = 0,\quad Y = 0,\quad dY(S)/d\tau = 0$$

The general solution of the differential equation is:

$$Y(S) = C_1\, e^{\alpha_1 X} + C_2\, e^{\alpha_2 X} \tag{7.6}$$

The values $C_1$ and $C_2$ are functions of the Laplace variable, $S$, determined by the upstream and downstream boundary conditions. The method of determining the coefficients for a wide variety of controllers and for a series of pools is outlined by Hâncu and Rus [14] and Hâncu et al. [15]. The values $\alpha_1$ and $\alpha_2$ are roots of the characteristic equation:

$$\alpha_{1,2} = \frac{2FS + \Gamma \pm \sqrt{(4FS + \Gamma)^2 + 4R^2\, S(S + \beta)}}{2R^2} \tag{7.7}$$

**b. Gate movement.**—The time-domain expression for the discharge fluctuation produced by a change in the gate position can be derived by assuming the discharge through a gate is given by:

$$Q_g = C_d\, B\, G_o \sqrt{2gY_u} \tag{7.8}$$

where:

- $B$ = width of gate
- $C_d$ = discharge coefficient based upon upstream depth
- $G_o$ = vertical distance between invert and bottom of gate
- $g$ = gravitational acceleration
- $Y_u$ = depth upstream from gate

The values of the discharge coefficient have been determined for typical types of gates. These coefficients are functions of the gate opening and the upstream and downstream depths. For radial gates, the coefficients are also a function of the radius of curvature of the upstream face of the gate and the height of the pinion above the canal invert.

The complex-domain expression for the discharge response was derived by Hâncu et al. [15], who assumed that the discharge through a gate could be written as:

$$Q_g = C_d'\, B\, G_o \sqrt{2g\,(Y_u - Y_d)} \tag{7.9}$$

where:

- $C'_d$ = discharge coefficient based upon depth differential across gate
- $Y_d$ = depth downstream from gate

The transform is given by:

$$Q(S) = \frac{G(S)}{G_o} + \frac{Y(S)_u}{2H_o} - \frac{Y(S)_d}{2H_o} \tag{7.10}$$

where:

- $G(S)$ = transform of the change in gate opening
- $Y(S)_u$ = transform of depth upstream from gate
- $Y(S)_d$ = transform of depth downstream from gate
- $H_o$ = head across gate = $Y_u - Y_d$

For this derivation, the change in head across the gate is assumed to be small enough so that the discharge coefficient can be considered constant.

## 7-6. Controller Components

The controller components are conceptually described in volume 1 (sections 3-3 through 3-8, pages 57 to 62). Some controllers may only have one component. Other controllers may have several components connected either in parallel or in series. The control element component of a controller processes the control algorithms. The control element may use one or more modes of control. The modes of control (also called functions) discussed below are three position: proportional, integral, and derivative. In addition, the controller may include a linear function with time, a filter, a deadband function, or an antihunt function. Sections 7-10 through 7-19 describe details of specific controllers used on Reclamation projects.

**a. Three position.**—The purpose of this function is to initiate a control action when the input is greater than or less than the setpoint value. *Deadband* is the range through which the measured signal can vary without initiating a control action. The purpose of the deadband is to prevent the controller from being actuated for infinitesimal deviations from the setpoint. A three-position function is nonlinear because a sinusoidal input produces a step output as shown on figure 7-5.

At steady state, the discharge from a canal pool has a specific value of the flow rate. However, the deadband causes the inflow into the reach to change in increments. Only under the most unusual conditions does the sum of the incremental changes in discharge equal the delivered discharge. Typically, the inflow discharge varies about the desired delivery discharge. Falvey [11] gives the time interval, $T_c$, for a cycle to repeat as:

$$T_c = \frac{2\,d\,L\,T_w}{K_1 Q_s} \frac{\frac{d}{G_o}}{(n+1)\left[\left(\frac{d}{G_o} - 1\right)\left(1 - n\left(\frac{d}{G_o}\right)\right)\right]} \qquad 7.11$$

where:

$d$ = deadband increment
$K_1$ = proportional gain of controller
$L$ = pool length
$n$ = truncated value of $G_o / d$ (an integer)
$Q_s$ = delivery discharge
$T_w$ = average top width of water surface in pool

The first term on the right side of the equation consists only of the canal parameters. Figure 7-6 shows the variation of the second term as a function of frequency. Frequency is defined as the number of times a periodic fluctuation repeats itself per unit time, or as the reciprocal of the time interval, $T_c$. The maximum possible frequency of oscillation, $f_m$, is given by:

$$f_m = \frac{K_1\,Q_s}{8\,L\,T_w\,G_o} \qquad 7.12$$

Many controllers contain a deadband function. For instance, the controller shown on figure 7-3 uses a deadband function in the comparator block for the gate position.

**b. Proportional.**—The proportional function is one in which the output of the action is directly proportional to the input. For a gate, the time-domain relationship is given by:

$$\Delta G_o = K_1\,\Delta Y \qquad 7.13$$

where:

$\Delta G_o$ = change in gate opening
$K_1$ = proportional constant
$\Delta Y$ = variation in water depth from target

The complex-domain relationship is similar:

$$G(S) = K_1\,Y(S) \qquad 7.14$$

where:

$G(S)$ = transform of the change in gate opening
$Y(S)$ = transform of the change in water level from target
$S$ = Laplace variable = $\sigma + i\,\omega$
$i$ = square root of $-1$
$\sigma$ = real part of the complex variable
$\omega$ = imaginary part of the complex variable

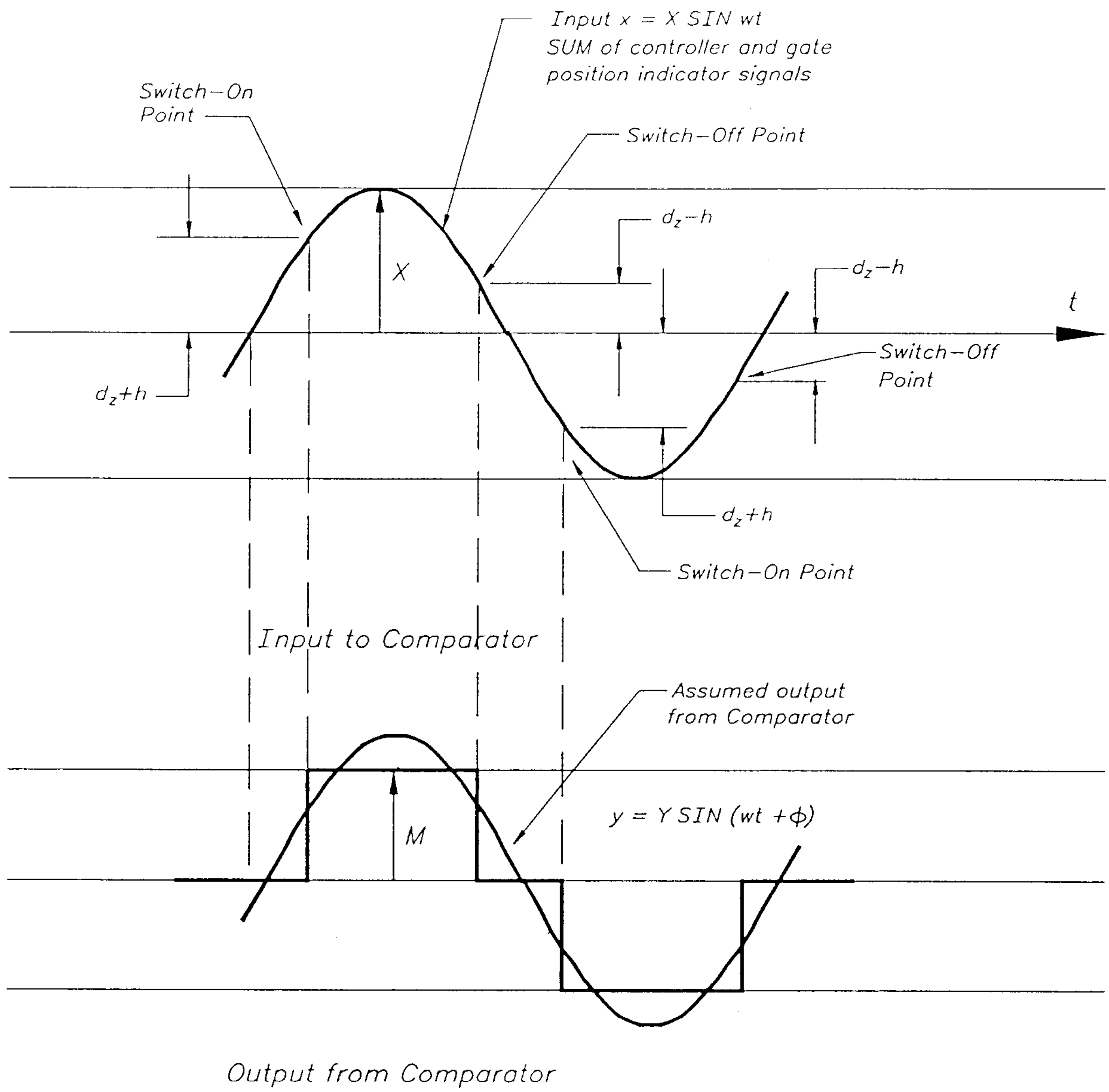



Figure 7-5.—Three-position control function.

The proportional constant, $K_1$, can be calculated in terms of pool-response parameters when variation in water depth at the water level sensor is caused by a surge wave as shown on figure 7-7.

The change in discharge caused by a surge wave is given by:

$$\Delta Q = \Delta Y\, T_w(V + C) \qquad 7.15$$

where:

$C$ = wave celerity (defined below)
$T_w$ = width at top of water surface
$V$ = mean velocity at sensor
$\Delta Y$ = change in depth (increases in depth are positive)

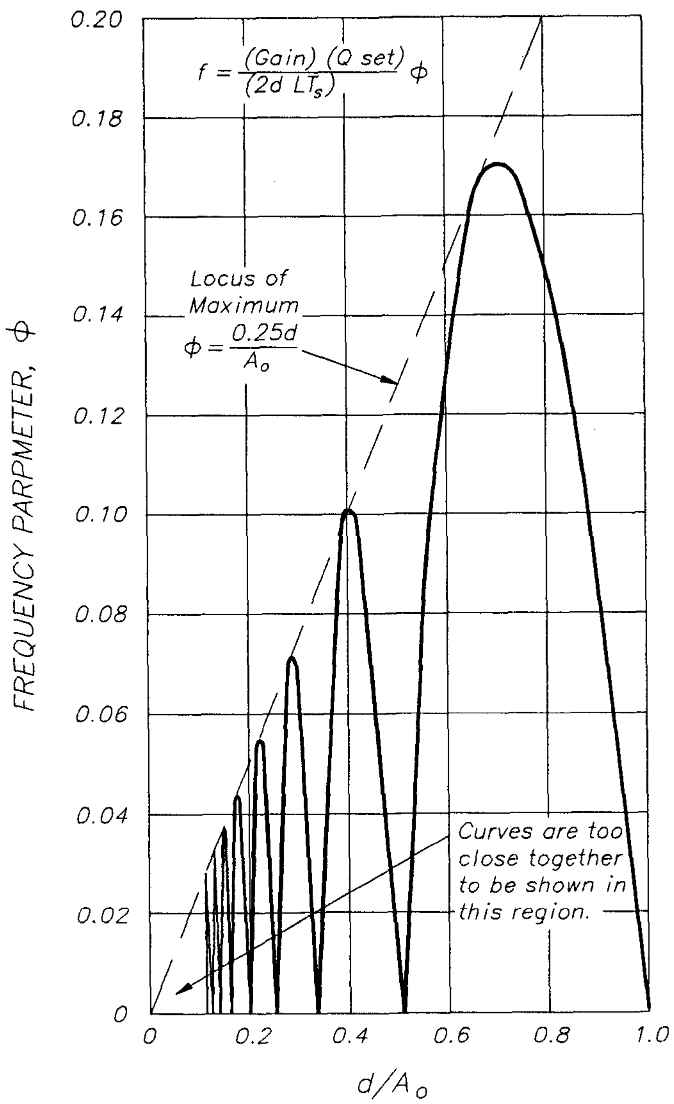



Figure 7-6.—Frequency of limit cycle for three-position controller.

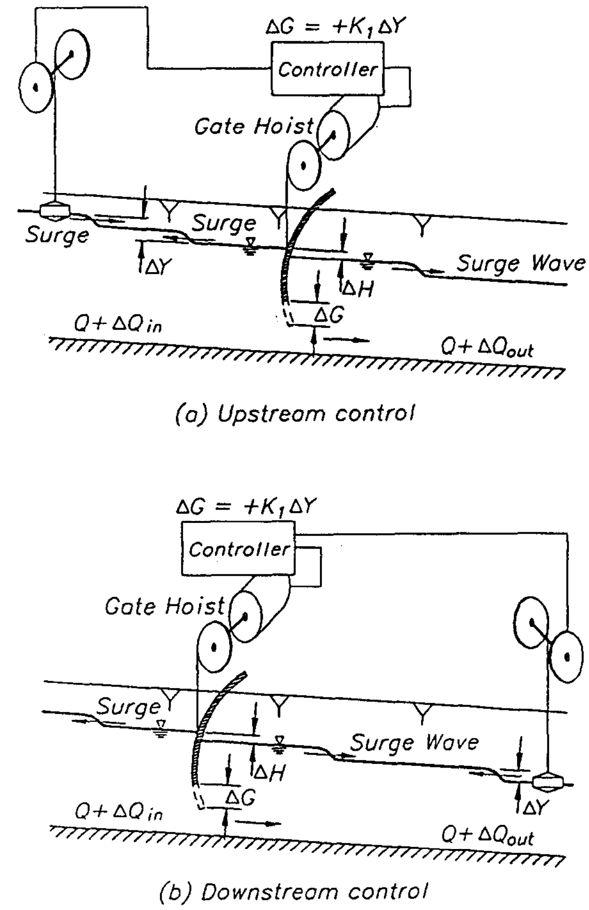



Figure 7-7.—Proportional control example.

By differentiating equation 7.8, the change in discharge through a gate is obtained as:

$$\Delta Q = C_d\,B\,\Delta G_o\sqrt{2g\,Y_u} + \frac{C_d B G_o g}{\sqrt{2g\,Y_u}}\,\Delta Y_u + G_o\,B\,\Delta C_d\sqrt{2g\,Y_u} \qquad 7.16$$

or

$$q = \frac{\Delta Q}{Q_g} = \frac{\Delta G_o}{G_o} + \frac{\Delta Y_u}{2Y_u} + \frac{\Delta C_d}{C_d} \qquad 7.17$$

For cases where the upstream depth, $Y_u$, is held constant, the $\Delta Y_u / Y_u$ ratio is equal to zero.

The wave celerity, C, is given by:

$$C = \sqrt{\frac{gA}{T_w}} \qquad 7.18$$

where:

*A* is the cross-sectional area of the canal prism. By equating the flow change caused by the surge wave (equation 7.15) with the flow change produced by a gate motion (equation 7.10), the proportional constant can be expressed as:

$$K_1 = \frac{\Delta G_o}{\Delta Y_u} = \frac{T_w(v + c)G_o}{Q} \frac{1}{\left[1 + \frac{G_o}{C_d}\frac{\Delta C_d}{\Delta G_o} + \frac{G_o}{2Y_u}\frac{\Delta Y_u}{\Delta G_o}\right]} \qquad 7.19$$

where:

$G_o$ = gate opening
$C_d$ = discharge coefficient of gate based upon upstream depth
$Y_u$ = flow depth upstream from gate

The variation of the proportional constant with discharge for a typical canal pool using upstream control is shown on figure 7-8.

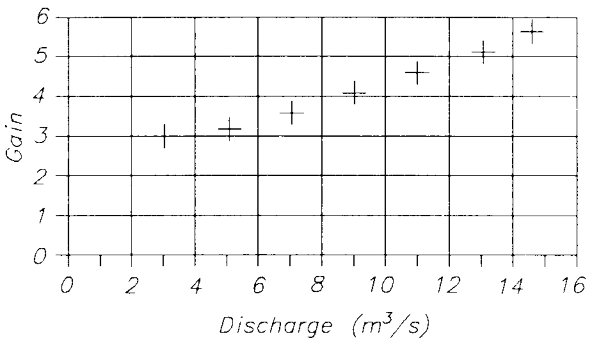



Figure 7-8.—Variation of proportional constant with discharge.

Some unique applications require relationships other than equation 7.19 to define the proportional constant. For example, with a diversion structure, the variation in the reservoir pool level can be equated to the flow change at a gate. This process leads to a definition of the proportional constant which is a function of:

- Maximum discharge in the canal
- Maximum water level in the pool
- Hydraulic characteristics of the diversion gate

The details of the method are discussed in section 7-14.

**c. Integral.**—The purpose of an integral function is to return the water level to its original elevation after a change in flow rate. Because of this action, the integral control function is called *reset.*

The integral function in the time domain is given in Buyalski and Serfozo [6] as:

$$G_o = K_2 \int_{t=0}^{t} \Delta Y \, dt \qquad 7.20$$

where:

$K_2$ = integration constant
$t$ = time

The complex domain expression for the integral element is given by:

$$G(S) = \frac{K_2 \; Y(S)}{S} \qquad 7.21$$

The gain, for an integral control element, is high at low frequencies and low at high frequencies. Therefore, the integral function acts as a low-pass filter. This characteristic tends to produce instabilities near steady state. The reduced gain at high frequencies results in slow response characteristics. Thus, an integral function has undesirable characteristics that require compensation.

The selection of the integration constant must be performed using stability analysis methods (discussed later). If the value is too small, the recovery of the water level to its setpoint value will take place slowly. If the value is too large, control instabilities develop. A typical value for the integration constant is 0.01 per minute.

**d. Derivative.**—The derivative function is proportional to the rate of change of the input. A derivative function can produce a significant correction before the error signal becomes large. When added to the proportional function, the derivative action provides a controller with high sensitivity. Currently, Reclamation has not used a derivative element in any canal controller.

The time-domain expression for the derivative element is:

$$\Delta G_o = K_3 \frac{dY}{dt} \qquad 7.22$$

where:

$K_3$ = the derivative constant

The complex-domain expression for the derivative element is:

$$G(S) = K_3 \; S \; Y(S) \qquad 7.23$$

e. **Filter.**—The purpose of a filter is to compensate for the wave travel time in a canal. The filter also eliminates the effect of high-frequency level fluctuations such as wind waves.

The time-domain expression for a filter is given in Buyalski and Serfozo [6] by:

$$Y_f = K_4 \; Y \left[ 1 - e^{-(t \,/\, T_c)} \right] \qquad 7.24$$

where:

$K_4$ = filter constant
$t$ = time
$T_c$ = filter time constant
$Y$ = depth at sensor
$Y_f$ = filtered depth
$e$ = Euler's number

The time constant is the time required for the gate opening to reach 63 percent of its final position when the water level experiences a step change. This result can be seen from equation 7.24 by equating the time to the time constant. With this substitution, the value of the expression within the brackets is equal to 0.6321.

The complex-domain expression for a filter is given by:

$$Y_f(S) = K_4 \; Y(S) \left( \frac{1}{S} - \frac{1}{S + T_c} \right) \qquad 7.25$$

Hâncu and Rus [14] have shown that the system can always be made stable by proper selection of the time constant, $T_c$ .

To avoid instabilities, the time constant for a filter with a downstream controller is chosen to be approximately equal to the wave travel time in the canal. The wave travel time is:

$$T_c = \frac{L}{C} \qquad 7.26$$

where:

$L$ = length of pool
$C$ = wave celerity

In equation 7.26, the wave celerity is based upon flow properties with normal depth in the canal pool. To eliminate the effect of wind waves for sensors that are close to a gate, use a time constant of 100 seconds.

The value of the filter constant, $K_4$ , is generally set equal to 1.0.

f. **Linear functions with time.**—The motion of a gate being driven by a constant-speed motor is an example of a linear function with time. The time-domain expression is given by:

$$\Delta G_o = K_5 \; t \qquad 7.27$$

where:

$K_5$ = the speed of the gate (distance per unit time)

The complex-domain expression for a linear function with time is given by:

$$G(S) = \frac{K_5}{S^2} \qquad 7.28$$

For a main canal system, the value of the gate speed is about 500 millimeters per minute.

## ANALYSIS AND PERFORMANCE SPECIFICATIONS

### 7-7. Objectives

The analysis objectives are to investigate:

- system stability
- steady-state performance
- transient response characteristics of the system

The transient response characteristics can be quantified through the use of performance specifications.

Performance specifications can take one of two forms, complex-domain specifications or time-domain specifications:

- Complex-domain specifications describe the stability characteristics of a system
- Time-domain specifications describe the real-time response characteristics of a system.

## 7-8. Methodology

Conventionally, two types of studies are used in the analysis of the controllers for an automated canal system: stability methods and time-domain simulation methods. The stability methods use linearized equations to describe small perturbations in the canal flow and of the control elements. Although the linearized equations are simplifications of the true nonlinear equations, they are sufficiently accurate to determine approximate values for the control parameters. In addition, the computational effort to analyze the linear equations is much less than is required for the exact nonlinear equations. The stability methods can be imagined as a screening method to determine values of the control parameters that will yield a stable system. The stable control parameters then must be investigated with time-domain simulation methods to determine the optimum values of the control parameters.

The time-domain simulation methods use the nonlinear equations for modeling flow in the canal and for simulating the control elements. The time-domain simulation accurately reproduces the characteristics that will be observed in the field. The computational effort for these studies is much greater than that required for the stability studies. Experience in both computer simulation and operation of canal systems is necessary to properly conduct the time-domain simulations.

Reclamation has developed computer programs to investigate only the time-domain simulations. One of these programs, which includes several types of controllers and is available for use on a personal computer, is called USM [17]. Hancû et al. [15], describe methods of performing the complex-domain simulations for stability analysis.

## 7-9. Performance Specifications

Performance specifications are constraints imposed on system characteristics. They are stated with particular measurable quantities in either the complex-domain or time-domain descriptions of the system behavior. Generally, the performance characteristics specify three important properties of dynamic systems [10]:

- Speed of response
- Relative stability
- System accuracy or allowable error

**a. Complex-domain specifications.**—The frequency characteristics of a system consist of amplitude and phase descriptions of the open- or closed-loop response characteristics over a specified range of frequencies. The complex-domain specifications define pertinent qualities of these characteristics. The most common specifications are:

- Resonant peak amplitude
- Resonant frequency
- Bandwidth
- Cutoff frequency
- Cutoff rate
- Gain margin
- Gain crossover frequency
- Phase margin
- Delay time

These specifications are described below and are illustrated on figure 7-9.

***Resonant peak amplitude***, $M_r$, is the maximum value of the magnitude of the closed-loop frequency response.

***Resonant frequency***, $f_r$, is the frequency at which the resonant peak amplitude occurs.

***Bandwidth***, $B_w$, is the range of frequencies of input over which the peak amplitude does not differ by more than –3 decibels (db) from its value at a specified frequency. A db is defined by:

$$\text{db} = 20 \log_{10}(\text{magnitude ratio})$$

The magnitude ratio is defined as the ratio of the input to the output, or the ratio of the actual value to the setpoint value.

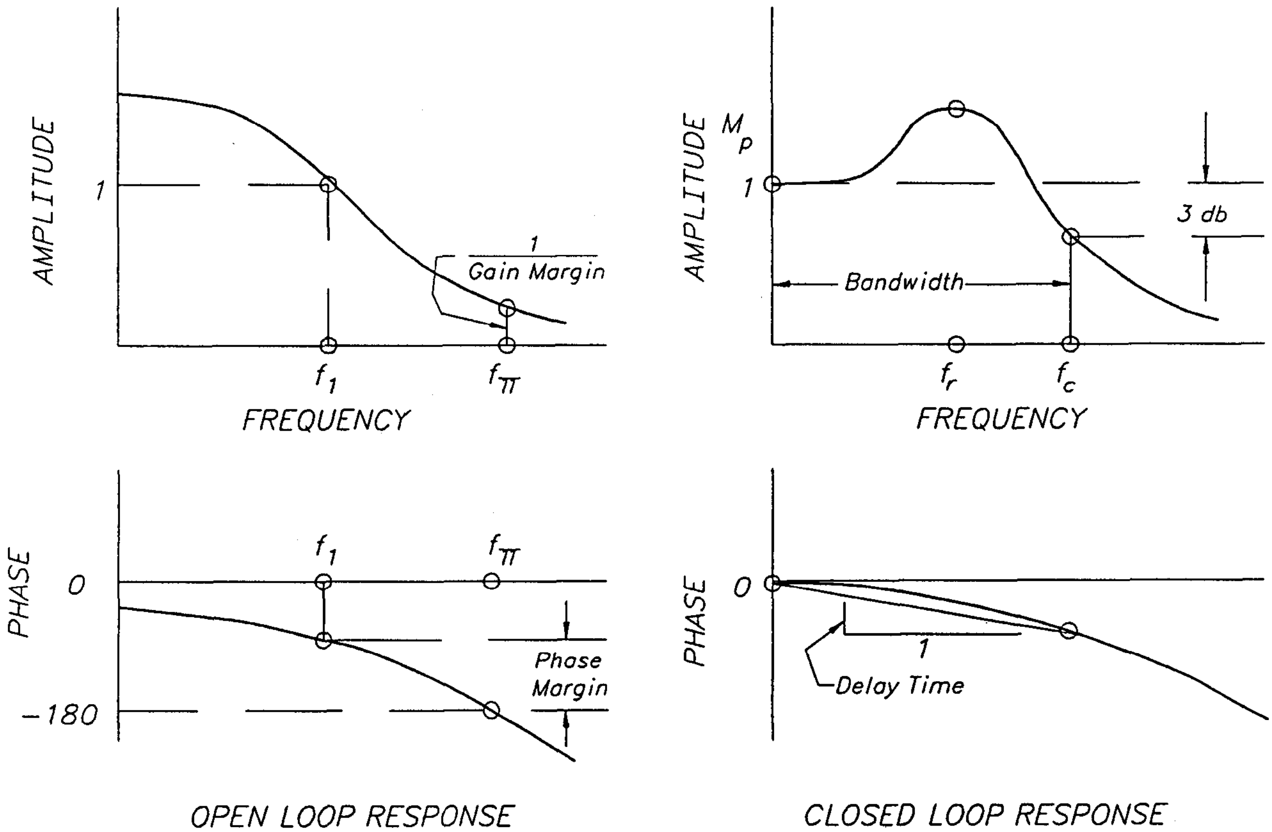



Figure 7-9.—Complex-domain specifications.

***Cutoff frequency***, $f_c$, is the frequency that defines the limits of the bandwidth.

***Cutoff rate*** is the rate at which the amplitude decreases with frequency beyond the cutoff frequency.

***Gain margin*** is the magnitude of the reciprocal of the open-loop transfer function, evaluated at the frequency, $f_\pi$, where the phase angle is equal to –180 degrees.

***Gain crossover frequency***, $f_1$, is the frequency at which the gain is unity.

***Phase margin*** is 180 degrees plus the phase angle of the open-loop transfer function at unity gain.

***Delay time*** is the negative derivative of the phase with respect to frequency for the closed-loop response.

**b. Time-domain specifications.**—The time-domain specifications are described by the transient response of a damped (second order) system to an initial step input. They consist of the following:

- Overshoot
- Delay time
- Rise time
- Settling time
- Peak time
- Predominant time constant
- Logarithmic decrement

These specifications are described below and are illustrated on figure 7-10.

***Overshoot***, $M_p$, is the maximum peak value of the response curve. The value of the overshoot is usually expressed as a percentage.

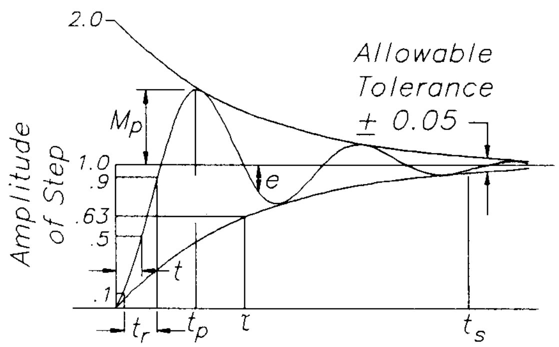



Figure 7-10.—Time-domain specifications.

***Delay time***, $t_d$ , is the time interval between the step change and the time for the response to reach 50 percent of its steady-state value.

***Rise time***, $t_r$ , is the time interval for the response to change from 10 to 90 percent of its steady-state value. Sometimes other percentages are used. The most common values are 5 to 95 percent and 0 to 100 percent.

***Settling time***, $t_s$ , is the time interval between the step change and the time for the response to be within the allowable tolerance. Theoretically, the oscillations never cease. However, they decrease to some acceptable limit. The acceptable limit is the allowable tolerance. The magnitude of the allowable tolerance is usually 5 percent of the step change. However, the magnitude of the allowable tolerance may be as small as 2 percent.

***Peak time***, $t_p$ , is the time interval between the step change and the time at which the response reaches its maximum value.

***Predominant time constant***, $\tau$ , is the time interval between the step change and the time for the envelope of the response to decay to 37 percent of its initial value.

***Logarithmic decrement***, $\delta$, is the logarithm of the ratio of two successive maximum (or minimum) values of the oscillations as:

$$\delta = \ln \frac{Q_2}{Q_1} \qquad 7.29$$

where:

$Q_1$ = a maximum value of discharge (or water depth)

$Q_2$ = the succeeding maximum discharge (or water depth)

The logarithmic decrement is easy to measure and represents the rate at which a disturbance decays in *nepers per cycle*. For a second-order, damped system, the logarithmic decrement is related to the relative damping by:

$$\frac{C}{C_r} = \frac{\delta}{\sqrt{\delta^2 + 4\pi^2}} \qquad 7.30$$

For $C/C_r < 1/\sqrt{2} = 0.707$, no oscillations are amplified.

Not all of these specifications apply in all cases. For example, in an overdamped system, the peak time and overshoot are not applicable.

A controller is designed by first specifying values of:

- Overshoot
- Rise time
- Settling time
- Allowable tolerance
- Delay time

Then the controller parameters are varied in an effort to meet the specified limits.

Intuition indicates that some values must be of the controller parameters that optimize the specifications. One method of optimizing the specifications is by analysis of the error signal, $\epsilon$ (figure 7-8). The error signal is the difference between the amplitude of the response and the final steady state. The analysis is done by varying some control parameter such as proportional gain. A value of the parameter is selected, and the integral or performance index is evaluated. The process is repeated with different values of the selected controller parameter, and a curve of the performance index versus the controller parameter is drawn. The minimum value of the curve represents the best selection for the value of the specific parameter. An insensitive performance index varies slowly as the parameter is varied. A sensitive performance index exhibits a distinct minimum value as the control parameter is varied. Each performance index produces a different controller characteristic.

The four types of performance indexes are:

- Integral square-error
- Integral-of-time-multiplied square-error
- Integral absolute-error
- Integral-of-time-multiplied absolute-error

*Integral square-error* is defined as:

$$E_s = \int_0^\infty \epsilon^2 \, dt \qquad 7.31$$

A controller designed with this criterion shows a rapid decrease in a large initial error. The response is fast and oscillatory. However, the system will have a minimum of power consumption. The criterion is insensitive to the selection of the parameters values.

*Integral-of-time-multiplied square-error* is defined as:

$$e_{st} = \int_0^\infty t \, \epsilon^2 \, dt \qquad 7.32$$

A controller designed with this criterion ignores large initial errors and emphasizes errors occurring late in the transient response. This method is moderately sensitive to selection of parameter values.

*Integral absolute-error* is defined as:

$$E_a = \int_0^\infty |\epsilon| dt \qquad 7.33$$

A controller based upon this criterion produces a reasonable damping and a satisfactory transient-response characteristic. The criterion is moderately sensitive to selection of parameter values.

*Integral-of-time-multiplied absolute-error* is defined as:

$$E_{at} = \int_0^\infty t|\epsilon| dt \qquad 7.34$$

A controller based upon this criterion produces a small overshoot, and the oscillations are damped. This criterion is sensitive to selection of parameter setting. Of the four performance indexes, the integral-of-time-multiplied absolute-error is the most applicable to automatic controllers.

## CLOSED-LOOP CONTROL OF INDIVIDUAL STRUCTURES

### 7-10. Development

The first and simplest form of automatic control used by Reclamation was a three-position type controller called the *Little-Man*. The addition of other control elements in the feed-forward path led to the development of the *Colvin Controller.*

Most automatic canal systems use water level as the input on which corrective action is taken. Reclamation has also developed controllers that use discharge as the input. These controllers are known as *Q-Controllers.* A Q-Controller does not control water levels. The Q-Controller has potential applications for local automatic control, particularly when combined with the Supervisory Control method.

Two types of Q-Controllers have been used: *Gate Q-Controllers* and *Differential Head Q-Controllers.* A Gate Q-Controller determines discharge from the gate opening and the upstream and downstream water levels at the flow control structure. Differential Head Q-Controllers determine discharge from flow meters, such as Parshall flumes and weirs, where the relationship between water level and discharge is unique.

The development and mechanical features of Little-Man and Colvin controllers are described in volume 1. Hence, only their algorithms will be considered in the following sections. The other controllers were not discussed in volume 1. Therefore, some of their mechanical features will be considered with emphasis on the control algorithm.

### 7-11. Little-Man Controller

The Little-Man controller is based upon the three-position control function described in section 7-6. The motor actuator of the Little-Man controller contains a timer that allows the motor to run for only a few seconds. Another timer provides an interval before the next operation of the gate takes place. This operation is also referred to as an SOT/SRT (set-operate-time, set-rest-time) control action. The action is shown on figure 7-11a.

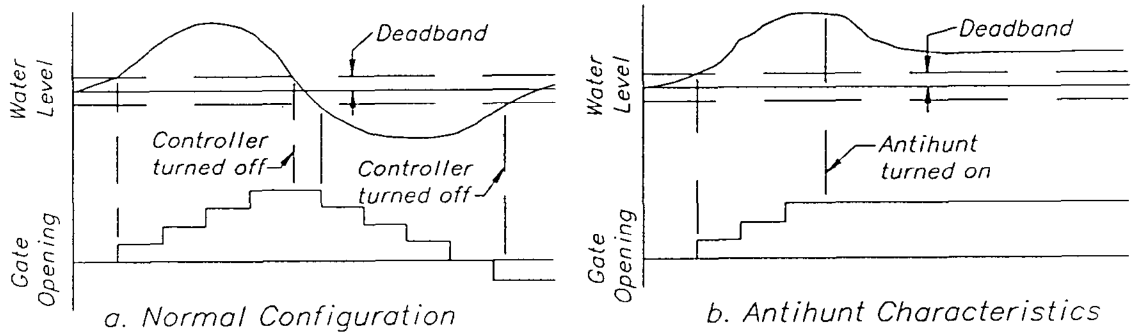



Figure 7-11.—Little-Man controller action.

An antihunt feature is sometimes contained in the comparator element of the Little-Man controller. The antihunt feature stops all control action when the water level begins to return toward the target deadband. Sometimes the water level does not return to the deadband. This action is shown on figure 7-11b.

Using methods for parameter selection discussed earlier, the proportional gain from equation 7.17 at maximum discharge is 5.7. If an incremental gate motion of 30 millimeters (mm) (0.1 feet [ft]) is selected, then the incremental water level change, $\Delta Y$, would be 5.3 mm (0.017 ft). Conversely, if the incremental water level change, $\Delta Y$, of 9 mm (0.03 ft) is selected, the incremental gate motion, $\Delta G$, is 51 mm (0.17 ft).

The time increment of the set-operate-time (SOT) gate movement to produce a specified incremental gate motion is given by:

$$\Delta T_g = \frac{\Delta G}{K_s} \qquad 7.35$$

where:

- $\Delta T_g$ = discrete time increment (seconds) for the SOT of the actuator
- $\Delta G$ = specified increment of the gate movement (vertical distance)
- $K_s$ = gate speed (distance per second)

The actuator time increment, $\Delta T_g$, for a selected incremental gate opening, $\Delta G$, of 30 mm (0.1 ft) and a gate speed, $K_s$, of 7.7 millimeters per second (1.5 feet per minute) is 4 seconds.

## 7-12. Colvin Controller

The Colvin controller is also based upon the three-position control function described in section 7-6 with some important modifications:

- Each time the water level changes by a preselected increment, $\Delta Y$, the controlled gate moves a fixed distance, $\Delta G$, based upon an SOT.
- The controller uses a variable-rest-time (VRT) between gate movements. The rest time will be short if the water level is changing rapidly and long if it is changing slowly.

The VRT provides a rate of control mode in combination with the three-position control mode. Figure 7-12 illustrates the water level response and recovery characteristics of the control action of the Colvin controller. The VRT feature permits the control action to be approximately proportional to the rate of change in the water level.

Similar to the Little-Man controller, deadband at the target is included for the Colvin controller. Gate movements will not occur when the water level is within the high and low limits of the deadband. The deadband reduces the number of gate movements at the steady-state flow condition, which improves control stability and reduces the frequency of operation of the gate hoist mechanism. The range of the deadband is at least one increment of $\Delta Y$ (preferably two or three).

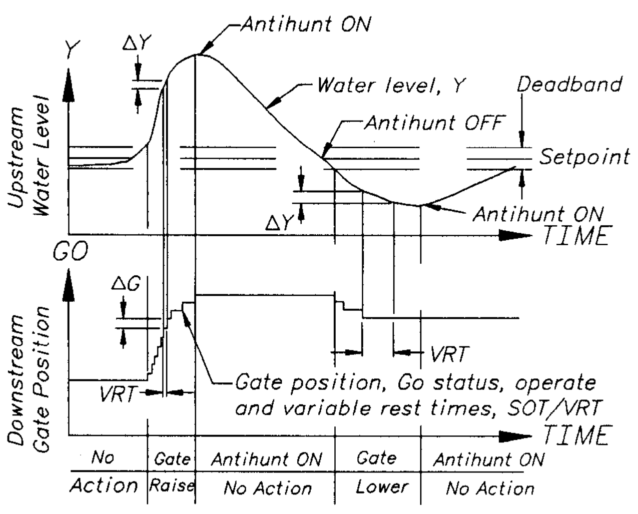



Figure 7-12.—Colvin controller SOT/VRT mode of control.

The Colvin controller can be used for check gate control with the downstream control concept only if the length of the downstream canal pool is short; i.e., less than 300 meters (m) (1,000 ft). The application of the Colvin controller for local automatic downstream control of a single check gate structure having a downstream canal pool length of 168 m (550 ft) is illustrated on figure 7-13 [4]. The water level sensor is located at the downstream end of the canal pool. The downstream flow demand is increased (figure 7-13e) by opening the downstream check gate. The water level immediately upstream decreases (figure 7-13c).

The upstream gate opens in $\Delta G$ increments (figure 7-13b) as the Colvin controller senses the $\Delta Y$ increments—increasing the upstream inflow (figure 7-13d) to match the water surface to the downstream demand. The gate movements are frequent—between 10 and 40 minutes apart. However, they decrease as the rate of change in the sensed (monitored) water level decreases. When the water level begins to return toward the target, at time 70 minutes, the antihunt feature is activated, and gate movement stops. When the water level crosses the upper limit of the target deadband, at time 110 minutes, the antihunt is deactivated, and the gate lowers until the water level returns inside the target deadband. A new steady state is established at time 200 minutes (figure 7-13f).

The control action cycles between the upper and lower limits of the target deadband. This action is known as the steady-state limit cycle. The limit cycle is a characteristic of the three-position control action. As discussed earlier, an exact position of the gate for steady-state flow cannot be established when the gate moves within a deadband. The frequency of the cyclical action can be predicted using the curves shown on figure 7-6.

A different procedure is used to determine the proportional gain for the upstream control of a diversion dam gate as shown on figure 7-14.

A maximum reservoir water surface elevation is selected. For an uncontrolled spillway-type structure, the maximum reservoir elevation is the elevation of the spillway crest. For a gate controlled spillway, the maximum elevation is set about 0.3 m (1.0 ft) above the normal water surface elevation. At the maximum reservoir elevation selected, the diversion dam gate (headworks to the supply oriented canal system) will be at a maximum opening to divert the maximum design flow of the canal diversion. The change in discharge can be expressed as:

$$\Delta Q_g = \frac{Q_m \, \Delta Y}{\Delta Y_m} \qquad 7.36$$

where:

$\Delta Q_g$ = change of discharge to be diverted through the controlled gate

$Q_m$ = maximum flow that can be diverted through the controlled gate

$\Delta Y$ = change in the reservoir water surface elevation

$\Delta Y_m$ = offset, difference between the normal (target) and the selected maximum reservoir water surface elevation

Equation 7.36 proportions the maximum reservoir water surface to the maximum capacity of the diversion. The gain is determined by equating equation 7.36 with equation 7.9 to obtain:

$$K_1 = \frac{\Delta G_o}{\Delta Y} = \frac{Q_m}{\Delta Y_m \, C_d \, W \sqrt{2g \, \Delta H}} \qquad 7.37$$

Based on the physical properties of a typical diversion dam (figure 7-12b), the proportional gain, equation 7.37, would be 5.1.

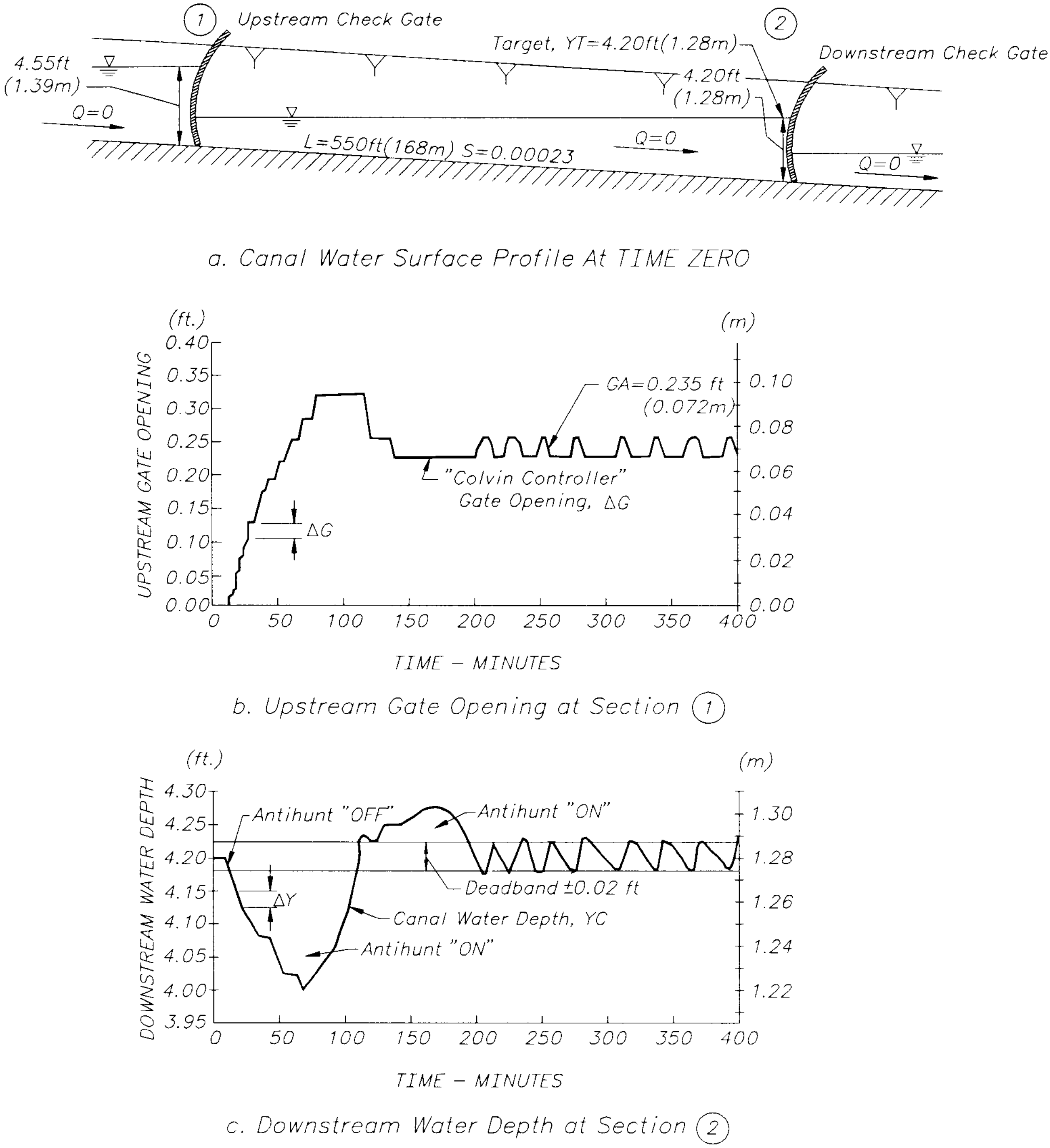
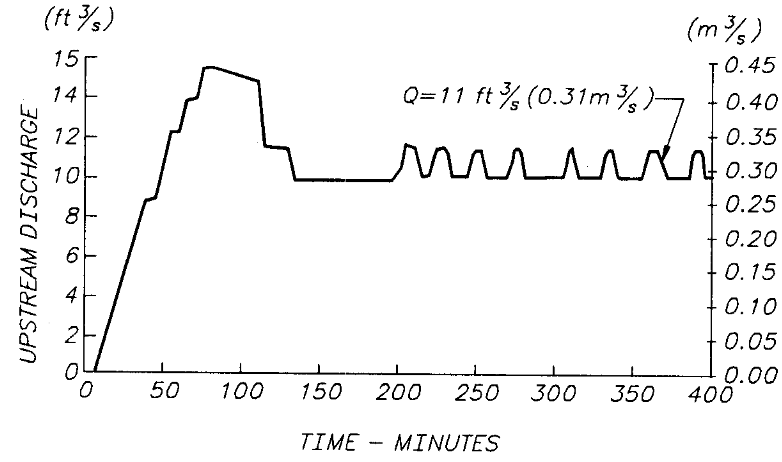
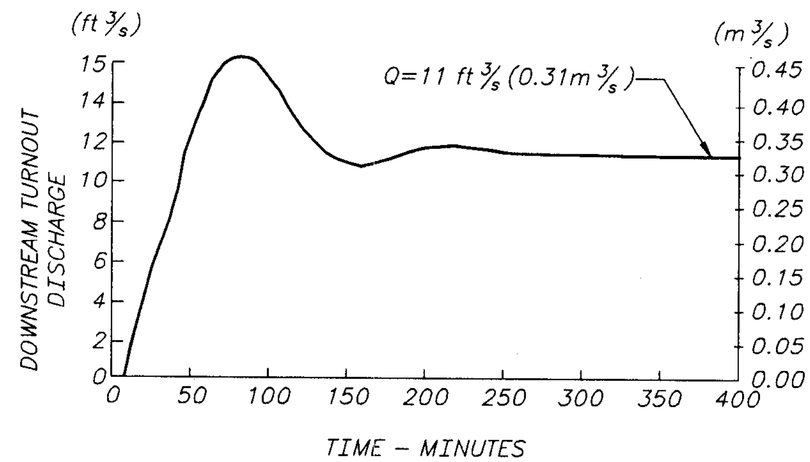


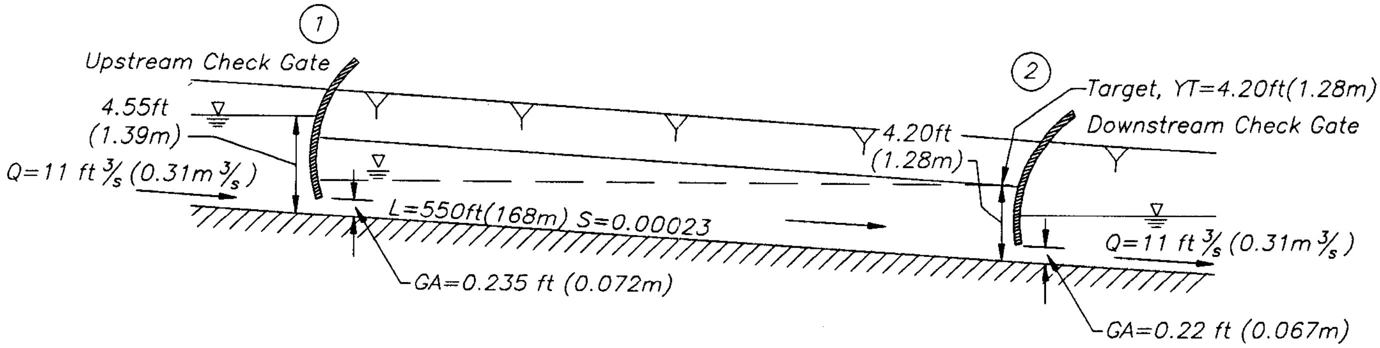

Figure 7-13.—Colvin controller response and recovery characteristics.




d. Upstream Discharge at Section 1




e. Downstream Turnout Discharge at Section 2




f. Canal Water Surface Profile TIME 400 Minutes

**Figure 7-13.—Colvin controller response and recovery characteristics-continued.**

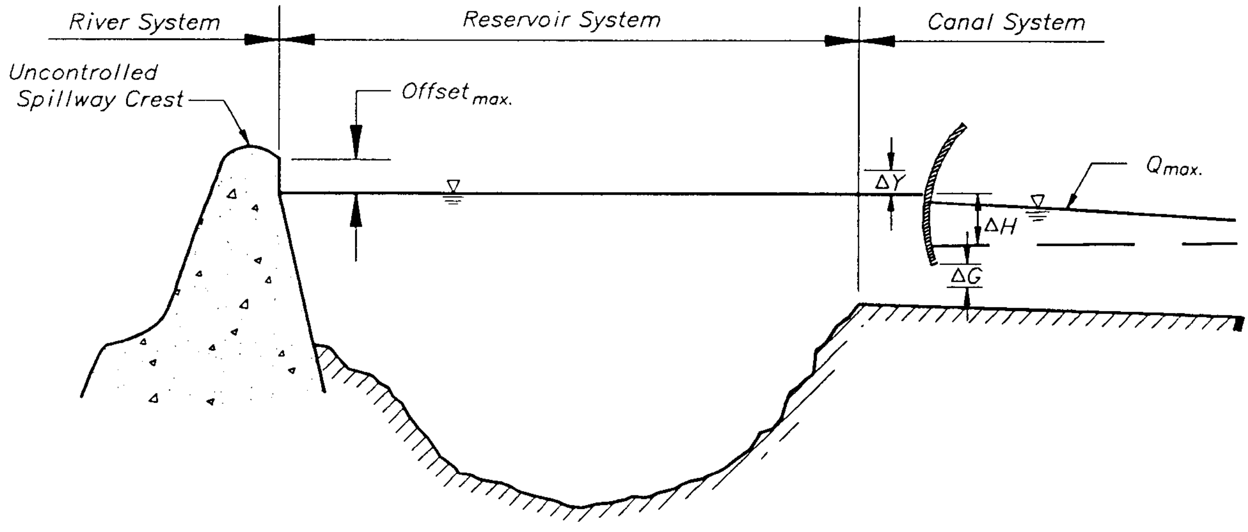



Figure 7-14.—Colvin control of a diversion dam gate.

As shown on figure 7-6, the proportional gain should be varied to maintain flow continuity. Controllers with SOT/SRT or SOT/VRT mode of control do not have the capability to vary the proportional gain as a function of change in canal flow demand. Therefore, the degree of control by Little-Man and Colvin controllers, even with the addition of multiple-stage and antihunt features, is limited to control at a diversion dam or at a single check gate flow control application because they do not have the elements to provide compensation.

## CLOSED-LOOP CONTROL OF CANAL SYSTEM

### 7-13. Controller Requirements

The controllers discussed in the previous section are not intended to control an entire canal system or even several pools in series. Lag or inertia introduced by a canal pool requires a compensation element in the feed-forward path. The basic element of a controller that is required to control an entire canal system is a proportional control mode. The proportional element moves the control gate in response to variations in the sensed water level. The gate opening is based upon a discharge equal to the change in discharge that caused the water level variation.

In addition to the proportional control mode, a filter as shown on figures 7-1 and 7-3 is often used to provide stability for the control loop when the setpoint is located at the downstream end of a pool. The magnitude of the filter time constant depends upon the surge wave amplitude attenuation and its travel time in the canal pool.

In addition to the filter and proportional control elements, a third element is used to eliminate the residual offset of the proportional control mode. The third element consists of an integral control mode called RESET. Stable control action of the feedback controller requires the careful selection of the three-control elements.

The local automatic controllers used by Reclamation to control an entire canal system are known as Hydraulic Filter Level Offset *(HyFLO)*, *ELFLO, ELFLO plus RESET*, and Proportional plus Proportional Reset *(P+PR)*. The choice of the specific control elements used with each controller determines the acronym used to define the controller. The HyFLO, ELFLO, and ELFLO plus RESET controllers are primarily used for downstream control applications. The P+PR controller is used for upstream control applications.

### 7-14. HyFLO Controller

The design of the hydraulic filter in the HyFLO controller is based upon the analogy to an electrical resistor-capacitor (RC) circuit [18]. The laminar flow in a small capillary tube is analogous to an electrical resistance. The volume of the well is analogous to the electrical capacitance. The hydraulic filter was designed because the equipment required to obtain the long time constants needed for canal control was impractical in the late 1960's. The hydraulic filter proved to be impractical in the field because debris would plug the small capillary tube [6].

## 7-15. ELFLO Controller

The ELFLO design is based upon an electronic RC filter circuit to produce the required long time constants. The generic name ELFLO is applicable to controllers consisting of an electronic filter and a proportional element. The ELFLO controller is primarily applied to local-automatic downstream control of canal system check gate structures. The elements of the closed-loop feedback system are shown on figure 7-3.

The first element of the controller path (figure 7-3) is the water level sensor. The sensor is located near the downstream end of the pool for the downstream control concept. The next element in the controller path is the filter. The filter dampens oscillations having frequencies higher than those of the surge wave that traverses the canal pool. Therefore, sustained water surface oscillations are attenuated.

The filter time constant is determined by:

$$T_f = R\,C \qquad 7.38$$

where:

$C$ = capacitance
$R$ = resistance
$T_f$ = filter time constant

A filter also can be simulated with microprocessor based equipment.

- With digital equipment, the filter output is given by equation 7.21, where $\Delta G_o$ is replaced by $Y_f$ (the filter output).
- The filter output signal, $Y_f$, is transmitted to the comparator, located at the upstream check gate.
- The proportional gate opening, $G_p$, is determined from the values of $Y_f$ and the target or setpoint depth, $Y_t$.
- The offset, $Y_t - Y_f$, is determined and multiplied by the proportional gain constant, $K_1$.

The characteristic response and recovery of a canal pool is illustrated on figure 7-15. The schematic on figure 7-15a shows the canal system and water-surface profile at time zero.

- At time 10 minutes, a downstream canal-side turnout demand is increased to 0.31 cubic meters per second (m$^3$/s) (11 cubic feet per second [ft$^3$/s]) (figure 7-15e).
- Figure 7-15c shows the resulting water level response, $Y_c$, and the output of the filter element, $Y_f$.
- The desired upstream gate opening, $G_d$, as computed by the ELFLO algorithm, is shown on figure 7-15b.
- An offset of 30 mm (0.097 ft) can be observed at the final steady-state flow condition (figure 7-15c).
- The actual gate opening (figure 7-15b), $G_a$, is the result of the inner closed-loop feedback control action of the comparator element.
- A deadband, $D_b$, of 9 mm (0.03 ft) was used to increase the resolution of the computed and actual gate openings, $G_d$ and $G_a$, at steady-state flow conditions.

Figure 7-15d shows the discharge through the upstream controlled gate. The ratio of two successive discharge maxima, $Q_2$ and $Q_1$, can be used to determine the degree of damping, or attenuation, of the initial disturbance [19]. At time 80 minutes, the first amplitude, $Q_1$, measured from the final steady-state condition of 0.31 m$^3$/s (11 ft$^3$/s) is 0.0538 m$^3$/s (1.9 ft$^3$/s). The second amplitude, $Q_2$, is measured at time 200 minutes and is 0.00566 m$^3$/s (0.2 ft$^3$/s). Therefore, the logarithmic decrement is:

$$\delta = \ln\frac{Q_2}{Q_1} = \ln\frac{0.00566\ m^3/s}{0.0538\ \ m^3/s} = -2.25 = -\left(\frac{\delta}{\omega}\right)\pi \qquad 7.39$$

In solving for δ/ω, the percent of critical damping is 0.72. The percent of critical damping also can be found using figure 7-16. As will be demonstrated later, the damping ratio tends to decrease when the RESET controller is included in the control path.

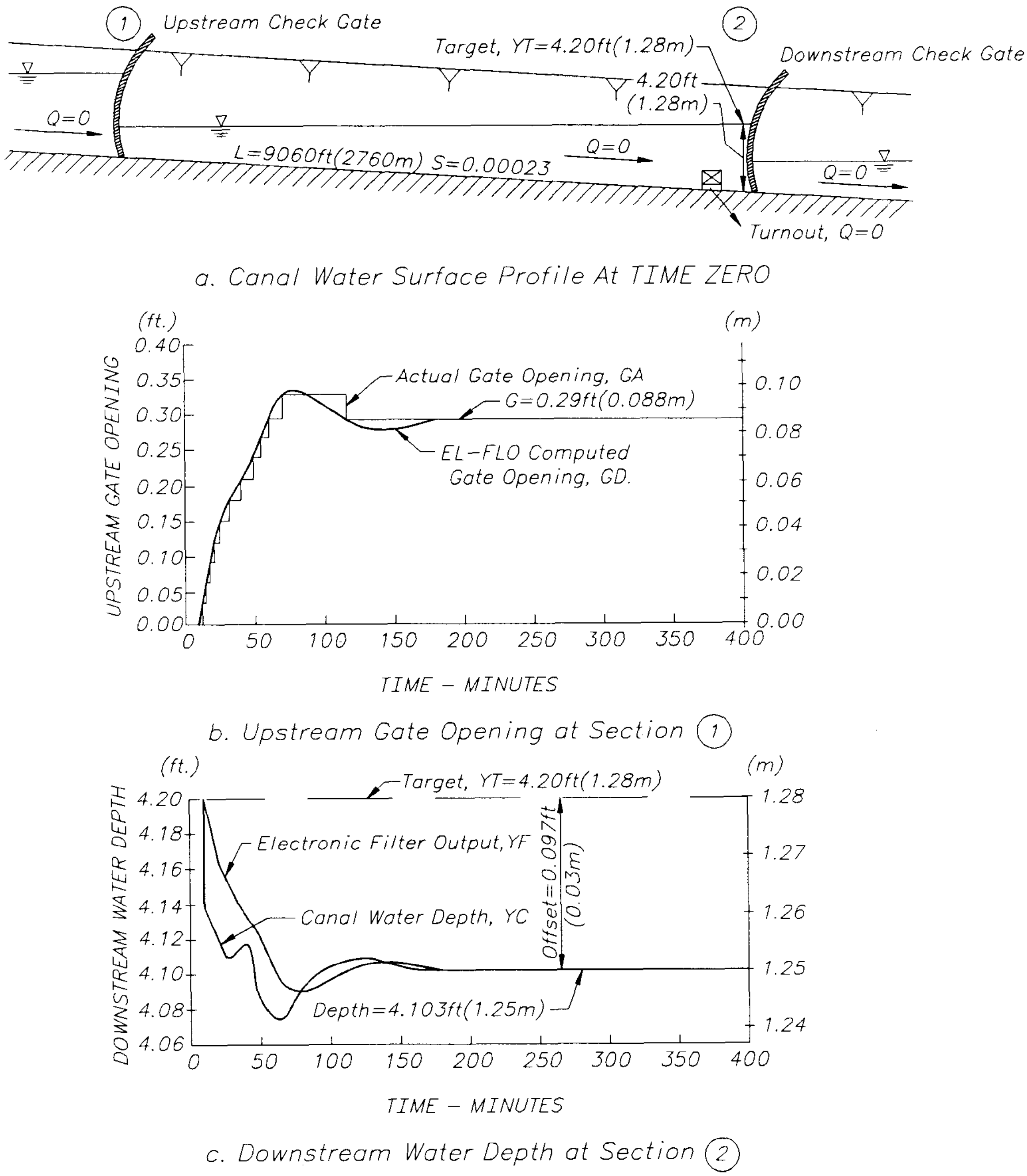
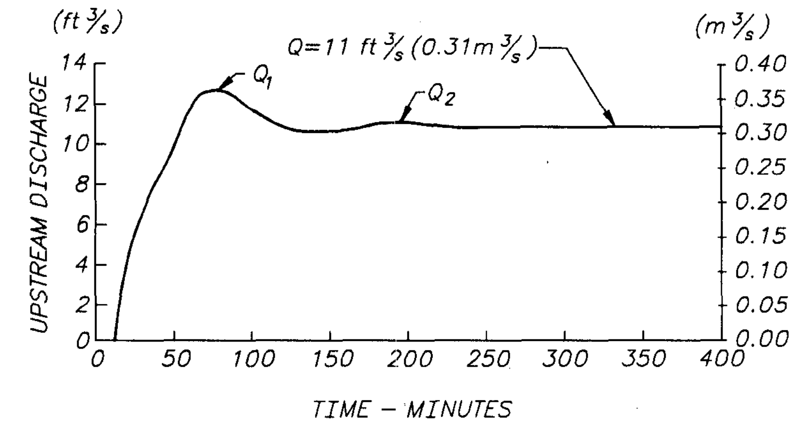
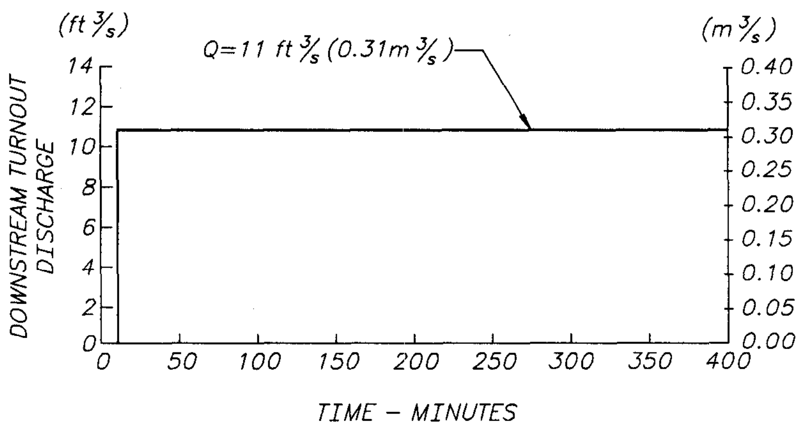


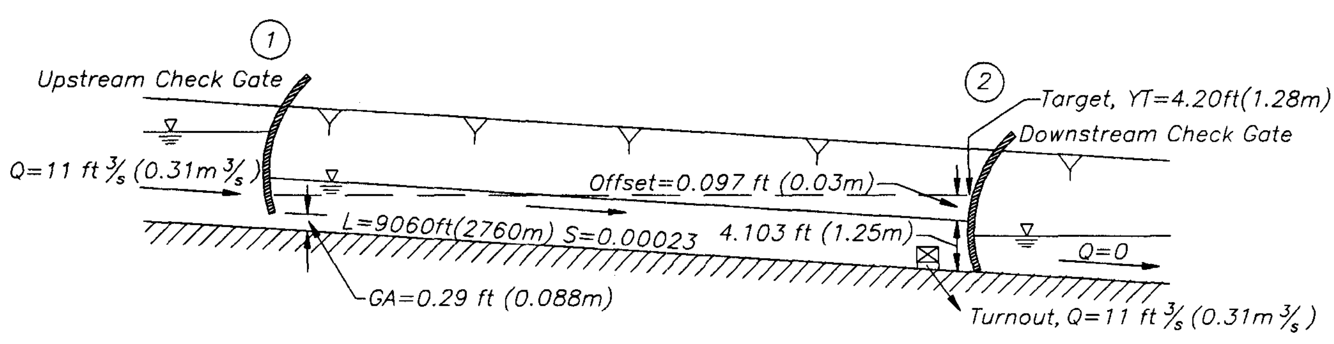

Figure 7-15.—ELFLO controller typical response and recovery characteristics for automatic downstream control.




d. Upstream Discharge at Section 1




e. Downstream Turnout Discharge at Section 2




f. Canal Water Surface Profile TIME 400 Minutes

**Figure 7-15.—ELFLO controller typical response and recovery characteristics for automatic downstream control-continued.**

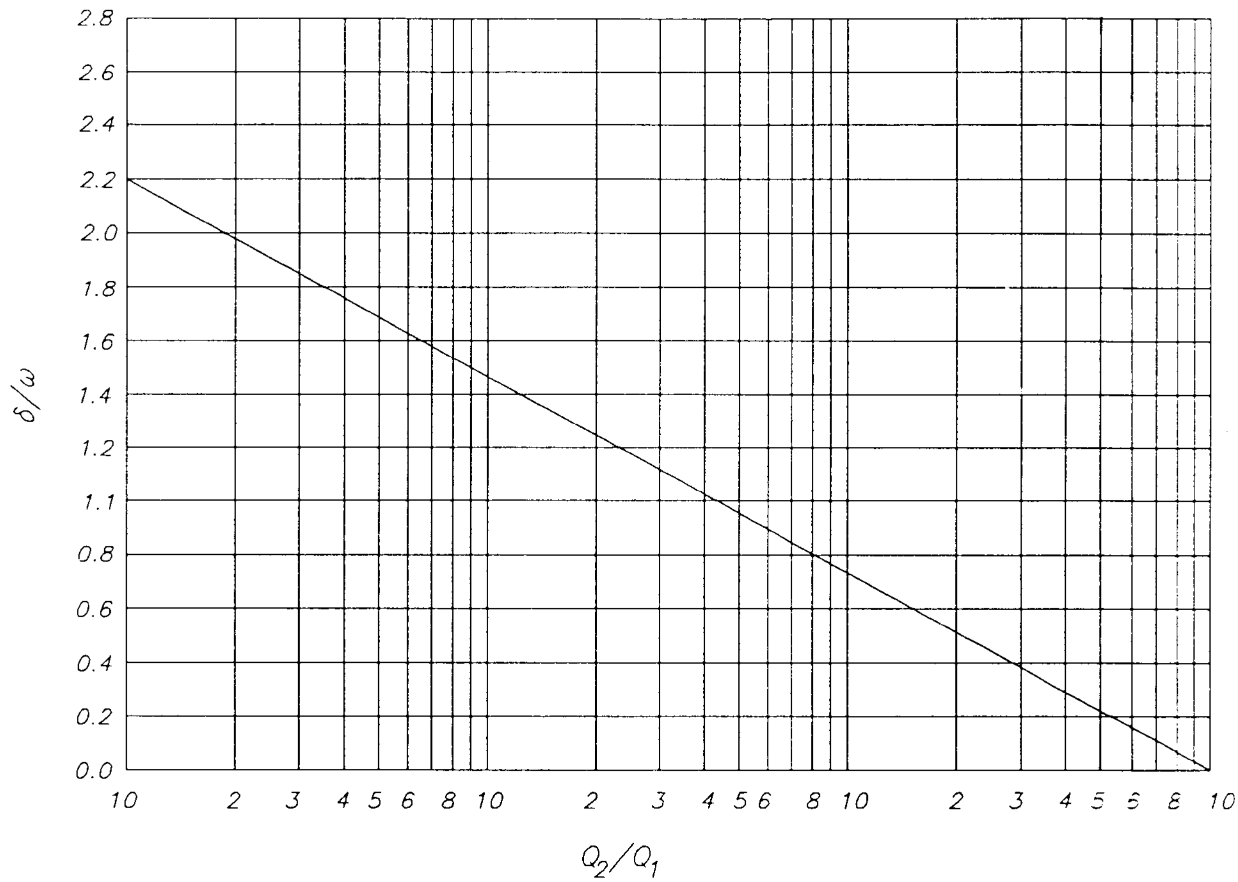



Figure 7-16.—Percent of critical damping versus the ratio of two successive discharges, $Q_2/Q_1$.

- The gain, $K_1$, was selected as 3.0 m/m.
- The target elevation is set to 1.28 m (4.20 ft).
- At time 275 minutes, the steady-state water level was 1.25 m (4.103 ft).

Therefore, offset is 0.030 m (0.097 ft), and computed gate opening, $G_p$ equals $G_d$, is 0.088 m (0.29 ft).

The upstream controlled gate inflow was matched to the downstream canal-side turnout flow change. The water surface profile at the new steady state is shown on figure 7-15f. The new steady state was developed at time 120 minutes, or about 2 hours after the demand occurred. The response and recovery is typical of the ELFLO controller.

The offset of the proportional mode of control imposes two restrictions on the canal pool operation:

- The maximum designed discharge of the canal pool cannot be achieved; i.e., the canal prism was designed to flow at the maximum rate at the target depth, $Y_t$, of 1.28 m (4.20 ft).
- The residual offset may interfere with proper delivery to the canal-side turnouts.

A controller with only the proportional function introduces an offset in the water level as flow demand increases. Limited operation is required unless adjustments to the target depth are made. One way to eliminate the restrictions is to raise the target to a higher depth. However, most canal pools are not designed to operate at depths within the canal freeboard. Another way to eliminate the imposed restrictions is to have the ditchrider change the target depth as the base flow of the canal delivery changes during the irrigation season. However, this operation negates some of the benefits of local-automatic downstream control.

## 7-16. ELFLO plus RESET Controller

The ELFLO plus RESET controller consists of three control components: the filter, proportional, and integral elements. A controller with an integral or reset function eliminates the offset. The reset function allows the water level to remain constant at the target depth, $Y_t$, for all steady-state flow conditions. The target depth is selected as the maximum designed depth required for the maximum flow in the canal pool.

- The integral control element determines the reset gate opening, $G_r$, using the proportional output, $G_p$, as the input.
- The proportional output is integrated with time and then multiplied by the integral control gain constant, $K_2$.
- The reset controller provides control when the reset gate opening, $G_r$, is greater than the reset deadband, $D_r$.

Usually, the reset deadband is set slightly higher than the gate deadband, $D_g$.

The outputs of the proportional and reset control elements, $G_p$ and $G_r$, are summed and then input into the comparator element.

- The two inputs are summed to determine the desired gate opening, $G_o$.
- The desired gate opening is compared to the measured gate opening, $G_a$, to determine the error, $\pm\Delta G$.
- If the error, $\pm\Delta G$, is greater than the gate deadband, $D_g$ (typically 0.03 m [0.10 ft]), the actuator element is energized to raise or lower the gate depending on the polarity of the error, $\pm\Delta G$.
- The gate continues to move in the proper direction until the error returns to zero.

The response and recovery characteristics of the ELFLO plus RESET controller are illustrated on figure 7-17. The canal pool and flow demand are the same as those used on figure 7-17.

- The recovery of the downstream water level, $Y_c$, to the target, $Y_t$, occurs at 140 minutes (figure 7-17c).
- The desired gate opening, $G_d$, represents the sum of the ELFLO and RESET controller outputs, $G_p$ and $G_r$, respectively.
- $G_d$, $G_p$, and $G_r$ are plotted separately as shown on figure 7-17b.
- Immediately after a downstream flow change occurs, the ELFLO proportional controller output, $G_p$, provides the primary control action.
- As a new steady-state flow condition develops, the proportional control output, $G_p$, approaches zero, and the integral controller output, $G_r$, provides the primary control action.

The ELFLO plus RESET control performance can be measured, as before, based on the ratio of successive amplitudes of the discharge plot shown on figure 7-17d. Using equation 7.43 or figure 7-16, the percent of critical damping is 0.61. The illustration demonstrates that damping is reduced from 0.72 without reset to 0.61 with reset. If adjustments are not made to the gain, the reset could cause a stable feedback system to become unstable. As the percent of critical damping is decreased, the amplitude of the overshoot increases. If the overshoot is too large, the water surface encroaches into the freeboard during a flow change.

The magnitude of the logarithmic decrement decreases as the flow change progresses upstream through each controlled check gate structure to the canal headworks. Therefore, flow change at the canal headworks could have the following consequences:

- Exceed the flow capacity
- Require additional storage
- Require additional pump units to satisfy the overshoot of the controller's recovery to a new steady state

An overshoot is necessary to recover the water level to the target when flow demand increases. When flow demand decreases, the overshoot is negative and usually does not present operational problems. Overshoot is directly related to the selection of the integral gain constant, $K_2$.

Figure 7-18 is a composite of figures 7-15 and 7-17. It compares the response and recovery characteristics with and without the reset controller. The elimination of the residual proportional mode offset can be observed on figure 7-18c. The initial water level drawdown is the same for both control methods until the surge arrives at the downstream sensor and the reset output, $G_r$, begins to have an effect on the upstream controlled-gate discharge. The upstream gate opening with reset

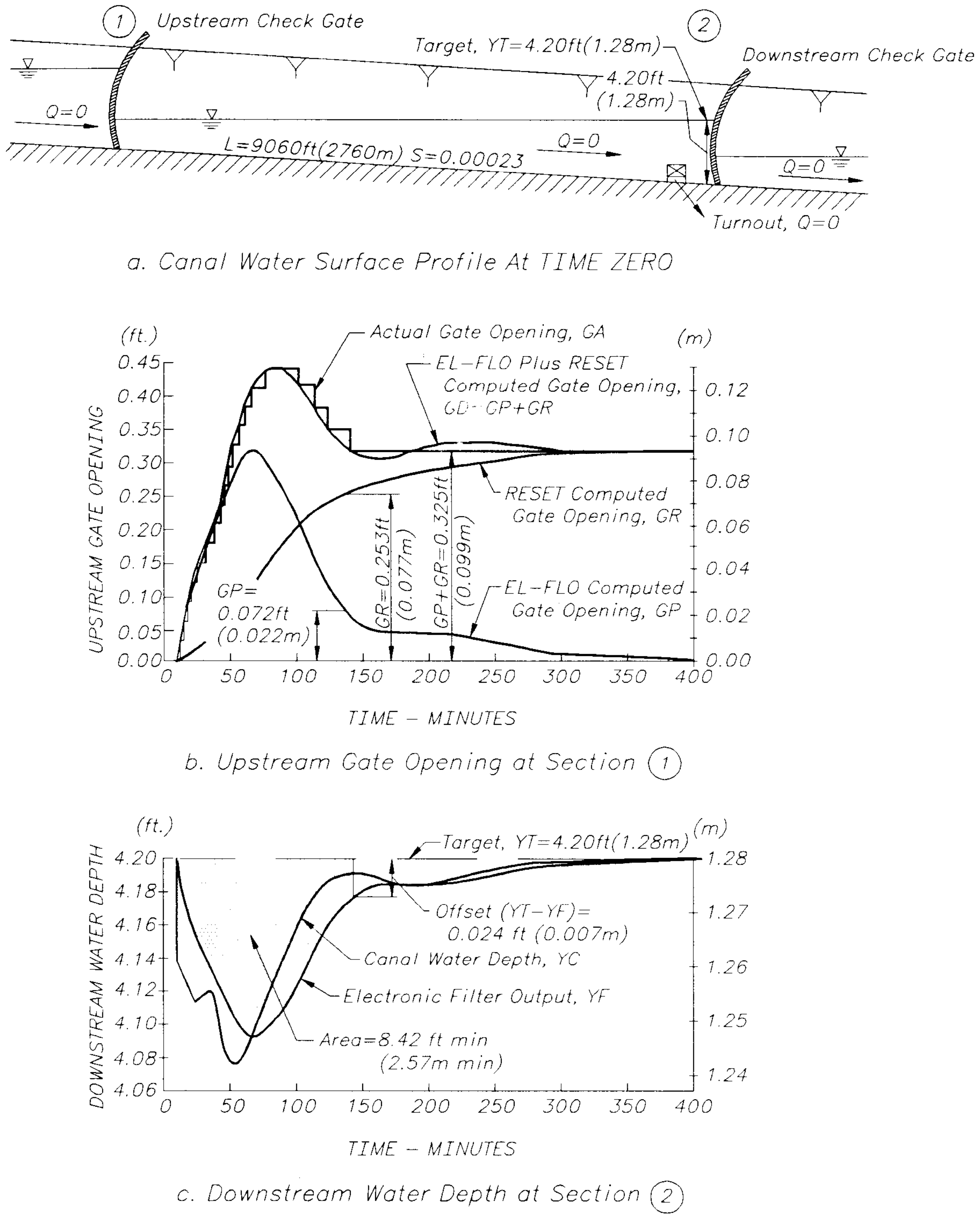
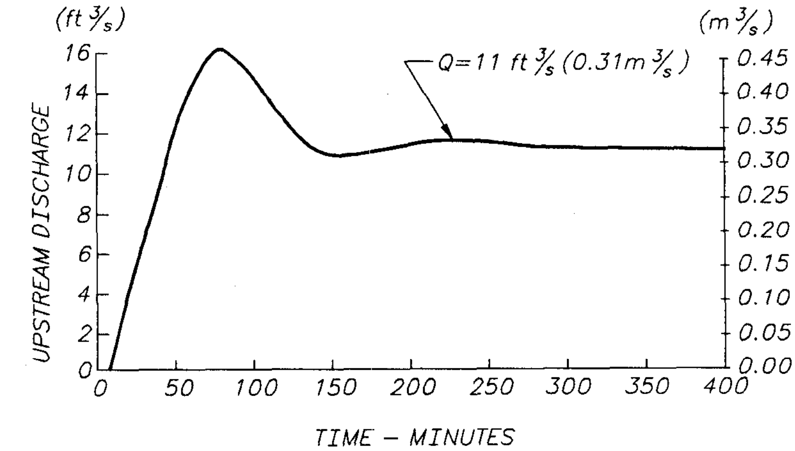
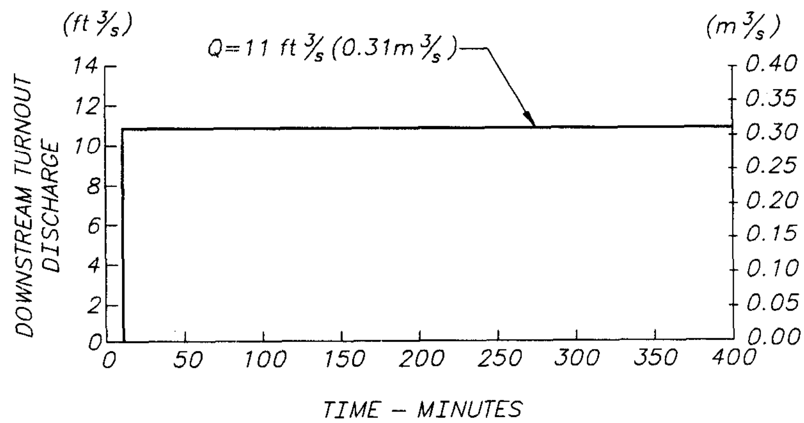


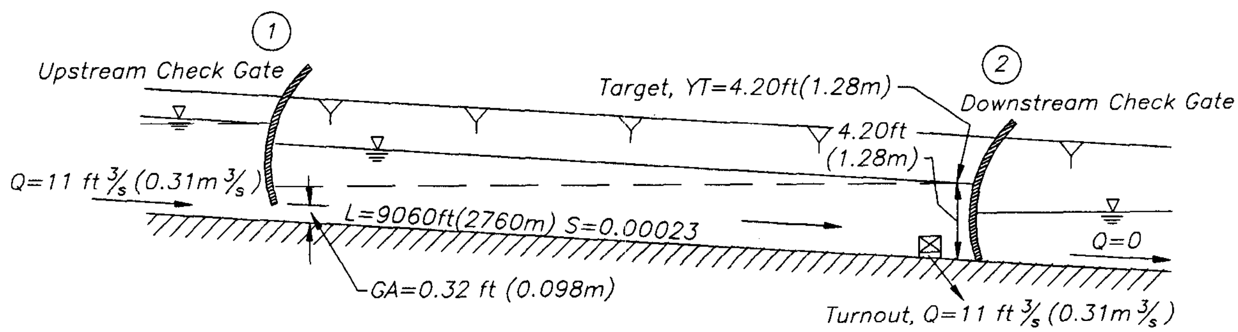

Figure 7-17.—ELFLO plus RESET controller typical response and characteristics.




d. Upstream Discharge at Section 1




e. Downstream Turnout Discharge at Section 2




f. Canal Water Surface Profile TIME 400 Minutes

Figure 7-17.—ELFLO plus RESET controller typical response and characteristics-continued.

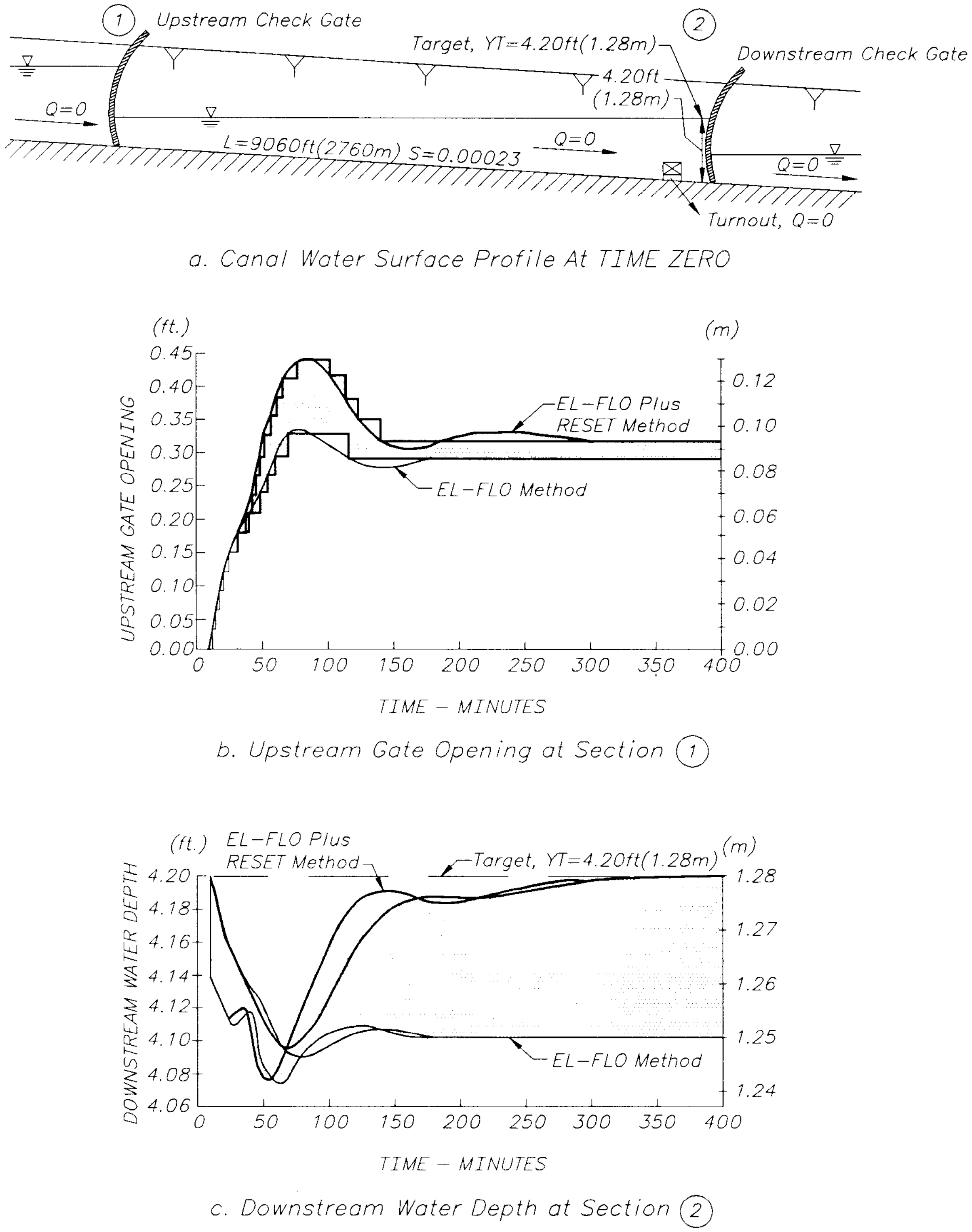
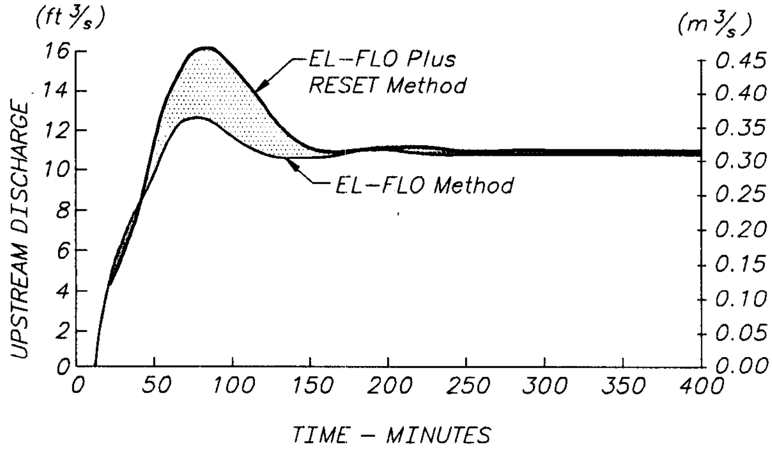
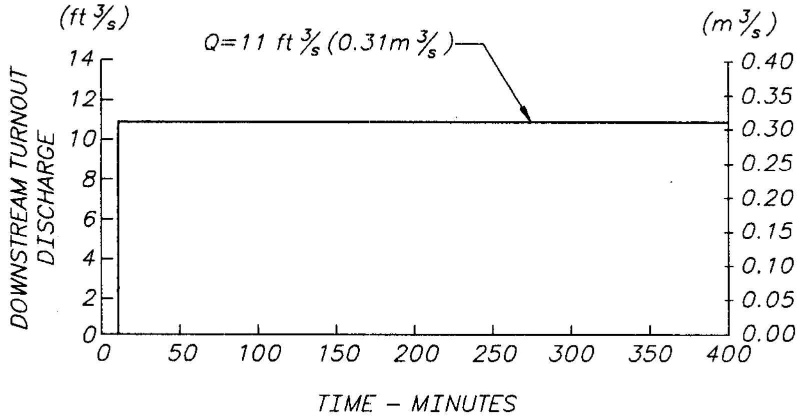


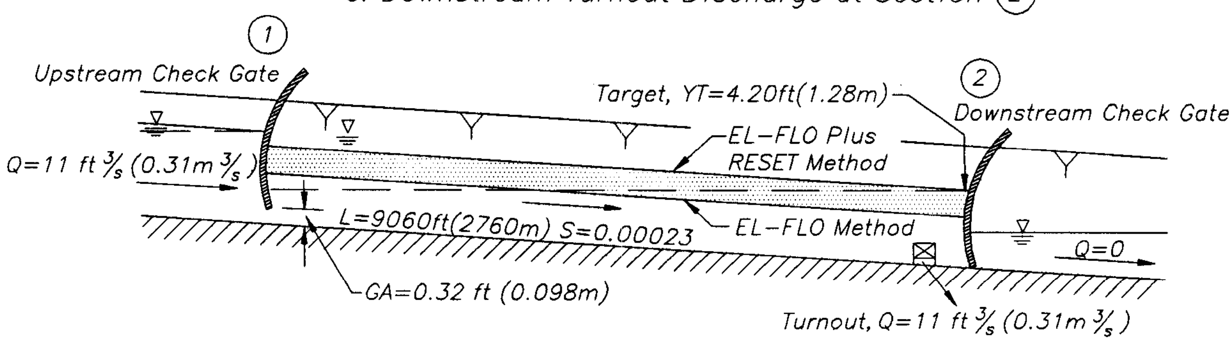

Figure 7-18.—Response characteristics of ELFLO controller with and without RESET.




d. Upstream Discharge at Section 1




e. Downstream Turnout Discharge at Section 2




f. Canal Water Surface Profile TIME 400 Minutes

Figure 7-18.—Response characteristics of ELFLO controller with and without RESET-continued.

(figure 7-18b) is much larger at time 80 minutes to supply the overshoot flow and to return the downstream water level to the target. At the new steady-state flow condition (figure 7-18f), the water surface profile is higher with reset. This higher profile decreases the head differential across the gate structure. The decreased head differential requires a slightly larger gate opening with reset to produce the same flow at the new steady state.

The control parameters, filter $T_f$, water level offset, and the controller gains $K_1$ and $K_2$ must be carefully selected. They are selected to give the quickest response and recovery without creating an excessive overshoot or causing instabilities. The controller must function over a wide range of flow demand changes. The filter time constant, $T_f$, has a significant effect on stability. The magnitudes of the offset and the $K_1$ and $K_2$ gains determine the response and recovery characteristics [6,19,18,20].

The control parameters are interdependent. They can be determined (approximately) using the stability analysis of Hâncu et al. [15] (discussed in section 7-9), or through trial and error using mathematical model simulation of the canal and control system [5,20]. As a first approximation, the filter time constant, $T_f$, is set equal to the travel time of the surge wave for the length of the canal pool. Initial values of the proportional gain can be estimated using the procedure discussed in section 7-6. The approximation for the integral gain is set initially to 0.01 per minute.

## 7-17. P+PR Controller

The P+PR controller is identical to the ELFLO plus RESET controller except for the lack of a filter control element in the control path. Some P+PR controllers contain a high frequency cutoff filter element. The only purpose of a high frequency cutoff filter is to dampen the effect of wind waves or other local disturbances. This filter is considered to be a part of the signal conditioning and not a part of the control action. A filter time constant of 100 seconds is usually adequate to filter out unwanted local disturbances.

The P+PR controller's purpose is to achieve local-automatic upstream control of the check gate of a canal system. The elements of the control path and their arrangement are shown on figure 7-19. The first element, the sensor, is located a short distance upstream from the controlled check gate for the upstream-control concept application. The time for the surge wave to travel between the sensor and the controlled gate is short. Therefore, a filter element is not required to provide control stability because the system has a fast response time.

The P+PR automatic upstream controller uses the proportional and integral elements of control. The mode of control is identical to the ELFLO plus RESET automatic downstream controller (figure 7-3). However, two major differences exist with an upstream control concept. First, the sign of the offset is reversed; i.e., offset equals $Y_f$-$Y_t$. Second, the input to the P and PR control elements is the water sensor output, whereas the ELFLO plus RESET includes a filter in the control path. With these two exceptions, the elements in the control path of the P+PR controller (figure 7-19) are the same as the ELFLO plus RESET controller shown on figure 7-3.

The hypothetical response and recovery characteristics of the P+PR controller are illustrated on figure 7-20. A sudden increase of flow from upstream (figure 7-20a) arrives at the sensor location (figure 7-20b). The water level rise produces a positive offset above the target depth, $Y_t$. The downstream controlled gate opens (figure 7-20c) to release flow downstream (figure 7-20d).

The P+PR local automatic upstream controller was applied to the Bypass Drain for the Yuma Desalting Plant, located near Yuma, Arizona [7]. A simulation of the Bypass Drain Check Gate No. 1 is shown on figure 7-21. Starting with an initial steady-state flow of 0.28 $m^3$/s (10 $ft^3$/s), a step increase of 0.51 $m^3$/s (18 $ft^3$/s) was made from the plant 3.2 kilometers (km) (2.0 miles [mi]) upstream at time zero. The increased flow change arrived at check No. 1 at time 18 minutes. The check No. 1 gate opened its first increment 0.03 m (0.1 ft) at time 20 minutes to begin transferring the increased flow downstream.

Figure 7-21 illustrates the controller performance while transferring the sudden increase of flow through check No. 1. The maximum rise of the water level at the check structure was about 0.3 m (1.0 ft) and was within reasonable limits for a temporary emergency condition. The water level returned to the target, and a new steady-state flow condition was reached within a reasonable period.

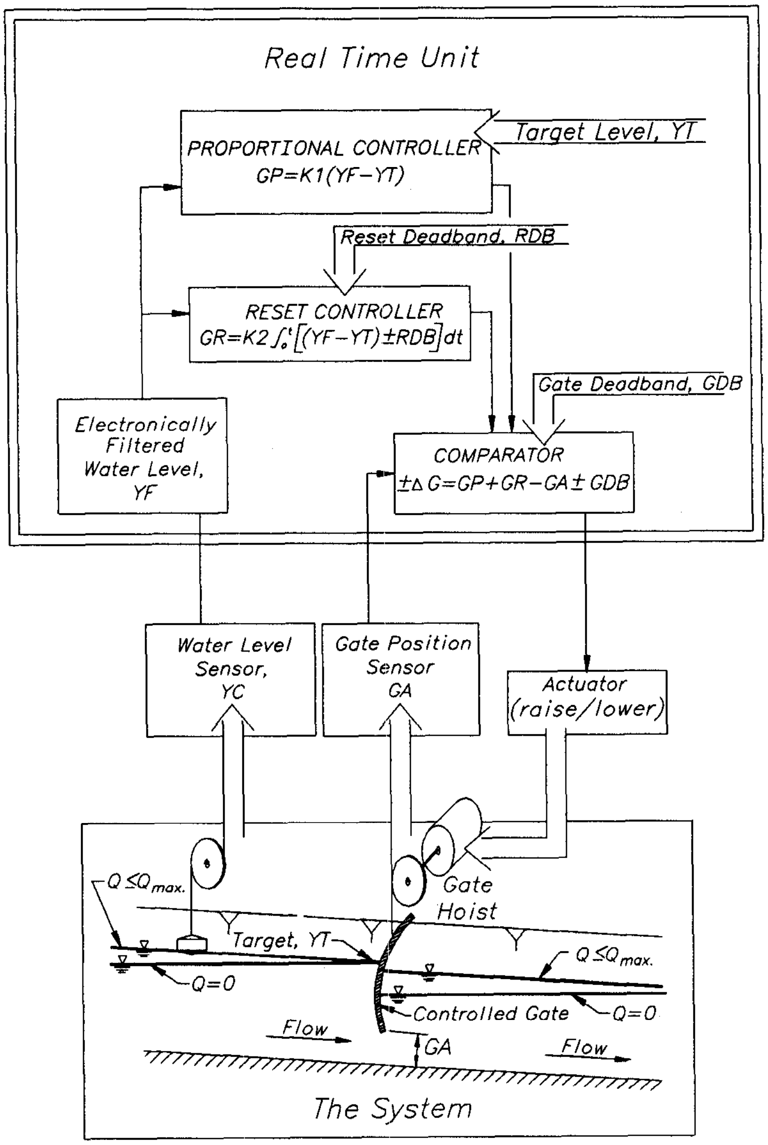



Figure 7-19.—P+PR controller schematic diagram for upstream control.

The selection of the P+PR controller gain is not difficult for the upstream control application. The proportional gain, $K_1$, can be estimated using the procedure discussed in section 7-6. A typical value of an initial estimate for the integral controller gain, $K_2$ , is about 0.03 per minute. Better values can be obtained by calculating the performance index. Verification studies of the controller parameters should be performed by conducting mathematical model simulation studies using various flow conditions.

## 7-18. Q-Controllers

A Q-Controller uses discharge as the input quantity instead of water level. The primary application of the Q-Controller is the automatic regulation of the controlled check-structure gate opening to maintain a constant flow downstream. The constant flow to be maintained is the setpoint or target value. The target must be changed when a different desired flow downstream is required. The target can be

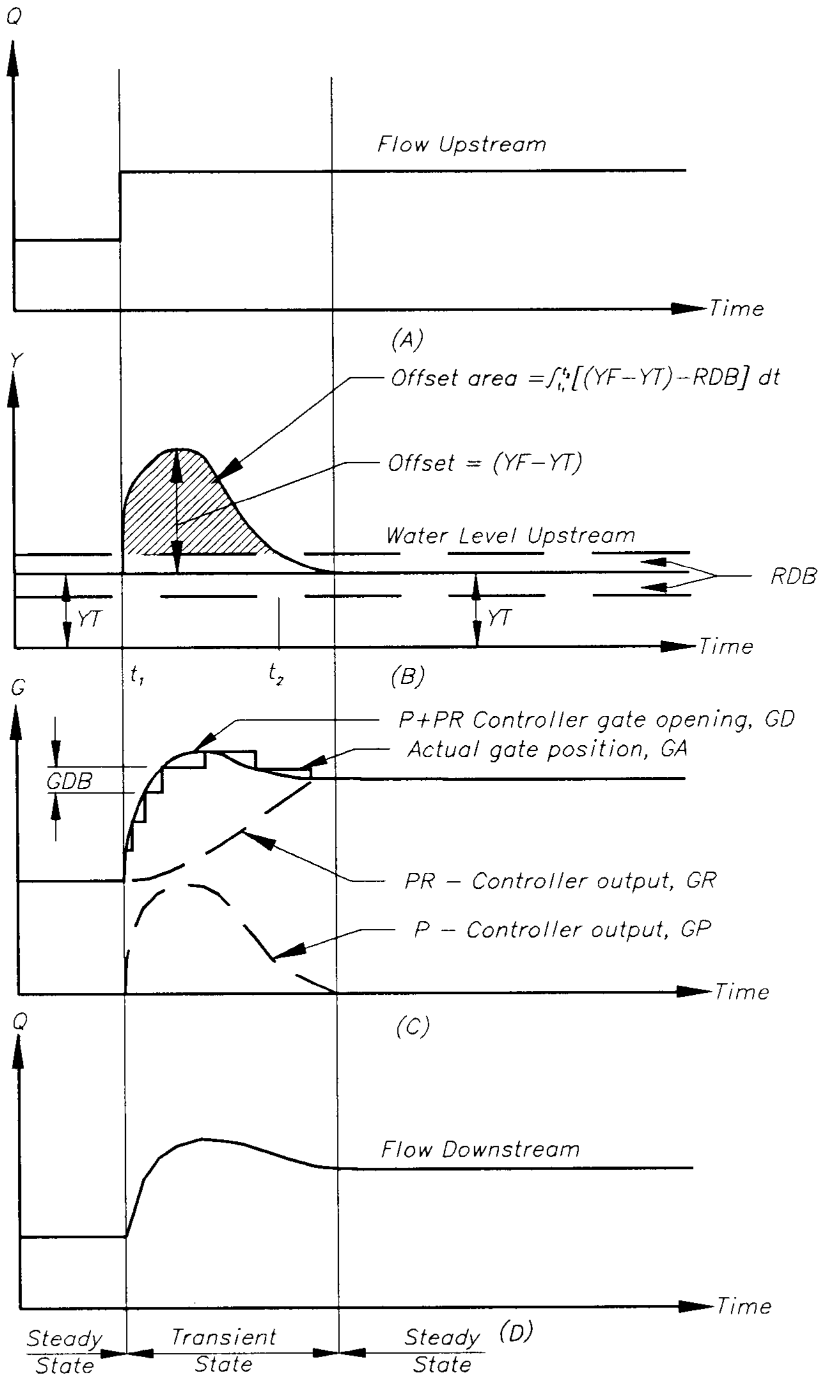



Figure 7-20.—P+PR response and recovery characteristics.

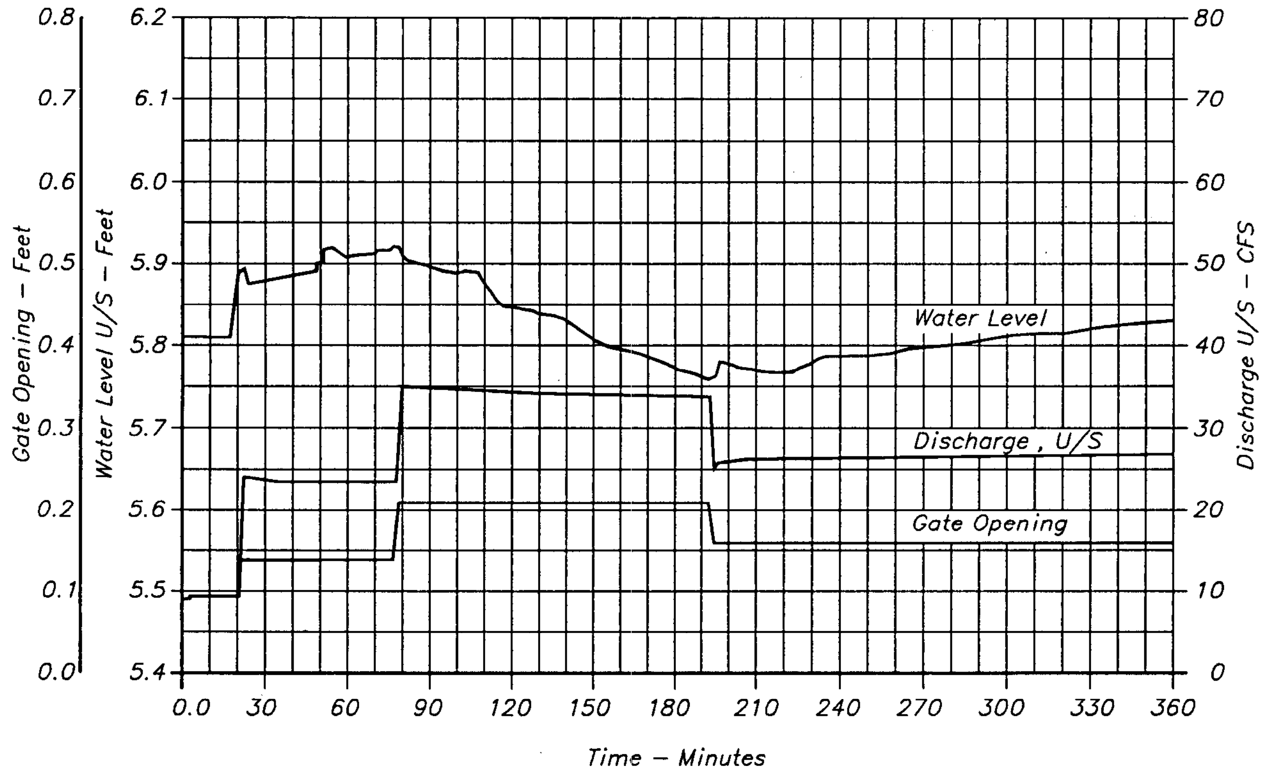



Figure 7-21.—Bypass Drain response characteristics with the P+PR automatic upstream control system.

entered manually by the ditchrider or by a supervisory control system.The application of Q-Controllers at all the check gate structures of a canal system that is operated by the local-manual method is not recommended. The ditchrider would have difficulty obtaining the correct target flow and adjusting each check gate structure, including the correction for errors, on an hourly basis. However, Q-Controllers can be successfully applied to:

- Canal headworks structures
- Canal-side turnouts with appropriate gates or valves
- Entire canals with supervisory automatic control

The application of the Q-Controller has its greatest potential when the canal system is operated by the supervisory automatic method. The flow for the entire canal system can be balanced on an hourly basis. At the master station, a steady-state mathematical model of the canal system is used to determine the desired target flow for each check gate structure. A communication system transmits the target flows to the remote terminal units (RTU's) located at each check gate structure. The RTU maintains the required gate opening by local-automatic control.

Periodic update procedures are incorporated at the master station to eliminate measurement and calculation errors. The update procedure provides minor adjustments to the target flow to maintain water levels within acceptable limits. Immediate corrections for emergencies or abnormal operations can be accomplished by resetting the target.

Generally, flow in an open channel can be measured by calibrating gates or using weirs and flumes. Radial gate algorithms and differential head algorithms are discussed below. In addition, other technology such as ultrasonic flow measurement may be used to monitor flow. In-line Q-Controllers for pipe delivery turnouts are commercially available.

**a. Radial gate algorithms.**—A series of empirical equations, referred to as algorithms, has been developed to accurately measure the flow through canal radial check gate structures [9]. The algorithms apply only to canal radial gates that are geometrically equal to those for which the algorithms were developed. These discharge algorithms can be applied as a local-automatic Q-Controller for canal system check gate structures as shown on figure 7-22. A microcomputer-based controller is needed at the site to continuously

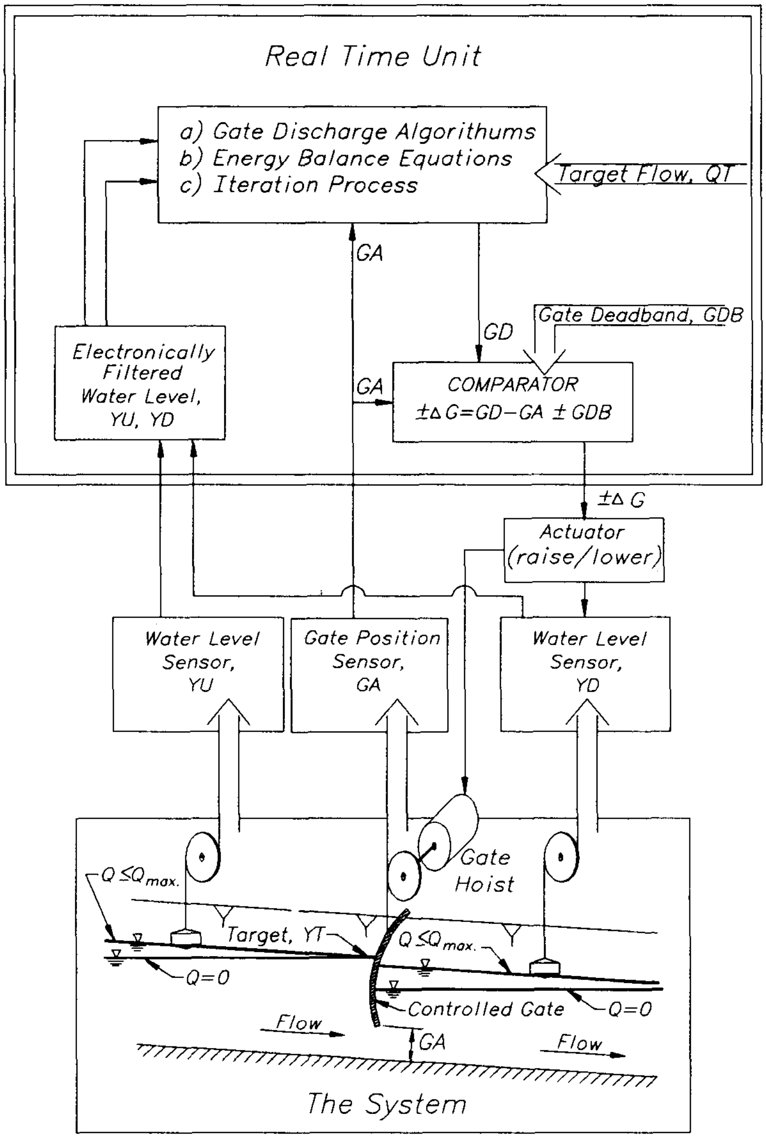



Figure 7-22.—Local automatic Q-Controller.

calculate the required radial gate opening for the desired target flow. The calculation is based upon the measurements of upstream water level, downstream water level, and gate openings—including gate geometry.

The comparator element determines if the gate(s) should operate (raise or lower) whenever the desired gate opening, $G_d$, differs from the actual gate(s) opening, $G_a$, by more than the prescribed deadband, $D_b$. Radial gate discharge algorithms are complex. The controller needs sufficient memory and an arithmetic coprocessor to obtain the solutions on a real-time basis.

The response and recovery of the Q-Controller discharge algorithm technique application is illustrated on figure 7-23. The flow arriving from upstream at check gate No. 2 was scheduled to change from 0 to 30.5 m$^3$/s (100 ft$^3$/s) at time 0.5 hour. Therefore, the master station scheduled the RTU's target to change by the same amount.

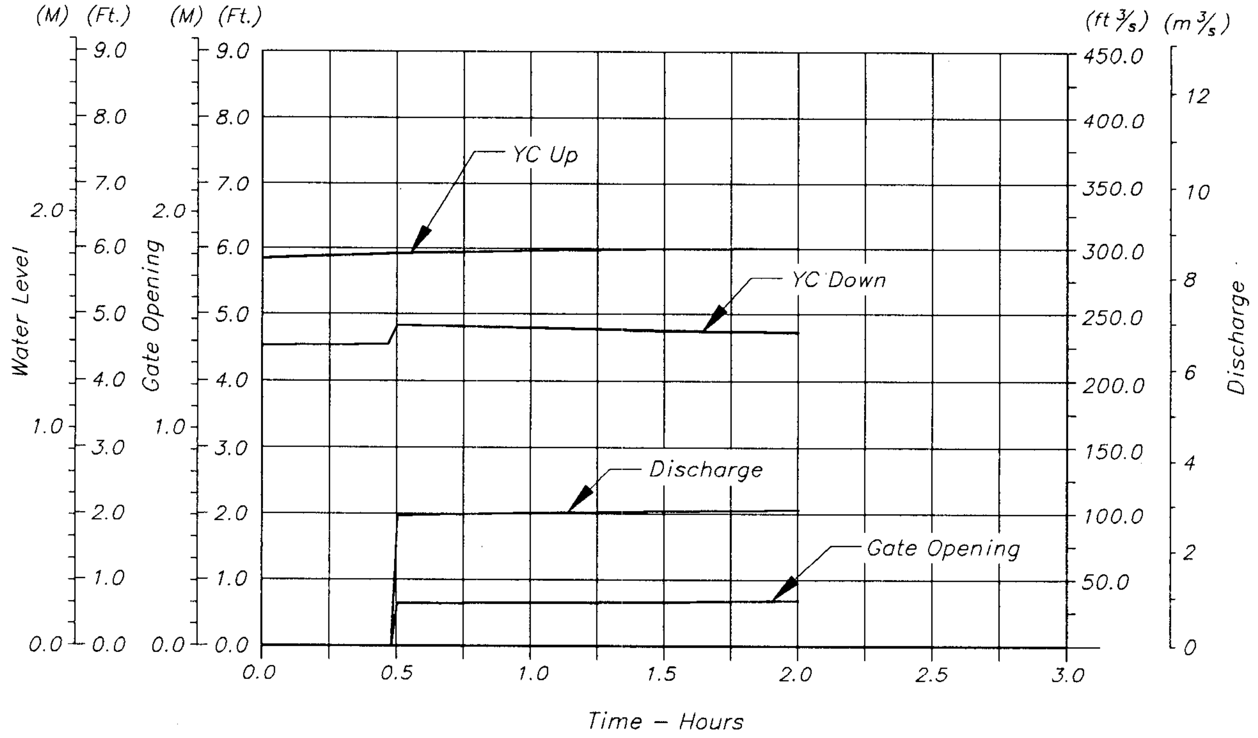



Figure 7-23.—Q-Controller applying the discharge algorithm's typical response and recovery characteristics.

As illustrated, the gate opened at time 0.5 hour and increased downstream flow to 30.5 m³/s. The upstream water deviation was insignificant; i.e., the scheduled arrival and gate operation times and the magnitude of the changes were compatible.

**b. Differential-head algorithms.**—The Q-Controller radial gate discharge algorithm technique is unique to canal-check radial gate structures. On many canal systems, flow measurement facilities such as the Parshall flume are used. A water depth measurement is used as a calibration of the discharge rating. Employing the head versus flow calibration uses the calibrated water level as the target input. The Q-Controller is based upon a unique algorithm which describes the head versus flow calibration.

The basic procedure to develop algorithms based upon the head versus flow technique is as follows:

First, the calibration of the flow measurement facility—water level versus flow—must be established as shown on figure 7-24a. For example, the calibration could represent a Parshall flume, a weir, or a river gaging station.

Next, the upstream controlled gate calibration (flow versus gate opening) is determined. If the water level upstream from the controlled gate is not constant (e.g., at a reservoir), the upstream water elevation should be included as illustrated on figure 7-24b. Usually, the calibration can be determined from field data. However, the gate rating curves can be developed theoretically by:

- Following the procedures developed by Shand [19,20]
- Applying the radial gate discharge algorithms [9]

The Q-Controller using the head versus flow technique employs the proportional mode of control. Therefore, the proportional gain can be expressed as:

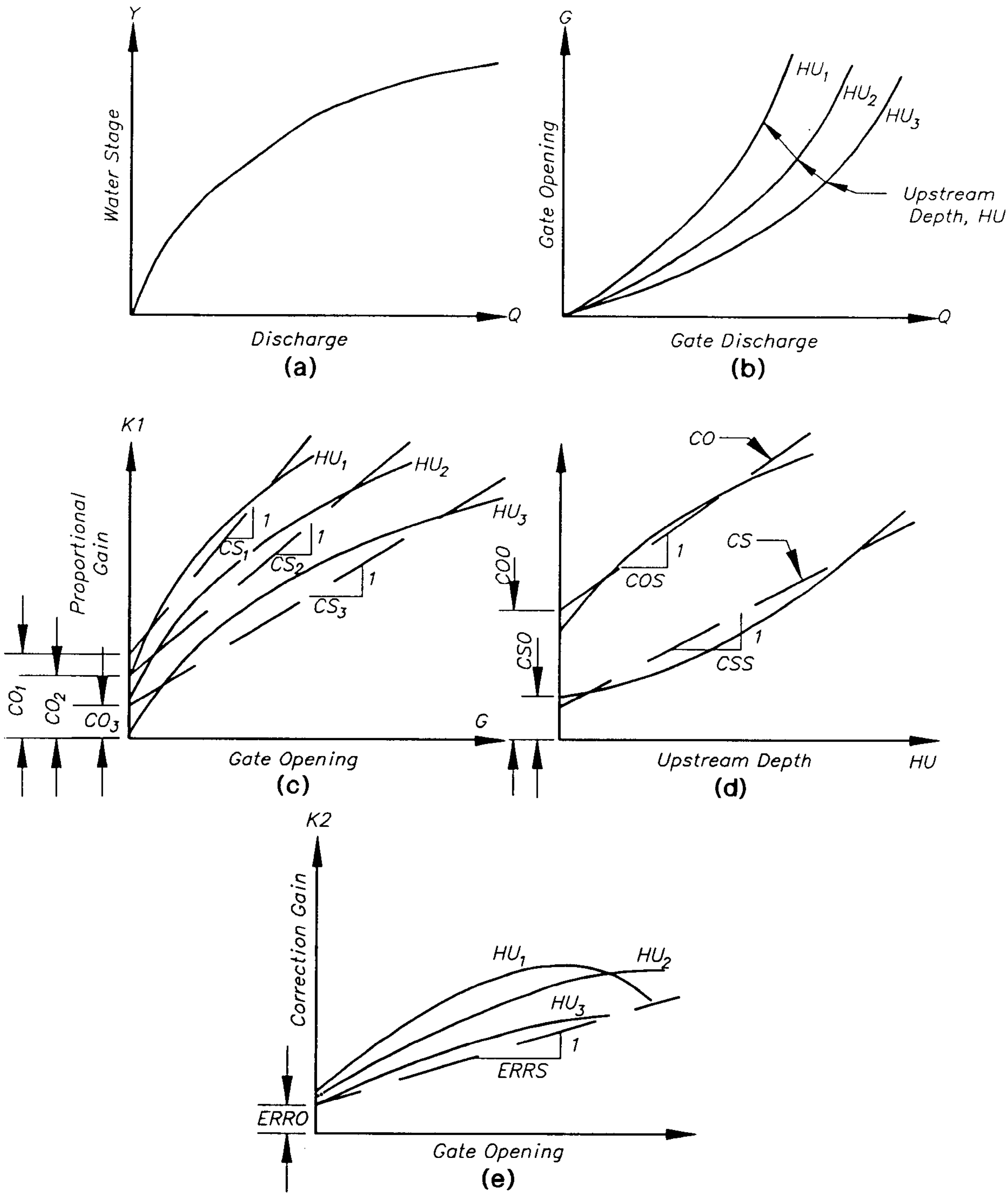



Figure 7-24.—Differential head algorithms—Q-Controller procedure.

$$K_1 = \frac{G_d}{Y_t} \tag{7.40}$$

where:

$K_1$ = proportional gain
$G_d$ = desired gate opening for the selected flow, $Q$ (figure 7-24b)
$Y_t$ = water level of the flow measurement facility for the same discharge, $Q$ (figure 7-24a)

Proportional gain, $K_1$, equation 7.40, is plotted on figure 7-24c as a function of gate opening. If the controlled gate upstream water level varies significantly, then the results must include various selected upstream elevations, $H_u$. Usually, one best-fit straight line through all the data points is not sufficient to represent $K_1$ versus $G_d$ with reasonable accuracy. Therefore, a family of best-fit straight lines is needed for each selected upstream water elevation, $H_u$, as shown on figure 7-24c. The proportional gain can be expressed as:

$$K_1 = G_d M + B \tag{7.41}$$

where:

$K_1$ = proportional gain
$G_d$ = desired upstream controlled gate opening
$M$ = slope of the best-fit straight line
$B$ = intercept of the best-fit straight line when the gate opening, $G_d$, is zero

The values of the best-fit straight lines for the slope, $M$, and the offset, $B$ (derived from figure 7-24c), are then plotted on figure 7-24d. A best-fit straight line can now be determined for the slope and offset data as a function of the upstream elevation, $H_u$, as:

$$M = H_u M_s + B_s \tag{7.42}$$

$$B = H_u M_b + B_b \tag{7.43}$$

where:

$B$ = intercept for figure 7-24c
$B_b$ = intercept of the intercept lines, figure 7-24d
$B_s$ = intercept of the slope lines, figure 7-24d
$M$ = slope for figure 7-24c
$M_b$ = slope of the intercept lines, figure 7-24d
$M_s$ = slope of the slope lines, figure 7-24d

For the family of curves shown on figure 7-24c, the calibration of the proportional gain, $K_1$, and the desired gate opening, $G_d$, may not be as linear as shown. It may be necessary to plot the data on log-log paper to obtain the proper relationship. Thus, equations 7.41, 7.42, and 7.43 would have to be expressed as a logarithmic function to achieve a better best-fit representation.

The RTU solves equations 7.13, 7.41, 7.42, and 7.43 in reverse order as follows:

$$M = H_u M_s + B_s \tag{7.44}$$

$$B = H_u M_b + B_b \tag{7.45}$$

$$K_1 = G_a M + B \tag{7.46}$$

$$G_d = K_1 Y_t \tag{7.47}$$

Equations 7.44 through 7.47 are only executed when a new target, $Y_t$, is desired. The $K_1$ is based upon the existing gate opening, $G_a$. Therefore, equation 7.47 provides an estimate of the new required gate opening, $G_d$, and remains at this value until the next flow change; i.e., a new target, $Y_t$, is made.

Computation of the new gate opening (equation 7.47) could be in error because of:

- Errors in calibration
- Deviations from the best-fit algorithms
- Change of the upstream water elevation, $H_u$

To account for these errors, a correction algorithm is used. The purpose of the correction algorithm is to convert the water portion of the flow measurement facility onto the desired target, $Y_t$. The correction algorithm also maintains the water level at the target as the upstream water depth changes. With the addition of the correction algorithm, the errors of equation 7.47 do not result in significant control problems. However, significant errors in the gate calibration (figure 7-24b) and the best-fit algorithms (figures 7-24c and 7-24d) will put increased emphasis onto the correction algorithm. Significant errors could cause larger overshoots and more cycling to occur in the response and recovery characteristics before a new steady state is reached.

The development of the correction algorithm is not difficult. It uses the proportional mode of control. However, the proportional gain, $K_3$, is based upon the ratio of the incremental changes of the gate opening, $G_a$, and the flow measurement water level, target $Y_t$:

$$K_3 = \frac{\Delta G_a}{\Delta Y_t} \tag{7.48}$$

where:

- $\Delta G_a$ = an incremental change of the gate opening, $G_a$, equal to 30 mm (0.1 ft) from selected steady-state flow conditions
- $K_3$ = proportional gain of the correction algorithm
- $\Delta Y_t$ = incremental change of the water level at the flow measurement facility caused by the incremental $\Delta G_a$ from the same selected steady-state flow conditions.

First, figure 7-24b is used to find $\Delta Q$ for the $\Delta G_a$ at selected steady-state flows. Then, figure 7-24b is used to find $\Delta Y_t$ for the same $\Delta Q$ at the same steady-state discharge, $Q$.

The results of equation 7.48 for selected gate openings, $G_a$, and the upstream elevation, $H_u$, are illustrated on figure 7-24e. Minimum values of the proportional gain, $K_3$, should be selected to avoid instability of control. The best selection would be the straight line drawn below all the data points:

$$K_3 = G_a M_e + B_e \tag{7.49}$$

where:

- $K_3$ = proportional gain of the correction algorithm
- $G_a$ = gate opening as measured by the sensor
- $M_e$ = slope of the straight line, figure 7-24e
- $B_e$ = intercept of the straight line when the gate opening, $G_a$, is zero, figure 7-24e

The corrected gate opening, $G_c$, can then be expressed as:

$$G_c = G_a + K_2 (Y_t - Y_c) \tag{7.50}$$

where:

- $G_c$ = cumulative gate opening correction
- $K_2$ = proportional gain as a function of $G_a$
- $G_a$ = existing gate opening
- $Y_t$ = desired water level of the flow measurement facility
- $Y_c$ = sensor measurement input of the water level at the flow measurement facility

The corrected gate opening, $G_c$, in equation 7.50 is cumulative. The correction can be either positive or negative because of the nature of the inevitable errors involved in the process. The cumulative gate opening correction, $G_c$, becomes a constant as the actual water level, $Y_c$ (of the flow measurement facility), approaches the desired target, $Y_t$. $G_c$ depends on the frequency of execution of equation 7.50. If the execution interval is less than 2 minutes, the proportional gain, $K_3$, will have to be reduced to prevent high overshoot characteristics. Also, $K_3$ must be reset to zero if the gate hoist becomes inoperative. Limiting the cumulative $G_c$ to a maximum value (representing the maximum error anticipated) would be an alternative to zero reset. The maximum error limit can be estimated from figure 7-24c.

The control action of the comparator element is typical of the proportional mode feedback control system and can be expressed as:

$$\pm\Delta G = G_d + G_c - G_a \pm D_d \tag{7.51}$$

where:

- $D_d$ = gate movement deadband
- $\pm\Delta G$ = distance and direction of gate movement
- $G_a$ = sensor measured input of the existing gate opening
- $G_c$ = corrected gate opening of the error correction algorithm
- $G_d$ = desired gate opening of the differential head algorithm Q-Controller to achieve the desired water level (or flow) target of the flow measurement facility

A microprocessor-based RTU located onsite should be programmed to execute the algorithms at a time interval of 2 minutes. Figure 7-25 is a schematic application of the Big Horn Canal Headworks, Yellowtail Afterbay Dam, 72 km (45 mi) southeast of Billings, Montana. The differential head algorithms are partly based upon logarithmic functions so as to achieve the best-fit relation. The flow measurement facility is a canal water level gauging station located about 305 m (1,000 ft) downstream. The Yellowtail Powerplant operation would vary the Yellowtail Afterbay Dam water elevation as much as 4.9 m (16 ft) in a 24-hour period. The response and recovery characteristics can be evaluated using figure 7-26.

Figure 7-26 shows the mathematical model simulation of the system and for a step change in the target. The model included an interpolation scheme to obtain the target in terms of the water level, $Y_s$ , from a table developed by the Water Resources Division of the U.S. Geological Survey based upon a series of current meter measurements. Periodically, the rating table was updated to provide a correction to account for changes in the canal prism rating station.

At time 10 minutes, the target flow was increased from 11.3 to 13.6 $m^3/s$ (400 to 480 $ft^3/s$). The interpolation of the rating table increased the target, $Y_t$, from 1.46 to 1.62 m (4.80 to 5.30 ft). At 2-minute intervals, the Q-Controller calculates the desired gate opening, $G_d$ . The response and recovery of the water level and the gate flow approaches the new steady state at time 50 minutes—40 minutes later. The step change (increase) caused a large overshoot at 20 minutes. Subsequent mathematical model runs indicated the overshoot could be reduced by changing the new target, $Y_t$ , at the rate of 0.9 mm per hour. The recovery time to the new steady state was about the same. Therefore, the ramp feature was adopted. The target flow is still entered as a step function by the ditchrider or through supervisory automatic control.

Mathematical model studies indicated that the Q-Controller, based upon the differential head technique, would provide satisfactory response and recovery characteristics for all flow conditions.

## OPEN-LOOP CONTROL OF CANAL SYSTEM

### 7-19. State Estimation Algorithms

*State estimation algorithms* are methods of predicting the motions of the control structures for a predetermined water demand or water surface profile schedule—scheduled operation. These methods are useful in controlling transients or in optimizing off-peak pumping. Reclamation has developed two state estimation algorithms—gate stroking and linear programming. Both of these state estimation algorithms require a supervisory control system for implementation.

**a. Gate stroking.**—Gate stroking is a technique used to control transients in a canal subjected to variations in discharge or water level [12]. The term comes from a similar procedure used in closed conduits known as valve stroking. Although the term "stroking" as used in this context cannot be found in the dictionary, its definition can be implied from the several meanings commonly listed. For example, stroking is defined as: "any of a series of continuous or discontinuous efforts to do, produce, or accomplish something, especially a successful result." Based on its technical usage and the general meaning of stroking, gate stroking can be defined as: a continuous or series of discontinuous gate motions that produce a predetermined variation in discharge or water level in a canal.

Gate stroking allows the rapid startup or shutdown of a canal without creating large disturbances in the

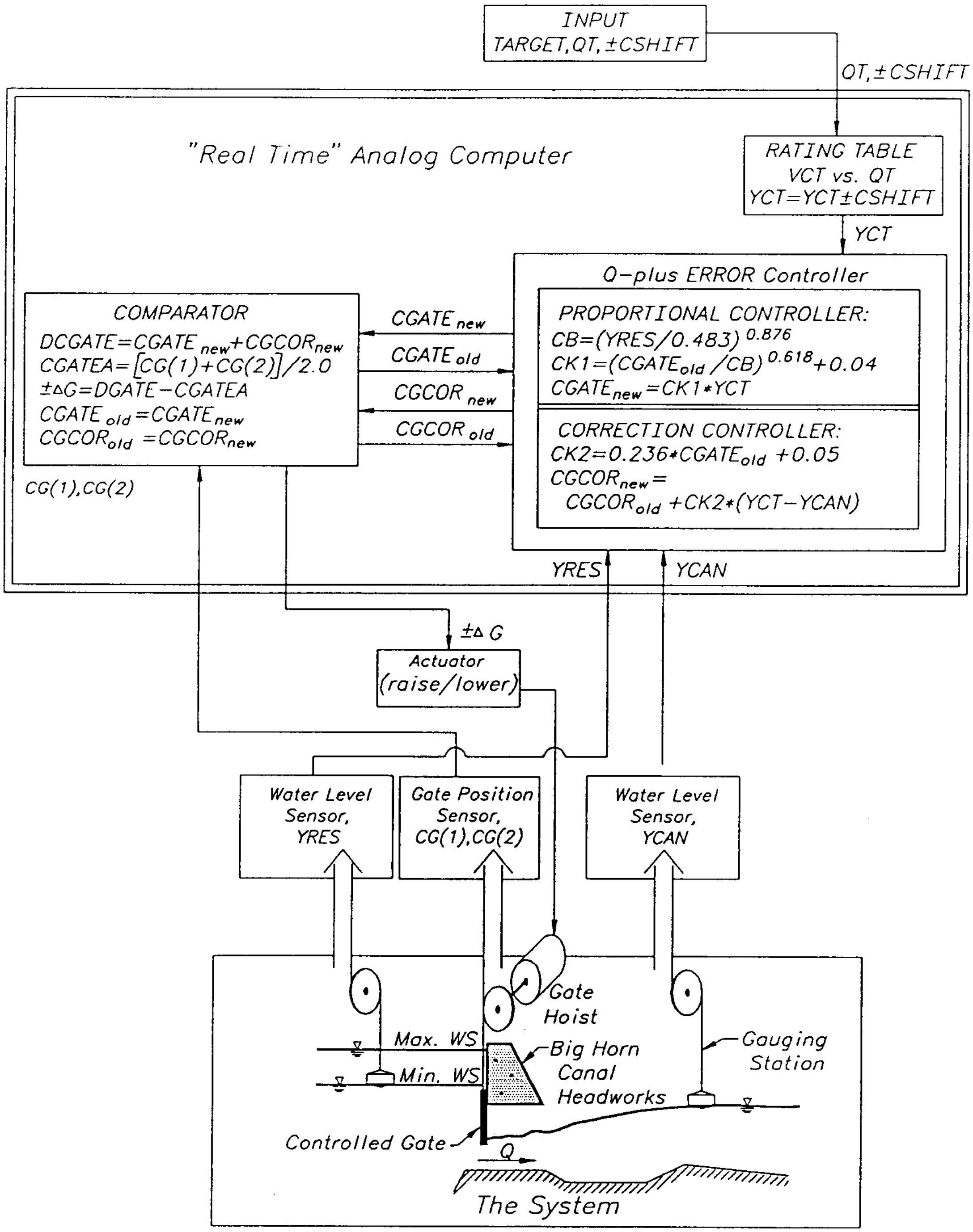



Figure 7-25.—Big Horn Canal Headworks Q-plus controller differential head algorithms.

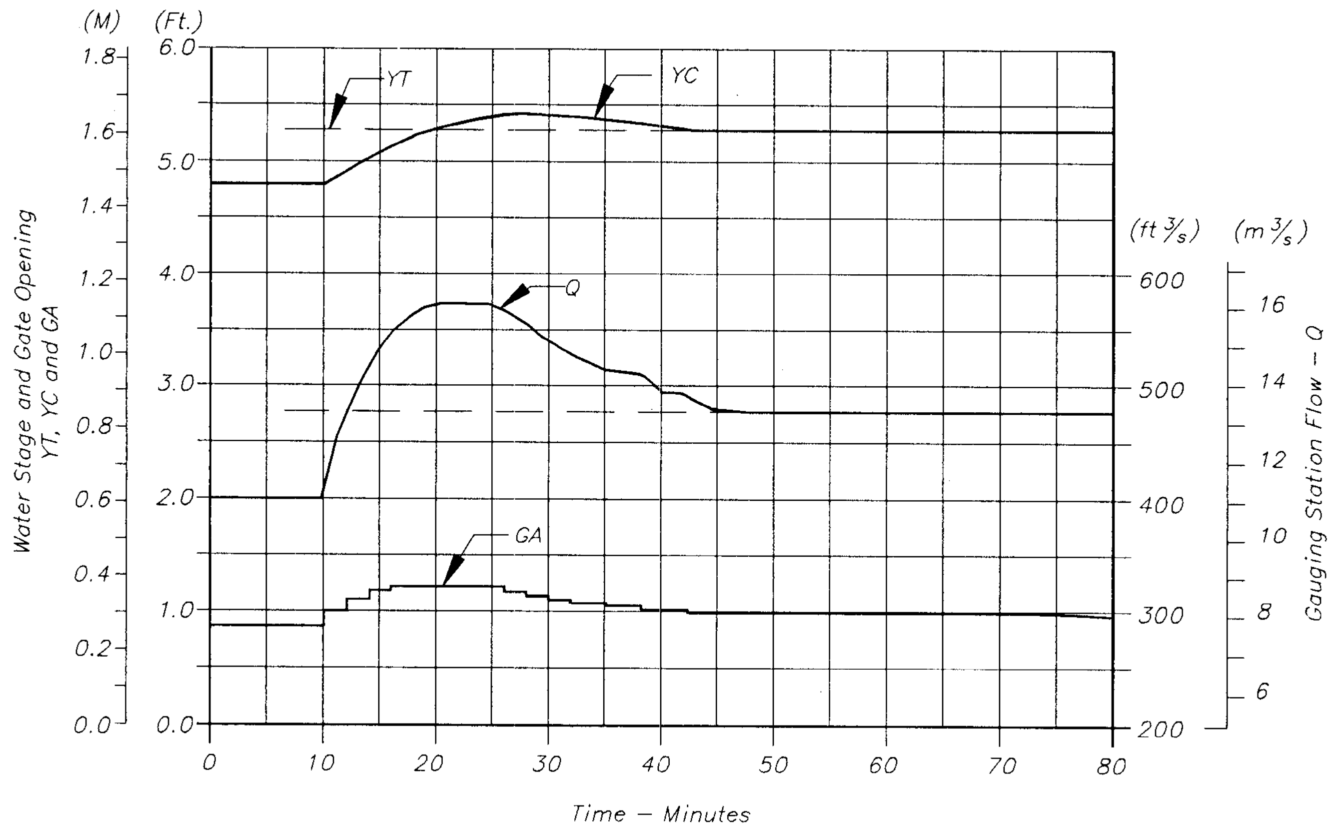



Figure 7-26.—Big Horn Canal Headworks Q-plus error controller typical response and recovery characteristics.

water level. With gate stroking, a flow change can be made about 20 to 30 times faster than with conventional manual operation techniques. Gate stroking also can be used to develop procedures for rapid shutdown of canal systems during emergencies.

The technique requires the solution of the unsteady equations of motion and continuity. Any computational scheme which accurately calculates the unsteady water surface profiles can be used. Reclamation has chosen the method of characteristics using a characteristic grid. The advantage of the grid is that it is adaptive. That is, it adjusts itself to be closely spaced where the water level varies rapidly and coarsely spaced where the water level changes slowly. This method requires time-line interpolation at boundaries.

The method of solution is as follows:

1. The depth and discharge are specified, as functions of time, at the most downstream end of the canal reach. Usually, the depth is held constant, but this is not a requirement.
2. The depth is specified, as a function of time, at the downstream end of each pool comprising the reach. In most studies, these depths also are held constant.
3. If turnout flows occur along the canal, their variation with time is also specified.
4. With given initial conditions and the temporal variations specified above, the unsteady-flow equations are solved for all locations in each pool. Either steady or unsteady flows can be specified as initial conditions.
5. Finally, using the computed depths and discharges at the ends of each pool, the variation of the gate openings between the pools is computed as a function of time.

The gate motions determined by this method are those required to produce the specified variations in depth along the canal reach.

Computer simulations have shown that the initiation of the gate motion is sequential, beginning with the most downstream gate. The timing of the initiation of the gate motion corresponds to the wave travel time in the canal. In general, initial motion of an individual gate is quite rapid with considerable overshoot as shown on figure 7-27. Then, the gate motion becomes slower, gradually converging to the final gate position. Variable-speed or multispeed motors are required to accurately follow the irregular motion dictated by gate stroking.

For increases in flow, the characteristic of overshooting and then settling on the desired final gate opening is called *creating push water.* Studies of the Phellps Canal in Nebraska showed that the time to increase the canal flow from zero flow to the design discharge could be decreased from 3 days for manual operation to about 3 hours using gate stroking.

**b. Linear programming.**—Linear programming is a standard technique of operations research. The purpose of linear programming is to obtain one of the following objectives:

- Minimize the input while a preassigned output is achieved.
- Maximize the output while a preassigned input is achieved.
- Maximize some functions of input and output values, such as their difference (profit) or their ratio (return on investment).

Operational cost of a canal system supplied by pumps can be large. For large power users, power can be purchased at bulk rates during periods of low demand. Costs can be reduced significantly if most of the pumping can be done during periods when low-priced rates are available. Pumping during the low-rate periods is known as *off-peak pumping.* Conversely, pumping during periods of high demand is known as *on-peak pumping.*

The objective of linear programming on a canal system supplied by pumps is to satisfy scheduled demands with minimum on-peak pumping. Thus, on a canal system, input is minimized while a preassigned output is achieved. This objective must be achieved within the physical constraints of the canal. The constraints include:

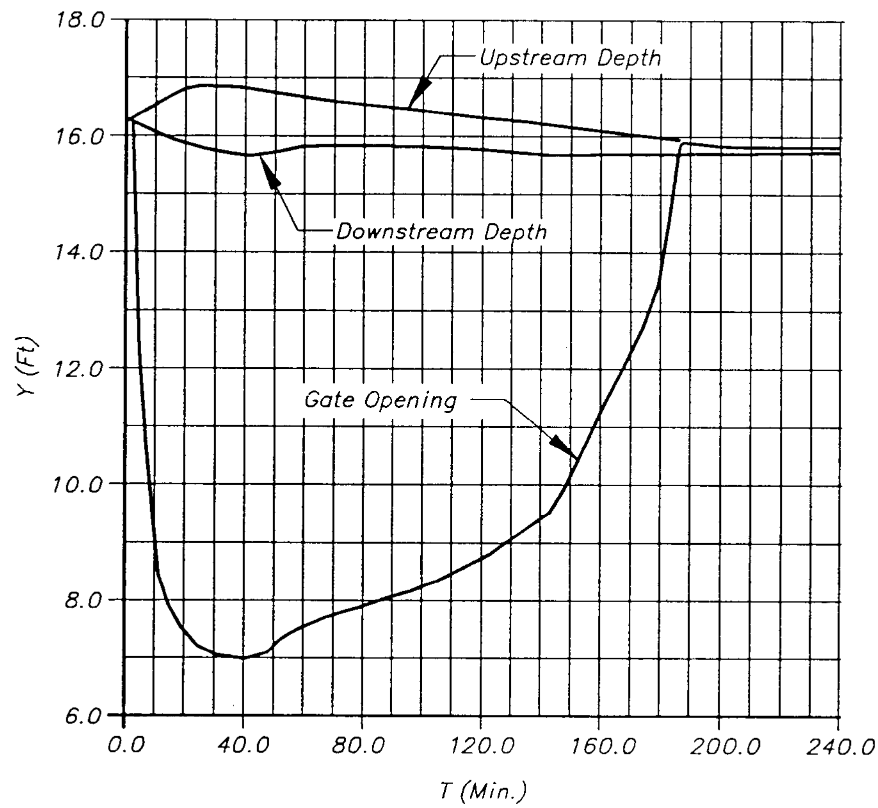



Figure 7-27.—Gate motions with gate stroking.

- Drawdown criteria
- Minimum pool levels in each pump forebay
- Minimum pool levels at canal turnouts
- Maximum pool levels
- Positive heads at gates
- Maximum pump capacities
- Pump cycling criteria (number of starts in a given time period)

As implemented by Reclamation, linear programming is used to determine gate and pumping schedules in such a manner that operating costs are minimized [6]. For example, linear programming predicts how on-line pumps are to be operated to minimize on-peak pumping costs.

With linear programming, hydraulic transients are not considered. However, after gate and pump schedules are determined by linear programming, the amplitude of the resultant hydraulic transients can be examined to determine if they are excessive.

The methodology of linear programming was developed with the assumption that all of the variables can be expressed as first degree equations or inequalities. The implication of this assumption is that the water level profiles in each pool are straight lines. That is, backwater effects do not exist with the linear assumption. A change in discharge consists of a translation of the water surface parallel to the original water surface level and a fluctuation of the water surface level about the center of the pool. In this manner, linear relationships between the discharge and water levels in each pool can be derived.

The procedure followed in the computations is to determine pump and gate discharge schedules that satisfy demand and simultaneously minimize on-peak pumping. Then, using linear discharge versus water level relationships, water level(s) schedules at each end of the pool are determined. From the discharge and water levels, gate opening schedules between pools are calculated.

For the Granite Reef Aqueduct, Central Arizona Project, gate opening schedules developed by linear programming did not produce large transients [19]. The smooth operation can be attributed to two factors: (1) only gradual changes in discharge were allowed (hourly flow changes of less than 15 percent of the design flow per pool) and (2) strict drawdown criteria (hourly water level changes of less than 3 percent of the design depth per pool).

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# CHAPTER 8

# COMMUNICATION SYSTEMS

## COMMUNICATION SYSTEMS DESIGN

### 8-1. Purpose of Communication Systems

Communication systems serve canal operations and maintenance by providing voice, alarm, telemetry, and control capabilities. These capabilities are essential for efficient and safe operation of a canal system.

The voice communication system allows the watermaster to give instructions to ditchriders related to adjustments of proper gate openings and water levels. The system also allows the ditchrider to report operating conditions and canal system abnormalities to the watermaster.

The alarm communication system provides the watermaster with automatic alarm reporting capability from each of the important structures within the canal system. The alarm information received can be used in conjunction with the voice communication system to help the watermaster provide the ditchrider with correct instructions. The watermaster can efficiently direct the ditchrider to the correct location during emergency and abnormal operating conditions based on automatic alarm information.

The telemetry communication system provides the watermaster with instrumentation data and equipment status information. The canal equipment control capability is usually combined with the telemetry communication system for most canal systems. This combination provides the watermaster with the capability to monitor *and* control the canal system without ditchrider assistance. When the functions of both telemetry and control are combined over the same communication system, the overall system is usually referred to as a supervisory control and data acquisition (SCADA) communication system. The SCADA type communication system provides the watermaster with the most flexibility in operating a canal system. The SCADA type communication system provides alarm information, equipment status information, and actual values for gate positions, water levels, and flows throughout the entire canal system. With this information, the entire canal system operation can be automated, creating more efficient use of the canal system and allowing maximum response to abnormal canal flow conditions.

### 8-2. Topics to be Covered

The methods available for providing general purpose communication systems vary from a simple two-wire line to sophisticated digital radio transmitters and receivers. This chapter will emphasize the important communication system design criteria that are specifically applicable to canal automation so that the best communication system can be selected for any canal system.

First, the various types of communication systems will be described, and a brief explanation of the design requirements will be presented. The advantages and disadvantages of each communication system described will be discussed with emphasis on the application to canal automation.

Second, the physical communication system layout and how each layout is applied to meet a particular communication requirement will be discussed, as well as how each layout can serve the canal automation criteria in the most efficient manner. Each type of layout will be discussed along with selection criteria to be used when applied to canal automation.

Next, the types of communication channels will be described, and how they are used for canal automation projects will be described. The information (voice or data) carried on a communication system is divided into channels. Various types of communication channel arrangements can be configured depending on the requirements of the canal system operation.

Finally, important information will be presented to allow selection of the most reliable communication system for the application. The information will include methods of protecting the communication system equipment from various electrical and environmental hazards. Because the communication system is the major link between the canal system and the operational headquarters, it must be designed to provide reliable service to the project. A communication system used to provide the important control and data acquisition information for the canal automation project must be extremely reliable. Because the canal operations directly depend upon the ability of the automatic control system to determine the actual canal condition at any time, loss of communications will result in serious degradation of the automatic control system.

## 8-3. Selection Factors

The selection of a communication system for canal automation requires consideration of:

- Canal system operation method desired
- Location of canal facilities to be automated
- Reliability requirements of canal system operation
- Lifetime communication system cost
- Communication channel configuration
- Number of control and data acquisition sites (remote terminal units [RTU's])
- Number of data acquisition and control points at each RTU site
- Design requirements of data acquisition and control system

The selection process also includes identifying the terrain in which the project is located so that communication systems that are not suitable for the particular canal system location can be eliminated from the evaluation process.

Each of these criteria must be evaluated before the appropriate communication system can be selected for the canal system automation. After the selection of the proper type of communication system, the design, installation, and quality of maintenance will determine the overall success of the communication system.

The types of communication systems that are most practical for canal system automation projects are:

- Metallic cable
- Fiber optic cable
- Ultra-high frequency/very high frequency (UHF/VHF) radio
- Microwave

The Bureau of Reclamation (Reclamation) has used these types of communication systems in canal automation projects, and they have proven to be the most economical and reliable. Although not used by Reclamation to date, cellular phone technology appears to have some application in SCADA systems.

Other types of communication systems sometimes used for canal system automation under certain circumstances are:

- Leased line
- Satellite
- Meteor burst

# METALLIC CABLE COMMUNICATION SYSTEMS

## 8-4. Background

Metallic cable systems are suited to applications requiring smaller bandwidths, lower data rates, and shorter transmission distances. Metallic cable systems can be used to carry voice frequency communications and data directly with minimal to no external electrical equipment other than the metallic cable itself. Metallic cable may also be used to carry multiplexed multiple voice frequency and data channels with the use of either analog or digital multiplexing equipment. Multiplexing also requires the addition of signal repeater equipment installed at evenly spaced electrical intervals along the metallic cable path. The discussion that follows deals with the most basic use of metallic cable used for transmitting unmultiplexed voice frequency signals.

On new installations where trenching is a viable option, serious consideration should be given to using buried cable for the transmission of voice and data communication. Reclamation communication designers prefer buried cable when communication security is important or where a series-type communication system is required.

For example, if a remote check structure needs to communicate with an adjacent check structure, then buried cable would be ideal; i.e., a series circuit. However, if the remote needs to communicate with a central computer 48 or 64 kilometers (km) (30 or 40 miles [mi]) away, then radio would be a better choice (i.e., a hub or spoke type of communication circuit configuration).

Rights-of-way must be obtained and cleared prior to considering buried cable. Trenching is expensive; therefore, buried cable should be used primarily for new installations (i.e., along canals or siphons) where the government owns or has right-of-way privileges.

Because the lifetime of buried cable is estimated around 20 years, the cost per year becomes attractive when compared to radio systems, which have an equipment lifetime of some 6 to 8 years.

Care should be used in the placement of the cable in the trench and the splicing techniques used because water leakage and cable damage by rodents can become a problem with buried cable.

Cable splices should be raised above ground using pedestals, and the cable should be protected from damage, heavy equipment, large rocks, etc., during the final filling of the trench. Protective cable coverings might be required when communication cable is buried in rodent-infested areas.

Be sure to leave some extra unused cable pairs for expansion and replacement. Four-wire circuits should be used for the same reasons as discussed in the "Four-Wire Versus Two-Wire System" section. The cable should be frequency compensated for the highest data bit rate to be used on the cable. A couple of pairs for an operation and maintenance channel will be helpful when maintenance personnel are checking for cable damage or setting up data levels. Buried cable system cable-loading techniques, which are described in the following section on system design, should resemble those used for overhead cable.

## 8-5. System Design

The twisted pair metallic communication cable uses multiple pairs of copper wires to carry electrical signals (voice or data) from one place to another. The number of wires in a cable varies from a single pair (two wires) to hundreds of wire pairs. The cable pairs are bundled into a compact cable used for either overhead or buried installation.

The practical transmission length of metallic twisted pair communication cable depends upon the electrical signal attenuation characteristics of the cable. The transmission distance is 24 to 32 km (15 to 20 mi) based on a 20-decibel margin between the transmitted and received signal. The transmission distance can be improved by applying signal conditioning equipment to each twisted pair. The addition of signal conditioning equipment will improve the frequency response of the cable. Applying signal conditioning frequency compensation to a twisted pair cable system is called *loading*.

*Loaded* metallic twisted pair communication cable is used when longer transmission distances are required. Loading coils are connected in each twisted pair, and the loading coils are designed for certain load coil spacing. The standard load coil spacings are 914, 1,372, and 1,829 meters (m) (3,000, 4,500, and 6,000 feet [ft]). The loading systems carry designations of B for 914-m (3,000-ft) spacing, D for 1,372-m (4,500-ft) spacing, and H for 1,829-m (6,000-ft) spacing. The loading system designation is followed by a number that designates the inductance of the loading coil in millihenries. A number preceding the loading system designation indicates the gauge of the twisted pair wire. Therefore, a designation of 19-H-88 loading system indicates the loading is for No. 19 American Wire Gauge (AWG) wire size at 1,829-m (6,000-ft) spacing using loading coils with 88 millihenries of inductance. The loading coils are manufactured in 44-, 66-, and 88-millihenry sizes.

An H-88 loaded metallic twisted pair cable can handle voice communications for 32 to 97 km (20 to 60 mi), depending upon which AWG wire gauge is used. Data communications using audio tones can be transmitted a distance of 13 to 40 km (8 to 25 mi) over the same loaded twisted pair cable.

Loading the twisted pair cable will approximately triple the transmission distance over the same unloaded twisted pair cable. Additional transmission distances are achieved using amplifiers to boost the signal strength when the decibel loss reaches about 24 decibels for voice communications and 10 decibels for data communications.

Tables 8-1 and 8-2 illustrate the characteristics of nonloaded and loaded cable pairs. The column headed *distortion penalty* has been developed by measurement and experience and represents the signal distortion for factors that influence the signal integrity. The 1,000-hertz signal attenuation caused by the cable impedance represents the largest signal distortion factor. The distortion penalty is almost insignificant when loading is applied to the cable and the signal distortion is caused almost entirely by the wire pair attenuation.

Table 8-1.—Characteristics of nonloaded cable pairs

| Wire gauge AWG | Capacitance per km (μF) | dB/mi (1 kHz) | Loop res (Ω/km) | Characteristic impedance, $Z_0$ (1 kHz) | Distortion penalty (dB/km) |
|---|---|---|---|---|---|
| 19 | 0.041 | 1.11 | 53 | 450 ∡43° | 0.14 |
| 19 | 0.052 | 1.26 | 53 | 400 ∡43° | 0.16 |
| 19 | 0.056 | 1.30 | 53 | 390 ∡43° | 0.16 |
| 22 | 0.051 | 1.79 | 106 | 580 ∡44° | 0.22 |
| 22 | 0.056 | 1.86 | 106 | 530 ∡44° | 0.24 |
| 24 | 0.052 | 2.31 | 170 | 720 ∡44° | 0.29 |
| 24 | 0.056 | 2.39 | 170 | 700 ∡44° | 0.29 |

Note: μF = microfarad, dB/mi = decibels per mile, kHz = kilohertz, res = resistance, Ω/km = ohms per kilometer, dB/km = decibels per kilometer.

Table 8-2.—Characteristics of loaded cable pairs

| Loading method | Wire size AWG | Capacitance per km (μF) | Cutoff frequency (kHz) | $Z_0$ at 1 kHz (Ω) | dB/km | Distortion penalty (dB/km) |
|---|---|---|---|---|---|---|
| B-88 | 19 | 0.052 | 4,930 | 1,405 | 0.20 | 0.0 |
| D-88 | 22 | 0.056 | 3,860 | 1,135 | 0.45 | 0.0 |
| D-66 | 24 | 0.056 | 4,420 | 1,025 | 0.79 | 0.0 |
| H-44 | 19 | 0.052 | 4,920 | 730 | 0.35 | 0.0 |
| H-88 | 19 | 0.052 | 3,480 | 1,025 | 0.26 | 0.19 |
| H-88 | 22 | 0.056 | 3,370 | 1,005 | 0.51 | 0.19 |
| H-88 | 24 | 0.056 | 3,360 | 830 | 0.78 | 0.0 |

The H-88 loading system provides the best overall frequency response and attenuation improvement when the required number of loading coil locations and costs are considered. The H-88 loading system requires 88-millihenry coils located every 1,829 m (6,000 ft) ± 2 percent. The cutoff frequency is about 3,500 hertz, and this loading method is used primarily for loops and trunk circuits having a total distance greater than 5,486 km (18,000 ft).

The D-88 loading system has essentially the same attenuation and impedance characteristics in the 1000-hertz range as the H-88 loading system. D-88 loading is desirable on twisted pair cables having a high mutual capacitance (about 0.09 microfarad per mile or higher). This loading provides an impedance characteristic nearly identical to that of the low capacitance cables loaded using the H-88 system.

The D-66 loading system requires 66-millihenry coils located every 1,372 m (4,500 ft) ±2 percent. The cutoff frequency is about 4,500 hertz, and this wider frequency range allows higher data rates to be transmitted over the cable. It is used for loops and trunk circuits having a total distance greater than 4,115 m (13,500 ft).

The B-88 loading system is justifiable for use, based on the number of loading coils required and cost, only when the objective of the loading system is to obtain a lower attenuation than is practical with the H-88 or D-88 loading systems and where a substantially higher cutoff frequency is also required. The higher characteristic impedance of the B-88 loading system is a distinct disadvantage. The cutoff frequency is about 5,000 hertz, and coils are required every 914 m (3,000 ft) ± 2 percent. The H-44 loading system may be desirable in special cases where lower impedance and relatively high cutoff frequency are needed for impedance matching purposes to other transmission systems. This loading method requires 44-millihenry coils located every 1,829 m (6,000 ft) ± 2 percent. The cutoff frequency is about 5,000 hertz. It is used for loops having a total length greater than 3,658 m (12,000 ft).

Each end section of a metallic twisted pair communication circuit needs to have loading coil spacing equal to one-half of the required distance for the loading method used. For example, an H-88 system should consist of 914 m (3,000 ft) of cable from the start of the communication circuit to the first loading coil location and 1,829-m (6,000-ft) spacing between loading coils thereafter.

## 8-6. Overhead Installations

**a. Cable types.**—Two types of construction are used for overhead cable systems. One requires that the cable be attached to a support strand strung between the poles. The other is a self-supporting construction that is sometimes called "figure 8" cable. A typical figure 8 cable is shown on figure 8-1. The Rural Utilities Services (RUS) has developed specifications that classify overhead cable types that are suitable to either installation

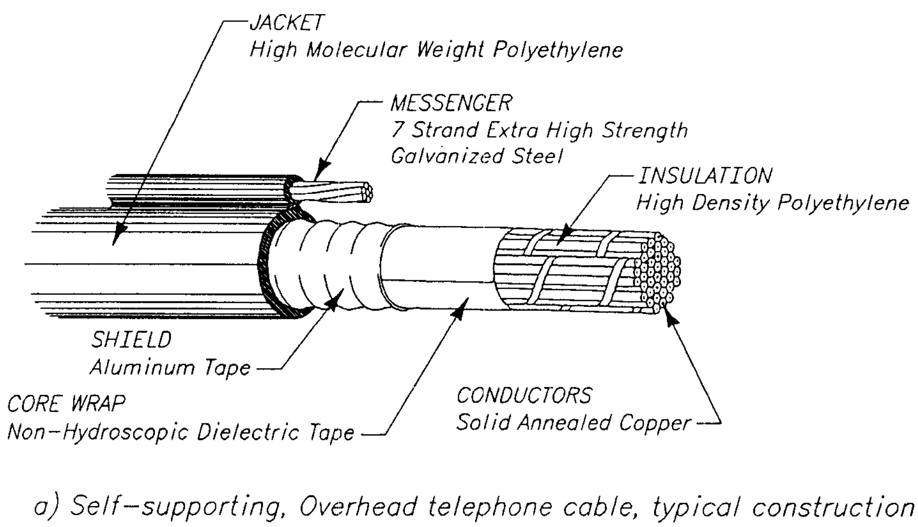


Figure 8-1.—A typical figure 8 cable.

method. The cable manufacturers supply cable that is constructed in accordance with the RUS specifications.

The overhead cable that requires a separate supporting wire or messenger is covered by RUS Specification PE-22. This cable core can be furnished in twisted pair configurations from 6 to 900 pairs. The cable is constructed using 19, 22, 24, or 26 AWG size wires to make up the core. The size of the wires determines the number of pairs that are assembled into one cable.

The figure 8 type of overhead cable construction is covered by RUS Specification PE-38. This cable core can be furnished in twisted pairs from 6 to 300 pairs. The cable is constructed using 19, 22, or 24 AWG size wires to make up the core. Smaller sizes are not used in this type of cable design because of the tensile strength required for installation.

Both cable types are constructed with an armor shield to protect the cable core from induced electromagnetic and electrostatic fields. The shield construction is either plastic-covered aluminum or fully annealed solid copper that is corrugated and applied longitudinally over the core covering.

No. 19 AWG is the recommended wire gauge for overhead cable. This gauge provides the desirable mechanical strength and sufficient cable pairs for canal automation communication systems.

**b. Installation methods.**—The overhead cable is attached to the poles using an independent messenger cable. The messenger cable can be installed on the poles first, and the twisted pair overhead cable can be laced to the messenger using steel lacing wire. The messenger is supported at each pole using clamps, and the cable is supported by the lacing wire. The figure 8 cable is installed by attaching clamps to the integral messenger cable at each pole.

The figure 8 cable installation requires only one pass to install the cable on the poles. Using a separate messenger requires two passes to install the cable on the poles.

Special grounding precautions must be taken when the communication cable is installed on poles that carry power lines. The communication cable shield should be grounded at regular intervals to prevent induced power line voltage from becoming too high on the communication cable. The induced voltage developed on the communication cable should not exceed 300 volts root mean square (rms). The grounding intervals will vary according to the power line voltage. The grounding hardware should be installed at the pole locations. Ground rods will have to be driven into the ground using sufficient numbers of ground rods to achieve a ground resistance of 5 ohms or less. Coordination of cable installation with the local power line utility is also recommended because the utility company can mitigate induced voltages.

**c. Splicing and splicing closures.**—The use of splices in communication cable systems should be kept to a minimum. The cable should be purchased in the longest reel lengths possible. The splices should be made on the poles to allow access to the cable splice closure. The splice joints should be covered with insulation equal to that on the conductors, and the integrity of the cable messenger should be maintained. Splice closures should not allow water to enter into the splice, and the closures should be of the re-enterable type.

## 8-7. Direct Buried Installations

**a. Cable types.**—The construction of the direct buried cable differs significantly from the overhead cable type. The cable construction must allow protection from moisture entry into the conductors, and it must allow protection against rodent damage. The RUS has developed specifications that classify direct buried cable into types that are suitable for various installation methods. The cable manufacturers supply cable that is constructed to the various RUS specifications.

The major differences in direct buried cable construction are the gauge of outer shielding used, number of jackets, gauge of armor shield, and the use of a filling compound. The direct buried cable is susceptible to rodent damage, installation damage, moisture penetration, and abrasion. To protect against these hazards to the cable, special construction is used for direct buried cables. Direct buried cable is constructed with and without a filling compound. Figure 8-2 shows the construction of a typical air core direct buried cable. Figure 8-3 shows the construction of a typical filled direct buried cable.

The direct buried cable construction shown on figure 8-2 is a double-jacketed type. This construction conforms to the requirements of RUS specification PE-23. The corrugated metal shield thickness determines whether the cable is

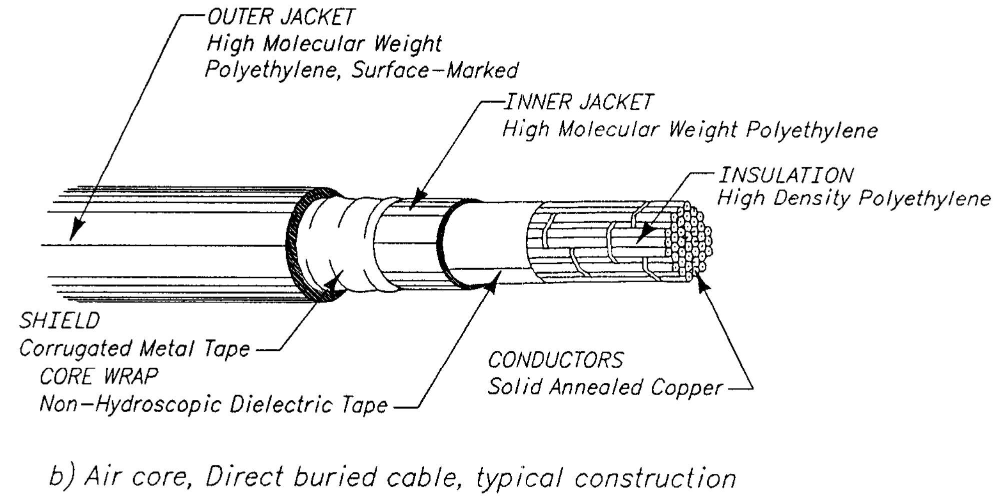


Figure 8-2.—A typical air core direct buried cable.

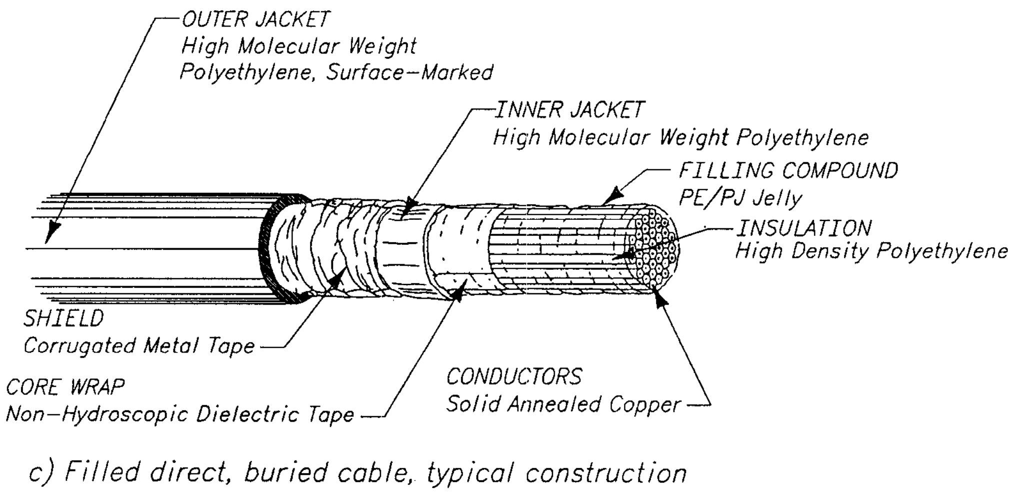


Figure 8-3.—A typical filled direct buried cable.

susceptible to damage by gnawing rodents. The shield must be corrugated to enhance cable flexibility and to minimize shield metal fatigue. The inner jacket provides additional mechanical protection, dielectric strength, and water ingress protection in case of outer jacket damage.

The direct buried cable construction shown on figure 8-3 is a double-jacketed filled type. This construction conforms to the requirements of RUS specification PE-39. The double jackets and armor shield provide the same characteristics as they do for the air core cable. The filling compound is used to prevent any moisture and water entry into the cable core and to prevent any moisture that enters the cable from migrating along the core length. The filling compound is petroleum jelly based and completely fills the cable core space between insulated conductors and between the core and the core wrap, including the core wrap tape overlap. The armor shield protects the cable core from induced electromagnetic and electrostatic fields. This shield also protects the cable from damage caused by gnawing rodents and cable installation hazards. To provide adequate protection from rodents, the metal shield must be 0.25-millimeter-

(mm) (0.01-inch- [in]) thick fully annealed solid copper, or 0.15-mm- (0.006-in-) thick bimetal (copper/iron/copper, copper/stainless steel). Other types of armor shields are also used to provide the same protection, but the copper and bimetal are the most commonly used materials.

The type of cable construction used for a canal communication system will depend on the soil in which the cable is being buried. A desert or dry location would indicate the use of the air core cable. The filled cable should be used whenever wet soil is anticipated at the depth of the cable installation. The recommended wire gauge for the buried cable is No. 19 AWG. This gauge provides the desired mechanical strength and electrical properties for buried cable communication systems used for canal automation systems.

**b. Installation methods.**—The installation method used to bury the communication cable is important to the success of the entire buried cable communication system. Early failure and cable outages will certainly occur if the cable is not installed properly. Two methods are popular for installing multipair cable systems.

One method involves the use of a special plow to install the cable without any excavation. The reel of cable is pulled behind a plow that cuts the earth, lays the cable, and returns the earth over the cut. Using this method, cables can be installed at depths of 0.6 to 0.9 m (2 to 3 ft). The other method is to dig a trench and lay the cable in the trench. The cable is covered with a sand cushion, and the trench is then backfilled. This method can be used to install cables at depths of 1.5 m (5 ft) or less.

The best technique for installing the cable in the trench is to use a crawler tractor with a side boom on which the reel is mounted. The cable feeds off the top of the reel directly into the center of the trench without contacting the side walls or being dragged along the bottom. The cable should always be removed from the reel by turning the mounted reel and not by pulling the cable off the reel. The cable should be *snaked* into the trench with sufficient slack to allow for ground settling and shifting during the life of the cable installation. At least 0.6 m (24 in) of slack should be left whenever a buried cable enters or exits a conduit. The additional slack will reduce the strain on the cable during backfilling.

Cable should be handled carefully at all times to avoid damage and should not be dragged across the ground. The ends of the cable should be sealed with manufacturer recommended caps to prevent moisture penetration. The ends of the cable should be terminated or sealed immediately after cutting the cable if a splice is not made at that time. The minimum bending radius of the particular cable should not be exceeded.

**c. Splicing and splicing closures.**—The use of splices in communication cable systems should be kept to a minimum. The cable should be purchased in the longest reel lengths possible. The direct buried cable should be spliced only in above-ground splice enclosures or buried splice vaults with manhole covers. The splice joints should be covered with insulation equal to that on the conductors, and the integrity of filled cable should be maintained. Splice enclosures should not allow water to enter into the splice, and the enclosures should be of a re-enterable design.

**d. Metallic cable testing.**—Metallic cable communication systems should be thoroughly tested before and after installation. The methods used to install metallic cable communication systems expose the cable to potential damage, resulting in poor communication signal transmission. The cable jacket can be damaged, causing the twisted pairs inside to be disturbed. Overtensioning the cable can cause failures in the twisted pairs. Bending the cable too sharply can cause twisted pair failures. The splicing process can cause pair mismatch and failures. These types of cable failures can occur during both overhead and buried types of installations.

The best method to detect and eliminate problems with metallic cable communication systems is to test the twisted pairs before and after installation. The results of these tests can be compared, and any differences can be investigated to determine the exact location and cause of the problem.

## 8-8. Applications

Metallic cable is probably the most preferred communication system for systems using real-time or remote control, telemetry, and alarms. Because metallic cable provides the versatility of separate circuits for alarms and data, it can easily be used in a party line or radial configuration.

## 8-9. Advantages and Disadvantages

Advantages:

- User owned; user has complete control.
- No Federal Communications Commission (FCC) licensing required.
- Suitable for radial or party line communications.
- Medium speed data rates and bandwidth available to 1,200 bits per second.
- Long life—20 to 30 years.
- System can be designed for expansion at low cost by installing additional future pairs.
- Additional pairs allow for easy channel expansion capability.
- A pair can be used for voice communications.
- Suitable for continuous data scanning supervisory control and data acquisition systems.

Disadvantages:

- Significant initial installation costs.
- Expensive to locate and repair cable faults.
- Cable is susceptible to vandalism, weather, and excavation.
- Lightning protection for each pair is required.
- Cable shielding and special grounding is required to prevent interference or personnel injury from electromagnetic fields.
- Special design and filtering is required to reduce crosstalk between cable pairs.
- Multipair cable requires special splicing enclosures; splicing the cable is time consuming for high pair count cables.
- High pair count cables can only be purchased in short lengths (because of size limitation of reels), so more splices are required.

# FIBER OPTIC CABLE

## 8-10. Background

Fiber optic cable systems are well suited to applications requiring large bandwidth, low noise, high immunity to electromagnetic and electrostatic interference, and high speed or data rates. Fiber optic cable is appropriate for applications with an unusually high data rate or where required to overcome the problems as noted above.

Reclamation designers normally consider fiber optic cable when items such as large bandwidths, low noise, electrical isolation, greater unrepeatered spans, lighter cable, and better electrical isolation are important.

Very basic fiber optic cable systems have a practical span length of 914 m (3,000 ft) for step-index type fibers and 7,315 m (24,000 ft) for graded index types.

Telecommunication systems normally use a graded index type cable because of its greater data handling capacity over very long lines. Step-index fibers can be used for data links equal to or less than 914 m (3,000 ft).

In general, the major loss occurs in the actual splicing of the fibers. Three splicing methods are currently being used:

- Mechanical
- Glued
- Fused or welded connections

Mechanical connections have from 1 decibel to 2 decibels of loss per connection; epoxy or glued connections have from 0.5 decibel to 1.5 decibels of loss per connection; and fused connections run 0.1 to 0.4 decibel per splice. This additional loss must, of course, be added to the loss per unit length of the basic cable.

Fiber optic communication links are normally designed by: (1) considering the system bandwidth requirements (i.e., number of channels and bandwidth of each subchannel); (2) the signal-to-noise ratio (i.e., maximum data speed required); and (3) the distance between the endpoints of the circuit or channel. The optical transmitter power required is determined by considering the bit-error rate (or signal-to-noise ratio).

Plastic fibers are used for spans of 91 m (300 ft) or so at data rates of 6 megabits per second or less. Plastic-clad glass fibers are used for communication links of 27 to 457 m (90 to 1,500 ft). Low-loss fibers are used for links up to about 7,315 m (24,000 ft), and bandwidths of 500 megahertz are common for standard 914-meter (3,000-ft) sections or spans.

Typical communication links of around 1,829 m (6,000 ft) can handle data bit rates from 100 hertz to 20 megahertz with bit-error rates of $1 \times 10^{-8}$.

Typical computer-to-computer and computer-to-peripheral distances run from 457 m (1,500 ft) for standard light emitting diode (LED) sources, to 1,981 m (6,500 ft) for premium LED sources. The advantages of reduction in electromagnetic interference and electrical noise shielding make fiber optic cables very useful in high noise areas such as switchyards or power generating plants. Fiber optic cables help to eliminate data circuit problems such as ground loops, crosstalk, electromagnetic interference (EMI), and transients caused by electrical surges or lightning.

Full duplex repeaters can be used every 914 m (3,000 ft) or so to maintain the 56-kilobit-per-second to 2-megabit-per-second spectrum. The repeaters can adjust for up to 28 decibels of link loss.

Some typical applications of fiber optics would be: control of valves and relays at remote installations from a central point; 9,600-baud computer-to-computer links; transmittal of data through hostile environments of hydroelectric dams, switchyards, etc.; 3,600-baud peripheral-to-central-computer links, and to fill communication link requirements through explosive or corrosive environments.

Receive signal levels should be kept to -35 decibels or above. Bit-error rates should be held to $10^{-8}$ or $10^{-9}$. Typical output powers of the optical transmitters run -7 decibels or so and require 115-volt alternating current (a-c) power sources. The system designer should allow 2 decibels of loss for connectors and splices, 6 decibels for time and temperature variations, and should consider the receiver sensitivity at a frequency of twice the system bandwidth. Splices are normally made every 914 m (3,000 ft) or so.

Recently, the first working installation of a fiber optic cable incorporated into an overhead ground wire was put into service in England. The cable handles 480 voice channels and is 34 km (21 mi) long. The conductor consists of an optical cable inside an aluminum alloy tube. The cable can handle a 140-megabit-per-second data stream if necessary.

## 8-11. System Design

Fiber optic cable has a transmitting distance of up to 914 m (3,000 ft) for step-index fibers and up to 7,315 m (24,000 ft) for graded index type fibers. Repeaters would be required every 6 to 8 km (4 to 5 mi) for graded index type fibers.

Installation of fiber optic cable is similar to that of metallic cable. The same precautions and requirements apply for installation (protection from moisture and rodents). Installation requires special equipment for splicing and testing.

## 8-12. Applications

Because of the present cost and complexity of fiber optic cable, fewer suitable applications exist compared to metallic cable. However, if the past is any indication, the cost of fiber systems will continue to drop with fiber possibly replacing many metallic wire installations at a lower cost. At present, a good fiber application might be the link between the control console and the master station where the master control console is not colocated with the master station computer and master to remote communications.

## 8-13. Advantages and Disadvantages

Advantages:

- Immunity to electromagnetic and electrostatic fields.
- High bandwidth or data rate capability.
- No crosstalk between fibers.
- Absolute immunity to lightning and electrical storms.
- No licensing required.
- Small physical size; easier to handle than metallic cable.
- Suitable for continuous scanning of supervisory control and data acquisition systems.
- Can handle multiple voice and data channels at the same time.
- Large expansion capability.
- 20- to 30-year life, comparable to metallic cable.

- User has complete control over communication system.
- High security against undesired monitoring of communications.

Disadvantages:

- High initial cost of installation.
- Repeaters require power, may be incorporated in cables; power requirement reduces immunity to lightning, particularly when incorporated in cables.
- Electronic equipment is required to convert electrical signals to light and back to electrical signals.
- Special equipment is required for testing and maintenance.
- Repair from excavation damage more complicated.
- Special termination and connector equipment required at termination points.

## UHF/VHF RADIO

### 8-14. Background

UHF/VHF radio systems are well suited to applications requiring smaller bandwidths and lower data rates. UHF/VHF radio systems can be used to carry voice frequency communications and data. In general, this type of communication system is the most economical of all systems, especially when no or very few repeaters are required, and frequency licensing is readily available. The final system end user should be considered at the time of licensing to avoid unnecessary cost and aggravation. For instance, in some cases, a Federal agency will procure licensing, furnish and install the system, and upon completion, turn the system over to a private water district as the permanent system owner and operator. Because the Federal agency no longer owns the radio system, the water district will, in some cases, be required to relicense the system, causing interruption of system operations, or even worse, a total shutdown of the radio system.

### 8-15. System Design

UHF/VHF radio systems span the frequency range from 30 to 300 megahertz (VHF) and 300 to 3,000 megahertz (UHF). UHF frequencies above 1,000 megahertz overlap the microwave band and do not use equipment classified in the strictest sense as UHF. UHF radio systems are line of site and have a range of 32 to 48 km (20 to 30 mi) on flat terrain. Licensing can become difficult for more densely populated locations and for frequencies in conflict with local military and commercial needs. Range and signal quality may be improved by specifying higher-powered transmitters, directional antennas, and/or antennas located at higher physical elevations such as on top of buildings, steel towers, or mountains. The legal requirements of staying within the allowable transmitter, government licensing restraints, and the availability and cost of good antenna locations should also be considered.

Additional radio range and mountainous coverage may be obtained by the use of repeaters. However, repeater installation cost may be excessive or prohibitive in cases where potential repeater sites are privately owned, costly, or unavailable; sites are located in geographically challenging terrain with no existing roads or commercially available power; and access during winter months can be accomplished only by aircraft or snowmobile. To be reliable, repeater sites should also be furnished with hot standby repeater units and backup power in case of primary power failure.

Repeaters are licensed in frequency pairs rather than a single frequency because repeaters operate in the full duplex mode, receiving on one frequency and simultaneously retransmitting on a different frequency. Repeaters also require additional antenna equipment, such as duplexers, which prevent transmitter signals from feeding back into and overloading the receiver connected to the same antenna. Circulators are also required to prevent the active transmitter signals from feeding back into and overloading an idle hot standby transmitter which, when present, is connected to the same antenna.

When designing the system, consideration should be given to dual use of the assigned frequency for both voice and data. The data transmissions are limited to 3 to 5 seconds per minute, allowing voice communications between mobile radio units during the remaining time. The optimal situation for this type of system would involve infrequent and minimal data transmittal. Major reporting from remotes could be scheduled for night or idle voice traffic times.

Lower cost UHF equipment in the 850-megahertz and above band could allow more dedicated channels and possibly higher data rates. These higher frequency systems are even more directional than the 390- to 470-megahertz UHF bands. This equipment can also link a remote location control site to a cluster of hard-wired controllers.

Prior to design and specification of radio system physical and electrical parameters, a computer modeled study should be made to predict radio signal coverage. The study results predict preferable antenna locations; if repeaters are required and where; required antenna signal gains; transmitter radio signal output power; and overall geographical coverage to be expected from the system as a function of system reliability (covered later in this chapter). To confirm the computer study results, actual onsite signal strength tests should be run. Test transmitters should be located at proposed transmitter and repeater sites.

### 8-16. Applications

UHF/VHF radio is best suited for systems where master station and RTU sites are distributed in a star or radial (compared to an in-line) configuration; in conditions where the radio system owner does not own right-of-way between the master station and remote terminal sites or where right-of-way provides a geographically unfavorable path for cable installation; where data volume and data rates per site are low; and where RTU sites are few and widely separated from the master station.

### 8-17. Advantages and Disadvantages

Advantages:

- System cost is low compared to microwave and cable.
- Installation time is minimal.
- System not susceptible to interruptions caused by cable faults and breeches.
- System expansion achievable at minimum cost compared to microwave and cable.
- Can share with mobile communications frequencies.

Disadvantages:

- Not optimally suited for high data volume and bandwidth applications.
- Licensing may be difficult, costly, and lengthy.
- Repeater site installation may be difficult and costly.

## MICROWAVE

### 8-18. Background

Microwave systems are similar to fiber optic cable systems in that they provide high speed and data rates and are suitable for applications requiring large bandwidth and high immunity to electromagnetic and electrostatic interference. In general, microwave provides a more secure data path than UHF/VHF radio and provides a much greater bandwidth.

### 8-19. System Design

Microwave systems occupy frequencies from 1,700 to 22,000 megahertz and are line of site only with a range of 32 to 48 km (20 to 30 mi), depending upon the terrain. Microwave system design is similar to UHF/VHF radio design in that some of the same factors apply and must be taken into account in antenna and repeater site selection and installation—factors such as frequency license availability and difficulty in locating and installing transmitter sites. Because of the line of site properties of microwave signals, the effects of signal reflection, refraction, diffraction, and absorption are more critical than with UHF/VHF radio.

As with UHF/VHF radio systems, a computer-modeled study is made of the microwave system prior to system physical and electrical parameter design and specification. The study results predict preferable antenna locations; if repeaters are required and where; required antenna signal gains; transmitter radio signal output power; and system reliability as a function of reflection, refraction, diffraction, and absorption. To confirm the computer study results, actual onsite signal strength tests should be run. Test transmitters should be located at proposed transmitter and repeater sites.

To provide a higher degree of reliability, microwave systems incorporate hot standby units, dual physically separate radio wave signal paths, dual frequencies, and backup power in case of primary power failure.

New microwave installations are of the digital type, in line with an overall industry trend toward all digital; older analog systems are being phased out as they become inoperable or obsolete. Digital microwave has the added advantage that time division multiplexed systems (like T1 and T3) can be interfaced directly to the digital microwave with no digital to analog modems required. The compatibility with digital communications industry standards allows dynamic bandwidth, dynamic routing, and mixed analog and digital source media to be transmitted digitally through a single communication path. Off-the-shelf digital microwave is available to link computer local area networks (LAN's) easily with no repeaters if LAN's are located within line of sight. This link can be accomplished sometimes at a considerable savings compared to telephone company wideband leased lines.

### 8-20. Applications

Microwave systems are used in applications that require large bandwidths and high data rates. Such applications might be between a master station and powerplant or pumping plant where large amounts of data are transmitted on a frequent basis. Another application would be as a part of a redundant data signal path from remote sites back to the master station simultaneously transmitting large numbers of both voice and data channels. For smaller bandwidths and data rates, microwave is not cost effective, and UHF/VHF radio or other communication systems should be considered.

### 8-21. Advantages and Disadvantages

Advantages:

- Installation time is small compared to cable.
- System not susceptible to interruptions caused by cable faults and breeches.
- System expansion achievable at a minimum cost compared to cable.
- System spare capacity can be coshared, and the cost can be shared with other agencies.
- Immunity to electromagnetic and electrostatic fields.
- High bandwidth or data rate capability.
- Suitable for continuous scanning of supervisory control and data acquisition systems.
- Can handle multiple voice and data channels at the same time.
- Large expansion capability.
- 20- to 30-year life, comparable to metallic cable.
- User has complete control over communication system.
- Higher security against undesired monitoring of communications when compared to UHF/VHF radio.

Disadvantages:

- High initial cost of installation when compared to UHF/VHF radio.
- Licensing may be difficult, costly, and lengthy.
- Repeater site installation may be difficult, costly, and lengthy.
- Maintaining radio signal reliability requires more care in design and installation.
- Structures (such as high rise office buildings, etc.) erected in signal path after microwave antenna installation may cause system to become inoperable.
- Not cost justifiable for small bandwidths and data rates.

## LEASED

### 8-22. Background

Virtually any communication system can be leased. Perhaps the most common commercial leased system is known as a Bell Telephone Type 3002 circuit, which is a customer-dedicated private line. This service is available with a one-time installation charge and a monthly charge per circuit. Some installations may also require a construction charge. A Type 3002 circuit can be either an unconditioned or a conditioned circuit. The type and speed of the transmitted data will determine the degree of conditioning involved.

### 8-23. System Design

The system design is performed in a manner similar to that required for the type of system being leased. The criteria for data, voice, and expansion must still be evaluated. However, the actual design and installation is passed on to the lessor. Often, future expansion costs can be delayed until the expansion is required.

### 8-24. Applications

Typical leased line applications would be for monitoring sites requiring low security data monitoring on an infrequent basis with minimal or no control. Such use might require an RTU using leased line to be scanned once an hour to once a day. Another application is for supplying a redundant backup communications path, which would need to be used infrequently, but still would be required during primary communications path failures.

### 8-25. Advantages and Disadvantages

Advantages:

- Eliminates capital investment of communications system.
- Licensing, land acquisition, rights-of-way, buildings, towers, power, and access road considerations are eliminated.
- Minimizes front-end expense.

Disadvantages:

- System down time is not controlled by user.
- Carrier can disrupt service at their convenience, not at the convenience of the subscriber.
- Rates can increase with each new lease period; user has no control of cost.
- Problems often time-consuming and difficult to resolve, particularly at the interface between the communications system and the control equipment.

## SATELLITE

### 8-26. Background

Satellite communication is similar to a repeater communications network with two notable exceptions. First, the repeater is located in synchronous orbit in space. Second, the satellite may only periodically be available because of the assigned time slot when it is available for use. The data may be stored and sent to the receiving site at a later time. Satellite communications require dependence on satellite service for communications. Communications can be lost because of difficulties with the satellite itself, loss of the satellite, or reassignment of the time slot to a higher priority customer. Figure 8-4 shows a typical satellite data collection system.

Satellite communication is reliable once established; however, link times are tightly scheduled. Satellite networks can provide the desired information on a tight schedule. Satellite-based systems are widely used for the collection of climatological data.

Satellite communications are an excellent choice for telemetry systems in which data are needed periodically and control is not required. Satellite use is not appropriate for alarm systems or real-time control. The most logical application is a situation where small amounts of data are required from numerous remote sites spread over a wide geographical area.

Control via satellite is only possible where control is done at the remote site, and control parameters are downloaded to the RTU's in advance.

Reclamation is now using the U.S. Department of Commerce geostationary operational environmental satellite (GOES) data collection system to relay some of its RTU data to central receiving stations and their associated computer centers.

Data inputs are limited to temperature, wind, rainfall, river level, tide gages, seismic detectors, environmental monitors, and balloon- and aircraft-borne environmental monitors.

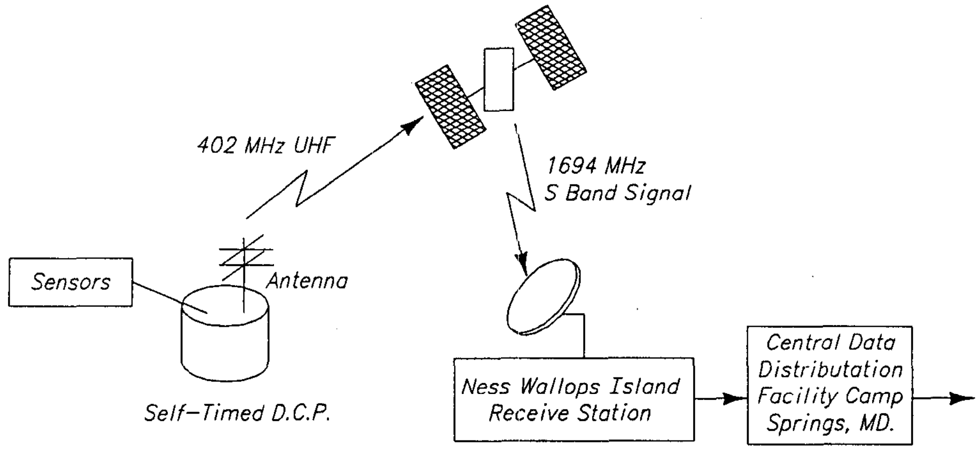


Figure 8-4.—A typical satellite data collection system.

Three modes of operation are currently available:

- Interrogated
- Self-timed
- Emergency (i.e., threshold detection)

Bit-error rates of 1 x $10^{-5}$ can be expected using this satellite, and the data must be limited to status because no command or control signals can be initiated by the ground stations to the remote data platforms.

The GOES system currently has five satellites in earth-synchronous orbit. The satellites are located at longitudes of 90.5° west, 112.5° west, 130° west, 135° west, and 178° west.

The satellite system provides the following services:

- Returns both visible and infrared pictures of the earth's surface
- Receives and retransmits weather information
- Measures the energy and trajectory of incident space particles
- Receives and retransmits data from data collection platforms located throughout the United States

Requests for use of the satellites are made to National Oceanic and Atmospheric Administration (NOAA) and are coordinated by Reclamation's Infrastructure Services in Denver, Colorado.

The user is responsible for purchasing and maintaining the remote data platform, which must be type-approved by NOAA. The system is designed to operate with earth-based transmitters having effective radiated powers (ERP) of 50 decibels (maximum).

The spacecraft's transponder can handle as many as 10,000 transmissions each hour if they are limited to 30 seconds each. Domestic users have access to 200 channels, and 33 channels are available for international users. Data bit rates must be held to 100 bits per second or less.

Data recovered from the remote data platforms can either be received directly by a 1,694.45-megahertz receiver and demodulator (at a level of -169 ±10 decibels) or can be obtained from control centers located in California, Missouri, Maryland, or Florida using either a full-time dedicated circuit, a dial-up 1,200-baud line, or a dial-up 110-baud line. The direct dedicated line handles data at a nominal 2,400-baud rate, full or half duplex, ASCII, odd parity, and is nontransparent.

The 1,200-baud dial-up circuit operates at 120 characters per second, half duplex, asynchronous ASCII, even parity, and must have the following modem options:

- "Auto-answer" line discipline
- "Answer-back" memory
- Bell 202C modem or equivalent

The 110-baud dial-up circuit operates at 10 characters per second, half duplex, asynchronous ASCII, and has even parity.

If a bit-error rate of about 1 x $10^{-5}$ is required (i.e., carrier-to-noise ratio [CNR] = 14), then an antenna gain of at least 30.3 decibels must be used to raise the received signal level to a minimum of -139 decibels. This gain requires an 8-foot parabolic antenna. Normally, 16-foot antennas will be specified for bit-error rates of 1 x $10^{-6}$ or so.

Data processing equipment used with this system must as a minimum:

- Have an interface to the frame synchronizer
- Be able to interpret the 31-bit data collection platform (DCP) address
- Have parity error checks
- Have adequate data storage capability
- Have a data retrieval system

Some typical receiver costs are as follows:

- Antenna and 300-foot cable
- Pre-amp
- Receiver/converter
- Computer (minibuffer) HP85 or equivalent
  Subtotal: $48,600.00

- Main computer: $40,000.00
  Total (less labor): $88,600.00

- Remotes
  (approximately): $3,500.00 (material)
  (plus installation)

### 8-27. System Design

The most essential part of a satellite system is the acquisition of time to use the satellite and determination if the available time is adequate for the intended purpose. The second part consists of the ground stations and master station. The timing of communication in satellite systems is the most critical element. The ground station equipment or data collection platform and central or master site are not much different than those for a radio, microwave, or wire system. Satellite communication uses the packet format for communications. Figure 8-5 is a diagram of a remote data collection platform.

### 8-28. Applications

Satellite systems are well suited to collecting weather data, rain and snowfall data, and other climatological data. These data are useful in forecasting irrigation demand and water availability. A satellite system would not be appropriate for a supervisory system.

### 8-29. Advantages and Disadvantages

Advantages:

- Low equipment costs
- No repeater required
- Master station is provided for telemetry-only systems

Disadvantages:

- Limited control
- Dependent on satellite and satellite owner
- Not suitable for real-time monitoring and control

## METEOR BURST COMMUNICATIONS

### 8-30. Background

Meteor burst communication or meteor scatter is a combination of parts of several communication types. This system uses packet radio techniques, VHF radio, and meteor trails for reflectors. Meteor burst is appropriate for medium range communications 40 to 483 km (25 to 300 mi) when hard wire or repeaters are not desired or too expensive and real-time communications are not necessary. Delays of several minutes are expected, and longer delays are common when using meteor burst. Meteor burst is only appropriate for digital communications because it does not have voice capability. Figure 8-6 illustrates the meteor burst communication technique.

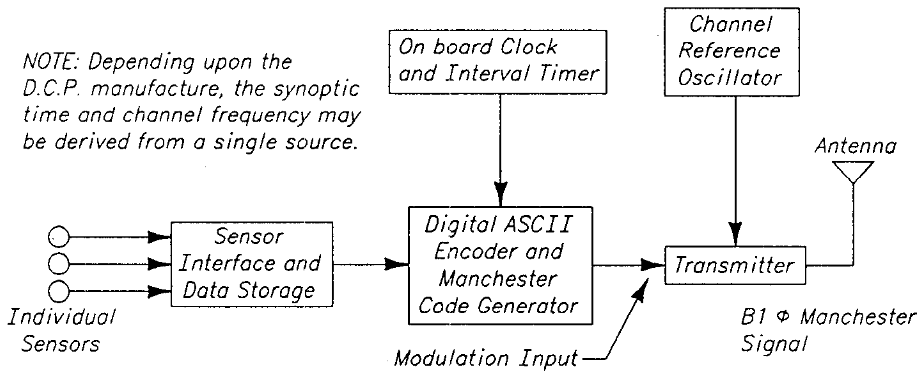


Figure 8-5.—Diagram of a remote data collection platform.

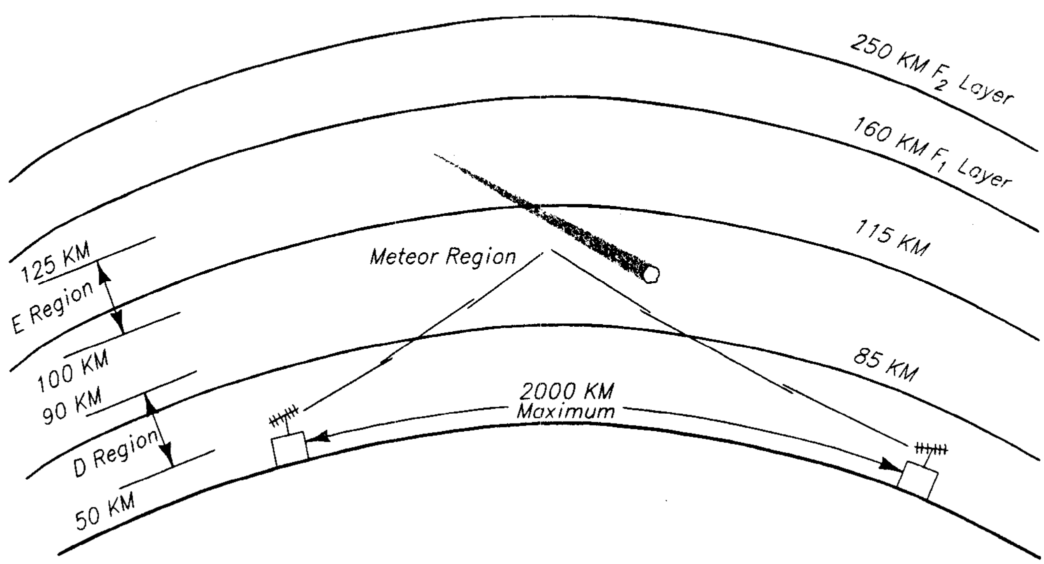


Figure 8-6.—Meteor burst communication technique.

Meteor burst takes advantage of the fact that radio waves are reflected off of the ionization trails of meteors which enter the Earth's atmosphere. Because of the relatively short time the communication path is established and randomness of those paths, the messages must be very short.

Packet communication techniques are used with meteor burst to provide the required short messages. The data are placed in a "packet" or data package along with routing and verification data. The data are then transmitted repeatedly at a fast data rate either upon request or based on a time schedule. The receiving station (remote or master) then verifies the data using the verification data in the packet and responds with a confirmation or re-requests the information. Other stations ignore the message unless they are in the routing.

This extensive "hand shaking" can cause delays in communications and is not appropriate for real-time remote control of irrigation facilities. Meteor burst is appropriate for a system where the canal-side

controllers are downloaded with the required control parameters and are able to maintain control independent of the communications link.
Meteor burst can provide message communication in addition to telemetry and limited control. A keyboard-entered message and routing information are entered into the master or remote computer. The message is formulated into one or more packets and then handled by the system like a data packet. The system software analyzes the packets and formats the messages, data, and system information for use by the users.

## 8-31. System Design

A meteor burst system is comprised of one or more master stations and a multitude of RTU's. Each site master or remote is comprised of a transmitter, receiver, power supply, antenna system, and a microcomputer. The RTU's can be battery/solar operated because they only transmit for very short periods of time. Only one frequency allocation is required for the system because the master maintains network control and the frequency is time-shared. The microcomputer is required to handle the message formatting, system protocol, data checking, and communications with the controller or operator terminal. The system can use both line-of-sight and meteor burst as determined by the network geography. The master station also includes the man-machine interface (display and software) to provide the data collected, usually in engineering units. The RTU's also include the various components to collect data such as water level, temperature, and wind speed.

The meteor burst portion of the system is usually bought as a package, which includes the necessary radio equipment, packet processor, and data handling processor. Other equipment includes power supplies, antennas, various transducers, and wiring.

## 8-32. Applications

Meteor burst is a logical choice for the collection of water levels, rain, or snow data, and simple on-off control. The snow telemetry (SNOTEL) systems in Washington-Oregon and the Egyptian Nile River data acquisition system are two typical examples. Both of these systems are comprised of over 100 remote stations with periodic reporting requirements of about 2 hours or greater. No meteor burst applications exist on canal systems.

## 8-33. Advantages and Disadvantages

Advantages:

- Relatively easy to install.
- No repeater sites required.
- User owned.
- Best suited for data acquisition and downloaded control data for canal-side controllers and telemetry.
- Single frequency required (party line).
- Specific sites can be addressed.
- Provides limited text communications via an ASCII terminal.

Disadvantages:

- Licensing from FCC required.
- Complex equipment requiring skilled maintenance and repair.
- Not suitable for continuous-scan SCADA systems.
- Extremely slow data response time—not suitable for real-time remote control.
- Not suitable for voice, but teletype conversation is possible.

# CONFIGURATIONS

## 8-34. Configuration Types

The two general types of communication configurations or networks are:

- The party line system, in which a single channel serves all the RTU's. In the party line system, each RTU has a specific address. The party line system requires communications overhead to handle remote addressing and can only service one RTU at time. A party line does allow direct communication between RTU's for systems that require it.

- The radial system, in which each RTU has a communication channel dedicated to the master station. The radial system provides rapid communication, a considerable number of data points, direct control, and a minimum of communications overhead. Communications between RTU's must pass through the master or hub of the communication system.

### 8-35. Configuration Selection

Numerous factors must be considered in selecting the best configuration. The number of RTU's, the quantity of data per RTU, the update time, and the data transfer rate all have an impact on the number of RTU's that a communication channel can service. The geography of the system has an impact on the type of equipment and the configuration. The type of equipment selected may limit the system to a radial or party line system.

A small canal system with the headquarters located in the center may lend itself to a radial metallic cable system. A 32- or 48-km (20-or 30-mi) canal system with the headquarters at one end would be served more economically with a party line metallic cable system. That same system with a major pumping plant in the middle might best be served with a dedicated line to the pumping plant and the remainder of the system in a party line configuration. Other systems covering mountainous terrain with widely scattered RTU's might best be served by a VHF or UHF radio system in a party line configuration.

Metallic cable can easily accommodate any configuration. Radio is best suited to a party line system by virtue of the FCC license requirements.

Mixed systems are comprised of more than one of the basic systems described. A mixed system might include a hard-wired configuration for a number of RTU's in one location linked to the control site using UHF radio. Such a system uses hard wire for short distances and radio for the long link, in which metallic hard wire is not economically desirable. In mixed systems, one of the RTU's may function to convert from one system to the other, especially if higher data throughputs are required.

## TYPES OF COMMUNICATIONS CHANNELS

### 8-36. Channel Types

The last consideration concerning communication is the channel type. Three major types can be considered:

- Simplex.—The simplest communication channel, in which the data flow in one direction only. Simplex channels are of little use in canal automation and are used for remote control in a few applications where the operator can see the effect of the control operation.
- Half duplex.—A half duplex channel provides two-way communication. However, communication is in one direction at a time. When the data flow in one direction is complete, a signal is sent to the receiving end to allow it to start sending. A party line system is possible with the master controlling the communication channel and the master passing control to the various RTU's as required.
- Full duplex.—Full duplex provides simultaneous two-way communication between the master and RTU's.

**a. Four-wire versus two-wire systems .**—Two-wire systems are normally used for voice circuits, and four-wire systems are normally used for data circuits, although a combination of both could be used to complete a long circuit. Hybrids are used to connect a two-wire system into a four-wire system.

A two-wire system (voice connection arrangements C27 or C2K) consists of, as the name implies, two wires which carry both the transmitted voice and the received voice (on the same two wires). A four-wire system uses two wires to carry the transmitted voice and a separate set of two wires to carry the received voice.

Four-wire systems (voice connection arrangements C24 or C2H) are required when simultaneous transmission in both directions is required. Real-time data systems are examples of four-wire full-duplex type systems. On larger multipoint circuits (i.e., greater than six points), four-wire channels are required to prevent "singing" or oscillations and high-level echoes.

Four-wire channels can be used to advantage on multipoint polling systems when the RTU's do not need to communicate with each other. Some of these advantages include faster turnaround times of the data, more possible points, and a prevention of false RTU startups caused by crosstalk. Most Reclamation microwave channels are designed to accommodate four-wire ear and mouth (E&M) type circuits or channels.

Normally, two-wire channels are used for telephone voice channels and data circuits (half/duplex) using acoustic coupled modems. Echoes on two-wire channels may cause intersymbol interference to data streams or false startup of the RTU's, thus limiting the data bit rate of the proposed control system.

Data systems that use a central computer facility transmitting to two or more remote terminals (the RTU's do not transmit back to the computer) could use a two-wire simplex channel. A four-wire channel is required when a control system uses the so-called "slave" configuration (where the computer talks, to all of the remote units at one time, and the RTU's talk only to the central computer).

The inherent stability problems of two-wire multipoint (i.e., 20 drops or more) systems limit the usefulness of such circuits for larger systems. Four-wire circuits should be used for proposed multidrop installations.

Here are some design constraints placed on both two- and four-wire interfaces to the commercial telephone system:

- The input impedance of the modems must be 600 ohms ±10 percent balanced and resistive in nature across the entire bandwidth of 300 to 3,000 hertz.
- The combined transmitted voice power (3-second average) should not exceed -6 decibels for four-wire circuits and -12 decibels for two-wire circuits. The power per circuit for a multicircuit channel should not exceed 10 log 10 ($n$), where $n$ is the number of circuits on each channel.
- If two or more channels are carrying the same information, then the power of each channel must be reduced by a factor of 1/n to reduce crosstalk between the channels. That is, if redundant data channels are used (to improve reliability), then the power in each channel must be cut in half; i.e., by 3 decibels. In fact, the equation -10 log 10 ($n$) decibels can be used to calculate the reduction in per channel power for any value of subchannels.

Each microwave channel will require a total of six wires to interface; i.e., two wires for the transmit signal, two wires for the receive signal, and one wire each for the E lead and the M lead. The signaling leads are referenced to circuit ground for the return paths.

All circuits should be protected by using 3-mil gaps (or equivalent) between each conductor and ground. The protectors should operate at 350 volts rms or 500 volts peak.

The mainframe terminal levels for the four-wire circuits should be set at a level of +7 decibels on the transmit pair and -16 decibels on the receive pair. The mainframe terminal levels for the two-wire circuits should be set at -16 decibels.

**b. Pulse code modulation.**—Pulse code modulation (PCM) techniques are used where noise or signal/noise ratios are not satisfactory using the more common frequency division multiplexer (FDM) schemes. Because of the increased bandwidth requirements of PCM (i.e., 56 kilohertz for a single voice channel compared to 4 kilohertz for a single FDM voice channel), PCM is used primarily on Reclamation hard-wire systems or on special commercial wide-band telephone channels.

Data bit rates of 1.544 megabits can be achieved using commercially available T1 carrier equipment.

Communication engineers do not place PCM and FDM in the same cable sheath. The reason, of course, is that the signal level of the PCM system is so high that indiscriminate mixing of the two systems could result in either partial or total destruction of the FDM information. On the other hand, PCM information will hardly, if ever, be affected by the presence of FDM information.

The planner or project manager who wishes to gradually phase out FDM systems and phase in PCM systems should adhere to the following ground rules:

- The highest frequency slot in the FDM system will always be the one of most concern. This slot will be vulnerable to PCM interference.
- The higher frequency FDM slots should be phased out first and be replaced with PCM high-frequency slots. Because the power spectrum of a PCM signal drops quickly below 96.5 kilohertz, interference to channels below 96.5 kilohertz is usually negligible. The point of maximum power in a PCM spectrum occurs around 710 kilohertz (i.e., the greatest amount of interference to an FDM channel located in this vicinity).
- The crosstalk coupling loss between two cable pairs increases with the number of cable pairs in the cable. This characteristic is caused by the increased physical separation of the pairs in a larger cable. Therefore, the larger the number of pairs in a cable, the less the interference. The actual value of crosstalk loss between the pairs depends upon the splicing methods used, the splicing groups selected, the gage of the cable, and the dielectric material.
- FDM channels in baseband slots at or adjacent to multiples of 96.5 kilohertz should be avoided.

Loading coils and line buildout networks must be removed from wire lines if any carrier system above 4 kilohertz is to be used. The loading coils should be replaced with PCM type repeaters because the repeaters are designed to reproduce PCM signals when placed at 6,000-ft intervals and used with No. 22 gauge wire having 0.083 microfarad of capacitance.

The advantage of a PCM system is that for every 2 cable pairs used to accommodate 2 voice channels using FDM, the same 2 cable pairs can accommodate 24 two-way voice channels using PCM.

In theory, any number of repeaters can be placed on the system; however, in actual practice, timing jitter limits the number of repeaters that can be added in series. The maximum number of repeaters used should be limited to 200 series repeaters. Once again, the number of repeaters used in the series circuit is not necessarily governed by the circuit distance, but rather by the combined jitter of the repeaters. Conservatively, 80 km (50 mi) is a good maximum limit. However, lengths of 322 to 483 km (200 to 300 mi) can be obtained. The potential user of voice-grade cables should first test the cable system with a PCM test set to determine its ability to handle PCM signals.

PCM requires that cables be able to transmit signals out to 2.5 megahertz, where normal voice cables are only required to handle 4-kilohertz signals. More care must be used with wire and cables when using PCM than when transmitting voice or slow-speed data.

The use of Reclamation microwave systems to transmit PCM data is not recommended at the present time because of the large bandwidths required for PCM systems. PCM systems should be limited to wire or cable systems.

## RADIO CIRCUIT RELIABILITY CONSIDERATIONS

Radio circuit path reliabilities are closely associated with a term called "fade margin." Fade margin is defined as the excess path gain above the minimum signal level required to produce a demodulated signal-to-noise ratio of at least 30 decibels.

For single-channel VHF applications, the designer should supply at least 25 decibels of excess path gain to obtain a path reliability of 90 percent and should provide a 40-decibel fade margin for Reclamation data circuits, which require 99.9-percent reliability.

A 90-percent path reliability means the radio path will be unusable for 0.1 x 8,700 hours, or 870 hours per year, which averages to roughly 3 days per month! Each individual outage will be of short-term duration (i.e., ≤1 minute), and the total accumulated outage time will be statistical in nature (based on experiments by Raleigh and upon the observed performance of 150-megahertz radio systems). Naturally, such designs would be limited to two-way radio usage where information can be repeated if necessary (maintenance radio systems, for example).

Radio equipment failure rates seem to increase after the radio equipment has been in operation for 4 or 5 years. After the initial installation checkouts, the "downtime" of a single-channel, nonredundant, repeater site seems to be limited to 4 hours a year (semiannual frequency and deviation checks) for an equipment reliability of 1 to 4 hours of down time per year divided by 8,700 hours per year, or about 99.95-percent reliability.

After the first 4 or 5 years, the average interval time for servicing is usually 1 year, and the failure takes 8 or so hours to repair, including travel time to the site. This down time gives a reliability of roughly 99.9 percent.

The above numbers show that Reclamation mobile radio systems will normally experience more outages caused by path fading (90-percent reliable) than by equipment outages (99.9-percent reliability). The outage time of a typical Reclamation-designed multichannel UHF radio data link (99.90-percent reliability) will be 0.001 x 8,700 = 8.7 hours, or 40 minutes per month. Again, more outage time will be lost because of fading (99.9 percent) than because of equipment failure or mandatory frequency and deviation checks (99.95-percent reliability). Hot-standby configurations should only be used (on low-density UHF radio systems) if ultrahigh reliability circuits are carried by the system (i.e., 99.99-percent reliability or greater).

As mentioned above, outage times can be further reduced by adding duplicate transmitters and receivers (hot-standby configurations). Total system and equipment reliabilities of 99.99 percent (i.e., less than 9 seconds per day loss in signal) can be achieved using fade margins of 45 decibels at 150 megahertz and 65 decibels at 450 megahertz, as well as hot-standby equipment configurations.

All 2-gigahertz and 7-gigahertz microwave systems should be designed with fade margins of 40 decibels and should use hot-standby equipment configurations. A reliability of 99.99 percent will be obtained, and a total system outage of no more than 9 seconds a day should be achievable. Some important facts to remember:

- Path reliability depends on the amount of excess gain in the radio path.
- Equipment reliability depends on redundancy and can be improved 100 times by using a hot-standby configuration.

## TYPICAL RELIABILITIES

VHF paths, single-channel, 25-decibel fade margins ≤ 90 percent

UHF paths, single-channel, 35-decibel fade margins ≤ 90 percent

UHF paths, 6-channel, 55-decibel fade margins (H.S.) ≤ 99.9 percent

2-gigahertz paths, 120-channel, 40-decibel fade margins ≤ 99.99 percent

## PROTECTION FROM LIGHTNING-RELATED OUTAGES

Lightning and other natural phenomena present a serious problem for equipment in the field. Commercial power is often not adequately protected. Hard-wire communications are subject to lightning and other interference. Antenna structures are also subject to damage from lightning. Furthermore, the possibility exists that computer data bases can be altered if left unprotected, and the danger to computer-based equipment from lightning is the same as for other communications equipment.

Lightning and other power transients can cause the immediate failure or gradual degradation of the controller. An immediate failure is often most favorable because the problem is easily recognized. Degradation, on the other hand, often results in intermittent failures, usually at the most inconvenient times. Similarly, problems are difficult to diagnose because it is almost impossible to be at the site when the problem occurs, and the equipment often recovers by the time someone can get to the site.

All canal control equipment must be protected from lightning to assure proper and reliable control. Protection must be provided at every point at which the transients caused by lightning can get into the equipment. Protective devices must be installed at the a-c power line, telephone or hard wire, antenna, and transducer inputs. All equipment must be grounded and bonded together.

## 8-37. Equipment for Lightning Protection

Several important components commonly used for lightning protection are:

- Fuses—A fuse limits the amount of current to a device. It can be used alone or preferably in conjunction with other devices.
- Metal oxide varistor (MOV)—A MOV is installed across the a-c line, a-c line to ground, and after the fuses. The MOV safely conducts overvoltage on the a-c line to ground and causes the fuses to blow and, thus, protects the equipment from the lightning.
- Gas discharge tubes—A device usually used for communications circuits that conducts lightning-induced transients to ground.
- Spark gaps—A spark gap is a device with an air gap set to break down and conduct when a certain voltage potential is exceeded across the gap. Spark gap devices are often used for protection of antenna leads.
- Radio frequency interference (RFI) filters—RFI or transient filters. RFI filters are resistor, capacitor, and inductor devices used to prevent high frequency transients, such as a-c power, telephone, or transducer signals from passing through a circuit. These devices are effective against lightning and also provide protection from motor and switching transients.

Figure 8-7 shows a typical power line protection circuit. It is comprised of a fuse, MOV network, and an RFI filter. For higher current equipment ratings, increase fuse size and corresponding filter rating accordingly. This circuit is usually adequate where transients associated with power outages can be tolerated.

Severe cases may require other techniques. These techniques include opto-isolators and isolation amplifiers. New controllers using microcomputers should incorporate opto-isolators in the control and digital inputs and outputs.

## 8-38. Grounding

Grounding is also essential for proper protection from lightning. All of the components of the automation system must be bonded together and securely grounded. This arrangement is important to provide a solid path for the lightning to ground and to prevent large voltage potentials from developing between the various components of the system. Grounding is accomplished by connecting a heavy conductor between all the metallic enclosures and chassis and connecting the conductor to the site ground mat or an array of ground rods.

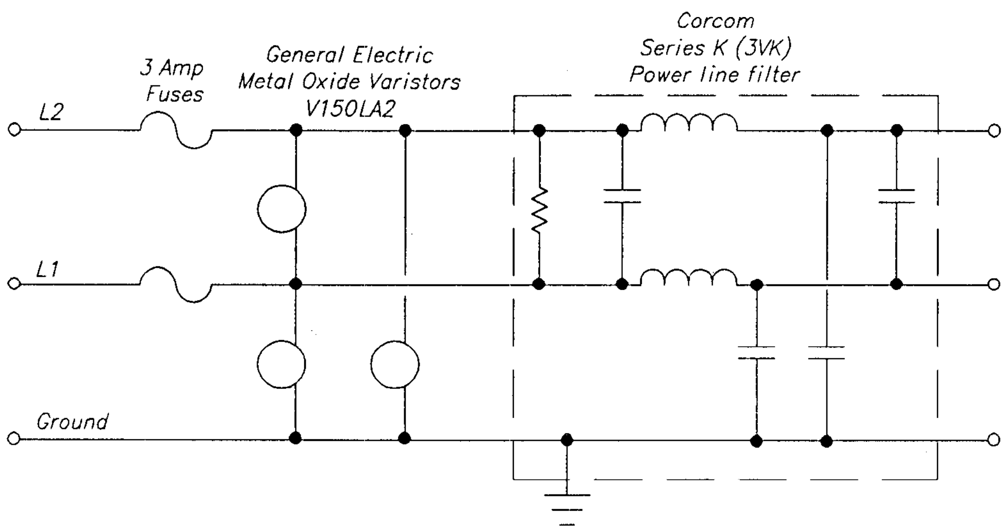


Figure 8-7.—A typical power line protection circuit.

## 8-39. Power Failure

Lightning and other phenomena also cause power outages. If these outages cannot be tolerated in the control system, other protective systems must be considered. These systems fall into two categories: (1) telemetry and gate control are required and (2) only telemetry is required.

The gate hoists must be operated where gate control is required. This operation requires an alternative source of a-c power such as a gas-operated motor generator with auto-start or a separate a-c line. Only battery backup operation need be provided when telemetry only is required.

# CHAPTER 9

# INSTRUMENTATION FOR PHYSICAL MEASUREMENT

## INSTRUMENTATION SYSTEMS

### 9-1. Instrumentation Systems

**a. Purpose.**—The most important function of any supervisory control system or data acquisition system is the ability to observe the conditions in the system being controlled. In manual local control, ditchriders perform this observation as they drive along the canal and check water levels and gate positions. In most control systems, the operator is located in a control building miles from the canal site where control is being performed. The instrumentation component of the canal automation system provides the "eyes and ears" to convey the ditchriders' information to the operator.

The instrumentation system converts the actual canal conditions to information in a form usable by the control and communication system. Data can then be used in calculations by the control system and provided to the operator. Water levels, gate positions, alarm conditions, power failure, and other site information are converted to electrical signals representing these data. The remote terminal unit (RTU) or local controller then uses these electrical signals in control decisions and in messages sent to the central site for decisionmaking, record-keeping purposes, and use by operators. The importance of these inputs dictates that accuracy and reliability be foremost in their selection, installation, and application.

The variety of sensors and equipment available for these processes requires utmost care in the design phase. The instrumentation converts the desired quantities first to an analog voltage and then to digital or directly to digital as with absolute digital encoders. Range, signal output, conversion, scaling, and offset must be considered throughout the process to assure that the desired signal is accurate, easy to implement, and meaningful to the operator.

**b. Selection factors.**—Numerous considerations exist that need to be made when selecting components for an instrumentation system. The number of sites and data required at each site are determined in the design of the control system. Typically, each site will include one or more water levels and one or more gate positions. Other information parameters that may be required to ensure proper operation at the remote site include high and low water alarms, various weather data, turnout information, and additional alarms such as enclosure entry and loss of primary power. The control scheme, information desired, and accuracy of that information must be considered as part of the instrumentation design.

Each variable parameter must be evaluated for resolution or accuracy required. The accuracy must be compared to that which can be reasonably expected for the instrumentation available for that parameter. For example, a float system, typically 1-percent overall accuracy, is used to measure water surface. A 10-bit analog-to-digital (a-to-d) converter or digital encoder with a 0.10-percent resolution assures that the conversion process does not further degrade the error. An 8-bit a-to-d converter with resolutions of 0.39 percent plus or minus one digit would degrade the accuracy of the mechanical output. A 14-bit a-to-d converter with resolutions of 0.006 percent is certainly not warranted for this conversion. Other parameters must be evaluated in a similar manner to determine the required conversion accuracy. A 12-bit a-to-d converter with resolution of 0.024 percent or a 14-bit a-to-d converter may be warranted when other variables at the RTU site are considered. Similarly, use of a 0.01-percent digital shaft encoder with a float water level system is not reasonable because of its cost, and the float system is not capable of the same accuracy.

Discussion of instrumentation systems would not be complete without consideration of reliability, cost, and maintenance. These factors must be weighed against accuracy requirements in choosing components for the control system. Additional accuracy almost always involves a more complex system, which increases cost and complicates maintenance. The simplest system is often the best choice, even when some accuracy is sacrificed to obtain a system which is reliable and easy to repair.

**c. Sensors and instrumentation systems.**—The sensors and instrumentation system components are an important part of any RTU or local controller installation. These components convert the required observable information to digital quantities for control or for transmission to the central computer.

The sensors and instrumentation system are comprised of all those components—mechanical, mechanical-to-electrical conversion (analog or digital), a-to-d conversion, and signal conditioning equipment—required to obtain a digital representation. Conversion can be accomplished in one step as in shaft encoders that convert rotational mechanical motion directly to digital electrical representation. Alternately, a multistep process may be used where the mechanical is first converted to an analog electrical signal, then to digital using an a-to-d converter. The digital representations are scaled and offset to provide quantities in real units, such as feet of gate opening, cubic feet of water per second, water stage in feet above sea level, feet above the invert, or their metric equivalents. Scaling and offsets can be accomplished in the instrumentation system, in the processor of the RTU or controller, or at the central controller. The display of canal system parameters in engineering units improves operator acceptance and operator ability to control the canal system.

## MEASUREMENT PARAMETERS AND EQUIPMENT

Water measurements for canal automation generally fall into two categories—level (stage) and flow. Water level, the most common parameter, is used to provide water depth and to calculate flow in many applications in conjunction with a weir, flume, or gate opening.

### 9-2. Water Level

Water stage or water level is perhaps the most useful and most common measurement made in canal automation. It is the level of water in the canal prism at a particular point. It is used to determine if the canal is operating correctly and safely, and if sufficient water is available to meet the user demands. Operators use this parameter to make adjustments to the canal. Water stage or level is used with level controllers and in many flow controller algorithms to determine flow. Measured water level is frequently compared to target water level in controlling the canal. The most common methods to measure stage or level in canal systems include:

- Float, pulley, and counterweight—with potentiometer or shaft encoder
- Pressure transducer—bubble gage and submersible transducer
- Capacitance probe
- Acoustic or ultrasonic methods
- Fluid gage—balance beam manometer

**a. Float, pulley, and counterweight systems.**—The float, pulley, and counterweight are the basic components of many systems for measuring water stage or level. These components have been borrowed from the paper chart recorders used for water level measurement worldwide. The application can be incorporated as a modification of an existing chart recorder, or the required components can be purchased and simply used alone. The pulley shaft rotation provides a water level representation.

Encoding the rotation is accomplished by attaching a multiple-turn potentiometer, resolver, or any absolute shaft encoder attached to the pulley shaft or gear assembly shaft of the recorder using a flexible coupling. The encoder can also be coupled using chain drive and sprockets. Absolute encoders, as opposed to incremental or single-turn encoders, are used to assure that turn information is not lost because of power outages and system resets. These encoders provide an output that can be scaled and offset to provide a representation or display analogous to the actual water level.

A typical system is an adaptation of the Leupold Stevens Type A5 water level chart recorder to drive a multiple-turn potentiometer. The installation includes a float pulley 0.5 meter (m) (18 inches [in]) in circumference directly connected to a 10-turn potentiometer. This combination will provide water measurement over a 5.0-m (15-foot [ft]) range. Other combinations of pulleys, gears, and potentiometers provide different ranges. The conversion relation is:

$$R = PC * GR * PT \qquad 9.1$$

where:

$R$ = range
$PC$ = pulley circumference
$GR$ = gear ratio
$PT$ = potentiometer turns

By using gear assemblies and different multiple-turn potentiometers or encoders, the system can accommodate a large range of water levels. A 2-to-1 gear assembly can be added to the above example to provide a 2.5-m (8-ft) range, or by reversing the gearing, a 10-m (33-ft) range. Similarly, the encoder turns can be changed to adjust the required range.

These systems are reliable, easy to verify, and easy to repair. System errors are predictable and consistent. The errors include float lag, line shift, and counterweight submersion. Mechanical accuracy is 0.1 percent or better. A 15-m (50-ft) encoder system using a 300-millimeter (mm) (12-in) float results in an error of 0.01 m (0.04 ft) or 0.08 percent in the mechanical system. A 0.1-percent linear potentiometer results in an additional 0.1 percent, resulting in a 0.20-percent system error. A typical float installation is shown on figure 9-1.

The Leupold Stevens, Inc., Telemark and Type P synchro systems, and other manufacturers' encoder systems, can be used with float-driven water level recorders. A modified Leupold Stevens Chart Recorder is shown on figure 9-2.

The float system should be incorporated in an enclosed stilling well to prevent the effect of wind waves, tampering, environmental damage, and vandalism. The system is subject to error from objects or animals falling on the float.

**b. Pressure method.**—Pressure transducers provide the basis for two additional methods: the bubbler gage and submersible transducer methods. Numerous types of pressure transducers are available to accommodate many ranges of measurement, environments, and desired outputs.

The bubbler gage is an adaptation of the manometer servo system. The bubbler gage provides an analog output from a pressure transducer. Bubbler gages use compressed nitrogen or air, a flow regulator, pressure transducer, and a long tube that goes from the instrument to fixed point in the canal below the lowest depth of water expected. Nitrogen is released at a very slow rate through the tube and bubbler orifice anchored at the low point under the water. The changing head over the orifice causes a corresponding change in the pressure at the orifice. Corresponding pressure is transmitted through the tube back to the regulator and pressure transducer. The pressure transducer converts the pressure to an analog electrical output. The depth of water over the reference point at the end of the tube can then be converted to a digital representation and, subsequently, to feet or meters of water depth by the RTU or controller. The bubbler gage allows the transducer to be located remotely from the measuring point by using the gas to transfer the pressure to the transducer.

System accuracy depends on proper installation, operation, and the accuracy and stability of the pressure transducer.

Bubbler gages require maintenance to replenish the compressed gas, inspection of the bubbler tube and orifice, and periodic calibration and verification of the transducer. The bubbler tube and outlet orifice are subject to damage or clogging.

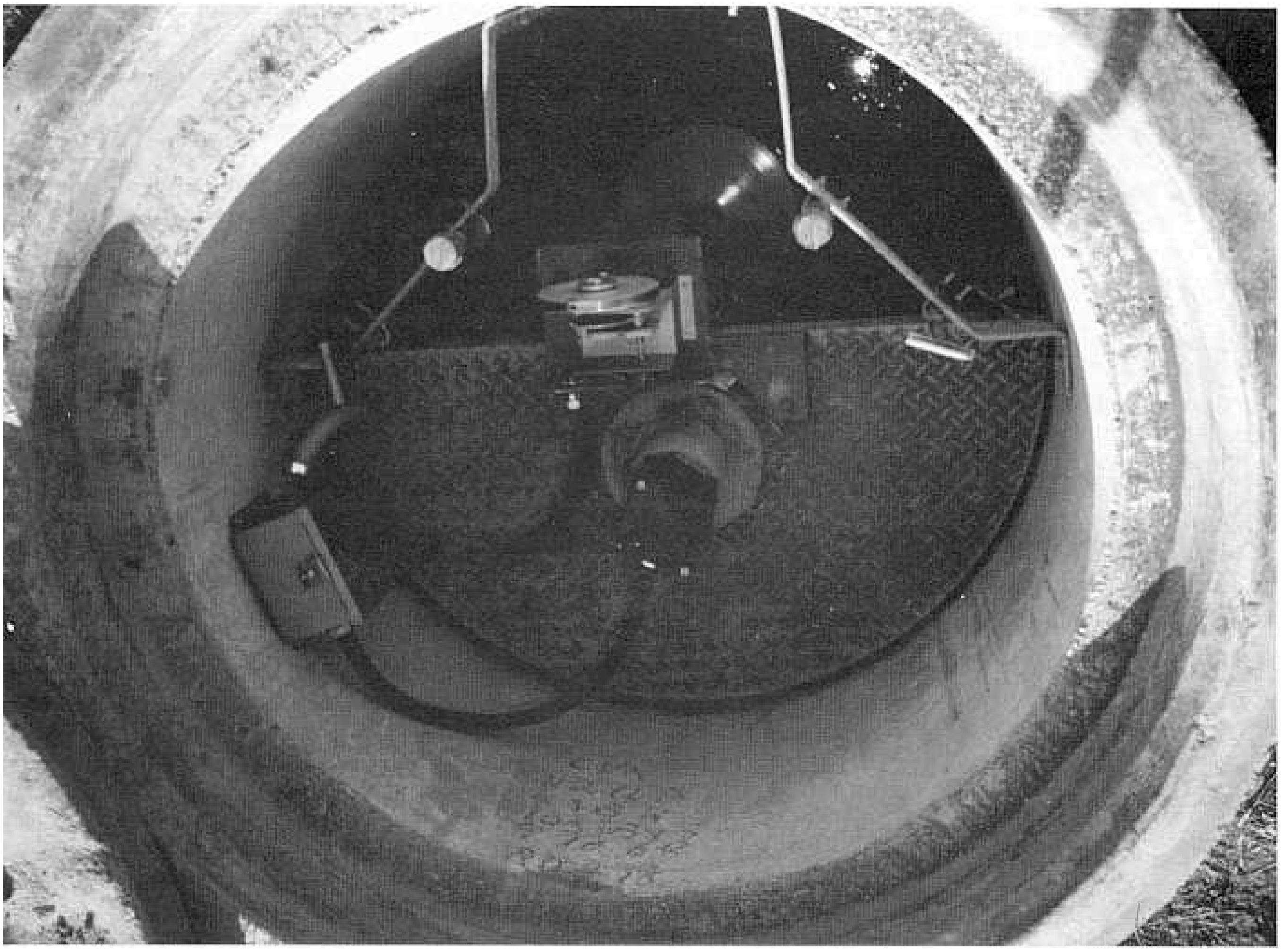

Figure 9-1.—Float, pulley, and counterweight.

Some bubbler systems are available with a small air compressor instead of the nitrogen or air cylinder to supply the gas to be released into the water.

A second pressure transducer method has become feasible with improved submersible transducer design. Pressure transducers are submerged and attached below the minimum water level. Submersible transducers do away with the regulator, compressed gas, and tube, therefore eliminating the maintenance for compressed gas and bubbler tube. These transducers are supplied with a small vent tube to equalize the pressure on the back of the diaphragm to the atmosphere. However, submersible transducers are subject to damage from freezing and must be removed to a dry location when freezing conditions exist. The transducer output is converted directly to head above the transducer, the same as the bubbler gage does for head above the bubbler gage. Pressure transducers designed for this application with a 4.0- to 20.0-milliampere output are often referred to as pressure transmitters, as shown on figure 9-3.

The conversion relation is:

$$D=(K_1 \times P \times CF_1)+CF_2 \qquad 9.2$$

where:

$D$ = depth in feet
$K_1$ = calibration constant
$P$ = pressure
$CF_1$ = scaling correction factor
$CF_2$ = offset correction factor

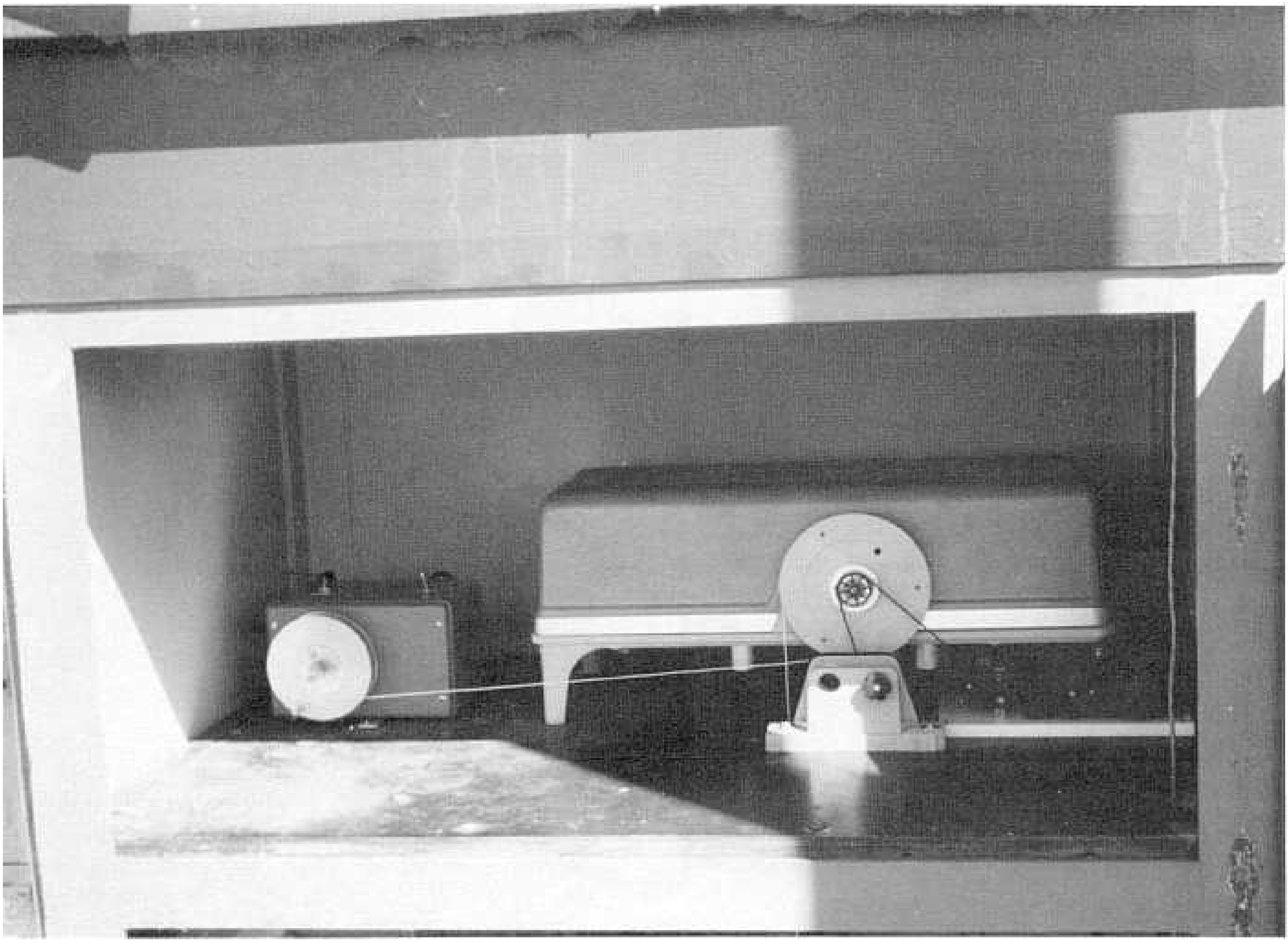

Figure 9-2.—Modified Leupold Stevens Chart Recorder.

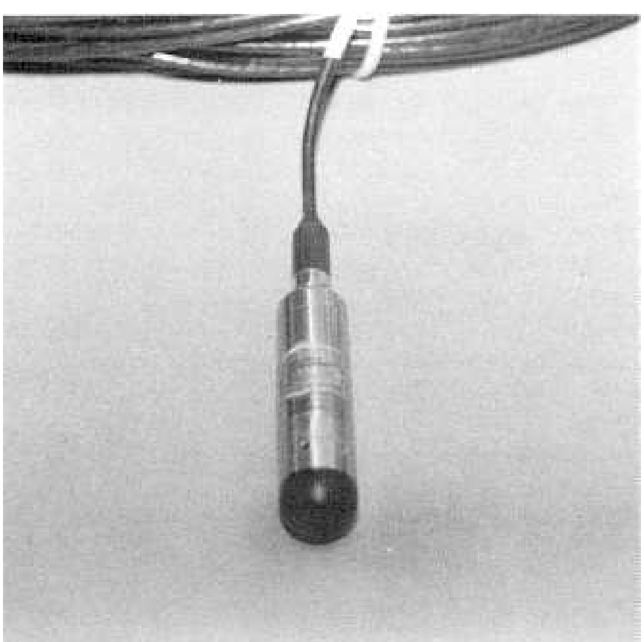

Figure 9-3.—Submersible pressure transmitter.

Bubbler gage transducers and submersible transducers can provide accuracies of 0.1 percent or better.

**c. Capacitance method.**—The capacitance method uses an electronics package and a Teflon-coated rod sensing element. Electronics in the probe convert the change in probe capacitance caused by the level of water on the rod to a proportional analog signal. Capacitance probes have provisions for setting offset and scale. This output is then directly proportional to actual water level. The analog signal can then be converted to digital, scaled, and offset to provide engineering units as in the other methods. The Teflon-coated rods are available in various lengths to accommodate a variety of water level ranges. Figure 9-4 shows a laboratory installation of a capacitance water level probe.

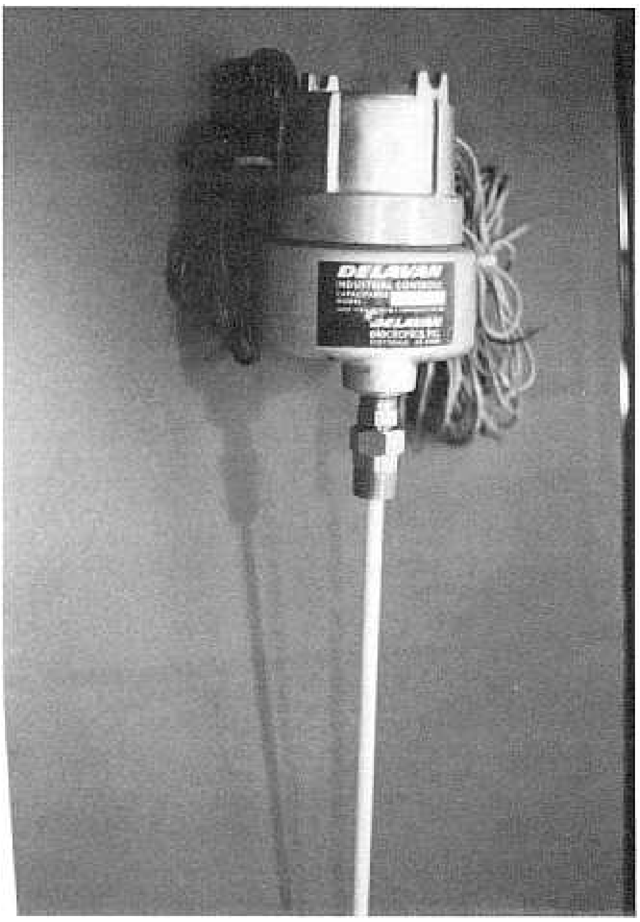


Figure 9-4.—Capacitance probe.

Accuracy in the laboratory for short probes of 0.33 to 1.0 m (1.0 to 3.0 ft) has been about 1 percent. Capacitance probes are subject to fouling and damage by debris, which can cause inaccuracies and even failures in output. Accuracy can be restored by cleaning the probe. Penetration of the rod coating causes failure, and the probe element has to be repaired or replaced. Temperature stability and failure of the electronics have also been a problem in laboratory use. This problem is caused, in part, by the moving and handling of probes in laboratory application. Temperature compensated units installed in stilling wells should result in satisfactory operation.

**d. Ultrasonic methods.**—Acoustic and ultrasonic level encoders have also been applied to canal systems. A sound pulse from an acoustic or ultrasonic transducer is used to measure the distance between the transducer and the water surface. The transit time of the pulses can be converted to the distance to the surface. The analog output can be converted to the actual water level. The more complex encoders provide for scaling, offset, and direction and can provide a digital output. A typical installation is shown on figure 9-5.

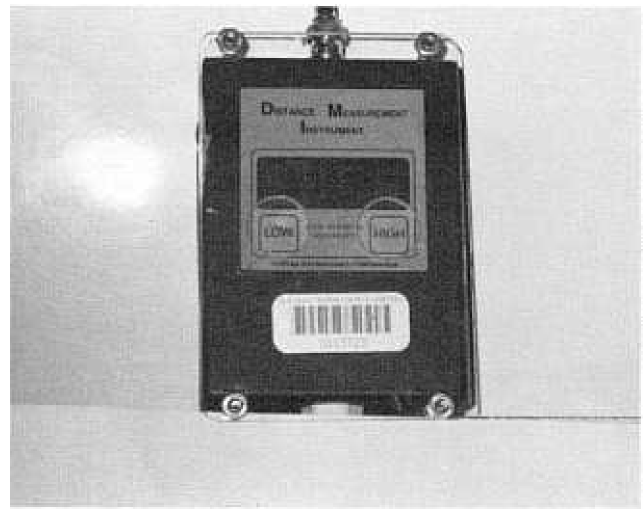


Figure 9-5.—Acoustic level encoder.

Acoustic and ultrasonic level encoders are non-contact devices and are not subject to fouling and debris problems. However, they do depend on the velocity of the acoustic or ultrasonic wave through air. Temperature and humidity affect that velocity. Acoustic and ultrasonic level encoders must have compensating circuits to correct for temperature and humidity for use in canal applications. Most require multiple readings within a small percentage to validate a reading; therefore, the encoders require a relatively still water surface or installation in a stilling well for the accuracies and reliability desired. Acoustic and ultrasonic level encoders require more complicated electronics. This complexity results in poorer reliability and more expensive repair, often requiring the equipment be removed and sent to the factory.

**e. Fluid gage—balance beam manometer.**—The balance beam manometer is a variation of the bubble gage that uses a balance beam-servo mechanism that provides a mechanical output (shaft rotation) in place of the pressure transducer. The device can measure head and can also be used for differential pressures. The systems are available for use with various air sources including nitrogen cylinders, air compressors, and direct water interfaces. The mechanism can drive a precision potentiometer, a resolver, or a chart recorder. The precision and accuracy are in the 0.01-percent range.

The unit is too complex and expensive for use in most automation applications. However, the balance beam manometer is a reliable, stable, and accurate device. It may have some applications where water accountability is of importance.

## 9-3. Flow ($Q$)

Flow is a measurement of the volume of water per unit time that passes through a plane perpendicular to the flow in the canal, a pipe, valve, or check structure. Flow is useful in making deliveries and delivery changes to meet the overall user needs and maintain the volume of water in the canal. The flow into the canal must match the flow out of the canal except when filling, draining, and short periods when the canal prism changes to accommodate flow changes.

Generally, canal operation is described in terms of flow. This procedure makes the measurement of flow highly desirable in canal operation. Water management, scheduling, turnouts, and releases are made in units of flow, or $Q$. Direct measurement of flow or $Q$ would make canal operation simply matching releases to demands. This process works well in closed systems but causes problems in canals that maintain target levels. Flow, though desirable, is more difficult to measure than water level. Most flow measurements involve one or more water level measurements, specific canal geometry, and calibration. In addition, most canal constraints are in terms of water level; e.g., drawdown criteria, bank overflow, minimum level for deliveries, and large waves in the canal. Methods to measure flow in a canal include:

- Acoustic and ultrasonic flowmeters
- Gate flow algorithms
- Parshall flume
- Ramp flumes
- Weirs
- Current meters
- Differential pressure
- Orifices

Flow measurement using flumes and weirs is derived from a water level. The various methods of measuring water level described are required to complete a flow measurement system. A weir or flume is calibrated such that a given water head equates to a flow. This head can be converted to flow using a calibration curve or look-up table.

Numerous methods to measure flow exist. Most rely on a water level measurement (or measurements) to calculate flow. In many installations, the careful installation of water level measuring devices can provide both level and flow information.

**a. Acoustic and ultrasonic flowmeters.**—Acoustic and ultrasonic flowmeters operate on a Doppler principle in which the difference in time of arrival of two simultaneously created acoustic or sound pulses traveling in opposite directions through the water can be related to velocity of flow. In one direction, the velocity of the flowing water increases the apparent speed of sound, resulting in a shorter transit time of the acoustic pulse. In the other direction, the velocity of flow delays the arrival of the pulse, resulting in a longer transit time for the pulse. The average flow velocity along the sound path can be obtained from difference in transit time of the two simultaneously created pulses using the following formula:

$$V_w = \frac{\Delta T C^2}{2L} \qquad 9.3$$

where:

$V_w$ = average velocity of waterflow
$\Delta T$ = difference in transit time of the two acoustic pulses in seconds
$C$ = speed of sound in the liquid
$L$ = acoustic path length between the transmitter-receiver

A typical installation is shown on figure 9-6.

The transmitter-receiver units are special transducers placed in or on the channel side slopes. Unlike the level transducers, these transducers must have contact with the water. One transducer is placed on one side of the channel, and a second one is placed on the other side far enough downstream to provide a measurable time difference (*dt*). The transducers convert electrical impulses generated at the instrument control station into sound pulses that travel through the water. They also convert the received sound pulses back into electrical signals for use in the flow calculation. A time comparator is housed in the instrument control station to measure the difference in times of

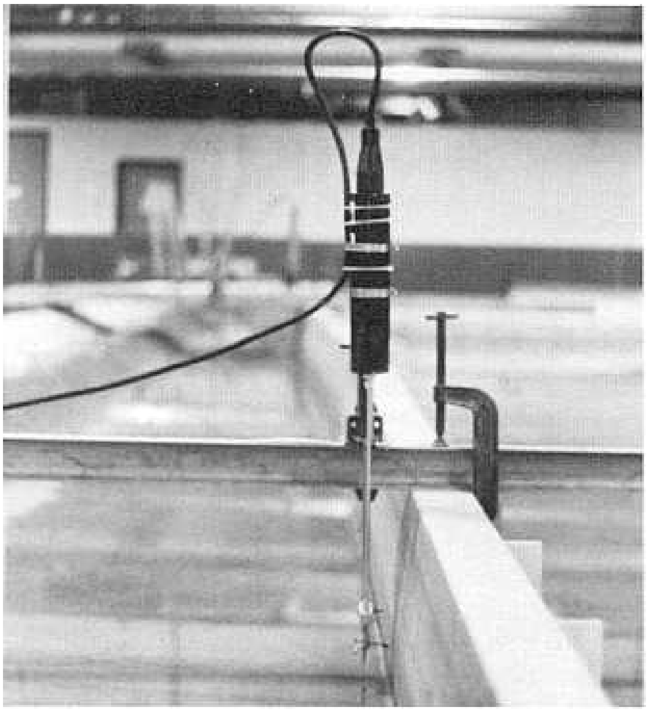

Figure 9-6.—Ultrasonic flow meter.

arrival at the receivers of the leading edges of the simultaneously created sound pulses emanating from the upstream and downstream transmitters.

The accuracy of the system depends upon positioning the transducers at the proper depths to obtain a true average velocity in the canal. Several pairs of transducers may be necessary to obtain a representative average if the velocity distribution is distorted. The transducers must be raised or lowered to compensate for changing velocity profiles for installations where appreciable changes in depth or stage occur. With a single pair of transducers, the average velocity at 0.6 depth has been found satisfactory for use with the flow cross-sectional area to find the discharge.

Acoustic flow meter equipment and flow-measuring techniques have improved considerably in reliability, accuracy, and operability. Local alternating current (a-c) power supply can now handle power requirements. Under optimum conditions, velocity measurement accuracies of 1 percent can be expected. Like other methods that measure only an average velocity of flow, the relationship of the particular velocity of flow to the average streamflow, together with the cross-sectional area of the flow prism, must be known to determine the rate of flow. The controller must calculate flow using area (a function of depth) and velocity.

Water temperature and quality (salinity) affect the velocity of the signals. The meters have to be calibrated to local water quality conditions.

**b. Gate flow algorithms.**—Gate flow algorithms use an existing gate structure and upstream and downstream water level to determine flow. A gate is a complex form of orifice. Gate flow algorithms are more complex than the previously discussed methods because of the complex relationship between gate position and both upstream and downstream water levels. However, gates are readily available, and often gate position and at least one water level are already provided. Most RTU and controller check sites only require a second water level and a gate calibration.

A gate algorithm is complex and depends on gate geometry and even the type of gate seal. The gate algorithm has the following general form:

$$Q=C_D*G_O*G_W*\sqrt{2*G_C*H} \qquad 9.4$$

where:

$Q$ = discharge
$C_D$ = coefficient of discharge
$G_O$ = gate opening
$G_W$ = gate width
$G_C$ = gravitational constant
$H$ = a definition of the head term

Application of the gate algorithm requires use of a computer program and specific information about the gate. Field test results show an accuracy of +0.7 percent can be obtained. However, 3 to 5 percent can usually be expected [3].

Advantages:

Structure already in place
Provides excellent accuracy
Operates with no additional head loss
Can be executed in RTU or controller

Disadvantages:

Sensitive to gate seal and other configuration changes
Requires complicated algorithms for calibration, requiring a computer analysis
Requires gate position and upstream and downstream water levels

c. **Parshall flumes.**—A Parshall flume is a specially shaped open channel flow section which is installed in a canal, lateral, or ditch to measure the rate of flow of water. The Parshall flume is a particular form of venturi flume. The constricted throat of the flume produces a differential head that can be related to discharge. The crest, followed by the downward sloping floor, gives the Parshall flume its ability to withstand relatively high degrees of submergence without affecting the rate of flow. The converging upstream portion of the flume accelerates the entering flow, thereby essentially eliminating the deposition of sediment that would otherwise reduce measurement accuracy.

Velocity of approach, which often is detrimental to the operation of weirs and orifices, is usually small and has little effect on the rate of discharge of the flume. However, the approaching flow should be well distributed across the channel and should be relatively free of turbulence, eddies, and waves if accurate measurements are expected. A Parshall flume equation using upstream and possibly downstream water levels can be used to calculate flow. A typical Parshall flume in operation is shown on figure 9-7.

The Parshall flume has four significant advantages:

It operates with relatively small head loss.
2. It is relatively insensitive to velocity of approach.

Figure 9-7.—Parshall flume.

3. It can make good measurements with no submergence, moderate submergence, or considerable submergence downstream.
4. Its flow velocity is sufficiently high to virtually eliminate sediment deposition within the structure during operation.

The equation for flow, $Q$, takes the form:

$$Q = KH^n \tag{9.5}$$

where:

$Q$ = discharge
$H$ = head (upstream)
$K$ = constant dependent on flume geometry and material
$n$ = constant dependent on flume geometry and material ($2 < n < 3$).

Discharge through a Parshall flume can occur for two conditions of flow. The first, free flow, occurs when backwater depth is insufficient to reduce the discharge rate. The second, submerged flow, occurs when the water surface downstream from the flume is far enough above the elevation of the flume crest to reduce the discharge (submerged flow). For free flow, only the head, $H_a$, at the upstream staff gage is needed to determine the discharge from a standard table. The free-flow range includes some of the range which might ordinarily be considered submerged flow because Parshall flumes tolerate 50 to 80 percent submergence before the free-flow rate is measurably reduced. For submerged flows (when submergence is greater than 50 to 80 percent, depending upon flume size), both the upstream and downstream heads are needed to determine the discharge.

A distinct advantage of the Parshall flume is its ability to function as a flowmeter over a wide operating range with minimum loss of head while requiring but a single head measurement for each discharge. The head loss is only about one-fourth of that needed to operate a weir having the same crest length. Another advantage is that the velocity of approach is automatically controlled if the correct size of flume is chosen, and the flume is oriented as it should be; that is, as an in-line structure.

Six disadvantages of Parshall flumes are:

1. They cannot be used in close-coupled combination structures consisting of turnout, control, or measuring device.
2. They are more expensive than weirs or submerged orifices.
3. They require a solid, watertight foundation.
4. They require accurate workmanship for satisfactory construction and performance.
5. They require upstream and downstream water levels if submerged.
6. Large flumes can settle and deform over time, requiring recalibration.

Parshall flume sizes are designated by the throat width, and dimensions are available for flumes from the 25-mm (1-in) size for discharges as small as 28.3 liters per second (0.01 second-foot), up to the 15-m (50-ft) size for discharges as large as 85 cubic meters per second ($m^3/s$) (3,000 second-feet). The flumes may be built of wood, concrete, galvanized sheet metal, plastic, or other desired materials. Usually, large flumes are constructed on the site. Smaller flumes may be purchased as prefabricated structures to be installed in one piece. Some flumes are available as lightweight shells, which are made rigid and immobile by placing concrete outside of the walls and beneath the bottom.

The addition of an accurate water level encoder to a properly installed Parshall flume provides an excellent flow measuring device for a controller or RTU. The controller can convert the water level to a flow or use the water level directly. Accuracy of flows from 3.0 to 5.0 percent can be expected in nonsubmerged applications.

**d. Ramp flumes.**—A ramp flume consists of a 3:1 approach ramp up to a horizontal broad sill or crest with a vertical downstream drop back to the canal invert. Ramp flumes are simple to form and construct. Also, ramp flumes are easy to install in existing canals. A typical installation is shown on figure 9-8.

Ramp flumes have relatively small head losses and are able to tolerate high submergence (85 percent of the measuring head for a vertical downstream

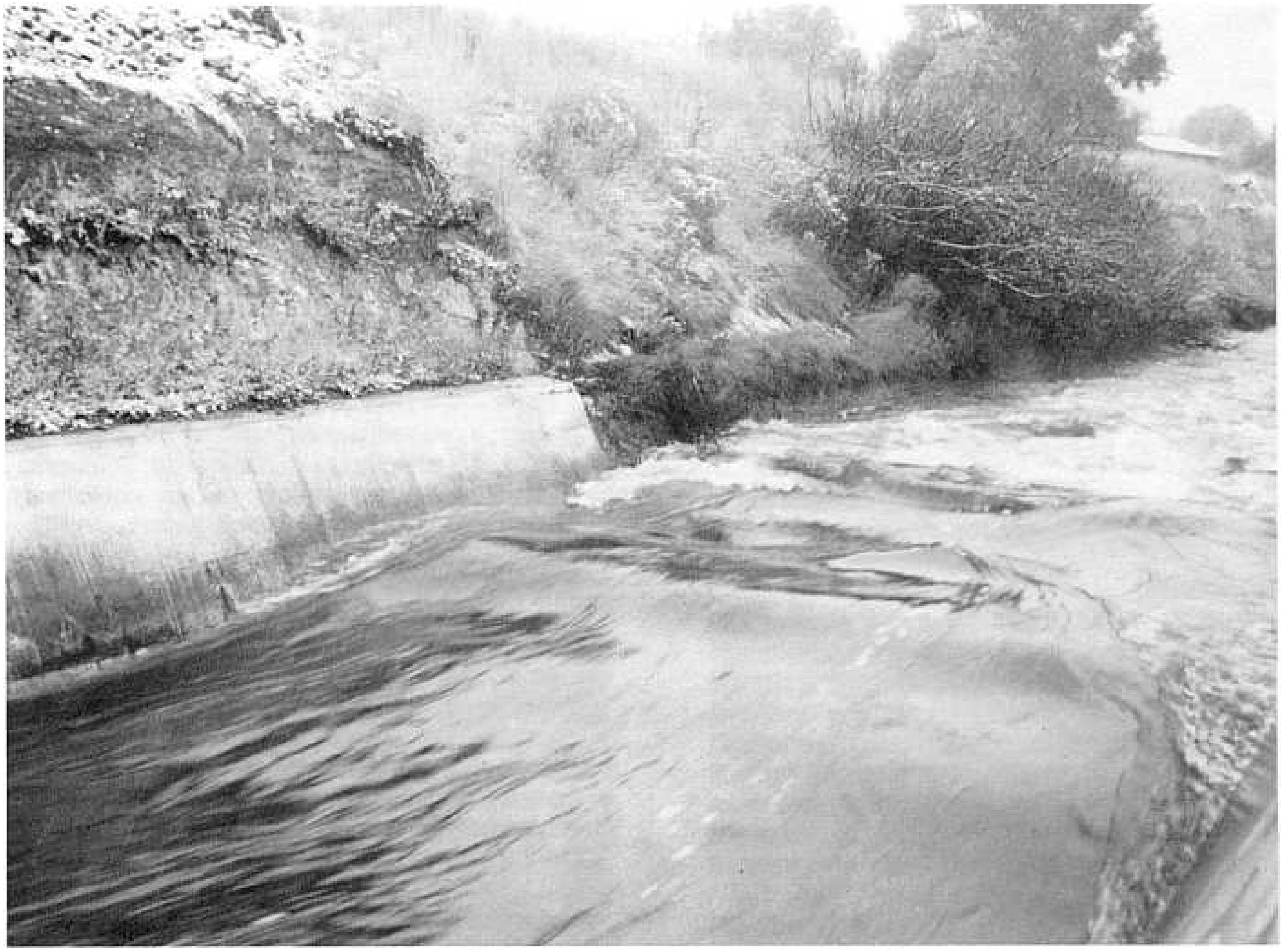

Figure 9-8(a).—Ramp flume.

crest face and 93 percent of the measuring head with an added 6 horizontal to 1 vertical diverging downstream ramp). Therefore, the minimum required head loss for flow measurement is 15 percent of the measuring head on flumes with vertical drops and 7 percent of the measuring head for ramp flumes with 6:1 sloped downstream diverging ramps. Discharge measurement errors increase rapidly beyond the submergence limit.

Generally, ramp flumes are designed for step heights from 40 to 60 percent of the approach canal normal flow depth. Thus, the minimum head loss (using 50 percent) that can be allowed while still permitting flow measurement is 7.5 percent of the approach flow depth for a ramp flume with a vertical drop and 3.5 percent of the approach flow depth for a ramp flume with 6:1 sloped downstream ramp.

A major advantage of a ramp flume is the ability to numerically calibrate the flume using post-construction dimension measurements. Thus, construction errors or flume settlement can be better accounted for with these measurements. A computer program is available to generate a discharge table. Another advantage of ramp flumes is that they can usually be installed in existing canal sections with minimal canal modification.

To ensure approximate parallel flow (assumed for numerical calibration purposes), the basic design criteria of approach measuring head, $H_1$, relative to the length of crest in the direction of flow, $L_3$, is:

$$(H_1/L_3) < 0.50 \qquad 9.6$$

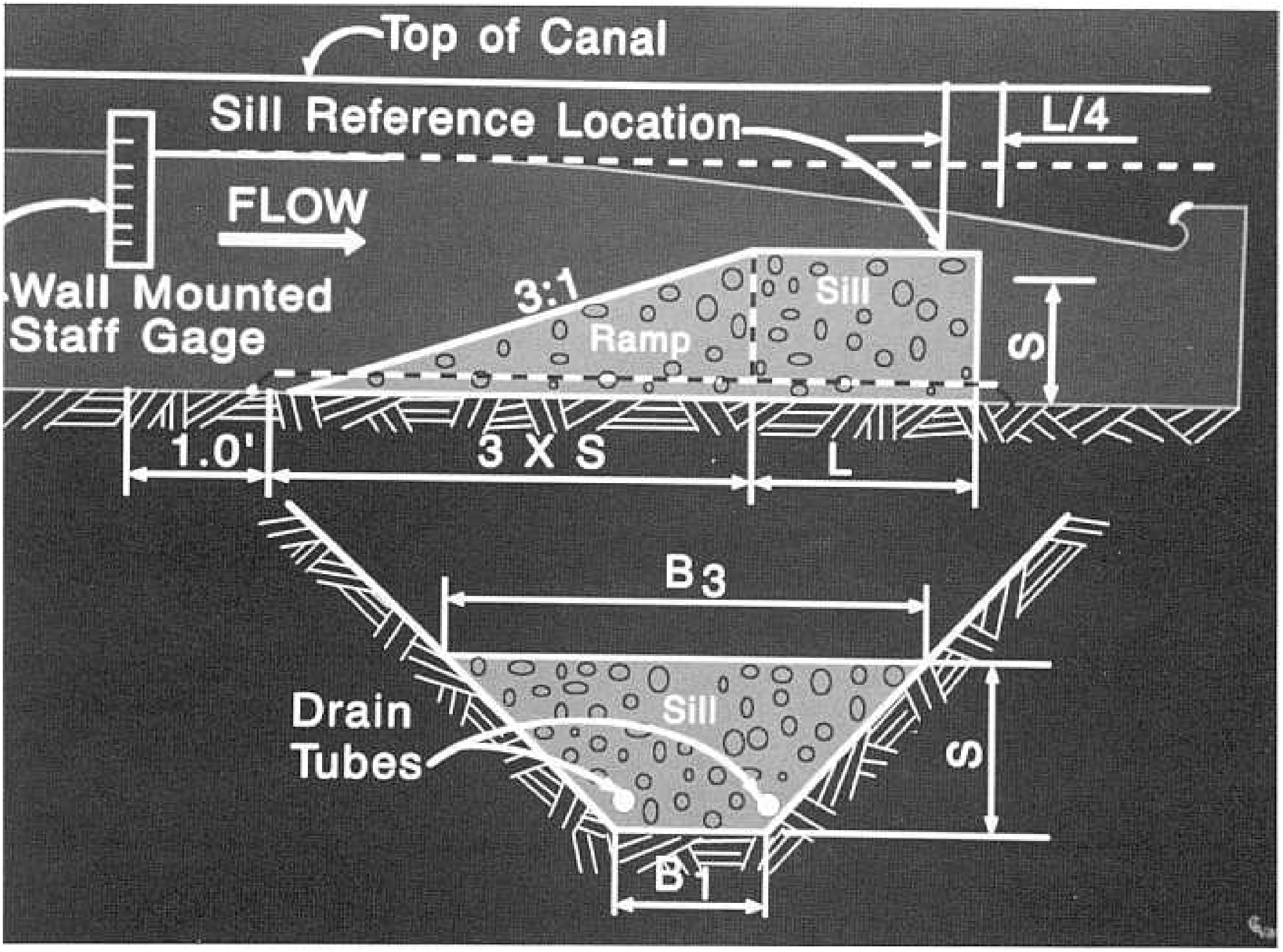


Figure 9-8(b).—Ramp flume schematic.

Also, the head at the measuring station should be greater than one-twentieth of the crest length to assure that undulating flow (caused by frictional control) does not occur on the crest. Thus,

$$(H_1/L_3) > 0.05 \qquad 9.7$$

Accuracy comparisons of field and model calibrations with numerical (computer program) calibrations indicate that numerically calibrated ramp flumes are as accurate as Parshall flumes (in the range of 3 to 5 percent) [6].

Addition of an accurate water level encoder to a properly installed ramp flume provides an excellent flow-measuring device for a controller or RTU. Flows accurate from 3.0 to 5.0 percent can be expected.

e. **Weirs.**—Weirs are one of the oldest, simplest, and most reliable structures that can be used to measure water flow in canals and laterals. Weirs are available in many designs, including rectangular, V-notch, trapezoidal, and Cipolletti. The critical components are easily inspected, and any improper operations can be easily detected and quickly corrected. Weirs can be used most effectively whenever a fall of about 0.15 m (0.5 ft) or more is available in the canal, lateral, or ditch. See figure 9-9 for a weir.

A weir may be defined as an overflow structure built across an open channel, usually to measure the rate of flow of water. Weirs are acceptable measuring devices because, for a weir of a specific size and shape with free-flow steady-state conditions and proper weir-to-pool relationships, only one depth of water can exist in the upstream

Figure 9-9.—Weir.

pool for a given discharge. Discharge rates are determined by measuring the vertical distance from the crest of the overflow portion of the weir to the water surface in the pool upstream from the crest, and then referring to computations or tables which apply to the size and shape of the weir. For standard tables to apply, the weir must have a regular shape, definite dimensions, and be set in a bulkhead and pool of adequate size so the system performs in a standard manner.

Depending upon the shape of the opening, weirs may be termed rectangular, trapezoidal, triangular, etc. In the case of rectangular or trapezoidal weirs, the bottom edge of the opening is the crest, and the side edges are called sides or weir ends. The sheet of water leaving the weir crest is called the nappe. Weirs operate best when they discharge freely into the atmosphere. In certain submerged conditions, the under-nappe airspace must be ventilated to maintain near-atmospheric pressure.

The addition of an accurate water level encoder to a properly installed weir provides an excellent flow measuring device for a controller or RTU. Flows accurate from 3.0 to 5.0 percent can be measured.

**f. Current meters and propeller meters.**—Current meters (propeller, pygmy, price) are not typically used to provide a measurement. These devices are useful in the verification and calibration of one of the flow measuring devices described above. A velocity profile is determined by making measurements at a number of points in a plane perpendicular to the flow of water. This velocity profile and the cross section of the stream or canal is then used to calculate flow. These devices measure the velocity and direction of the water at a given place.

**g. Differential pressure (venturi meters).**—Differential pressure (venturi) meters are not usually applicable to open channel flow. Venturi meters are usually applied to pipe turnouts and pumping plants where conditions are appropriate. Venturi meters are perhaps the most accurate type of flow measuring device that can be used in a water supply system. They contain no moving parts, require very little maintenance, and cause very little head loss. Venturi meters operate upon the principle that flow in a given closed-conduit system moves more rapidly through areas of small cross section than through areas of large cross section.

Total energy in the flow, consisting primarily of velocity head and pressure head, is essentially the same within the meter. Thus, the pressure must decrease in the constricted throat where the velocity is higher. Conversely, the pressure must increase upstream from the throat where the velocity is lower. The reduction in pressure from the meter entrance to the meter throat is directly related to the rate of flow passing through the meter and is the measurement used to determine flow rate. Tables or diagrams of this head differential versus rate of flow may be prepared.

The relationship of rate of flow, or discharge, to the head and dimensions of the meter is:

$$Q=\frac{CA_2\sqrt{2gh}}{\sqrt{1-r^4}} \qquad 9.8$$

where:

- $A_2$ = cross-sectional area of the throat
- $h$ = difference in pressure head between upstream pressure measuring section and the downstream pressure measuring section
- $g$ = acceleration caused by gravity
- $r$ = ratio of the throat diameter to pipe diameter = $D_2 / D_1$
- $C_d$ = Coefficient of discharge for the venturi meter
- $D_1$ = upstream diameter of pipe
- $D_2$ = downstream diameter of pipe

The coefficient of discharge for the venturi meter will range from about 0.935 for small throat velocities and diameters to 0.988 for relatively large throat velocities and diameters.

Historically, the expense of venturi meters and the fact that they must always operate with the pipeline full have restricted their use on a broad scale in irrigation systems. Requirements for more accurate flow measurements in pressure conduits will probably result in greater use of the meters in the future. Many variations of the meter exist, each of which is tailored to meet the requirements of specific types of installations.

**h. Orifices.**—An orifice is a well-defined, sharp-edged opening in a wall or bulkhead through which waterflow may occur. If the upstream water surface drops below the top of the opening, the flow ceases to follow the laws of orifice flow and tends to follow those of flow over a weir. Flow through an orifice may either discharge freely into the air or into water as submerged flow. The submerged orifice conserves head and is therefore used where insufficient fall exists for a weir, and where for some reason, a flume cannot be justified. Both free and submerged orifices may be contracted or suppressed. In a suppressed orifice, the perimeter partly or fully coincides with the sides of the approach channel.

The discharge through a vertical, sharp-edged, contracted, submerged orifice is given by Corbett and others as:

$$Q=C_dA(2gH)^{1/2} \qquad 9.9$$

where:

- $Q$ = discharge
- $C_d$ = coefficient of discharge
- $A$ = area of orifice
- $g$ = acceleration caused by gravity
- $H$ = head on orifice, equal to difference of head on upstream and downstream sides of orifice

A negligible velocity of approach, complete orifice contractions, and an effective head large enough to minimize errors in its measurement are essential for obtaining accurate results.

When velocity of approach becomes applicable, the equation becomes:

$$Q=C_dA[2g(H+h)]^{1/2} \qquad 9.10$$

where:

- $h$ = the velocity head in the approach to the orifice, and the other terms are as previously defined

## 9-4. Gate and Valve Position Measurements

**a. Radial gate hoist, drum rotation.**—The radial gate (tainter gate) is commonly used in canal systems. The radial gate is positioned with a drum and cable hoist mechanism. As the drum rotates, steel cables attached to the drum and gate raise and lower the gate. The drum is rotated using a gear assembly with a motor or handwheel. Gate position can be derived from a rotational sensor attached to the drum shaft or an intermediate shaft in the gear assembly. Rotational sensors for gate position include potentiometers, digital shaft encoders, rotational voltage differential transformers (RVDT), and selsyn encoders. Figure 9-10 illustrates a radial gate showing the installation of a potentiometer gate position sensor.

Radial gate position is often considered linear, and a straight line relationship between the encoder output and the gate position is assumed. A gate position equation or look-up table can be provided where more accurate gate position is required. This approach will probably be required to provide the necessary accuracy to determine flow using gate opening and water levels.

An inclinometer or angle transducer can also provide radial gate position. The inclinometer provides an accurate trigonometric output which is then converted to a linear gate opening. The inclinometer is attached to one of the arms of the radial gate. Installation is easy because no other mechanical connections are required. However, the installed location of the inclinometer on the gate makes repair and maintenance difficult.

**b. Slide gate position.**—Slide gates are used in many canal systems. The slide gates may be installed vertically or set at an angle. Slide gate opening requires a different hardware approach. Two applications are described.

Figure 9-10.—Radial gate hoist with sensor.

Usually, the hoist mechanism is a screw hoist for a threaded rising stem attached to the gate. The screw hoist operator may have a geared auxiliary shaft that can be used to drive a rotational sensor as for the radial gate hoist. The rotational sensor (potentiometer, RVDT, or digital encoder) must match the rotation of the shaft. The geared shaft with a rotational sensor provides an accurate gate position signal. The slide gate travel is linear; therefore, the gate output signal is linear and requires only offset and scaling to provide English or metric gate position output. A typical installation is shown on figure 9-11.

Figure 9-11.—Slide gate hoist.

If the hoist mechanism does not have a geared shaft output, a system similar to that used with a water level float system can be used. The cable is attached to the gate rather than a float. The cable to the gate must travel in the same plane as the gate. A rotational encoder is attached to the pulley shaft to provide gate position output. Because the cable, pulley, and counterweight can be tampered with or fouled by debris, they must be housed in a protective enclosure. This method can be applied to radial gates.

A linear voltage differential transformer (LVDT) can also be used. The linear device is attached to the gate using a cable or rod parallel to and in the same plane as the gate. The linear device must have a range of travel at least equal to the gate travel or the lever equivalent. Protection from tampering and the environment is required.

**c. Gate and valve position.**—Closed conduit gates and valves are used in canal systems for turnouts, canal-side pumping plants, and in-line canal pumping plants. Position indication may only require open or closed status or may require actual position such as in metering and flow control applications. Mechanically coupled limit switches can provide status—open or closed. The switches can be set to change position as the valve starts to open or when the valve is fully open.

Actual position of these devices can often be derived from an intermediate or main shaft of an operator using rotational transducers. Many gate and valve operators include a position output device as part of the operator.

All gates and valves, when operated remotely or automatically, must be equipped with limit switches to stop operation beyond their normal operational range.

## 9-5. Electrical Quantities

**a. Observations.**—Many of the observations and measurements desired in manual operation of a canal system can be included in a canal automation system. Various transducers, encoders, and switches can be installed on equipment and incorporated into the automation system. The output signals are then used in the control process, generation of an alarm, or are transmitted to the central control site for monitoring, recordkeeping, and advising the operators (master station).

The information can be used to assist in control operation or site security, or provide an indication of an impending problem. Equipment measurements are interrelated such as an analog water level and high and low water limit probes. The high and low probes are used to verify the analog water level data. Equipment information can be used to determine component failures, a need for site maintenance and repair, or even a local emergency where manual or local onsite control is required.

Equipment measurements can be made in almost any form—analog signals (voltage or current), single or multiple digital voltages, or on-off voltage signals.

**b. Analog signal.**—An analog signal is a measured variable (voltage or current) that varies with time. The signal from a pressure transducer, for example, may vary from 0 to 5 volts as the pressure increases from zero to maximum. An operator can provide an input parameter by setting an analog quantity using a potentiometer. An operator can provide a local control setpoint—target water level, for example.

Analog signals are subject to noise because the information is represented by the amplitude of the signal. Noise appears on the signal as a random variation in the amplitude. This noise can be reduced by using current output devices when available and by using good wiring practice and proper shielding.

Analog quantities cannot be used directly by computer-based canal-side controllers and RTU's. The analog quantity must first be converted to digital using an a-to-d converter.

**c. Digital signal.**—A digital signal is a variable represented by a series of one or more on and off signals or voltages. Each signal in the series has a weighted value. The simplest signal is an alarm or status represented by one position or digit (binary digit). If the voltage is present, the digit represents the "on" state. If the voltage is not present, the digit represents the "off" state. A mechanical limit switch or a contact switch on a door can also provide this input.

A digital variable such as the output of an absolute digital shaft encoder can be represented by 8, 10, or more positions or digits. Each digit has a weight or value; an 8-digit output would include the following weighted values: (128+64+32+16+8+4+2+1 = 255). The first has a value of 128, the second 64, the eighth 1. An 8-binary-digit representation provides a count from 0 to 255, a resolution of 1 part in 256.

Digital signals are not subject to distortion or interference that degrades analog signals. Because the quantity is either on or off, a small variation in the amplitude is not a problem. However, digital implementation is more complicated. Digital data require either multiple conductors or a multiplexing system to provide for communication of each weighted position or digit between the digital instrument and the RTU. Inputs for each signal or demultiplexing is required for each digital variable.

## 9-6. Equipment Status

Equipment status can often be determined by a simple on/off status contact. Many of the types of equipment used in canal systems are provided with auxiliary switches for this purpose. Motor-operated valves are often equipped with open and closed limit switches. Motor controllers have auxiliary contacts that can be used to determine if a motor is running or stopped. Some additional examples of two position or on/off status are:

- Gates—open/closed limit switches
- Pumps—running/stopped
- Electrical power—on/off voltage sensor
- Temperature—high/normal
- Control switches—on/off position

These parameters allow various conditions and operations in a control sequence to be used by the controller and monitored by the control operator.

Equipment status is not limited to simple on/off status. Analog signals can also provide useful information. Battery voltage, a typical analog parameter, provides information on condition of the electrical system. This information can indicate a defective battery charger and warn of a possible power loss to an RTU. Other analog signals include:

- Motor speed
- Wind speed
- Temperature
- Water quality
- Air or hydraulic pressure
- Water level

## 9-7. Alarms

Alarms are an essential part of the control and data acquisition package. Alarms get an operator's attention when something is out of the ordinary, equipment has malfunctioned or failed, or a serious condition has developed. An RTU with its extensive message capability can generate the specific alarm information from its data base and send an ASCII message to the master station. However, a local controller alarm may only be capable of generating a common alarm that is initiated when any one of several events happen.

An alarm may be initiated by a limit switch on a piece of equipment, a high or low water level float switch in a stilling well, or an intrusion alarm initiated by a door switch on the equipment enclosure. Alarms actuated by the opening or closing of a switch contact are contact alarms.

An alarm can also be calculated from analog and digital parameters and a set of limits or conditions, or can even be inferred when a certain combination of status inputs and/or calculated events occur. These "logic alarms" are derived from a formula or calculation.

Many types of both contact and logic alarms exist. Some general headings useful in canal control will be provided, followed by some specific examples:

**a. Water level alarms.**—Water level alarms can be generated several ways. Both contact and logic alarms can be used. Separate limit switches, such as high and low water, can be provided to indicate low or high water. The analog water level can be checked against preset limits in the software to derive high or low water alarms, or two analog water levels may be used to verify and control water level based on the most realistic signal. Often, several schemes are combined to provide a redundant system. The following example illustrates some applications of water level alarms.

The water level signal is limit checked. A set of limits, called soft limits, is set slightly above and below the desired water level. These limits warn the operator that something may need attention but not immediately. A second set of limits is provided to initiate different levels of response. The second set of limits has a wider range and might indicate loss of control, equipment failure, or a serious control problem. A third set of limits, zero and full scale, is often included. This set usually indicates an equipment problem, such as a transducer failure, rather than an actual water level.

A set of alarms controlled by a separate float or level switch can also be used. These limits are set at points above and below the normal range of water operations. These alarms act as a backup system and confirmation of a serious problem such as loss of control, stilling well problem, encoder problem, or transducer failure. Figure 9-12 illustrates the level switch, which can be used as an alarm or limit switch.

Water level is probably the most important variable used in canal control. Most control schemes are based on water level or flow derived from a water level. Multiple sensor configurations are worth consideration for important parameters such as water level. A dual sensor system with limit checking and comparing will assure an almost fail-proof system for providing water level input.

**b. Status alarms.**—Status alarms include many contact or on-off alarms. Loss of a-c power and entry alarms are included in this group.

An RTU cannot respond without power. The master station can detect the lack of a response with a software communication routine. However, a more responsive system can be provided by using battery power for RTU's. Gates and other equipment cannot operate when primary power is lost, but a battery operated RTU can continue to provide information not only on the power failure, but also valuable telemetry from the site. The telemetry provides complete information about the site to evaluate the urgency of corrective action, such as manual onsite operation and site repair. A communications failure or RTU failure will still cause a no response or communications failure alarm. Obviously, specific information is not available without information from the RTU. However, many other failures such as gate failure to operate, water level encoder failure, and even loss of primary power (when the RTU is operated on batteries) can be provided to the master station when the RTU is operational.

Loss of communications can result from a number of failures, including loss of RTU power, RTU failure, or actual failure of the communication system. The alarms can be made more specific by operating the RTU and communications equipment from battery power and continuously charging the batteries. In this way, a-c power failure can be detected and specifically alarmed. A simple mechanical or solid-state relay provides the status alarm point.

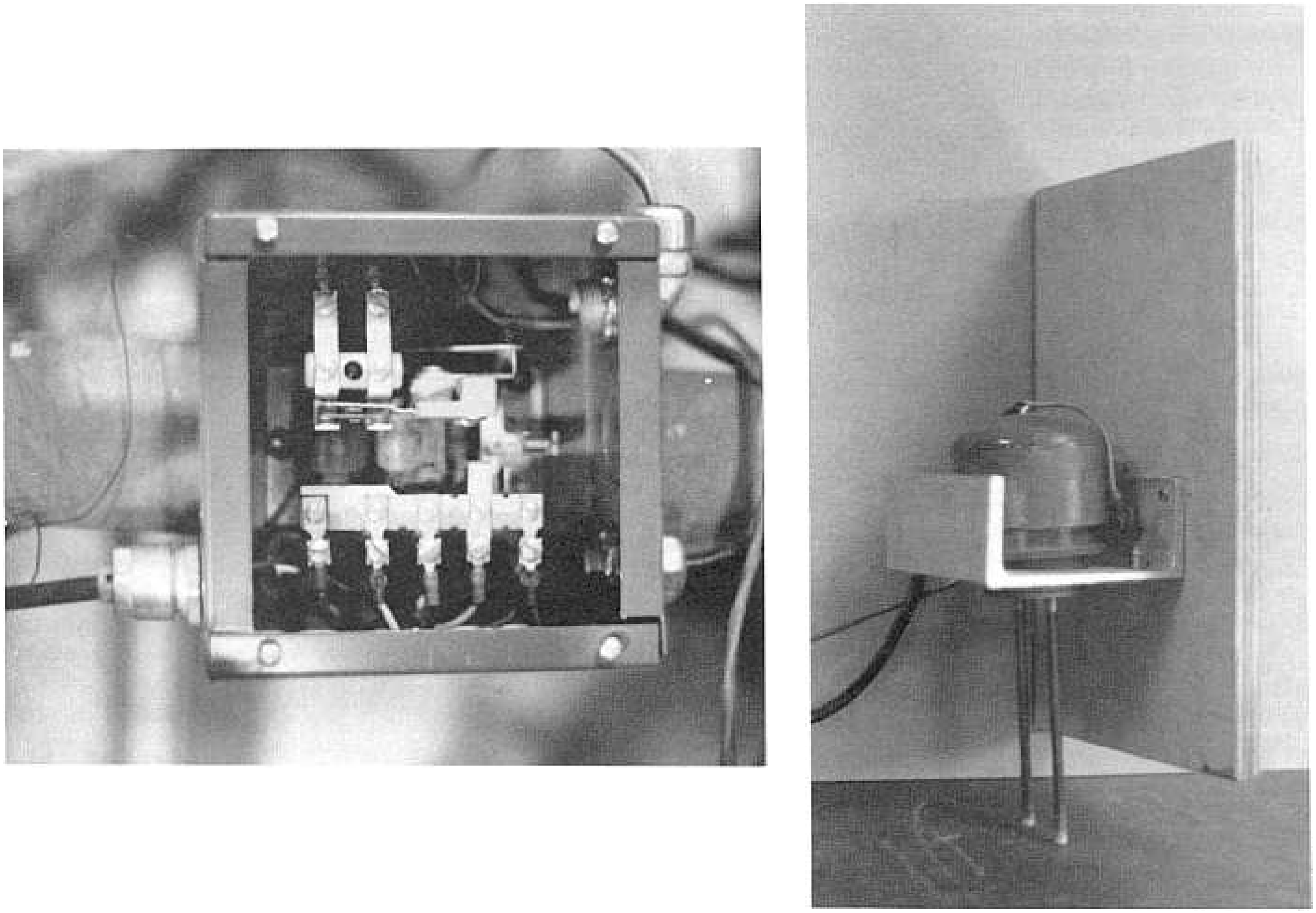

Figure 9-12.—B&W water level alarms (relay is displayed on the left; probe is displayed on the right).

Intrusion or entry alarms are used to detect unauthorized entry into a structure or enclosure. The alarm consists of a hardware switch located near and operated by the entrance door to the structure or enclosure. The alarm initiates an indication at the master station to advise the operator of entry. The alarm contact can also trigger a horn, siren, or lights at the local site to discourage the intruder.

**c. Equipment failures.**—Equipment failures include two types of failure: (1) the equipment did not operate and (2) the equipment operated incorrectly. The type of failure can often be determined by logic (software). A motor-operated gate will be used to illustrate these failures. The gate position is monitored in most control algorithms. When gate operation is required, the algorithm calls for the gate operation and then monitors the gate movement. Incorrect gate operation includes failure to stop, incorrect position, wrong direction, and exceeding limits. The control algorithm generates an alarm if an incorrect operation is detected.

A multiple approach should be used. The algorithm must be provided with travel limits and direction checks to detect problems. The same algorithm should also override the control function and stop control. The function may allow a retry of the control function or stop control all together. An additional safeguard for most control functions is a mechanical limit switch to lock out continued operation beyond the limits. This function helps prevent damage to the equipment and can be used to generate an external alarm to the RTU.

Equipment failures can include many subsystems and components. A number of alarms are described to assist in maintaining system integrity and safe operation of a control site.

**d. Control failures.**—Control failures can be caused by any of a number of problems in the hardware from the RTU or controller to the controlled structure or the input sensors. Control failure requires continuous program monitoring of the variable and status inputs. Variable inputs require limit parameters in the RTU or controller data base to verify the variables are within the expected range. Input readings outside the range should cause an alarm. RTU's can provide specific alarms to the master station.

Water level is an excellent indicator of control problems. Software program limits are operator-adjusted software high and low limit alarms that provide a specific alarm when the monitored parameter (water level) moves out of the limits. Hardware limits are mechanical switches that are adjustable at the site and provide indication when operated. These limits are external or hardware generated and detect loss of control by detecting operation (water level) out of the expected control range. These alarms function similarly to the gate limit alarms in that they provide a check on the analog input parameters.

## 9-8. Sensors

A description of sensors will complete the discussion on gates and valves. Numerous sensors are available for application in canal automation. The actual sensors used will depend on the adaptability to the application, the desired accuracy, cost, and maintainability.

**a. Potentiometers.**—Potentiometers have been used in many canal automation applications. Potentiometers are available in many different varieties and are easily adapted to gate hoists, water level devices, and many other applications in which the desired input is represented by a rotating shaft. Potentiometers are available in single and multiple-turn applications, including 2, 3, 5, 10, 15, and 20 turns, and in a variety of resistance values from about 10 ohms to 1 megohm. Potentiometers are available with resistance tolerances of 3 to 10 percent. Linearity of a potentiometer is about 0.1 to 3.0 percent.

Lower resistance values dissipate more electrical power, and higher resistance values are more susceptible to electrical interference and noise. Good results have been obtained with 2,500- to 10,000-ohm values. The number of turns required will depend on the specific application. In most applications, the potentiometer is used as a voltage divider. In divider applications, the linearity controls the accuracy of the output, and the resistance is not a major factor in determining accuracy. The voltage divider output is supplied to an a-to-d converter to provide digital information for the RTU. The digital information can then be scaled and offset to provide a representation in engineering units.

Potentiometers have shown excellent reliability with an installed life of over 10 years when used as an encoder for a float, pulley, and counterweight water level measurement system or radial gate hoist mechanisms. Overall accuracy is in the 0.1-percent range for a linear travel of 15 inches or more.

Potentiometers are also available as linear devices and have been used for slide gates in some field applications. Linear potentiometers are used similarly as rotational potentiometers to convert linear motion directly to an analog voltage.

**b. Digital shaft encoders.**—Digital shaft encoders can be used in place of potentiometers for rotational encoding. The encoders are available as both absolute and incremental encoders.

Absolute digital shaft encoders are rotational devices in which the input position is converted directly to digital data. Absolute encoders use coded disks with wipers or light-emitting diodes and light-detecting semiconductors to provide the encoded position. The data are then transmitted in parallel using multiple conductor cable or converted to a serial data word and sent over a wire pair. Absolute encoders are used to prevent lost count during power interruptions. Digital shaft encoders are available from 1 to 64 turns and overall accuracy of 1 part in 65,536. The position is represented by up to 16 binary bits either in a serial string or 16 parallel transistor logic compatible signals. The major deterrent to using absolute digital shaft encoders is the increased cost and the difficulty of maintenance and repair. Reliability can be a problem in some field sites with weather and power surges.

Incremental encoders provide a step and direction output or separate step-up and step-down pulse outputs. Incremental encoders rely on a computer to maintain the accumulated position. Accuracy of incremental encoders is in the 3.0-mm (0.01-ft) range for a 100-count-per-revolution encoder. The position count can be lost any time a power interruption or movement of the encoder occurs while power is off. When this loss occurs, the position must be reset to agree with the actual measured quantity. This operation is not desirable in canal systems because the position must be reset by an operator at the site. Incremental encoders are not recommended for use in canal automation. Figure 9-13 shows a potentiometer and digital encoder.

**c. Linear voltage differential transformers.**—LVDT's and RVDT's are also analog output devices. The transformers use a moving core to change the coupling between transformer windings, resulting in a change in the voltage output. An electronic component uses the output from the transformer to produce a linear output proportional to the linear displacement or angle of rotation. These devices can provide a more accurate output than potentiometers, but the cost and complex electronics restrict their use in canal applications. These devices are used in many motor-operated valves for position indication. Because of close tolerances between the core and transformer, RVDT's and LVDT's can bind or be damaged by sand and dirt. LVDT's and RVDT's therefore require a protected environment. They provide excellent accuracy and good reliability when built into an operator such as a gate valve operator or slide gate operator.

**d. Inclinometers.**—Inclinometers (angle transducers) produce a sine or linear output corresponding to the angle of rotation of the transducer. The transducer need only be mounted on the radial gate arm. The output of a sine wave must be converted to a linear function, then scaled and offset to gate opening. The inclinometers should work well with computer-based equipment. Inclinometer operation requires that the transducer be rotated through an angle to produce an output. Radial gate arms move through an angle as they are opened and closed and can easily be instrumented with inclinometers. Overshot gates, such as bladder type gates, also work well with

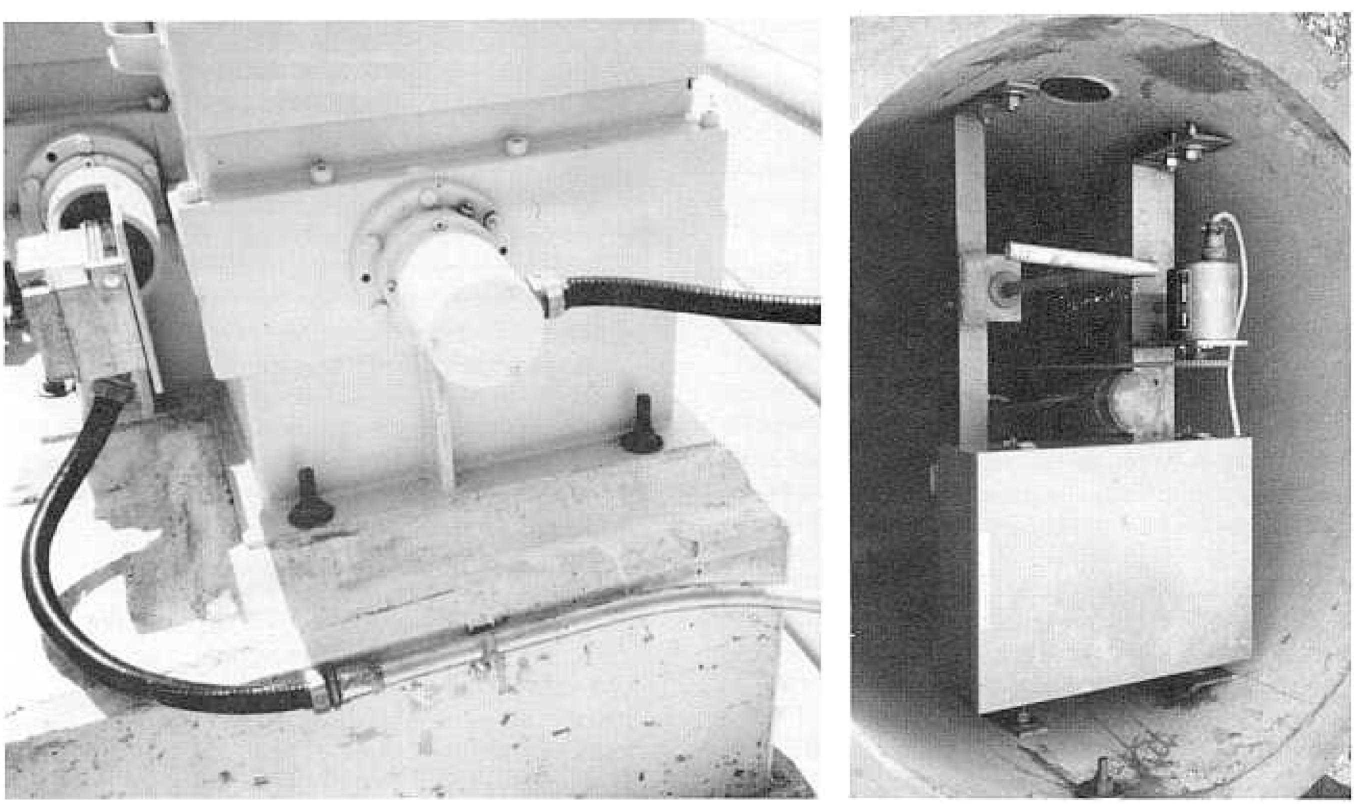

Figure 9-13.—(a) Potentiometer and (b) digital encoder.

inclinometers. Inclinometers should be installed close to the pivot point of the gate to minimize the velocity of the pendulum or liquid in the transducer. Though easy to install, inclinometers are more difficult to maintain because of their location away from the gate hoist structure over flowing water. An inclinometer is shown on figure 9-14.

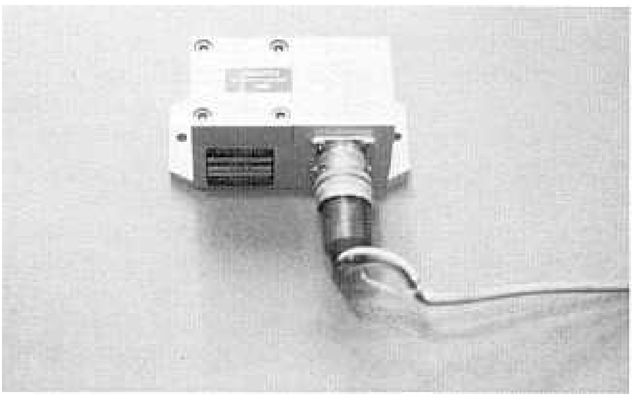

Figure 9-14.—Inclinometer.

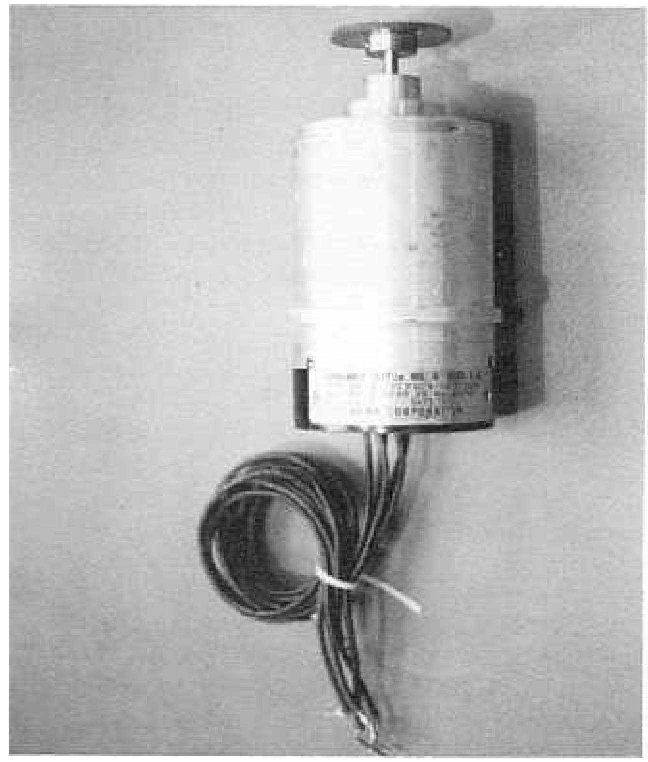

Figure 9-15.—Syncro.

**e. Selsyns and syncros.**—Selsyns and syncros can be used for rotational measurement. Selsyns provide a 3-phase voltage output in which the voltages represent a specific shaft position. This voltage relationship can drive a second selsyn device to output the same mechanical position and drive a conventional encoder. The output can also drive an electronic system which outputs a digital or analog signal that represents the mechanical position. The single-turn (or speed) devices are not recommended for much the same reason that incremental shaft encoders are not recommended. The actual position is generated in the RTU. New multistage selsyns use two encoders to maintain coarse and fine position. The second selsyn is geared to the first and provides turn indication for the first. These devices provide an absolute position output. Multistage selsyns can be applied to canal systems where single-turn selsyns are not recommended for canal automation. Figure 9-15 is a photograph of a syncro.

**f. Resolvers.**—Resolvers are similar to selsyns in that the output is converted into electrical signals. The difference is that the output is resolved into two signals that are perpendicular to each other. The output consists of the sine and cosine of the angle of rotation. These devices can be mechanically linked or driven by a gear assembly to provide multiple-turn resolution. Accuracies approaching 3.0 mm (0.01 ft) can be obtained.

**g. Pressure transducers.**—Pressure transducers are finding their way into canal automation for measurement of water levels. They are an excellent choice where an onsite chart record is not required. Pressure transducers are available in numerous pressure ranges, signal outputs, and actual transducer types. Many transducers are submersible and easily adapted to canal automation. Transducer outputs include a range of voltages and currents. Current outputs are available in 0- to 1-milliampere, 0- to 5-milliampere, and 4- to 20-milliampere ranges, all easily used for inputs to RTU's. Voltage outputs range from 0 to 10 millivolts to 0 to 10 volts; the higher outputs are desirable for automation use. Figure 9-16 is a photograph of a pressure transducer.

Transducers with current output are excellent choices for automation. The current output provides a high noise immunity and simple installation. These advantages are particularly useful for long wire runs of up to 1.6 kilometers (1 mile) and noisy environments.

Figure 9-16.—Pressure transducer.

## ENVIRONMENTAL MEASUREMENTS

Environmental concerns have a significant impact on irrigation practices. Environmental issues regarding water quantity and quality are becoming more important to both the water user and the water district operator. Quantity environmental issues include the use of water, how much is diverted, minimal flows in streams and rivers, and use for fish hatcheries. Quality environmental issues include minerals and salts leached from irrigated lands, chemicals from fertilizers, insecticides and herbicides in irrigation return flows, and biological changes in the water. Projected use and availability are only two parts of a complex formula to solve these questions.

Measurements required to solve this formula include weather data, soil conditions, and water quality.

### 9-9. Types of Measurements

Types of measurements required to address environmental concerns include the following:

**a. Temperature and humidity.**—Temperature and humidity measurements are typically taken by analog transducers with a low voltage output. These transducers require an analog input to the RTU. Considerable attention to shielding and routing is required to minimize noise and ground loops. Temperature and humidity are useful in predicting the demand for water.

**b. Rainfall.**—Rainfall gages usually provide a digital toggle output. The output changes state for each measured volume of water collected. The RTU must check the status and increment the rainfall total for each count. Rainfall can be used to determine the increase in water availability, decrease in irrigation water use, and provide warning of potential flooding.

**c. Wind speed and direction.**—Wind speed and direction, though less a factor, do determine the drying rate of crops. Wind speed data can take any form of output: analog, digital word, or a digital pulse; wind direction data may be output as an analog voltage or a digital word.

These five measurements comprise a typical weather station, shown on figure 9-17, and allow the operator to use local weather conditions to anticipate the upcoming water needs. The use of weather forecasts can provide generalized information which, together with local conditions, can help in anticipating changes in water requirement and minimizing losses and waste.

**d. Soil moisture content.**—Soil condition monitoring is an even more direct method of forecasting needs. Soil moisture can allow the water user to more accurately estimate water requirements.

**e. Water quality.**—Measurements include dissolved oxygen, pH, and conductivity. These measurements can assist in fertilizing and pH correction.

Proper fertilization, pH correction, and the proper amount of water can minimize water runoff and reduce the chemicals in the water returned to the drainage systems.

Water quality is impacted by many irrigation activities. Diversion of water from normal river and stream channels can impact the quality of water and the wildlife dependent on it. Return water is

Figure 9-17.—Weather station and satellite platform.

often polluted with agricultural chemicals (fertilizers, herbicides, and pesticides) and topsoil. Many of these effects can be minimized with the proper use of irrigation.

Application of the proper amount of water to croplands will reduce the runoff and the associated pollutants. Decreased runoff results in a lower demand for water, reducing the diversion from natural water systems. Lower water demand allows increased flows in our rivers and streams.

## EQUIPMENT HOUSING AND ENVIRONMENT

### 9-10. Gaging Stations and Instrument Platforms

Gaging stations and instrument platforms are the most common facilities for providing data collection for reservoirs, rivers, streams, and canal systems. Gaging stations and instrument platforms provide valuable information such as water level, flow, turbidity, and weather data. This information is collected and used to determine water availability, releases, and distribution.

Instrument platforms perform much the same task as gaging stations except that they are interrogated and report electronically, either by radio or satellite. The data are available on a more real-time basis. Instrument platforms are essentially gaging stations with a small RTU provided for data collection and transmission, but with no control applications.

**a. Gaging station and instrument platform enclosure.**—Enclosures are often constructed by extending a corrugated pipe or reinforced concrete pipe stilling well above ground, installing a roof on top, and installing a platform or enclosure inside for the equipment. Existing cabinets, such as those located at a gate structure, can also be used. A sealed box, such as a NEMA 4 weatherproof enclosure, can be mounted on the structure, power pole, or a separate pole provided for that purpose. These enclosures are also adequate for small canal-side controllers or RTU's.

**b. Power requirements.**—Power requirements for gaging stations and instrument platforms are usually small. Chart recorder gaging stations can be provided with spring motors to drive the paper chart for remote sites and do not require any other power. Some might use batteries to supply the low power requirements. Information must be retrieved manually from these sites.

Instrument platforms require electrical power for the electronics and communications equipment. Equipment with very low power consumption is available for battery operation. Remotely located instrument platforms are usually battery powered and use either solar panel chargers or a-c chargers to maintain the batteries. This equipment can switch essential components on and off as required either by clock or received command message. The system then powers up the instrumentation and other components required to provide the required information, then transmits the data and powers down again. Figure 9-17 shows a weather station and satellite platform.

**c. Location.**—Location of the equipment is by necessity at the site where the information is derived. The equipment is thus located along the canal near a control structure, and by virtue of the canal, susceptible to lightning (and power surges if a-c powered and/or if wire communication circuits are used). Tampering and malicious mischief can also be a factor because of the remote location of the equipment.

A satisfactory and reliable installation can usually be accomplished with proper installation techniques, the required protection from lightning and power transients, and features to minimize tampering. A typical RTU or controller installation is not much different than these installations. The same concerns and guidelines apply.

The following considerations need to be evaluated in selecting a site:

1. The parameters are being measured.
2. The power requirements can be met:
   - Power (a-c) for larger facilities
   - Adequate sun for solar powered systems
3. Communication requirements can be met:
   - Communication line
   - Radio path to repeater or base
   - Satellite path

### 9-11. Control and Environmental Enclosures

Special equipment requirements are generally the same as requirements for instrument platforms and gaging stations. The enclosures need to be weatherproof. Considerations must include protection from vandalism and malicious mischief. The systems are larger and therefore require larger enclosures. Environmental and power requirements are usually larger.

**a. Enclosures.**—Enclosures will generally be larger and require more substantial mounting. Increased power requirements result in more internal heat, which requires cooling. The larger enclosures are more visible and therefore need to blend into the environment.

**b. Power requirements.**—Power requirements increase as the amount of equipment in the controller or RTU increases. The use of solar panels for charging battery powered systems may become too expensive, and the panels may be too large to be practical. The use of a commercial power source is almost always preferred and often required where radial gate or large gate control is anticipated. A considerable amount of the power required for the equipment is dissipated as heat. This heat can complicate the problem by requiring cooling in the summer. Additional power may be required in the winter to heat the enclosure to maintain temperature above a system minimal required temperature.

## INSTRUMENTATION

### 9-12. Instrument Classification

Instrument classification for almost all devices falls into one of two output categories—analog or digital. Many of the instruments are available in either digital or analog form. Analog and digital classifications have been introduced in preceding sections. This discussion will cover the specific characteristics, advantages, and disadvantages of each. The end result of either must be a digital representation of the data so a microcomputer can then manipulate the data by offset, scale and/or compare, or telemeter data over a communication circuit.

### 9-13. Analog Instruments

**a. Description.**—Analog instruments provide a continuously variable electrical signal that can exist at any point between two limits. For example, a 0- to 68.9-kilopascal (0- to 10-pound-per-square-inch [lbf/in$^2$]) pressure transducer with a 0- to 5.0-volt output can provide an output at any point within that range. Most pressure transducers are linear, so the 68.9-kilopascal (10-lbf/in$^2$) transducer at 32.7 kilopascals (4.75 lbf/in$^2$) would output 2.375 volts. Devices that provide an analog current output are also available. Ultimately, all analog instruments require conversion to digital for use in micro-computer-based equipment (instrument platforms and RTU's). An analog output is shown on figure 9-18.

**b. Protection.**—Analog devices require proper shielding and grounding to prevent electrical interference and minimize ground potentials. Lightning protection is required to prevent damage to both the RTU and analog instrument.

**c. Wiring methods.**—Analog instruments require a single loop of wire to interface with the multiplexer and/or a-to-d converter input. Usually, the single electrical loop is provided as two shielded conductors. A nonshielded twisted pair can often

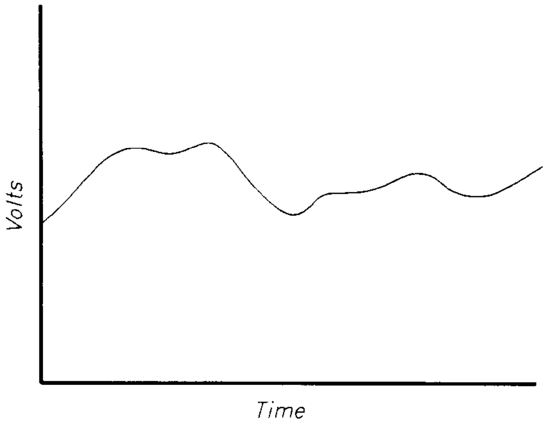


Figure 9-18.—Analog output.

be used for current output transducers. A second shielded pair is required if power is remotely supplied to the instrument. However, this simple wiring is complicated by several characteristics of analog systems. The magnitude of the output is the representation of the measured quantity. Any interference to the signal causes an error in the measurement. Any electrical noise impressed on the signal loop causes a corresponding change in the output. A signal path near a motor or radio transmitter will be affected when the motor or transmitter operates. The output is also affected by the voltage developed when a difference exists in ground potential between the system and the analog instrument. The problem is caused by the ground potential influence on the wire loop.

The problems are eliminated or minimized by shielding the conductors and grounding the system at one end only. Power may have to be provided by an isolated power supply by the grounded control end using the additional conductors noted above. Optical isolation must be used in severe cases.

**d. Advantages and disadvantages.**—The advantages of analog instruments include:

- Simple interface (wiring) requires only one or two pairs of shielded conductors.
- Simple electronics are often field serviceable.
- Fewer components that can fail provides good reliability.
- Maintenance can be accomplished using only a volt-ohmmeter to check operation.
- The unit can easily be repaired or replaced.

The disadvantages are:

- The magnitude of the signal represents the data, which increases noise sensitivity.
- Temperature sensitivity, ability to separate signal from noise, and mechanical to analog transformation result in less accuracy.

## 9-14. Digital Instruments

**a. Description.**—Digital instruments provide the digital encoding at the instrument. The transformation may be mechanical to analog and then to digital, or mechanical directly to digital. The information is encoded as a series of on and off signals. Each signal has a weight or value such that any instrument output can be represented by a number of on-off digits. Using the 0- to 68.9-kilopascal (0- to 10-lbf/in$^2$) transducer for an example, 68.9 kilopascals (10 lbf/in$^2$) will be represented by 12 on-off digits. A pressure reading of 32.7 kilopascals (4.75 lbf/in$^2$) is represented by the following digits: 0110 1001 1001. This code is straight binary and represents 475/1000 * 4095 (the total count possible with 12 binary digits). The 12-bit output, considering the low order digit is in error, provides an accuracy of better than 0.05 percent.

The representation can also use binary coded decimal (bcd), where each group of 4 digits represents a decimal digit. A pressure of 4.75 lbf/in$^2$ would then be represented by 0100 0111 0101. The total count is now 1,000. The bcd output, considering the low order digit is in error, provides an accuracy of 0.2 percent. The signals in this example are either on or off. Therefore, noise on the signals is of little impact unless it is of a magnitude to change the unit value. Any small variation in the amplitude of the signal is ignored. However, 12 signals must now be conveyed to the RTU rather than one. A digital representation is shown on figure 9-19.

**b. Electrical interface requirements.**—A digital instrument requires that multiple signals be conveyed to the data platform or RTU. In the example above, 12 pieces of information require 12 circuits (12 conductors and a common) to convey the data to the RTU. An alternative method is to use a single circuit and send the data as a

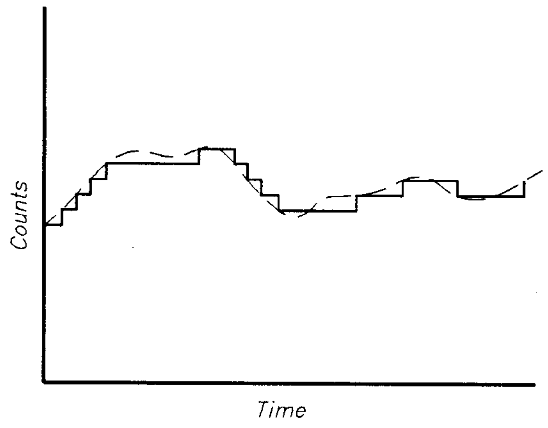


Figure 9-19.—Digital representation.

digital string. This procedure reduces the required number of circuits but adds a requirement for digital encoding at the instrument and decoding at the RTU.

**c. Absolute versus incremental.**—Data may be generated as either absolute or incremental. Absolute encoding results in only one output data code for a specific input. Incremental encoding provides an output that is the continuing algebraic sum of the changes in the input. The sum is then incremented or decremented based on changes of the input. Absolute encoding is required to prevent the corruption of data caused by a transient, power interruption, or other electrical problem. The change in count will be lost if power is lost or if the encoding device moves while not powered. The incremental encoder sum must be recalibrated if this happens.

**d. Protection.**—Protection requirements include proper shielding and grounding to prevent electrical interference and minimize ground potentials. However, digital instruments have more tolerance for noise. Lightning protection is required to prevent damage to both the RTU and digital instrument.

**e. Wiring methods.**—Wiring methods are more complex because each transducer or encoder produces multiple signals. Shielding the conductors and grounding the system at one end is still required. Optical isolation may also be used. Optical isolation is easy to accomplish because only on-off status need be determined. However, wiring methods are less stringent than analog circuit methods because the signals are less affected by noise and ground loops. Power may have to be provided by an isolated power supply or from the grounded end using additional conductors. Optical isolation must be used in severe cases.

**f. Advantages and disadvantages.**—The advantages of digital instruments include:

- The digital representation of data provides better noise immunity. The signal need only convey on or off information.
- Better overall accuracy is possible because the output is not degraded in transmission to the RTU. Some systems convert from mechanical direct to digital, thus minimizing loss of accuracy through conversion.

The disadvantages are:

- Complex interface requires additional conductors or a multiplexing scheme between sensor and RTU.
- Complex electronics are required to accommodate the digital format and provide multiplexing.
- Digital instruments are less reliable because of the increased number of electronic components located away from the protection of the RTU.
- Digital components are more difficult to repair because of the coded format, increased electronics, and repair equipment required.

## 9-15. Instrument Selection

Proper instrument selection requires both an understanding of the application as well as the instrument. The process requires the balance of many parameters to obtain the best results. The designer or engineer must investigate the application of the measurement, the measurement conditions, and the measurement device itself. These parameters include accuracy, resolution, repeatability, environment, uncertainty, reliability, maintainability, calibration, availability, and cost.

**a. Accuracy requirements.**—Accuracy is the percent of value that the error will not exceed, usually based on the full scale of the instrument. The accuracy of a reading depends as much on the measurement conditions and methods as on the measurement instrument. Each part of the measurement system must be evaluated to determine the accuracy of the end result. Overall accuracy must then be considered in the application of the measurement in the control algorithm.

Using a water level float encoder and stilling well as an example, the following items must be evaluated:

- Flow approach to the stilling well
- Entrance conditions to the stilling well
- Lag caused by the ratio of stilling well area to inlet opening
- Error resulting from the float-pulley assembly (0.2 to 1.0 percent)
- Error caused by the encoder (0.05 to 1.0 percent)
- Conversion error caused by the a-to-d encoder (1 count or 0.02 percent for a 12-bit encoder)

The system accuracy is the square root of the sum of the squares of all the individual errors.

$$\pm Accuracy = \pm\sqrt{AccuracyA^2 + AccuracyB^2 \ldots AccuracyN^2}$$

The result is compared to the accuracy desired for the control application. For a water level based canal control, 1 percent may be adequate. However, if the level measurement is used for billing purposes or to determine flow, 0.1 or even 0.05 percent may be required.

**b. Resolution.**—Resolution is the smallest distinguishable increment into which a measured quantity is divided. The resolution should be comparable to the quantity being measured. A system such as the float-potentiometer system may be able to provide an overall 0.1-percent accuracy, or 1 part in $2^{10}$ (1,024).

The a-to-d converter for the system should maintain this resolution. The electrical resolution of a 10-bit a-to-d (or 12-bit converter if bcd is used) converter provides 1 part in 1,024 ($2^{10}$) accuracy. Allowing for the indeterminate low order bit provides a 0.2-percent accuracy, or 1 part in 512. A 12-bit a-to-d converter provides 1 in 4,096 accuracy. Allowing for the indeterminate low order bit provides 1 part in 2,048 accuracy, or 0.05 percent. A 14-bit a-to-d converter provides 1 part in 8,174 accuracy, or 0.012 percent.

A 12-bit a-to-d converter is the appropriate choice to maintain the accuracy of the water level input. The net accuracy is:

$$\pm\sqrt{.1\%^2 + .01\%^2} = \pm 0.1007\%$$

Using a 12-bit a-to-d converter provides a 0.1005-percent accuracy and does not significantly degrade the accuracy of our original water level signal. The 10-bit a-to-d converter provides a 0.1414-percent accuracy and appreciably affects the overall accuracy of the measured quantity.

**c. Repeatability.**—Repeatability of a measurement is the agreement of multiple readings of the measurement system for the same value of input made under the same measurement conditions, approaching from the same direction, and using full scale traverses.

**d. Measurement uncertainty.**—Measurement uncertainty is the estimated amount by which the measured quantity may depart from the true value.

The effect of all the identifiable errors must be considered to properly use the measurements. The impact of each condition affects the final reading. This impact must be considered to assure confidence that the technique provides the usable results. Uncertainty is not necessarily the same as error. Uncertainty encompasses two factors—random and systematic. These factors apply to the statistics of the error rather than the error. A given reading differs from the actual value by a fixed number—the error in that reading. The uncertainty accounts for the variation in readings. Two factors can contribute to this uncertainty:

1. Randomness—A phenomenon that does not produce the same result or outcome every time it occurs under the same circumstances is a random phenomenon. These errors are predictable only in that the error will remain within known limits.

2. Systematic error—A process that produces the same result or outcome every time it occurs under the same circumstances is producing systematic error. A system that produces a result that is always 0.2 percent low is producing a systematic error. A more complex systematic error could result in a reading that is 0.2 percent low when approached from the low side and 0.2 percent high when approached from the

high side. Systematic errors can often be corrected by offset, scaling factors, or a logic equation.

**e. Reliability.**—Reliability is the ability to operate without failure, repair, or adjustment over a long period of time. Foregoing some accuracy to obtain a more reliable instrument is usually an acceptable option.

**f. Calibration requirements.**—Calibration requirements could be considered part reliability and part maintainability. If the device is difficult to calibrate, calibration will be delayed, carelessly done, or even not done at all. If the device requires calibration often, the task will not be done in a timely manner, and the desired accuracy may not be provided.

**g. Availability.**—Availability can also be considered in two parts. The original installation should use equipment that is readily available from a recognized supplier. Secondly, a readily available product will be easier to replace, and spare parts for repair will be easily obtainable.

**h. Environmental requirements.**—Environmental requirements have a considerable impact on the successful implementation of an instrumentation system. The environmental effects include temperature, water, and humidity. All instrumentation has a temperature coefficient and environmental limits beyond which conditions are detrimental to the device. Exposure to water or even high humidity can also damage a device, change the output, or permanently affect a device. Submersible pressure transducers cannot be subjected to freezing temperatures while in contact with water because the formation of ice will damage the diaphragm. Watertight enclosures are required for equipment not housed in buildings.

The exposure to severe weather must also be evaluated. Lightning can destroy the electronic components in equipment not adequately protected. Attention to proper installation of grounding systems, power systems, and communication is of the utmost importance to prevent lightning damage. Lightning and powerline transients can also alter the contents of information and programs contained in the memory of computer-based equipment.

Concrete blockhouses or heavy steel enclosures may be required in areas of high vandalism. Relocation of the equipment is sometimes a possible solution to vandalism.

**i. Maintainability.**—Maintainability is a primary consideration in automation projects. The equipment will be difficult to maintain if it is unreliable, and numerous trips will be required to keep it functioning. Components will not be repaired if they are difficult or costly to repair. The system should function with the failure of some of the components and, ideally, should provide some indication of the problem. In a Supervisory Control and Data Acquisition system, the telemetry data should contain some diagnostics and component failure notification.

**j. Cost.**—Cost is always a consideration. Budget and procurement constraints exist. Nonetheless, the best equipment with regard to reliability, accuracy, and repair and maintenance must be considered. Usually, the simplest equipment is the most reliable and lowest in cost but will typically have lower accuracy specifications.

All these factors play a part in selecting the instruments used in automation. Each must be considered for its contribution to the overall system. The final selection must produce the required data at the required accuracy while providing the reliability and maintainability of the overall system. These factors often require a tradeoff between quality at the time of purchase and maintenance and replacement later.

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# CHAPTER 10

# ELECTRICAL AND MECHANICAL SYSTEMS

Automated canals include control structures with electrical and mechanical components. This chapter discusses gates, gate operators, pumps, motors, and other electrical and mechanical equipment for canal control. Most Bureau of Reclamation (Reclamation) canals use check structures with radial gates or slide gates for primary control. Recently, AMIL gates and Obermeyer gates have been used on a few projects. Other types of gates (e.g., motorized overshot gates) are not discussed in this chapter because they have not been widely used in Reclamation projects.

## 10-1. Gates and Gate Operators

Radial and slide gates are primary control devices for regulating canal flow. These gates are used in canal systems to regulate or shut off the flow of water through check structures, siphons, turnouts, and wasteways or sluiceways. Each of these gates can be operated manually, electrically, or hydraulically. Because canal automation typically requires automatic or remote operation of the gates, this chapter will only deal with the electrically and hydraulically operated systems.

**a. Radial gates.**—Radial gates (sometimes referred to as tainter gates) regulate open channel flow through a rectangular opening. The face of the gate is rectangular in shape and has a width to match the opening and a height greater than the depth of the water surface, as shown on figure 10-1. The radial gate is a welded and bolted steel structure consisting of a leaf, arms, and pin bearing assemblies. The leaf consists of a radially curved faceplate stiffened by horizontal beams and vertical end girders. At each vertical end girder, the leaf is connected to a radial arm. The arms pivot on pin bearing assemblies anchored to concrete pedestals integrally formed with the walls of the structure. The resultant thrust from the water pressure against the faceplate is transmitted through the beams, girders, and arms to the pin bearings and wall pedestals. Music-note-type neoprene side seals are mounted on the upstream faceplate, and a rectangular or music-note neoprene seal is mounted across the bottom of the faceplate. The seals contact stainless steel wallplates and gate sills embedded flush in the concrete walls and floor of the structure. The gate is raised by lifting the faceplate and allowing the gate to pivot on the pin bearings, providing a wide, clear, water passage under the gate. In some installations, a radial gate may be used in a rectangular orifice opening by providing a top sealing surface.

The gate size is based on the hydraulic requirements of the structure, keeping in mind that the gate width should not be more than three times the height, and normally the height should allow for about 300 millimeters (mm) (12 inches [in]) of freeboard. The geometry of the gate and structure should conform to the criteria on figure 10-1.

Generally, the vertical height of the pin should be between 0.5$P$ and 1.00$P$. The vertical height should not be greater than 1.00$P$ unless $R_1$ is increased over 1.25$P$. In no case should $S$ be greater than $T$.

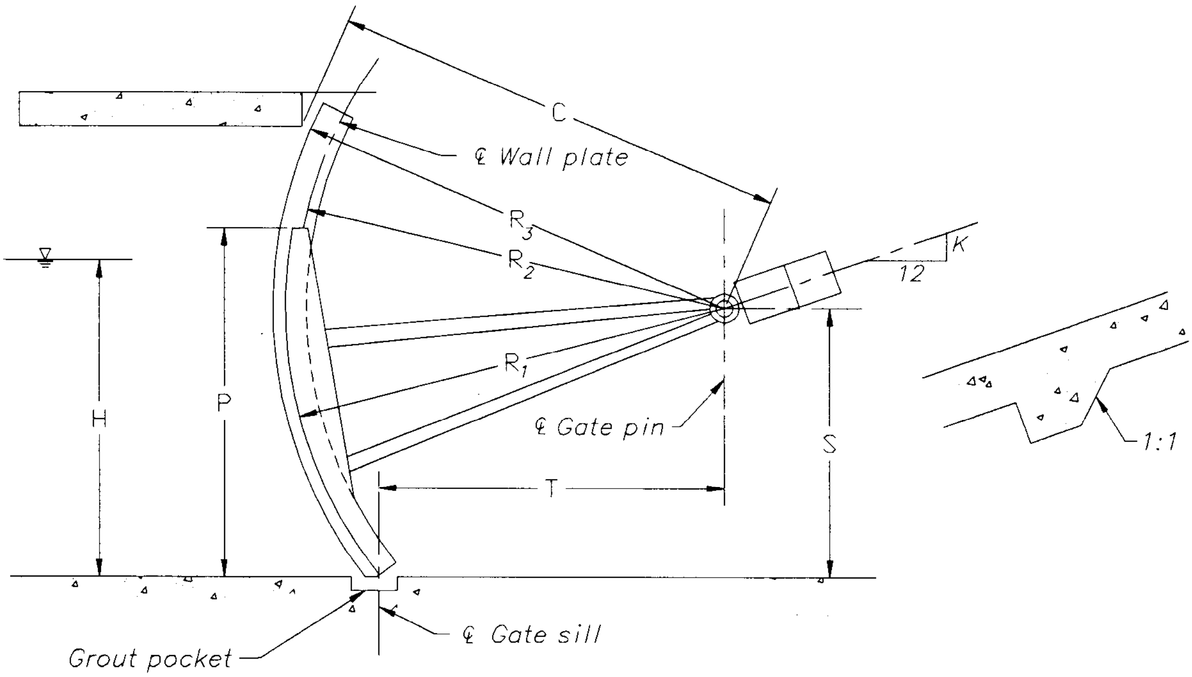


Figure 10-1.—Radial gate structure.

where:

- $P$ = vertical height of gate
- $S$ = vertical height of pin
- $T$ = horizontal distance—centerline of sill to centerline of pin
- $R_1$ = radius to inside of faceplate = $1.25P$
- $R_2$ = radius to centerline of wall plate = $R_1$ - 63 mm
- $R_3$ = radius to outside of wall plate = $R_2$ + 126 mm
- $C$ = minimum radius to deck = $R_3$ + 63 mm

The slope of the pin block, $K$, should be calculated to the nearest 1/4 using:

$$K = \frac{12\ (S - P/3)}{[R_1^2 - (S - P/3)^2]^{1/2}} \qquad 10.1$$

Total water load on the gate is calculated from the following formula:

$$W = 34\ BP^2 \qquad 10.2$$

where $B$ equals gate width. Each radial gate arm is designed as a column with an $R_1/r$ ratio not greater than 120, where $r$ is the least radius of gyration. Each lower arm is designed to carry a load of $0.31\,W$; each upper arm is designed to carry a load of $0.21\,W$.

Raising the radial gate requires a tangential pull of the faceplate. An operating platform must be placed above the gate spanning the chute. The design of the operating platform accounts for the hoist capacity and the weight of the hoist.

**(1) Gate hoist.**—Normally, radial gates are hoisted by a two-drum, manually or power-operated wire-rope hoist. Usually, the hoisting ropes are connected to lugs near the bottom of the upstream face of the gate. In the case of top-seal radial gates, the connection is made at the top of the gate. A typical radial gate hoist appears on figure 10-2.

Gate hoists come in standard sizes and are selected based on the horizontal projected area of the gate, as shown in table 10-1.

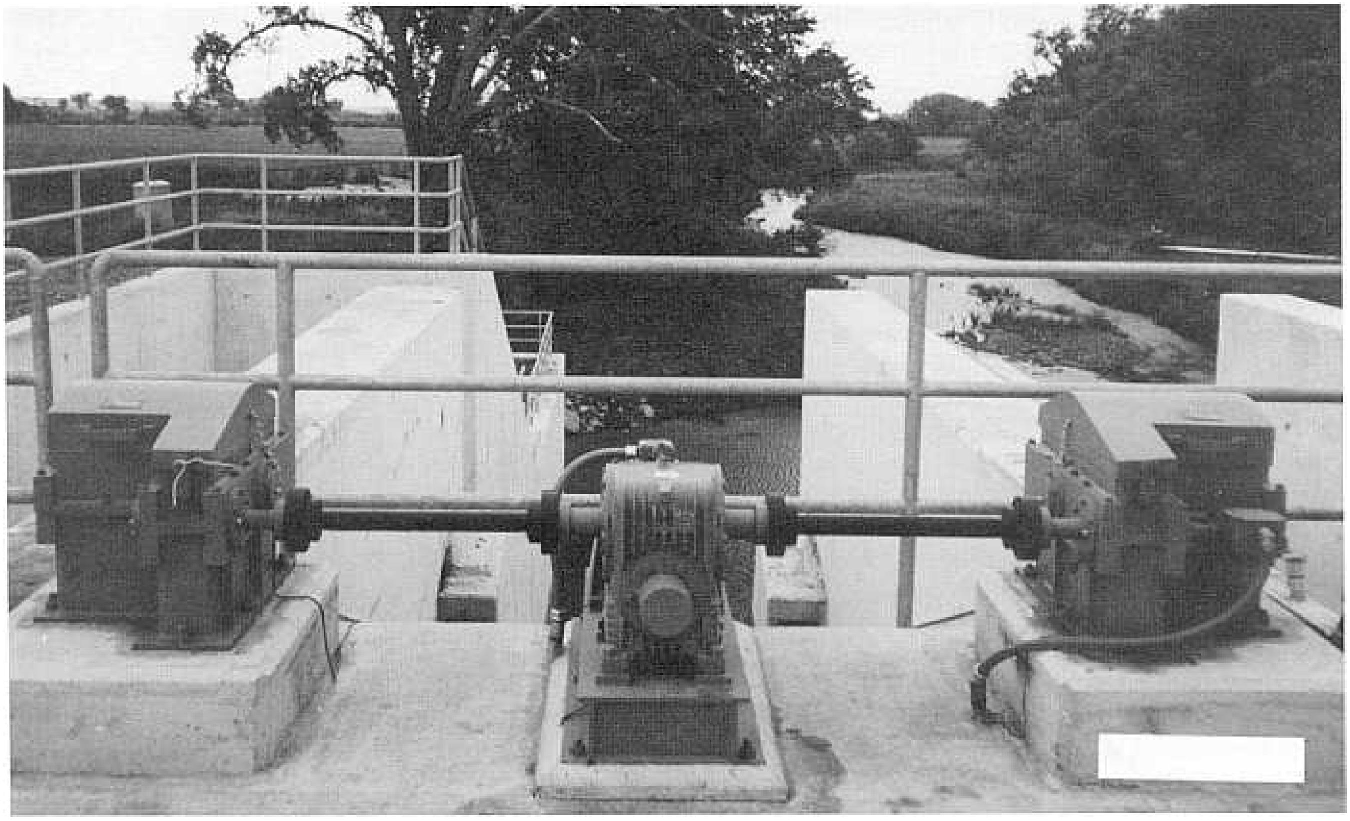

Figure 10-2.—Typical radial gate hoist.

Table 10-1.—Radial gate hoist capacity

| Gate area | | Hoist capacity | |
|---|---|---|---|
| $m^2$ | $ft^2$ | N | lbf |
| 00-10 | 000-109 | 682 | 3,000 |
| 10-15 | 110-164 | 1,136 | 5,000 |
| 15-20 | 165-215 | 1,705 | 7,500 |
| 20-24 | 216-255 | 2,273 | 10,000 |
| 24-30 | 256-320 | 3,409 | 15,000 |

Note: $m^2$=square meters, $ft^2$=square feet, N=Newtons, lbf=pound-force.

The drive unit for a motor-operated hoist consists of a gear motor with disc brake connected to a worm-gear reducer. Hoists of up to 1,705-N (7,500-pound [lb]) capacity have ungrooved rope drums connected to the worm-gear shaft. The drums have a minimum diameter of 18 times the diameter of the rope used. Hoists 2,273 N (10,000 lb) and larger have centrally located drive units with a spur gear drum unit at either end. The drums are grooved and have a minimum diameter of 20 times the diameter of the rope. On hoists 3,409 N (15,000 lb) and larger, two ropes are used on each drum to permit smaller drum diameters and to reduce the torque required. All drums are sized to maintain a minimum of two dead wraps of the rope. Hoists of up to 3,409-N (15,000-lb) capacity have an extended reducer worm shaft with a square end for ratchet-wrench operation in case of power failure. A rotating-type limit switch is used to limit the extremes of gate travel.

Hoisting speeds are typically from 1 to 2 feet (ft) (0.3 to 0.6 meter [m]) per minute. The weight of the gate is used to select the capacity of the hoist. All parts of the hoist equipment should be designed to withstand 250 percent of the stall torque of the motor.

**(2) Hydraulic hoist.**—Hydraulic cylinders are rarely used for radial gates other than with the top seal type of gate. Top seal radial gates use a single hydraulic cylinder attached to the top inside face of the gate. On standard radial gates, hydraulic cylinders have been attached to each edge of the gate along the inside face. When using two cylinders, care must be taken to ensure the cylinders are synchronized to prevent racking of the gate during operation.

**b. Slide gates.**—Slide gates regulate flow through a circular or rectangular orifice by raising or lowering a cover plate or leaf, allowing water to pass through the exposed opening. These gates are mounted on the upstream face of a headwall covering the water passage, allowing the water pressure to be transferred to the structure. To prevent leakage, a frame surrounding the orifice provides support for the leaf and a sealing surface. Slide gates may also be used for open channel flow by mounting the gate frame in slots on the side wall and floor of a rectangular chute. Slide gates are separated into two distinct groups based on their construction—cast iron sluice gates (also referred to as cast iron slide gates) and fabricated slide gates.

The manufacture of cast iron sluice gates is governed by the American Water Works Association (AWWA) Standard C501. These gates have frames and leaves of cast iron construction, with machined seating surfaces of bronze, or stainless steel on the frames and the leaf. The gates have adjustable wedges on the frames that force the leaf against the frame in the closed position, allowing the gate to seal against an unseating head. Because of their machined seating surfaces, these gates have an AWWA specified leakage tolerance.

The manufacture of fabricated slide gates is not presently governed by any standard, although an AWWA standard is currently being drafted. Fabricated slide gates are constructed from standard structural steel, stainless steel, or aluminum shapes. These gates do not normally have machined seating surfaces or wedging devices.

The size of the slide gates to be used will depend on the flow requirement and the relative head on the structure. Structural design details for various gate structures and procedures for sizing gates can be found in other texts, such as Reclamation's *Design of Small Canal Structures* [1].

Lifting devices for both cast iron and fabricated slide gates are identical. The platform needed to lift the gate leaf must be located directly above the centerline of the gate and above the fully raised position of the leaf. The platform may either be part of the gate frame (self-contained gate) or part of the headwall structure. The gate stem must be sized such that the $L/r$ ratio does not exceed 200, where $L$ is the unsupported length of the stem and $r$ is the radius of gyration of the stem. Stem guides firmly mounted to the structure must be used to reduce the unsupported stem length. The load required to lift a gate leaf is calculated from:

$$L = \mu A H \partial + W + w \qquad 10.3$$

where:

- $L$ = load on the lift
- $\mu$ = coefficient of friction
- $A$ = area of the gate opening
- $H$ = head from water surface to center of the closed leaf
- $\partial$ = density of water
- $W$ = weight of the leaf and stem
- $w$ = wedge force

To start the gate leaf from the closed position, a coefficient of static friction of 0.6 is used. Wedge force (cast iron sluice gates) is equal to half the leaf weight.

The diameter of the stem for the gate must be sized to safely handle the maximum column loading on the stem. Euler's column formula is used to calculate the critical buckling load, $P_c$, for the stem:

$$P_c = C\pi^2 EA(r/l)^2 \qquad 10.4$$

where:

- $C$ = 2 (defines end restraint conditions)
- $E$ = modulus of elasticity
- $A$ = area of stem
- $r$ = radius of gyration
- $l$ = length or span between stem guides

The stem design load shall not be less than 1.25 times the output thrust of the motor-operated gate lift unit in the stalled motor condition (locked-rotor torque) or 1.25 times the maximum thrust of the hydraulic cylinder.

Both cast iron sluice gates and fabricated slide gates are readily available commercially from gate manufacturers. Sluice gates are available in standard sizes ranging from 152 mm (6 in) square to over 3 m (10 ft) square. They are normally designed for seating heads up to 30.5 m (100 ft) and unseating heads to 15 m (50 ft), depending on size. Under designed seating heads, the sluice gate leakage should not exceed AWWA Standard C501.

Fabricated slide gates are available in standard or nonstandard sizes. Normally, these gates are designed for heads less than 3 m (10 ft), although some manufacturers have gates in some sizes with design heads to 7.6 m (25 ft). No standards exist for leakage rates for fabricated slide gates. These gates can be provided with various types of rubber seals to reduce leakage.

**(1) Motor-operated gate lifts.**—One of the most common methods of remotely operating slide gates is with the motor-operated gate lift shown on figure 10-3. These lifts, which are commercially available, use a reversible electric motor to raise and lower the gate by rotating a stationary nut (lifting nut) on a threaded gate stem. The electric motor, through a system of gears, turns a worm gear which rotates the lifting nut. The units come equipped with a weatherproof enclosure, limit and torque switches, position indicators, electrical controls, and a handwheel for manual operation. The lift should also be equipped with a "hammer blow" feature, which allows the motor and gearing to pick up full speed and momentum before torque is applied to the gate stem.

Figure 10-3.—Slide gate motor-operated lift.

The motor operating torque must be calculated to properly size the lift. The gate load, gate stem diameter, and pitch and lead of the gate stem threads are required. Because the hammer blow feature imparts an instantaneous force several times the rated output of the lift, the lifting load may be calculated using the sliding friction coefficient of the gate ($\mu$ = 0.35) rather than the static friction coefficient.

$$\textit{Motor Operating Torque} = \frac{\textit{Stem Torque}}{\textit{Unit Ratio} \times \textit{Unit Efficiency}} \qquad 10.5$$

$$\textit{Unit Efficiency} = 0.5\ (\textit{typically}) \qquad 10.6$$

$$\textit{Unit Ratio} = \frac{\textit{Motor}\ (r/\text{min}) \div \textit{Gate Speed}}{\textit{Stem Lead}} \qquad 10.7$$

$$\textit{Stem Torque} = \textit{Lifting Load} \times \textit{Stem Factor}\ (FS)$$

where:

$$FS = \frac{d\ (0.96815 \tan\alpha + 0.2)}{24\ (0.9815 - 0.2 \tan\alpha)} \qquad 10.8$$

and:

$$\tan\alpha = \textit{Stem Lead} \div \pi d$$

$$d = \textit{Stem Outer Diameter} - 1/2\ \textit{Stem Pitch}$$

Other factors that must be considered in selecting the lift are the locked rotor torque and the duty cycle. The locked rotor torque (maximum possible motor output) should not be less than 2.5 times motor operating torque. The duty cycle, which can be defined as permissible running time at maximum load (typically 15 or 30 minutes), should not be less than the full cycle operating time of the gate.

The slide gate manufacturer will normally size the gate lift given the maximum head on the gate, gate speed, voltage, elevation, and ambient temperature extremes.

**(2) Hydraulic operators.**—Normally, hydraulic operating systems for slide gates consist of a hydraulic cylinder to raise and lower the gate and a hydraulic power unit used to control one or more cylinders. Hydraulic motors attached to manual gate lifts are sometimes used to operate gates.

Typically, hydraulic operators are used in the following situations:

- Multiple gate installations where one control system can be used to operate all of the gates
- Where frequent gate operations are required
- Submerged operating conditions which would be unsuitable for electric operators
- Where emergency operation is required in the event of a power failure and accumulators can be used for limited operations

Hydraulic cylinders must be sized to lift the maximum gate load at the desired operating pressure. The operating pressure should be about 75 percent of the maximum system pressure. The operating pressure, $P$, is calculated as follows:

$$P = L \times (A_c - A_s) \qquad 10.11$$

where:

$L$ = maximum load
$A_c$ = area cylinder
$A_s$ = area stem

The operating pressure must also include the system and line pressure loss at the desired operating speed. When using sluice gates with wedges, the closing pressure must be reduced to compensate for the larger closing area at the top of the piston.

Position indication may be obtained by using a hydraulic cylinder equipped with a linear displacement transducer (LDT). The LDT is attached to the top of the cylinder with a rod extending through a bore hole down the axis of the piston stem. A magnet attached to the top of the piston stem provides the position indication as it moves along the rod. Another method of position indication involves attaching a line with a counterweight to the piston stem outside of the cylinder and running the line through a pulley mounted to the cylinder, which is attached to an encoder or potentiometer. A line may also be attached from the stem to a direct-line-type position indicator.

**c. AMIL, AVIS, and AVIO gates.**—The AMIL gate, shown on figure 10-4, is a specialized radial gate that automatically maintains a constant water level on the upstream side of the gate. It operates without any outside power or motor, free of any manual intervention, irrespective of incoming flow or downstream water level. The gate is directly actuated by the water level it controls. The supporting frame rotates about a horizontal shaft and includes ballast containers for easy and accurate balancing of the gate. Frictionless, non-stick operation is guaranteed by the tapered shape of the leaf.

AVIS and AVIO gates are similar except they are designed for downstream control.

**d. Obermeyer gates.**—The Obermeyer gate, shown on figure 10-5, belongs to a larger gate category generally referred to as overflow gates. Because of its unique design, it has found applications in canal systems. Normally, this gate is used as an adjustable weir or wasteway gate. The gate is simply a rectangular plate sized to match the width of the channel and has a height greater than the water depth. The bottom edge of the plate is hinged to the floor of the structure. An inflatable rubber bladder which extends the entire width of the gate is attached beneath the gate at the hinge. Air pressure in the bladder is used to support the gate in position, and varying the pressure will raise or lower the gate. Stainless steel plates are mounted flush in the chute walls to provide a seating surface for rubber seals mounted on the gate.

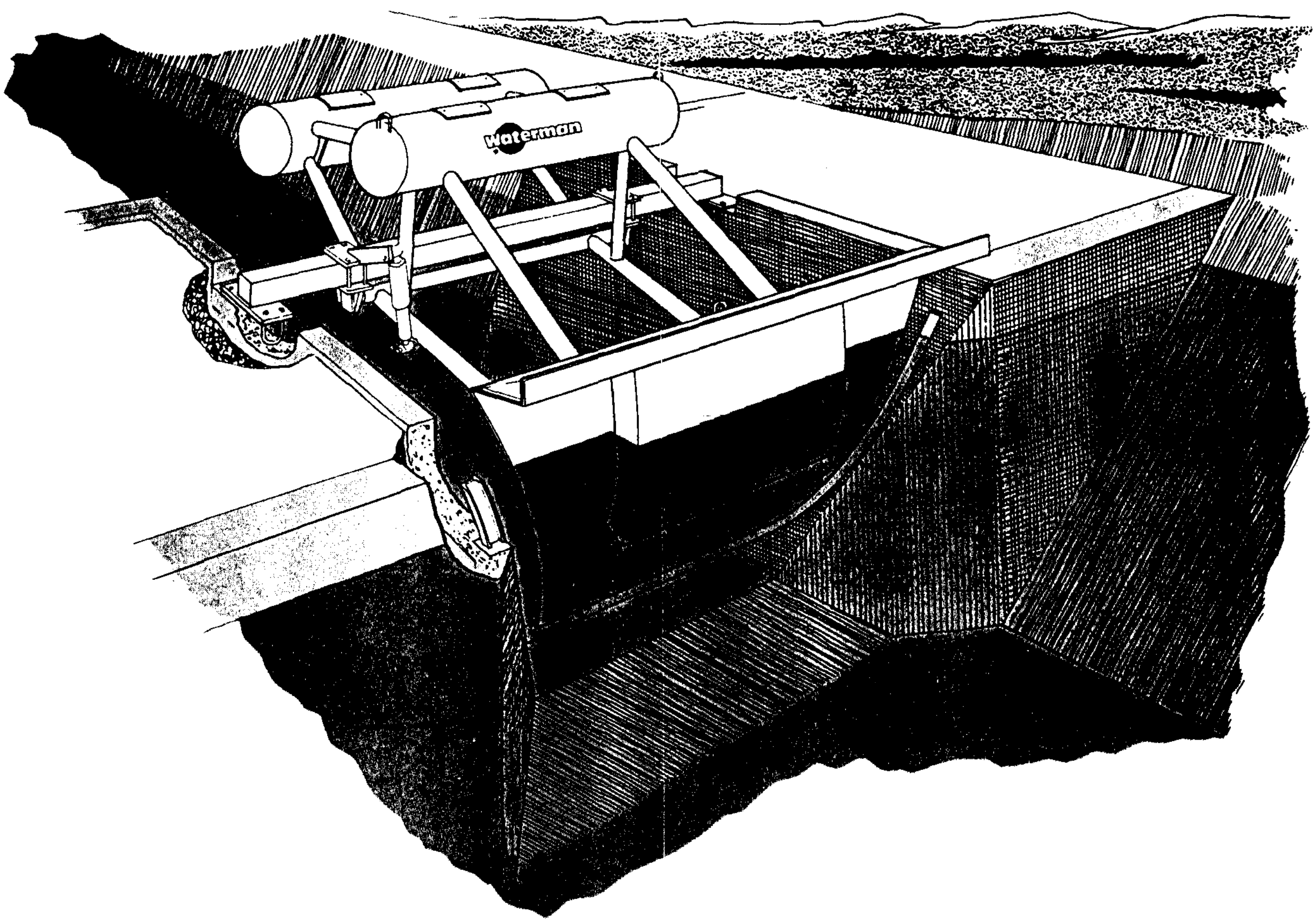


Figure 10-4.—AMIL gate.

## 10-2. Canal-Side Pumping Plants

Canal-side pumping plants are used to pump water from the main canal to elevated distribution systems. Vertical turbine pumps are the type most often used. The vertical turbine pump operates with its bowl assembly submerged in a sump and is suspended by the pump discharge column. The pump base supports the unit over an opening in the concrete floor above the sump through which the assembled pump column and bowl assembly can be installed and withdrawn.

**a. Selecting number and size of units.**—In selecting the number and size of pumps, consideration must be given to reliability, flexibility, efficiency, and cost. One or two pumps may be adequate where service is intermittent, thus permitting time for maintenance of the units with a minimum of outages. However, one unit should not be used for a water supply dependent on continuous operation; a standby pump should be provided.

When regulation of the water delivery is required, a number of pumps, or even two or more pump sizes, should be used. A common selection uses two units at 1/3 plant capacity, one unit at 1/6, and two units at 1/12 plant capacity. This combination provides flow increments of 1/12 plant capacity, and only 1/3 capacity is lost when the largest unit is out of service. The nominal discharge of each pump is normally increased by 5 percent (commonly called a wear factor) to assure that the plant will continue to deliver the required discharge after it has been in operation a number of years.

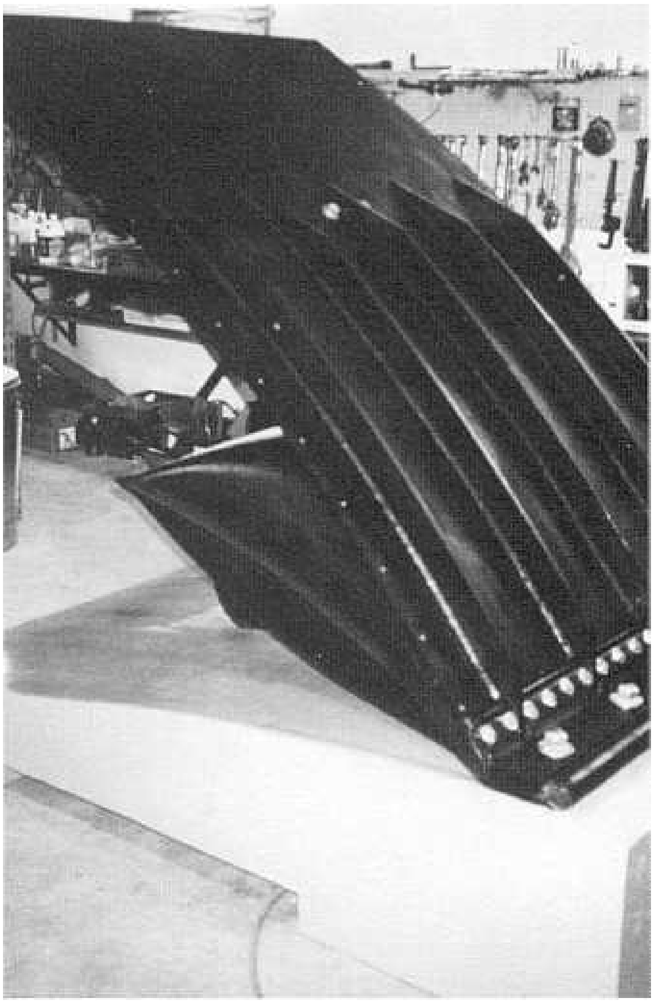

Figure 10-5.—Obermeyer gate.

Some installations may use pumps equipped with adjustable speed motors to satisfy the operating conditions. Variable speed is a means of dealing with varying head and capacity requirements and is becoming more attractive as variable speed controllers become more readily available and more efficient. The use of adjustable speed pumping units must be carefully reviewed for each installation to determine cost effectiveness. Other methods for obtaining flexibility in discharge involve throttling the pump flow with discharge valves or bypassing a portion of the water back to the sump. These methods are inefficient and are seldom cost effective.

Chapter 5 contains additional information on pumps and pumping plant design.

**b. Sump design.**—The sump is designed after the number and the capacity of the pumps have been determined. The intake structure to the sump should contain either trashracks or moss screens to prevent debris from reaching the pumps. Spacing of the trashrack bars is based on the size of the largest object that will pass through the pump impellers. Sufficient area should be provided to limit the gross velocity through the trashrack or screen to 0.015 meters per second (m/s) (0.5 feet per second [ft/s]). Screens over the pump suction are not desirable because they are difficult to clean and may interfere with the flow of water into the pump. A typical installation is shown on figure 10-6.

Sump dimensions are based on the expected diameter of the pump suction bells. The velocity of the water in the sump as it approaches the pumps should not exceed 0.015 m/s (0.5 ft/s). Minimum sump clearances, in terms of the pump suction bell diameter, *D*, are:

- 0.75*D* from the pump centerline to the sump rear wall
- 1.00*D* from the pump centerline to the sidewall
- 0.50*D* from the bottom of the bell to the sump floor
- 2.00*D* between centerlines of parallel units
- 5.50*D* between pump centerline and nearest change in flow pattern
- 2.50*D* between minimum inlet water surface and sump floor

In a plant containing three or more units of 708 liters per second (25 cubic feet per second) or larger, the sump width based on necessary trashrack width does not generally permit setting the units in a line parallel to the trashrack. In this case, the pumps can be placed in a line diagonal to the trashrack. Normal clearances are used between the walls and floors of the sump, and clearance between pumps is provided normal to the direction of flow.

## 10-3. Motors and Drives

Motors provide the required torque to operate gates, valves, and pumps. A variety of motors can be expected for various equipment and structures which make up the canal system. The types of motors used will depend on the application and available power source at the site. Most applications will use single- or three-phase

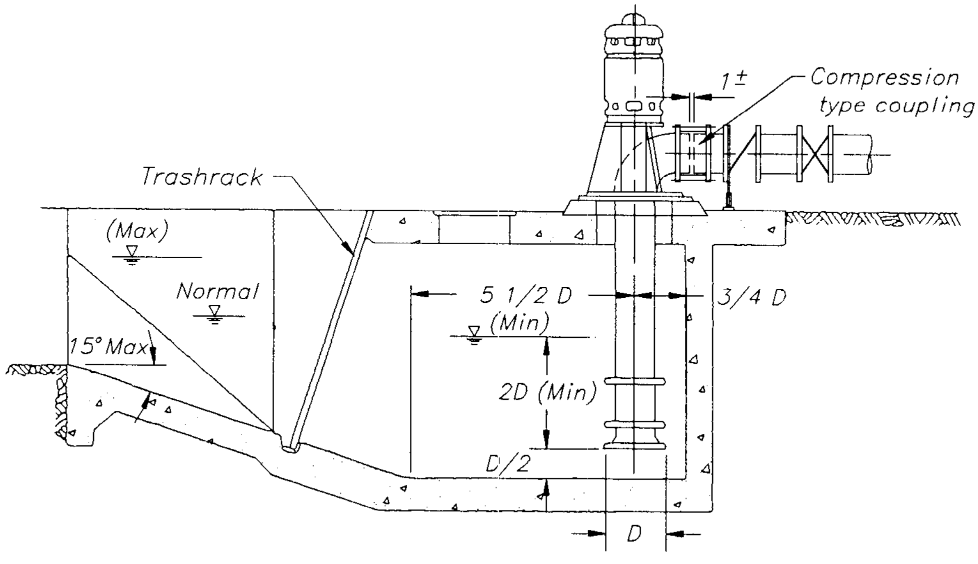


Figure 10-6.—Vertical pumping unit in open sump.

alternating-current (a-c) motors. Typically, motors are provided in a weather-protected enclosure such as weather-protected Type II or totally enclosed fan cooled to protect them from the elements and environmental factors.

When retrofitting existing installations for canal automation, an understanding of the characteristics of existing motors and driven equipment is important to assure that the desired automation operation does not cause excessive wear to the equipment or exceed equipment capabilities. Most motors have limitations in start-stop cycling and minimum rest-run times which should be considered in implementing an automated system.

For high torque applications such as slide gates or valve operators, the motor operator may have a time duty rating such as 15 or 30 minutes, which limits the amount of run time allowed during one time interval. This run time limitation should be factored into the overall design of the canal control system.

**a. Alternating current motors.**—Alternating current motors are used in almost all motor-driven equipment whenever commercial power is readily available from nearby powerlines or underground utility circuits.

Single-phase motors are typically used when only single-phase power is available. Single-phase motors are generally lower in cost but have several deficiencies with regard to canal automation. Single-phase motor applications which involve reversing operation present several problems. Single-phase capacitor start motors require special wiring and controls to provide reversing features. For radial gate applications, electrical brakes are required to stop motors from coasting, and if the brakes should fail, a fail-safe detection circuit is needed to prevent continued operation in the wrong direction.

Three-phase motors are preferred where three-phase power is available. These motors are built for reversing operation which is easily achieved by reversing the electrical phase rotation of the motor power through the use of motor contactors. Three-phase motors will always start in the proper direction without the problems noted above for single-phase motors.

The greatest stress on motor windings and driven equipment occurs on initial startup. Automation controls should try to minimize start and stop operations and significant cycling of equipment. Additional motor accessory equipment which reduces these startup stresses while allowing greater control flexibility consists of soft start controllers and adjustable speed drives discussed below.

**b. Direct current motors.**—Direct current (d-c) motors are not usually considered for motor-driven equipment for canal systems. However, for isolated sites where commercial power is not available, d-c motors may be used in conjunction with a battery and solar cell charging system. These battery-operated remote sites are normally only considered for small gates with limited control because of limitations in power supply.

Direct current motors are also readily adaptable to adjustable speed applications because of their inherent characteristic to maintain high torque output over the entire speed range. When using d-c motors, this feature should be incorporated where applicable to enhance control flexibility.

**c. Soft start controllers.**—Full voltage starting of motors places high mechanical stresses on the motor windings; inrush current values can reach 600 to 700 percent of rated. Most soft starters today are solid-state devices with microprocessor controls. Soft start controllers gradually ramp up the voltage and current to the motor during starting. These controllers are used in conjunction with a-c motors to limit current and voltage to the motor during starting and will therefore minimize motor winding stress and extend motor life.

Special coordination in the application of these devices with the motor and motor load is required to assure that adequate torque is available during initial breakaway conditions when reduced voltage and current are applied to the motor. Most controllers have a kick-start or boost feature to provide a high current pulse (500 percent of full load current) to provide necessary breakaway torque. Soft starters generally cannot be used effectively for constant high torque applications such as slide gates because sufficient torque is not available during startup.

Because soft starters gradually accelerate motors up to speed, some fixed time interval (typically 2 to 10 seconds) must be allowed for the unit to come up to speed. This acceleration ramp period is normally adjustable and must be coordinated with the other control system parameters.

To implement an effective control scheme, soft starters should be considered whenever frequent cycling of the motors is anticipated. For existing or retrofit applications, the soft starter can be placed in-line with the motor incoming leads.

**d. Adjustable (variable) speed operation.**—A clear understanding of the operating criteria for gates, valves, and pumps is necessary to evaluate whether adjustable speed operation of this equipment is desired or needed for a given system. Chapter 5 addresses how to determine operating criteria for various components of the canal system.

Automatically controlled gates will typically require significant gate movement with variables such as maximum gate movement per hour, minimum increment of movement, gate movement speed, etc. As the number of gate operations per hour increases, and as the need for closer regulation increases, adjustable speed becomes more advantageous.

Adjustable speed operation of gates and pumps will allow greater flexibility in operation by adjusting the speed of this equipment through an open or closed loop control scheme to regulate flow. Fixed speed operation requires step increments to achieve desired flow and can be limited by minimum motor rest-run times. Adjustable speed control is also the preferred method for large systems when Proportional-Integral Derivative (PID) loop control is being used.

The two general systems being used today to achieve adjustable speed operation for canal equipment are hydraulic and electrical. Hydraulic systems achieve adjustable speed by using a regulating valve in the hydraulic system which controls flow to a hydraulically operated gate or valve, thus providing adjustable speed. The electrical method of adjustable speed involves controlling the motor speed through the use of a solid-state electronic device called an adjustable speed drive.

Adjustable speed drive equipment for motors involves an electrical conversion from fixed frequency a-c input power to variable frequency a-c output power. The variable frequency output of the drive controls the motor speed directly. Adjustable speed drives for motors on canal systems are generally sized for constant torque application (constant torque over speed range). The two most common drives are the voltage source inverter and the pulse width modulated inverter.

Standard induction motors are generally suitable for adjustable speed applications; however, the drive manufacturer should be contacted for any special considerations. Coordination among the drive manufacturer, motor supplier, and driven load supplier is critical to achieve satisfactory operation. The drive is selected and programmed based on the automation requirements and characteristics of the motor and driven load. Once adequate coordination is achieved, the equipment can continually operate based on the varying speed signal received from the control system. In retrofit applications where adjustable speed is being applied to existing motors, it is important to determine the maximum torque required over the speed range and size the drive well above this value.

Some additional features and benefits of using adjustable speed drives include the following:

- Some drives will accept a single-phase source and convert it into a variable frequency three-phase source. This capability allows the use of three-phase motors, which are preferred for any reversing operation.
- Adjustable speed drives improve equipment reliability and longevity by permitting gentle starts (soft start capability) and gradual slowdowns or shutoff (dynamic braking).
- Adjustable speed drives provide instant and automatic control of equipment speed according to changing canal operation requirements.

## 10-4. Power Requirements

Electrical power requirements must be established for each type of structure which is used to control flow or water level for the canal system. In general, the power requirements for a gate will increase as the gate size and weight increase, as the head requirements increase, and as the speed of gate operation increases. A comparison of the differing power requirements for different structures is presented in table 10-2.

The power requirements provided in table 10-2 are a general guideline to compare with the power available at a particular site and to provide a baseline for equipment power requirements. Each canal regulating structure will have specific power requirements based on the design of the overall electrical and mechanical system design.

## 10-5. Alternative/Backup Power Systems

Many sites have readily available a-c power. Some sites may be subject to frequent outages and interruptions. At other sites, a-c power is not available. Some alternative systems or system enhancements can be used to provide power or improve the local power system. Some power systems might employ a combination of the following.

**a. Solar panels with battery system.**—For remote sites where no commercial electrical power is available and where power requirements for gate operation are low (0.17 kilowatt [kW] (1/8 horsepower [hp]) or lower), a solar-powered system using d-c motors is feasible. Typically, the d-c gate motor operators for this application are sized at or below 0.17 kw (1/8 hp) with a 12- or 24-volt battery and solar system to provide power to the gear motor. Reclamation has demonstrated this application with great success at an automated solar-powered slide gate site at Richfield, Utah [2].

Deep cycle marine batteries are used as the source of power for the gear motors, and the solar panel system is used as the charging system for the batteries. Two 40-watt solar panel arrays and associated controls made up the charging system for the 24-volt battery system used at the Richfield site mentioned above.

Special coordination is required to assure that the erratic and variable output of the solar array is sufficient to adequately charge the batteries under worst case power consumption conditions (full open and close operation or excessive cycling). The solar panel and battery system characteristics should be carefully reviewed under all site conditions to assure that sufficient power is available to perform gate operations when desired.

Special coordination is required to assure that the erratic and variable output of the solar array is sufficient to adequately charge the batteries under worst case power consumption conditions (full open and close operation or excessive cycling). Large-scale solar arrays and battery systems have also been used to provide power to d-c motors in

Table 10-2.—Typical power requirements for canal flow control structures

| Canal flow control structure | Mechanical equipment | Electrical/mechanical operating mechanism | Typical motor range | Typical power supply |
|---|---|---|---|---|
| Check structure | Radial gate hoist | Gear motor connected to worm-gear reducer | a. 1,705 N (7,500 lb) 1.3 to 4 kW (1 to 3 hp) | a. 1-phase 208 volts (V) or 3-phase 208 or 480 V |
| | | | b. 2,273 N (10,000 lb) 4 to 7 kW (3 to 5 hp) | b. 3-phase 208 or 480 V |
| | | | c. 3,409 N (15,000 lb) 7 to 10 kW (5 to 7.5 hp) | c. 3-phase 208 or 480 V |
| Turnout structure | a. Motor-operated gate lifts | a. Motor operator connected to threaded gate stem | a. Varies with motor torque requirements and motor revolutions per minute, typically 0.4 to 6.7 kW (1/3 to 5 hp) | a. 1-phase 120 or 208 V for 0- to 1.3-kW (0- to 1-hp) loads; 3-phase, 208 or 480 V for 1.3 to 6.7 kW (1 to 5 hp)<br><br>12- to 24-V dc (solar) for up to 0.17 kW (1/8 hp) |
| | b. Hydraulic operators | b. Gate hydraulic cylinder actuated from hydraulic power unit | b. Varies with gate load, speed, and operating pressure, typically 1.7 to 6.7 kW (1 to 5 hp) | b. Similar to a. (1 to 5 hp) |
| Canal-side pumping plant | Vertical or horizontal pump motors | Typically sump pumping units which pump into a discharge line | Varies with flow capacity and head conditions | 3-phase 480 V for 13 to 536 kW (10 to 400 hp)<br><br>Above 536 kW (400 hp) 2,300 V or higher |
| Adjustable weir gate | Obermeyer gate | Adjustable air pressure within bladder controls gate position | Air compressor motors sized for system and will be in 1.3- to 4-kW (1- to 3-hp) range | 1- or 3-phase 230 V<br><br>12- to 24-V dc (solar) for up to 0.17-kW (1/8-hp) compressor |

the range of 1.3 to 13 kW (1 to 10 hp). These demonstration projects require a massive network of solar panels and a large battery bank to meet this high power demand. Costs for these systems are extremely high and cannot normally be justified for any automated canal structure.

**b. Battery and alternating current system.**—The battery and alternating current system is similar to the solar battery except that a-c power is readily available and is used to charge the batteries in the system.

**c. Air systems.**—Compressed air can be used as an alternate or a backup system. The air compressor is used to compress air in a 76- to 84-liter (20- to 30-gallon) tank. The compressor can be driven by a fractional to 1- or 3-kW (1- to 2-hp) motor when a-c power is available. Motors of about 0.17 kW (1/8 hp) or less would be used for the solar-based system. The tank of air provides the reserve power to operate a system such as the Obermeyer gate or other air operated systems.

These systems work well with battery powered controllers where a small separate battery provides the power for the controller, radio, and air control solenoids. The air stored in the tank provides the energy to fill the bladder or operate an air motor. The air is replenished while power is available and provides a reserve should the power fail.

**d. Hydraulic accumulators.**—Hydraulic accumulator systems are sometimes used for temporary backup power operation of hydraulically operated slide or radial gates. Accumulators store hydraulic oil under pressure that may be used to operate the hydraulic hoist without the assistance of electric or motor-operated pumps. Piston or bladder type accumulators are commercially available.

Because of their limited capacity, accumulators are normally sized to provide an emergency opening or closing cycle or limited operation. The accumulators are a part of the gate control system and are charged during the normal operation of the gate. An automatic charging cycle must be included in the control system to maintain maximum pressure in the accumulators.

**e. Engine-generators.**—Engine-generators are sometimes used to provide electrical power. Where no commercial electrical power is available, engine-generators can be used as the prime power source. Engine-generators can be used for standby power when commercial power is available. Propane powered engine-generators can be used for power requirements up to 100 kW. Above 100 kW, diesel powered engine-generators are the only option.

The engine-generators are sized to provide the necessary surge for the load without exceeding a 10-percent voltage drop. Staggered starting of motors will reduce the size of engine-generator required. Tables listing characteristics of typical load and sizing programs are available from engine-generator manufacturers.

Accessories for engine-generators include automatic transfer switches, monitoring and control equipment, exhaust systems, and fuel systems. Diesel tanks that are located above ground must be double walled and must comply with Underwriters Laboratories Standard 142. Propane tanks are rated for a 17-bar (250-pound-per-square-inch) working pressure and are American Society of Mechanical Engineers code stamped. Propane fuel tanks comply with National Fire Protection Association Codes No. 30, 54, and 58, and any other Federal, State, and local codes. Electric or propane fuel vaporizers are sometimes used with propane fuel systems. The minimum ambient temperature determines when vaporizers are necessary.

## 10-6. Safety Requirements for Automation

A number of safety considerations must be included in an automated system. Without the onsite operator to observe the operation, some additional features must be included in the automation scheme. These features include both hardware and software components to ensure that the system operates correctly, initiates an alarm, or stops automatic operation.

**a. Mode selector switches.**—The four basic control modes for canal automation are local manual, local automatic, supervisory manual, and supervisory automatic. Each of these modes was discussed previously in chapter 3 of this manual, which covered general features and level of control.

At each gate or pumping plant structure, a local control board will be provided which typically has a MAN-OFF-AUTO (manual-off-automatic) selector switch. An operator will select a particular control mode based on the desired level of control for that structure and its related interface with the rest of the canal control system. Typically, one master selector control switch will be provided for all equipment associated with one system (i.e., one selector switch for all radial gates at a check structure), although multiple levels of selector switches are found on some installations.

The manual mode of operation places control of the equipment under an operator (pushbutton initiation) at the equipment site location. The off position disables operation of equipment from any source and locks out equipment from operation. The automatic mode allows control of the equipment to be initiated through either local controllers or a supervisory system.

When operating in any of these control modes, safety features have been provided to minimize damage to equipment, recognize improper operation or erroneous signals, and provide a fail-safe mode of operation should problems develop.

In the manual mode, the motor is protected from overload by the motor overload relays, which will trip out the motor for high sustained motor currents. Limit switches (pressure switches for hydraulic units) are also provided for any gate operation to shut down the driving motor when the gate reaches either extreme of travel (fully opened or closed). These safety features are also inherent in all other modes of operation (automatic and supervisory) and serve as the primary means for protecting equipment.

In the local automatic mode, a control algorithm is typically implemented to adjust the gate based on water level signals. These control systems are typically tied into a centralized control station to alarm for abnormal conditions such as equipment failure, high or low water levels, control equipment failure, local power outages, and communication channel failure. A backup feature should also be in place which transfers over to manual control whenever any emergency problem occurs within the automatic control system (loss of control signal or control logic malfunction).

In the supervisory automatic mode, additional protection is provided by constantly monitoring all parameters of the canal system and associated equipment to achieve desired operation. Problems with any part of the system, whether gate equipment or control related, are detected early and adjustments or alarms are provided accordingly. As in the automatic mode, if problems are detected within the supervisory mode or the communication channels, then the automatic controls should revert to the next appropriate level of control (manual supervisory or local manual).

**b. Equipment limit settings.**—Typically, limit switches are provided for motor-operated gates and valves for remote indication and to limit operation or travel of the gate or valve past the fully open or closed position. Limit switches for hydraulic hoists are used for remote indication in the full open or closed position. Motor-operated valves have the limit switch mechanism provided within the valve operator. Radial gate structures typically have the limit switches mounted within an enclosure on one of the drum units. Hydraulic cylinders have externally mounted switches which are operated by a lever or bracket. Some float-operated cam systems (Little-Man, Colvin [chapter 3]) use limit switches to set upper and lower limits of the deadband.

Limit switches in motor-operated gate lifts are set in the field by adjusting the cam portion of the limit switch to make mechanical contact at the desired travel limits (typically fully open or closed). Electrical contacts off the limit switch are then used in the control circuit to stop the gate or valve operation. Normally, at least one set of contacts is arranged to open in the fully closed position and one set of contacts is arranged to open in the fully open position. These switches are highly reliable and provide primary protection against gate or valve overtravel and motor or hoist damage.

Limit switches may need to be adjusted periodically as the gate hoist cable or valve seal seating characteristics change. Auxiliary contacts can be provided off the limit switches to provide indication at the control board or master station that the gate or valve is fully opened or closed.

**c. Float and pressure switches.**—Float switches are used in oil reservoirs of automated hydraulic power units. The switches are used to protect the hydraulic pump by automatically stopping it at low oil level. The switches typically use a two-stage circuit—one for warning indication and the other for pump shutdown.

Pressure switches are used in hydraulic power unit circuits to stop the pumps when the gate reaches the end of travel. As the gate reaches the end of travel, the pressure in the hydraulic hoist rises. This pressure is sensed by the pressure switch, which breaks the electrical circuit to the motor-operated oil pump. The pressure setting of the switch is set typically at 75 percent of the system design pressure and should not be used instead of the system relief valve.

**d. Dual measurement.**—Different methods of measuring water level and flow and the associated instrumentations systems were discussed in chapter 9. The reliability and accuracy of these measuring devices must be considered when integrating them into a canal automation control system. Dual measurement of critical level or flow parameters should be provided if erroneous signals or loss of signals could lead to unstable or erratic operation, which may lead to potential damage or safety problems.

Dual measurement for critical water level parameters in the system can be achieved by having two different measuring systems (float and pulley, pressure transducer, capacitance probe, etc.) or by having similar measuring methods at two different locations along the canal. The method for transmitting the control signal (cable, fiber optic, microwave) can also be used to provide redundancy by allowing more than one control path back to controlling location.

The methods for evaluating control signal integrity for resolution and accuracy are discussed in chapter 9. A dual measurement system provides another method to check the accuracy of the water level or flow signals received through a comparison check. A dual measurement system also allows continued full capacity operation as long as at least one of the signals is within range and reasonable.

**e. Parameter verification.**—Each variable parameter signal must be evaluated for accuracy which would be reasonably expected for the instrumentation provided for that device. Signals which are clearly outside the design range for a parameter, abruptly change state, or have a rate of change which is not physically possible, should initiate an alarm within the control system and either transfer control to a backup operation or shut that portion of the system down.

Simple checks for analog control signals would include verification that the control signal is within the 4- to 20-milliamp, 0- to 1-V d-c, or 0- to 5-V d-c range as applicable. Also, lower and upper limits of the parameter representing normal equipment operation should be checked for agreement with calibrated value (i.e., 4-milliamp lower limit, 20-milliamp upper limit). A signal which indicates a 3-m opening for a 2-m gate would obviously constitute an erroneous signal that should be disregarded. However, the signal system should be checked.

Digital signals can also be monitored in a similar fashion to that described above for analog signals. In addition, a need may exist to monitor excessive rates of change (abnormal fluctuations) of a parameter signal to alarm and transfer control for control signal problems.

**f. Vandalism protection.**—Automated gates and control systems are particularly susceptible to vandalism, so special precautions must be taken as shown on figures 10-7 through 10-10. Hydraulic cylinders, exposed fluid lines, and pushbutton stations must be protected from damage by covering them with bulletproof enclosures. Control houses should be windowless or should have protection over window openings.

## 10-7. Other Equipment

**a. Trashracks.**—Trashracks are positioned in the flow of waterways and conduits that serve equipment needing protection. Trashracks, which usually consist of rows of parallel bars, are used to protect equipment and waterways from objectionably large or damaging debris or as a safety rack for unwary swimmers or boaters. Trashracks are also used for the protection or restriction of fish.

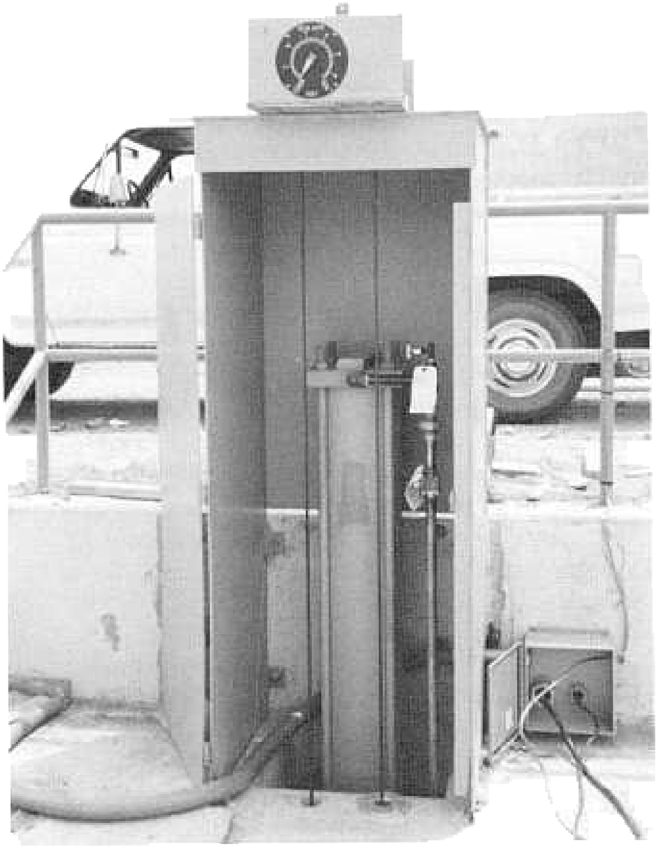

Figure 10-7.—Hydraulic cylinder protective enclosure.

Figure 10-8.—Gate pushbutton controls.

Figure 10-9.—Small box attached over pushbuttons.

The details and general construction of trashracks vary with the service required, configuration of the trashrack structure, depth of water, and accessibility for replacement. Usually, trashracks are constructed of rectangular cross sectional vertical bars held together with lateral bars or structural shapes.

**b. Hydraulic trash rake and conveyor/transporter system.**—A hydraulic trash rake is an automated raking device that will rake all portions of the trashracks and can deposit debris into the downstream trough of a conveyor or transporter (figure 10-11). The hydraulic trash rake uses a cyclical raking motion that resembles manually hand-raking the trashracks. The automated conveyor or transporter system deposits the raked debris to the end and out of the trough. The end of the trough can be positioned at the side of the trash collection pit or elevated to allow dumping into a trailer.

Figure 10-10.—Canister locked over assembly.

A hydraulic trash rake as shown on figure 10-11 works very well with the type of structures and debris associated with canals. The hydraulic trash rake is economical for removing debris from multiple and wide trashrack bays. When this type of system is not in use, the trash rake is completely out of the water, therefore preventing corrosion problems.

A sweep cycle timer and differential water level control system can be furnished to initiate startup of the automatic cleaning cycle of the hydraulic trash rake and the conveyor-transporter systems. The timer should be adjustable in 30-minute (minimum) increments up to a 24-hour (minimum) period. When a preset time period is reached, a contact will close, which initiates startup of the cleaning cycle.

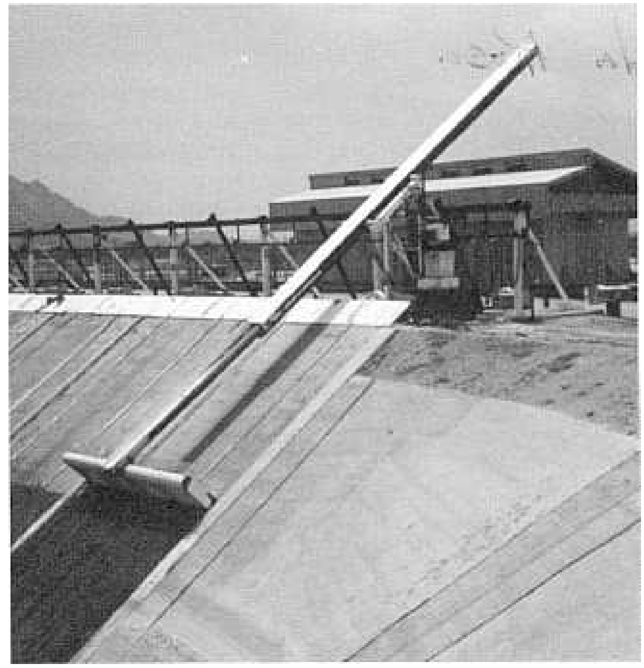

Figure 10-11.—Hydraulic trash rake.

The differential water level control device measures and compares the water levels across the trashracks. When a preset differential is reached, the remote contact from the differential water level control device closes, initiating startup of the cleaning cycle. The differential controls protect the trashracks from being overloaded by large quantities of debris coming against the trashracks between the sweep cycle timer setting.

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[2] Bureau of Reclamation, *Water Operation and Maintenance Bulletin, No. 171,* 21 pp., Denver, Colorado, 1995.

# CHAPTER 11

## CANAL AUTOMATION EQUIPMENT

### 11-1. Planning, Failure Mode Studies, and Site Preconditioning

**a. Planning.**—For new projects, the engineering group should determine the type of automation that will provide the best control. Existing systems present difficulties in identifying the most likely group to start planning for a new control system, upgrading, or expanding an existing control system. Typically, operation or engineering personnel recognize the need for improved or expanded control or replacement of obsolete equipment. Then an attempt is made to justify purchasing a new control system, upgrading, or expanding the existing system.

Planning for a new control system or for upgrading or expanding an existing control system should be accomplished by an automation team. The automation team should include one control systems expert and representatives from each major area of the organization that will be affected by the new, upgraded, or expanded control system. The automation team should produce at least two reports which contain the data necessary to evaluate the operation of the new, upgraded, or expanded control system. The automation team should produce a requirements report and a justification report.

The requirements report should establish:

**(1) New, upgraded, or expanded system requirements.**—For example, new or modified control processes and new or modified data collection requirements.

All functions needed in the new control system and all the hardware interfaces envisioned should be included. The new control system should serve the entire project (not only the operators), although the operators are the primary users.

This phase also encompasses a thorough review of expansion plans and the definition of operational requirements and procedures to be supported by the new control system over its expected life. Based on the review, the hardware and software components can be identified and evaluated to provide a man-machine interface (MMI) configuration satisfying the functional requirements of the operators. The agency can issue a request for budgetary estimates by vendors. For competitive reasons, such budgetary estimates are often purposely vague. Budgetary cost estimates and schedules can then be refined to determine project funding requirements.

A failure mode study should be made for the new, upgraded, or expanded control system. Each piece of control system equipment should be listed with the anticipated failure modes and the effect of the failure upon control system operations. A more detailed study dealing with simultaneous failure modes may be desired depending upon budgetary constraints and the acceptable degree of system reliability. Based upon the study results and the acceptable degree of system reliability, a plan should be made to mitigate different failure mode consequences and maximize the system reliability. The plan should define operator or hardware-software procedures to be executed for each failure mode or modes to attain this goal. The plan might consist of adding equipment redundancy and software to define actions for each failure condition.

**(2) System reliability and maintainability.**—System reliability and maintainability are dictated by the quality of the system hardware and system software and the expertise of the maintenance personnel.

The system design team can dictate hardware and software quality by writing a stringent system design document. The design document should encompass all system hardware (current and future), all system software (current and future), and maintenance personnel training.

Maintainability begins with quality hardware and software and is completed by a highly skilled and motivated maintenance staff. The system design team can dictate the system training requirements, including training aids and duration of training in the design document.

**(3) System availability.**—The automation team must determine the acceptable system availability. Some criteria to examine in order to determine an acceptable availability are: the size of the control system (number of remote control sites and the number of status and control points per site), the type of control system, the equipment being controlled, the replacement cost of the equipment being controlled, the location of the remote control sites, and the cost of catastrophic failure. The list of criteria is not exhaustive and is not in order of importance.

**(4) The acceptable system life cycle.**—The automation team should examine the life cycles of each major hardware and software component that is intended for use as part of the control system. Selecting components that are well advanced in their life cycle will dramatically affect (shorten) the life cycle of the control system.

**(5) Facility requirements (site preconditioning).**—The automation team must determine what site preconditioning is required for existing and future control sites. Site preconditioning must include each site in the system and each aspect or each site: power, environment, communications, status, and control. The following items must be considered and exist prior to the control system installation:

- The power requirements at each site for the current and future system must be determined (e.g., quantity, type, requirement for backup power, length of time backup power is to be available, etc.).
- The environmental requirements at each site for the current and the future system must be identified (e.g., the ambient and electrical environments).
- The communications requirements to/from each site for the current and the future system must be determined (e.g., type, how often, failure mode communications, etc.).
- The status and control requirements for each site current and future must be identified. For each site in the system, a site input and output points interface must exist or be created. A site input and output points interface is created by terminating all required input and output circuits at one location. Each input and output point should be terminated on terminal blocks. Each input and output point should be clearly labeled. Input and output points should be arranged in a logical manner (e.g., grouped by device). Extensive and costly retrofitting will be required if existing equipment does not provide auxiliary contacts and routing paths to the interface from the controlled devices for input and output points needed for the control system.
- Modification to equipment control circuits may also be required if the circuits are not compatible with the proposed control. Attention must be paid to required status and control circuits, control circuit voltage, and current ratings to assure proper insulated conductor ratings, terminal block terminal ratings, and conductor shielding.
- The site interface should be located near the site control device to avoid unnecessary voltage drops and noise in the control device's input and output circuits. A primary power source, communications channel via metallic wire, radio, telephone leased line, microwave, etc., for the control device should be provided. Conduit or cable tray paths to the control device for power, communications, and all input and output points should be installed.

- Physical space for the control device, its power supply, and backup batteries if required must be allocated with adequate clearance for enclosure ventilation and maintenance.

(6) **The schedule.**—An important part of the requirements report is the proposed project schedule showing the various tasks leading to the procurement and installation of the new, upgraded, or expanded control system. It is important that the schedule be realistic in the time allotted to complete the various tasks.

(7) **Cost estimate.**—During the initial stage of the planning process, reliable budgetary cost estimates are impossible to determine. The primary reason for the lack of a definitive estimate is the lack of data concerning the requirements of the new, upgraded, or expanded control system. An accurate, detailed estimate for the new, upgraded, or expanded control system should be produced from the requirement studies.

The justification report should contain:

1. Review and evaluation of present operating procedures, facilities, and staffing
2. Review of existing and future plans for control system features and resources
3. Review of likely features to be automated
4. Review of alternate control system configurations and procurement methods
5. Determination of the best possible control system solution and procurement method
6. Definition of a preliminary implementation plan including:
    - Budget estimates
    - Basic system block diagrams for the recommended system
    - Preliminary manpower requirements
    - Preliminary facility requirements

It is important to realize that justification reports for large control systems have many, possibly lengthy, review and approval cycles that can add as much as a year to the overall schedule.

## 11-2. Local Control Systems

Control systems are considered to be "stand-alone" local control systems if they are not controlled or reprogrammed remotely. Local control systems can range from being totally mechanical to being microprocessor based with electromechanical circuitry. Local control systems operate by sensing current site conditions and executing a control operation dictated by the control algorithm that has been implemented in the local controller. Typical types of local controllers include:

a. **Water-powered controllers.**—Water-powered controllers are the most basic type of local controllers. These controllers use floats that are attached to regulating gates to emulate an upstream or a downstream control algorithm. Controlling the water level immediately upstream or downstream from the controlled gates is the only control possible. Floats must be sized and placed in the proper position on the regulating gate to assure accurate emulation of upstream or downstream water level control.

b. **Microprocessor-based controller with electromechanical circuitry.**—Microprocessor-based controllers are the most sophisticated type of local controller. These controllers use transducers to measure process variables and can emulate multiple upstream and downstream control algorithms. Controlling the water upstream and downstream from the regulating gate or valve is only one of many control functions that the controller can provide.

A well-designed, microprocessor-based local control system can contain failover and failsafe operating procedures to:

- Detect bad input data by comparing data values to a predefined rate of change, deadband, or predefined data characteristic
- Detect defective transducers
- Detect defective system hardware components
- Detect defective system software modules

## 11-3. Telemetry Systems

Control systems are considered to be telemetry systems if they transmit status and/or measured analog data to a site remote from the collecting site. Telemetry systems can range from hard-wired telemetry systems to microprocessor bases with alarming functions. Telemetry systems consist of one or more signal converters that convert the collected data to signals usable by the telemetry system; a communications system which conveys this collected data to a remote site; and the remote-site, MMI which remotely displays collected data in a useful form to the end user. The type of data transmitted (status and analog), the accuracy of the control algorithms, the MMI display requirements, the distance from the collecting site to the controlling site, and the alarming capability determine what type of telemetry system and equipment are required.

a. **Hard-wired telemetry systems.**—The simplest telemetry systems consists of remote readouts hard wired to transducers. Short distances between the transducer and the readout for a few measurements are a good application for hard-wired telemetry systems.

Hard-wired canal depth and gate position telemetry systems can be either current or voltage output circuits with remote readouts located from 9 to 2,300 meters (m) (30 to 7,500 feet [ft]) from the transducer. The readout device consists of a high accuracy and high precision, temperature compensated, scalable process meter with a current to voltage conversion circuit.

For greater range in depth or gate position measurement, a multiturn resolver may be used with the measurement displayed up to 150 m (500 ft) from the measurement site. The resolver, resolver signal encoding method, and the readout device are unique and proprietary to each resolver manufacturer.

Hard-wired status data consist of a contact closure transducer connected to an alternating- or direct-current voltage source. The readout device can consist of something as simple as a light-emitting diode or incandescent panel lamp. The distance from the measurement sight to the readout is limited by current induced voltage drop in the hard-wired circuit.

Hard-wired water flow in a conduit is usually a pulsed direct-current output signal; the frequency of pulses is proportional to the rate of flow. The pulses are transmitted to a readout which counts the pulses and displays instantaneous and cumulative flow. Transducer to readout distances involved may be up to 305 m (1,000 ft) or greater depending upon the signal and cable characteristics involved.

b. **Multiplexed telemetry systems.**—Where larger quantities of measured signals and greater readout distances are required, the telemetry system will be comprised of units that function as multiplexors and demultiplexors. The multiplexor's purpose is to convert multiple measured analog or status signals into a single analog or digital signal. The signal is then transmitted over a communications media and demultiplexed at a MMI. A variety of equipment may be used to function as multiplexors or demultiplexors. The equipment selected will depend on the quantity and type of monitored signals, the speed at which the monitored signals will be transmitted to and displayed at the MMI, and the available multiplexor to demultiplexor communications link type and speed.

The simplest and least expensive multiplexor used in canal systems automation is a data concentrator which, depending upon the manufacturer, will output either a digital signal or an analog frequency division multiplexed signal. Programmable logic controllers may also function as multiplexors and demultiplexors. Multiplexors and demultiplexors are purchased as a unit because the multiplexor to demultiplexor communication software protocol used is proprietary to the specific manufacturer. However, some vendor protocols are public, which is very useful when interfacing an existing multiplexor signal to an existing system is desired.

One can expect the following from inexpensive telemetry systems: slower measured signal scan rates; limited number of measured signal types; may not provide measured signal optical isolation; multiplexor protocol proprietary to one manufacturer; minimal MMI readout devices; and output signal availability at an output terminal board. The more costly telemetry systems will typically provide: higher measured signal scan rates; telemetering of all types of the standard transducer signals; input signal optical isolation; a high level of communications system data security to prevent erroneous control and readout signals; MMI readout at the multiplexor side of the telemetry as well as at the demultiplexor side; sophisticated input signal conditioning and processing to minimize erroneous and extraneous data; and multiplexor communications protocol to communicate with numerous existing telemetry systems and with supervisory control and data acquisition systems.

The alarming portion of a telemetry system may use public telephone system dual-tone multiple frequency subscriber lines or ultra-high frequency/very-high frequency (UHF/VHF) radio to deliver alarm messages. Ultra-high frequency radio-based personal pager systems and cellular phone systems may also be used effectively and economically to transmit alarm messages. Telemetry systems can be used to notify an operator of an analog or digital status change requiring immediate attention if the MMI is not manned 24 hours per day, 365 days per year.

Telemetry communications system requirements range from 300- to 3,000-hertz full duplex bandwidth analog communications channels to a 44-megabit-per-second fiber optics channel. These communications systems may be metallic wire, fiber optic, UHF/VHF/microwave radio, public telephone leased lines, cellular phones, satellite, and meteor burst. System selection is determined by the required system bandwidth.

## 11-4. Supervisory Control And Data Acquisition (SCADA) Systems

This section will discuss some of the more important features of large, complex SCADA systems. The discussion will focus on large systems because the features for smaller, less complex SCADA systems can be selected from the features discussed elsewhere in this manual.

In this manual, SCADA systems are considered to be control systems that operate and coordinate all project facilities from a single site. System operations and coordination include all normal operations, maintenance operations, an efficient method for responding to equipment and/or device malfunctions, an efficient method for responding to system and/or device misoperations, and an efficient method for responding to emergency situations that arise within the project. SCADA systems require a communication system to maintain the data link or links between the master station and each project site where control and monitoring are required. The master-station equipment will perform the functions of data collection from each project site and all data storing, logging, and manipulation tasks required by or for the operator. Each project site requires remote-site monitoring and control equipment, referred to as a remote terminal unit (RTU), to monitor and control the remote-site operations based on internal algorithms or commands received from the master station.

SCADA systems may operate in one of several modes that allow project resources to be scheduled or optimized. The modes of control refer to the participation of an operator in overall project control. The typical modes of control were discussed in sections 1 through 7 of volume 1.

**a. Types of control.**—Four types of control will be discussed. The use of a particular type of control is based on the operational constraints of the equipment, the operational requirements of the system, and the particular control requirements of the selected control algorithms. The four types of control are:

- Supervisory/manual
- Supervisory/automatic
- Computer directed
- Optimization

**(1) Supervisory/manual.**—Bureau of Reclamation (Reclamation) designers refer to operator control of project facilities from the master station as the *supervisory/manual* mode of control. The RTU at each remote site executes operations such as ***open/close***, ***on/off***, and ***start/stop*** as commanded by the operator. This type of control requires the operator to monitor the control variables and make the necessary corrections to the remote-site equipment. Local automatic control operation is not performed at the remote site in this mode of control.

Supervisory/manual mode of control is used when the control requirements of the system are relatively simple and the system constraints are maintained by the operator; i.e., this mode of control is used when the operation of a remote-site device provides predictable results. Examples are the operation of a two-state gate, pumps in small pumping plants, power circuit breakers, and emergency generators.

Data monitoring at the remote sites must be similar to that required for site local/manual control of the facility equipment. All information necessary for the operator to make proper decisions regarding the results of a control action must be collected by the RTU and transmitted to the master station. Data presentation at the master station should be in a clear format because the data presented to the operator will direct the operator to make proper or improper decisions throughout the control process.

Control of a device by the master station via a communication channel rather than providing the additional capability in the RTU to perform the required calculations for the necessary control is called open-loop control because the process hardware and the process software do not reside at the same site. Open-loop control is not a recommended control method.

**(2) Supervisory/automatic.**—Reclamation designers refer to automatic control of project facilities, by an RTU functioning without intervention from the master station, as the ***supervisory/automatic*** mode of control. The RTU adjusts each controlled device to the desired position or setpoint value and maintains the device position based on system conditions without operator intervention.

Data monitoring requirements at the remote sites must be extensive enough to execute the required supervisory/automatic control functions and/or algorithms. Alarm monitoring should be extensive, so the operator is notified of abnormal and/or aborted control functions or algorithms. Data presentations at the master station should allow the operator to alter each control function and/or algorithm parameter, limit, and deadband. Data presentation at the master station should be in a clear format because the data presented to the operator will allow the operator to check for proper function and/or algorithm execution and to decide on proper corrective action or actions.

**(3) Computer directed.**—Reclamation designers refer to ***computer-directed*** mode of control of project facilities as control functions being performed by the master-station computer in conjunction with the communication equipment and the RTU's. This control mode requires no operator intervention to perform the necessary system control. In this mode of control, each remote-site RTU is polled by the master station, the master-station computer performs the necessary algorithm calculations using the system data and other appropriate data as input by the operator, and control commands are then issued to the RTU's to adjust facility equipment operation as necessary. For this mode of operation, the commands issued to each RTU should be schedules. Schedules can be executed by the RTU for long periods of time without intervention by the master station.

The RTU may operate in the supervisory/manual mode or in the supervisory/automatic mode when the system is operating in the computer-directed mode. The RTU operation is based on the type of control necessary to provide the desired overall system operation. For example, a schedule may be based on facility equipment operating parameters, or it may be based on control variables. If the schedule produces actual device settings for each facility, then the RTU is operating in the supervisory/manual mode. If the schedules produce control parameters such as flow and water levels that require the RTU to maintain a particular rate or level, then the RTU is operating in the supervisory/automatic mode.

This type of control is used for system operations that require adjustment of facility equipment based on unpredictable system loads or demands.

The data acquisition requirements for this mode of operation are similar to those required for the supervisory/automatic mode of operation with the addition of system data that may be collected at additional sites. System information is required to perform the necessary calculations to operate the system to meet load or demand, reject load or demand, and operate in an efficient manner. These data are not always available at the remote site, and additional remote-site equipment may be necessary to collect the required data.

**(4) Optimization.**—The ***optimization*** mode of control refers to the same mode of control as the computer-directed mode, except that system operation is optimized to produce the most efficient system operation. This mode requires data regarding facility equipment rating curves and efficiency data. For example, generators and pumps may have a certain capacity in which they run most efficiently based on their calibration/efficiency curve data. This type of information would be used, in conjunction with the system data, to produce the most efficient operation of the pumps or generators. In addition, electrical demand type functions such as onpeak and off-peak pumping requirements can be used with the optimization mode to produce the most efficient and economical system operation. The optimization mode can be used, in conjunction with a scheduling program, to provide the most efficient system operation during the particular scheduled time.

The optimization mode requires no operator intervention during operation of the system. If the system demands are such that the optimization process will not allow the demands to be satisfied, the computer-directed mode is automatically initiated, and the operator is notified that a particular facility is no longer being optimized. The operator may then try to correct the facility operation to obtain the best operation. Operator control would be initiated from the supervisory/automatic mode. Any system emergencies that occur during the optimization process will cause the optimization mode to be automatically transferred to the computer-directed mode. In all cases, the optimization mode can be initiated or canceled by the operator as desired or as necessary.

The data acquisition requirements for the optimization mode of operation are the same as for the computer-directed mode of operation. Additional data required by the optimization mode of operation would be the equipment rating and efficiency data for the facility equipment.

**b. Benefits of centralized control.**—A properly designed and implemented SCADA system provides numerous benefits to the operators of a water project. The two most obvious benefits are the increased efficiency of overall project operations and the reduction of operating cost because of reduced personnel requirements. The efficiency of overall project operations cannot be obtained with any of the other methods of project automation. Although the initial cost of the SCADA system is greater than the other automation methods, the long-term overall system operation, reaction to abnormal conditions, correction of operating problems, and efficiency of operation will provide benefits that the other less expensive methods of automation cannot provide. Cost/benefit ratio calculations for SCADA system control must include cost factors that account for more efficient operation, less waste, and rapid identification of system operational abnormalities. The specific benefits related to SCADA system control will be discussed for both normal and abnormal operations.

**c. Normal operation.**—The primary purpose of a SCADA system is to provide water system operators with information and control capabilities that are necessary and desirable to properly manage water system operations. The information collected and control capabilities are intended to alert the operator to abnormal system conditions and to allow a timely and effective response to emergency conditions that occur in the water system. The data collected are also used for the operator to generate reports and compile records of the overall system operation for which the operator is responsible.

The data collected also satisfy the need for data from other segments of the organization. For example, the data could be used to provide records for scheduling and billing purposes. Operations personnel and designers would be interested in the operation of protective equipment after failures or abnormal operations occur. Maintenance personnel would use the data in regard to the frequency of operation of certain equipment and records for the determination of periodic maintenance required for the facility equipment. Planning personnel would be interested in the data for determining the required water releases that may be required to meet operational demands of the system. Also, various levels of management would use the data in the form of summary reports that provide information on the performance of the overall water system operations.

Because many departments within an organization may be interested in the data collected by the SCADA system, the needs or desires of all departments must be considered during the design of the system.

The ability to schedule and optimize the water system operations is possible with a SCADA system because the data required for the operation of the system are centralized. Scheduling operations can be performed well in advance of implementation, and these schedules can then be implemented at the correct time through the SCADA system. Scheduled operation can be either automatic or manually controlled by the operator. To provide scheduled operation, data from all facilities within the system must be collected, and the equipment within each remote site must be controllable from the master station.

Optimizing water system operations is also possible with SCADA systems. Optimization of system operation is intended to provide the best and most efficient operation of a system during normal operation. Changing system conditions are immediately detected and analyzed by the SCADA system and used in the optimization process. In addition to data collected by the control system, data received from other systems, agencies, or water districts can be used to further optimize water system operation.

**d. Abnormal operations.**—The SCADA system provides the operator with system data in real time, so reaction to abnormal system conditions can be performed in a short time. The data presentations at the master station can be organized into logical groups, so when an abnormal condition is present, the appropriate alarms can alert the operator to the abnormal condition, and the operator can react to the problem without long delays.

With all of the system data available at the master station, the organization of alarm presentations is extremely important. Overwhelming the operator with too much alarm information can cause long delays in correcting system problems. The ability to prioritize alarm information and present only information that has changed since the last data request is important in maintaining efficient system operation during abnormal conditions.

Historical data before, during, and after abnormal conditions occur can be automatically obtained by the master station; therefore, when an abnormal condition occurs in the system, analysis of what caused the abnormality can be performed by engineering personnel.

## 11-5. SCADA System Performance Requirements

SCADA system designs use computer-based equipment for the master station and RTU's that range from single computer master, to single RTU configurations, to multiple computer masters with hundreds of RTU's connected through complex communication networks. The RTU's range from simple data acquisition and control types of equipment to extremely complex stand-alone automatic controllers. In the design of the SCADA system, the designer must first consider several basic criteria regarding the project before an appropriate computer-based control system can be designed. A short discussion of the major design criteria elements follows.

**a. System response time.**—The system response time is defined by two separate intervals of time. One is the control and data acquisition scan time, and the other is the system information update time. The control and data acquisition scan time is defined as the interval of time required by the master station to interrogate all of the RTU's for data. The typical scan times for water systems can vary from 2 seconds to 10 minutes. The system information update time is the interval of time required by the master station to record the data it collects from the RTU's in the data base and modify all system data to reflect the most recent scanned data. Typical system information update times for water control systems can range from 0.5 second to 5 seconds. In general, the system total response time can range from 1.5 seconds to 10 minutes.

It is important to determine what the data monitoring and control requirements are for each remote site so the master station and the communication system can be designed to provide the proper real-time response to each remote site to maintain control of the system. It is also important to determine how the data will be used at the master station so the data being monitored can be collected at the proper frequency to maintain the correct system or process control response time. For example, if water flow data are needed for online optimization, the flow data should have frequency of collection consistent with the requirements of the control algorithm.

**b. Availability requirements.**—Availability is defined as:

$$\mathit{Availability}\ (A) = \mathit{uptime}/(\mathit{uptime} + \mathit{downtime})$$

The uptime is defined as the total time period for which the availability is being measured. The downtime is defined as the period of time that normal system operations cannot be performed. Usually, normal operation is considered interrupted for hardware and software failures that: (1) cause incorrect operation or result in the inability to operate the water system, (2) cause the inability to exchange or disseminate correct data to application programs, (3) cause the inability to store, retrieve, or disseminate any data to hard or soft copy media. The availability is a measure of the master-station performance. It takes into account both reliability of the system and the maintainability of the equipment. To demonstrate reliability and maintainability, the availability of the subassemblies of the equipment can be defined in terms of the "mean time between failures" (MTBF) and the "mean time to repair" (MTTR) as follows:

$$A = MTBF/(MTBF + MTTR)$$

The design goals for obtaining high system reliability are: (1) a single component failure will not result in a critical system failure or incorrect operation of the remote-site equipment, and (2) eliminate and protect against multiple and cascading component failures.

The design goals for the system maintainability are as follows: (1) minimize the time interval between a failure of a system component and the call for maintenance service (administrative time), (2) minimize the time interval between the call for maintenance service and the arrival of the maintenance personnel at the site with the necessary test equipment and repair parts (transport time), and (3) minimize the time required to repair the failed equipment and to restore to normal operations (repair time).

The availability figure is usually expressed in percent. This percentage indicates how well the overall SCADA system will perform. For computer-based SCADA systems, the availability figure can range from 95 to 99.9 percent. The system configuration, spare equipment assemblies, spare parts inventory, and type of maintenance service determine directly the availability figure. It is important for the automation team to define how long the master station can be out of service. The out-of-service time should be based on the overall system requirements. After the out-of-service time has been determined, the system configuration can be defined, and the control system equipment can be designed to meet the availability requirement.

**c. System security requirements.**—The SCADA system must be designed to operate the equipment at remote sites over a communications network. Because control information is being transmitted over a communication network, some type of data security must be employed to prevent incorrect remote-site equipment operation. Generally, two types of data security measures are used in SCADA systems: ***message security*** and the ***select-before-operate sequence***.

Message security is the process of attaching a security code to all messages that are transmitted over the communication network. The security techniques must provide a high degree of protection against error in the message received by the RTU and must also maintain a relatively high data transmission rate. The most common method of message security employed by the SCADA systems is the Cyclical Redundance Check-16 method. The 2-byte security code will detect all single and double bit message errors in multiple byte messages. Long messages should be transmitted as packets of 256 bytes.

The efficiency of the message transmission can be defined as follows:

$$Message\ Efficiency = (TMB - [SB + OB])/TMB$$

where:

*TMB* = total message bytes
*SB* = security bytes
*OB* = overhead bytes

Message efficiency for short messages should be greater than 55 percent. Short messages are messages of less than 17 bytes. Return messages from RTU's that contain no data under the report by exception method of operation should not be considered when determining message efficiency.

The select-before-operate security sequence is primarily associated with controlling remote-site equipment. The select-before-operate sequence is usually designed to perform the following functions: (1) prohibit control operations at the RTU site if both the select and execute messages do not coincide to define the same control output, (2) reset the selected control output if any other message is received prior to an execute message, and (3) reset the selected control output if the execute message is not received by the RTU within 10 to 60 seconds.

In general, the select-before-operate sequence is designed to operate as follows:

Select—The device to be controlled is selected by the operator at the master station. The control message is sent to the RTU. The RTU checks the message and arms the requested control output. The RTU retransmits the message to the master station. The master station compares the message with the original message sent. If all checks pass, then the master station is ready for the operate command.

Operate—The device execute function is performed by the operator at the master station. The operate command is transmitted to the RTU. The RTU checks the message and, if it passes the checks, the previously armed control output is executed.

In addition to the above security features, the following items should also be taken into consideration as part of the overall system security scheme:

1. An error message should not result in a critical failure of the system.
2. A positive indication should be available when the RTU does not receive or respond to a valid message.
3. The proper operation of the communication channels should be verified on a regular basis by normal use or by a test message.
4. The use of party-line or switched communication channels, or both, should be carefully defined such that two RTU's with the same address do not share the same communication channel.

**d. Accuracy requirements.**—The data being monitored throughout the system should have an accuracy requirement. The accuracy requirement defines the hardware components that can be used as part of the system. The accuracy achievable by computer-based equipment is usually much greater than that available for transducers; therefore, the resolution requirement for each transducer should also be defined as part of the overall system data requirement. The accuracy and resolution of transducers are greatly affected by the transducer power supply; therefore, RTU's should include a precision power supply to ensure correct operation of the data transducer equipment.

**e. Environmental conditions.**—The environmental conditions that the SCADA system equipment will be exposed to should be defined so that the designer can make appropriate design decisions on the equipment operational design requirements.

The ambient temperature and humidity conditions for both the master station and RTU must be defined so decisions on the need for supplemental air-conditioning or heating equipment can be made. At the master station, the computer equipment may need to be installed in an air-conditioned location. Most master-station computer and associated peripheral equipment is sensitive to temperature and relative humidity variations, and the ambient conditions must be regulated. For small systems, the master-station equipment may not need supplemental air-conditioning equipment and can be installed in an office-type ambient environment.

The RTU does not usually require any supplemental air-conditioning equipment; however, heating equipment is usually required. Typical environmental data for RTU's are:

- Relative humidity 0 to 95 percent
- Ambient temperature -10 to 55 °C

The electrical environment in which the equipment is to be located is also an important design consideration. At the master station, equipment must be operated from a well-regulated, transient-free, electrical power source. Normal practice involves installing a precision power center containing filters, regulators, monitors, and a distribution system that is specially designed for computers and computer-related peripheral equipment. The power center will protect the master-station equipment from raw power voltage fluctuations, noise, voltage spikes, and radio and electromagnetic interference conditions.

The RTU that interfaces to the remote-site equipment must be protected from surge voltages, transients, overvoltage, short-circuit conditions, and electrostatic voltages that may be present on the interface control circuits. The surge withstand capability is defined by ANSI/IEEE C37.90.1 standards, and all circuits in the RTU that interconnect to the site equipment are protected in accordance with this standard. RTU wiring and anchor cabling ratings of 1,000 volts (V) plus twice the rated operating voltage that the remote-site equipment needs for operation are required. The minimum dielectric withstand capability should be 1,500 V regardless of the remote-site operating voltage. For remote locations that have 60 V or less for their primary operating voltage, a dielectric withstand capability of 500 V for 1 minute would be acceptable.

The electrical environment required for power and larger pumping plants is quite different than that required for small pumping plants, water treatment plants, and at canal gates. The designer must know how the external control circuits are designed so that an adequate RTU can be designed. Usually, all remote-site inputs and outputs to the RTU should be optically isolated, and the power input to the RTU should have at least one stage of transient protection and one to two stages of regulation and filtering.

## 11-6. SCADA System Design

**a. SCADA system hardware.**—A SCADA system consists of the following basic elements or subsystems:

- Power centers and uninterruptible power supply equipment
- Central processing equipment and peripherals
- Operating system software
  - SCADA software including man-machine interface software
- Communication system
- RTU
  - Data acquisition and control equipment
  - Transducers

The SCADA system equipment design and configuration are based on the requirements of the application, as discussed in the previous section, and on the particular elements that comprise the overall water system. The designer needs information regarding the functions to be performed by the system, the desired operational capabilities and features, and the initial and projected ultimate size of the project in order to provide the proper master-station configuration design. These data allow the designer to propose the most efficient and economical configuration to satisfy the needs of the overall project operations. The following is a general discussion on the basic elements of data acquisition and control, central processing equipment and peripherals, and RTU's. Software packages will be discussed under the SCADA system software section. Power centers have already been discussed in previous sections. MMI and RTU's will be discussed in the paragraphs that follow. Communications systems and basic equipment grounding are discussed in chapter 8.

**(1) Equipment configurations.**—The data acquisition and control subsystem consists of the RTU for interfacing to the remote-site equipment, master-station equipment for interfacing the operator to the system, and the communication system. The configuration of the master-station equipment depends upon the data acquisition and control subsystem in terms of:

a. Do the communication channels allow a separate channel for each RTU, or do RTU's have to share a communication channel on a party line basis?
b. How many analog data are required to be sent to the master station in the defined response time?
c. Is collection of status data based on reporting all status changes on each data request, or is it based on reporting only the changes in status since the last data request?
d. How frequent is the closed-loop control algorithm required to calculate changes in equipment operating points and issue appropriate control commands?

Based on the answers to these questions, the designer can make some decisions on the master-station hardware configuration and the RTU requirements. If the data acquisition and control requirements are significant and the response time is short, the designer must consider a communication front end processor (FEP) to provide the processing and execution of data acquisition and control commands. By processing the system communications data in a separate computer, the master-station main computer system is free to do other system-related tasks, and the system response to operator requests and actions can be maintained. If the communication messages to the RTU's require security encoding and decoding for safe control operations, the FEP can perform the necessary message security processing.

The quantity of data being collected throughout the system will give an indication of the size of the master station's main computer. If the response of the system can be relatively slow, then an auxiliary memory device (usually a disk drive) may be acceptable for data base storage.

**(2) Central processing equipment and peripherals.**—The configuration of the master-station equipment will depend upon the system operational requirements. The design criteria mentioned above concerning the response time and availability (reliability and maintainability) will influence the master-station computer equipment configuration. In large control systems, the dual redundant/ computer configuration is the most common. The dual redundant computer system is shown in simplified form on figure 11-1.

The on-line computer equipment and its associated auxiliary memory devices must be large enough to manage all of the real-time functions for the

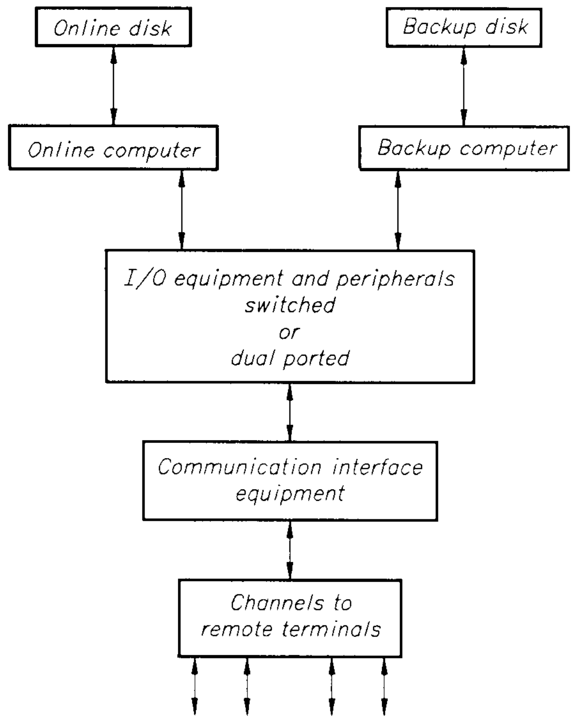


Figure 11-1.—Dual redundant computer system.

system. Common practice involves having the on-line computer store information collected from the system (data base) on both the on-line and backup auxiliary memory devices. This redundancy ensures that, when the on-line computer fails, the backup computer has an updated copy of the system conditions stored on the auxiliary memory and can assume real-time operation with minimum system interruptions. The same scenario applies to a failure of the on-line disk. The backup disk can be used by the on-line computer without causing system operation interruption or loss of real-time data.

The backup computer system can be used to do other functions associated with the real-time system. These functions include scheduling, system modeling, training, report generation, and other functions related to the system operations. By allowing the backup computer to perform these tasks, the on-line system response is maintained, and real-time system operations are not interrupted because of long processing delays.

If the data collection requirements are large and the required response time is extremely short, then a dual redundant computer configuration with FEP's to handle the communications is used. This configuration is shown on figure 11-2.

The FEP's provide all of the polling, data acquisition, message security encoding and decoding, data formatting, and communication channel monitoring functions so that the on-line computer system is free to perform the other real-time related functions. This configuration enhances system response time and allows the on-line computer system to perform many closed-loop control functions in addition to the supervisory control functions. The FEP configuration allows more flexibility for adding communication channels and operating channels with different communication protocols.

Another configuration that is becoming more popular for larger systems is the distributed processing approach. In this type of configuration, a symmetrical backup system to the on-line system does not exist. Backup is achieved by having one computer as a dedicated backup or having a degraded backup in which a computer performs its own function and picks up the function of the failed processor. Each processor has its own set of tasks, but neither one acts as the primary processor. Communication between processors occurs through a combination of communication channels, shared memory, and shared auxiliary memory. A simplified distributive processing configuration is shown on figure 11-3.

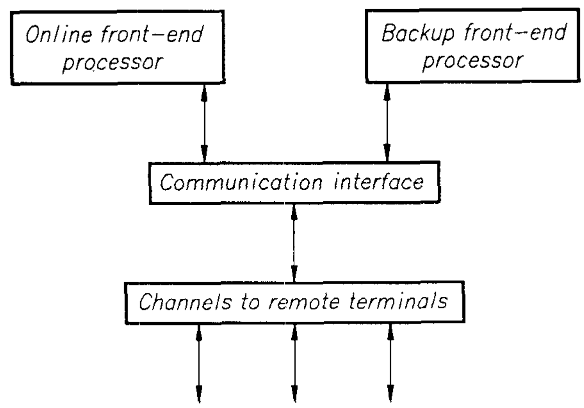


Figure 11-2.—Dual redundant computer configuration with front-end processors.

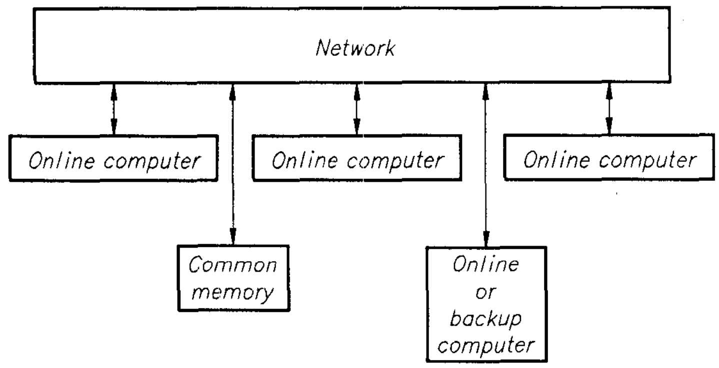


Figure 11-3.—Distributive processing computer configuration.

The selection of peripheral equipment necessary to support the master-station computer is based on the overall workload of the system, extent of the data collected, number of special applications, requirement for program maintenance or development, and ultimate expansion capabilities. The major peripherals that should be made part of any SCADA system are:

- Moving head disk drives
- Backup storage media (optical disk drives or magnetic tape drives)
- Cathode ray tube (CRT) terminals (operator workstation)
- Communication controllers or modems
- Hard copy loggers

Additional peripherals that need to be considered based on the particular project operation requirements are as follows:

- Programming CRT terminals
- Line printer
- Laser printer
- X-Y plotter
- CRT screen copier
- Configuration panel
- Scheduling CRT terminals
- Training CRT terminals

The characteristics of these peripherals in terms of capacity, speed, and quantity are based on the planned system operation and expected growth of the project during the life of the SCADA system. For example, historical data records may necessitate additional disk storage capacity or additional magnetic tape drives.

The designers must work closely with the project operations personnel to encourage the necessary discussions that are required to determine the peripherals that are required for the particular project. The peripherals that are required to support real-time operations are based primarily on the master-station configuration and are usually determined as part of the overall supervisory control and data acquisition, scheduling, and optimization requirements of the system.

(3) **Man-machine interface equipment.**—The MMI subsystem consists of the operator's console(s), color CRT's, cursor control device(s), and keyboards. The operator's console design should be carefully planned so that the operator can communicate with the SCADA system in an efficient, simple manner. The console should be of modular construction to allow for modifying control room arrangements and convenient shipment. The main operator's console should have a minimum of two color limited graphic CRT's so that the operator can view overall system diagrams at the same time plots, trends, bar charts, or remote-site conditions are being viewed. The operators console should contain one operations keyboard with a cursor control device (lightpen, trackball, etc.).

The keyboard should contain special user definable function keys. Sample canal automation function keys are raise/lower, start/stop, alarm acknowledge, etc. The operations keyboard (also referred to as the alphanumeric keyboard) controls the editing and interface to the CRT display system. This keyboard is also used for alphanumeric entries required on the control displays. The CRT's should be built into the console to allow easy viewing and cursor control by the operator. A low-profile console design will be required if the operator must look over the top of the console to observe a large mimic panel. The CRT's must be mounted in the console in such a way that they will not obstruct the view of the operator. Sometimes, this type of a console design is not suited for lightpen or touch screen methods for cursor control; therefore, the designer must be aware of the "basic" console design decisions early in the project design.

**b. Master-station software.**—The two critical components of the master-station software are the operating system and the SCADA software. System operation will be enhanced if these two components are properly selected because the software will aid the operator in making decisions, or the system will make decisions automatically based on accurate real-time data and a well-defined set of rules. If neither the operating system nor the SCADA software are selected properly, the SCADA system will not function as effectively as is possible, and the operator cannot function as effectively as is possible; hence, system operation will be degraded. The severity of degradation depends upon how many critical factors were not considered or known when selecting the operating system or the SCADA software.

The following paragraphs and subparagraphs contain guidelines to aid in the selection of an operating system and SCADA software and to briefly discuss some of the more important features of operating systems and SCADA software. The larger and more complex a SCADA system is, the more important each of the following features becomes.

(1) **Operating system software.**—An operating system is defined as an organized collection of system programs that interface computer hardware (the central processing unit [CPU], disks, CRT's, printers, etc.), computer software, and users. An operating system provides the users with a set of tools to simplify the design, coding, debugging, and maintenance of system and application programs; at the same time, the operating system controls the allocation of computer hardware and software to assure execution of scheduled system and application programs.

The three basic types of operating systems are: batch, time-sharing, and real-time. An operating system is defined as real-time if it services on-line external processes having well-defined timing constraints that generate interrupt signals that direct the resources of the operating system. A SCADA operating system must be a real-time, interrupt-driven operating system.

The operating system components described in this manual are not all the components contained in any manufacturer's operating system. The operating system components described in this manual are those components experience has shown to be critical to satisfactory operation and maintenance of a SCADA system. Not all manufacturers have named the components of their operating system with the same name used to describe the recommended critical operating system components in this manual. It is vital that the features contained in each component description be performed by an operating component before the operating system is considered for use as part of a SCADA system.

**(a) Command control language.**—The operating system should be furnished with an extensive command control language. The command control language allows the SCADA system manufacturer to write command procedures that cause the master-station software and hardware to function as a real-time SCADA system.

**(b) Executive.**—The executive coordinates all CPU processing by performing the functions of task scheduling, resource allocation, queuing, software interrupt processing, and input/output (I/O) control. Queuing and scheduling processes must take place according to the type and priority of the request.

**(c) Device drivers.**—As a minimum, a device driver for each different piece of master-station hardware (disk(s), tape(s), printer(s), plotter, keyboard, communications ports, etc.) should be included as part of the operating system. Each device driver should operate in conjunction with the remainder of the operating system to process all I/O requests for the device. The operating system should identify the I/O device requested via the hardware vectored interrupt method and transfer control to the correct driver so the device dependent task can be completed.

**(d) Diagnostic software.**—Diagnostic software aids in producing and maintaining a high degree of confidence in system operation and aids in the reduction of MTTR. To accomplish the tasks of producing and maintaining a high degree of confidence in system operation and reducing the MTTR, two levels of diagnostic software should be included as part of the operating system:

**i. Periodic on-line diagnostics.**—On-line diagnostic software should provide periodic analysis of each piece of master-station hardware. Master-station hardware that should be analyzed periodically includes the CPU, the solid-state memory, the disk memory, the controllers, the printers, and all other peripheral devices. The on-line diagnostic software should detect failures or faults in the master-station hardware and should be periodically executed without being requested by an operator.

Periodic on-line communications diagnostic software should perform operational checks on each of the communication links and on the communication system hardware.

**ii. Off-line diagnostics.**—Off-line diagnostic software should provide detailed diagnostics for every piece of hardware that is part of the master station. These diagnostic routines should provide extensive printout and interactive input via a CRT and keyboard. These detailed device diagnostics should provide more details on device failures that have been identified by the periodic on-line diagnostics. The off-line diagnostics should identify a device failure down to the chip level.

**(e) System management services.**—The following system management services software should be provided as part of the operating system:

**i. System configuration.**—System configuration software should provide reconfiguration of the system hardware by assigning or deleting devices from the system based on device availability.

**ii. System backup.**—A disk memory management (DMM) utility should be furnished as part of the operating system. The DMM should operate on all types of disk and tape media furnished as part of the master station; i.e., hard disks, floppy disks, optical disks of all types, and tapes of all sizes and types. The purpose of the DMM is to provide an easy means of creating and modifying program and data records to the system. The DMM should assist in these operations by controlling and recording the allocation of disk memory. Disk memory management software should determine how the areas of disk memory are used and by what software. DMM should be structured to allow the programmer to create files (including naming them, locating them, etc.), delete files, append files, substitute files, concatenate files, merge files, move files, sort files, and display the contents of a file or the disk memory map on a designated output device.

**iii. Device utilization software.**—The operating system should include device utilization software that measures and outputs utilization data for the CPU and disk memory devices. The types of utilization data available upon request should include:

- CPU utilization.—Performance measurements of the CPU should consist of measuring processing time, bookkeeping time, and idle time. CPU utilization should always be the total processing time added to the total bookkeeping time and should be defined in percent utilization per second.

- Disk memory utilization.—Performance measurements of the disk memory should consist of processing time and idle time. Idle time is defined as that time when neither the write queue nor read queue has any memory transfer requests. Processing time is defined as that time in which memory transfers are being performed to and from disk memory and/or a queue has a memory transfer request. Disk memory utilization should always be the total processing time and should be defined in percent utilization per second.

**(f) System software tools.**—The system software tools should allow a programmer or operator to: (a) design, code, debug, and execute real-time application programs in a higher level language using the system data bases; and (b) maintain all existing SCADA software and special application software. The software tools provided should include as a minimum:

**i. Debugger.**—The debugger is the tool the software engineer or programmer uses to debug software. The more features the debugger has, the more user friendly the debugger is; and the more information the debugger provides to the user, the better the debugger.

**ii. Performance analyzer.**—The performance analyzer collects data concerning the performance of software being developed (e.g., the analyzer determines processing time, paging time, disk utilization time, memory utilization time, etc.). This software is a must if applications are going to be added to the SCADA system after acceptance of the SCADA system.

**iii. Math library.**—A STANDARD mathematical and statistical library eliminates the need for reproduction of existing and accepted mathematical processes, functions, etc. The math library should include arithmetic, trigonometric, logarithmic, exponential, statistics, curve fitting functions, etc. All math library functions must be "called by name" from the high-level programming language or from the assembly language.

**iv. Assembler.**—An assembler is a language processor that translates a sequence of machine language instructions into an executable object file. The assembler should output a listing of the source (input) file and the assembled object file to the requested peripheral. The assembler should output comments concerning syntax errors, unsatisfied reference, etc.

**(2) SCADA software.**—SCADA software can be easily divided into components just as operating system software can be divided into components. The SCADA software components described in this manual are not all the components contained in any vendor's SCADA software. The SCADA software components described in this manual are those components believed to be critical to satisfactory operation and maintenance of a SCADA system. Not all vendors have named the components of their SCADA software with the same name used to describe the recommended critical SCADA software components in this manual. It is vital that the function contained in each component description be performed by a SCADA component before the SCADA software is considered for use as part of a SCADA system.

**(a) I/O points data base manager.**—The I/O points data base manager is used to generate, maintain, and modify the SCADA system's I/O points data base. Use of the data base manager must be password protected, and the data base manager must be interactive.

The data base manager should request each required data entry from the user using a template. The use of a template or templates helps to create a more user friendly environment. Data formats should be representative of the data base point and its associated attributes. All data base entries must be checked for reasonability and validity before being accepted. During modification, old values should be displayed in conjunction with new values within an entry area to increase speed and accuracy. Users should be able to enter the data required for data base generation through any of the system peripherals. Inputs required for data base(s) generation should be user oriented and consist of the following types of information:

**i. System data.**—Complete definitions of all the inputs and outputs of the system, including input origins and output destinations (RTU name), scan times, priorities, etc.

**ii. Calculated data.**—Complete algebraic equations defining calculated analog data as well as Boolean equations defining calculated status data.

**iii. Alarm data.**—Complete definitions of all alarm limits, messages, and conditions.

The I/O points data base manager should be able to output complete and detailed hard copy data base(s) maps for user reference.

The data base editor should be furnished as part of the data base management software. The data base editor should be furnished with adding, deleting, and changing functions. Any data base parameter affecting system performance and operation should be modifiable using the data base editor. The data base editor should execute from any workstation or console in the system. As a minimum, the data base editor should perform the following:

- Add, delete, or change any data point in the system
- Change any equation that defines calculated data
- Modify I/O terminals
- Add new RTU(s)

References made to points in the system data base by an applications program should be made directly by device designation, not by RTU device address. When a data point is defined, its device designation should be defined. All further references to that point should allow use of the device's designation number.

Modification to the data base should be buffered; direct modification to the system's on-line data base is not recommended. A copy of the old (unmodified) data base should be maintained while the new data base is verified. The new data base should be verified by being placed on-line. Following verification, the new data base should be given permanent status. At any time during the verification process, the programmer or operator should be able to command the system to revert to operation using the old (unmodified) data base.

**(b) High level programming language.**—The SCADA system software should be written in a high-level programming language. The high-level programming language should have real-time extensions for operating in a real-time environment defined by supervisory control, data acquisition, CRT display, and logging requirements. The high level programming language should be an accepted standard (ANSI, IEEE) high level programming language.

**(c) CRT display compilers.**—A CRT display compiler must be provided for the generation of new color CRT displays and modification of existing CRT displays. These display generation and editing facilities should allow on-line production of CRT graphic and alphanumeric displays of any format. The programmer or operator should be able to specify all parameters, including color designations, required to generate both alphanumeric and graphic displays. The dynamic data control points and data entry fields shown on displays should be automatically established by the compiler. The linkages should be designed such that any data base(s) modification(s) (even those modifications resulting in insertions into a table or file and changes in table or file sizes) do not require redefinition on existing displays.

- Data entry fields, control points, and poke points may be selectively added, relocated, or deleted from new or existing displays.
- Color may be associated with individual characters when defining the fixed portion of displays.
- Different characteristics, such as the number or type of characters, color, blink, etc., should be definable for the same data point being displayed on different displays or on different portions of the same display.
- Any data field on a display may be defined by the user as nonenterable or enterable dependent upon the mode of the workstation on which it appears.
- Reasonability limits or references to special conversion calculations should be associable with each data entry field.
- Any display may contain dynamic data fields presenting data acquired from any number of RTU's.
- Any data may be shown on more than one display.
- Dedicated alarm display and message entry areas should be user assignable during the definition of the display(s) format.
- Any data field on a display may be defined as controllable or noncontrollable dependent upon the mode of the workstation from which control is being attempted (only if hardware to control the point associated with the data field exists).
- The software should allow the programmer or operator to edit text strings.
- The software should allow the operator to copy functions or any part of a CRT display.

**(d) Data archival.**—As data are collected by the system, provisions must be made for archival or deletion. The method of archival and the quantity of data stored will determine the type of archival system required. As large amounts of data are stored, the archived data can be off-loaded to tapes or optical disks and stored onsite or offsite.

**(e) Inventory records.**—Spare part inventory management software can be furnished to allow spare equipment and parts to be identified and to provide total records management. The spare part management system is interfaced to the SCADA data base.

**(f) Maintenance records.**—Maintenance scheduling and management software can be furnished to allow equipment to be identified for maintenance based on maintenance data information entered into the scheduling system. Equipment or systems requiring periodic maintenance can be automatically identified when the equipment or system has reached an in-service time that would indicate preventive maintenance is needed. The maintenance scheduling software should be interfaced to the SCADA data base.

**(g) Report writer.**—A report writer should be provided as part of the SCADA MMI software. The report writer should be menu driven, should stack menus, and should allow the user to define both content (input and output data and comments) and format (layout) for reports or logs made from active data files or historical data files containing the following data:

- On-demand snapshots of one or more real-time data items
- Periodic (hourly, etc.) snapshots of one or more real-time data items
- Hourly or half-hourly accumulator data
- On-demand snapshots of one or more calculated values
- Periodic snapshots of calculated values
- Conditional snapshots of one or more real-time data items
- Conditional snapshots of one or more calculated values
- Conditional statements including "if then" blocks
- "Go to" statements

The report writer should provide the user with the following report/log building features:

- Access to all data base items
- Algebraic calculation capabilities using both numerical data base items and constants; arrays for calculating, storing, and reporting data within the report writer
- Boolean operation capabilities using any logical data base items
- Automatic page and margin handling using either default or specified values
- Summation, multiplication, exponentiation, division, maximum or minimum determination, addition, subtraction, logarithmic operations, statistical analysis, averaging, subtotals, and totals to be performed on report or log data on a column or row basis
- Page line location specifiable by either an absolute line number or as a displacement from the previous line
- Columnar location of data specifiable by either an absolute column or as a displacement from the previous item within the line
- Data conversion and output formatting support for:
  - Alphanumerics with optional right and left justification
  - Decimals with automatic insertion of the decimal point, +, -, and $ signs
  - Automatic insertion of commas to separate groups of three decimal digits
  - Scientific and engineering notation
  - Automatic zero suppression of leading zeros with defeat option
  - Optional suppression or inclusion of variable numbers of trailing zeros to the right of the decimal point
  - Automatic daylight savings time handling
  - Optional precision selection of report data

Conditional capabilities should be provided to allow the production of reports or logs based upon the occurrence of some events (i.e., a status change, analog limit excursion, etc.). The following additional capabilities should be provided:

**i. Editing.**—

- Report or log addition
- Report or log modification
- Report or log deletion

**ii. Output control.—**

- Demand outputs, executing any named report on demand
- Scheduling periodic outputs
- Output device selection and assignment
- Conditional outputs

**iii. Miscellaneous.—**

- Line numbering
- Report or log and row-and-column headings
- Default value entry (for data flagged as not updated; and values not found, out of range, beyond format capabilities, etc.)
- Complete flexibility in creating printing formats and error messages
- User (operator) definition and location of labels and user (operator) definition of variables
- User (operator) definition of borders, tables, and associated column headings, row descriptions, and titles; user definition of the location of all column headings, row descriptions, and titles
- A "Help Menu" that can be entered by pressing a certain key

**(h) Man-machine interface.—**The MMI software allows the system operator to control and monitor the SCADA system. The physical access to this software takes place through CRT display screens, keyboards, pushbuttons, and other hardware.

The software should present all possible system information in an easy to understand form and should enable the operator to control the system as efficiently as possible. The following functions are often included in the software:

**i. CRT displays.—**The interface to system information and control occurs via the CRT displays. The operator interacts with these displays using cursor control devices. The operator should be allowed to select and page through all available displays in an orderly manner.

The date and time are usually shown on every display. The date is automatically updated by a software perpetual calendar including leap years. The time is updated each second. The software should be designed to allow the time to be adjusted for daylight savings time.

Color is usually used as the primary means of conveying information through the screens. Flashing of symbols and text is used to call attention to specific displayed information such as devices in alarm, device selection, alarm messages (unacknowledged), and erroneous manually entered data. The colors and flashing of symbols and text should be consistent on every display. Inverted color (a black character in a color background) can be used to highlight text and should be used in a consistent manner on every display.

Some typical color conventions are as follows:

- *Alarm acknowledge status*: normal (discrete equipment)—the annotation is not displayed, normal (analog equipment)—white, unacknowledged alarm—blinking yellow, acknowledged alarm—yellow, and unacknowledged return to normal—blinking white
- *Motorized equipment*: unavailable—yellow, ready—green, running—red, and failed—blinking yellow

Other items that should be represented by colors are gate and valve position, status of analog measurements, equipment tagging, and computer system status.

Appended characters and annotations are shown next to items on the display screens. These items can be used to provide indications pertinent to data points and information appearing on CRT displays. A consistent scheme for portrayal of these indications should be used to minimize the potential for confusion. Appended characters and annotations should be easily distinguishable from data or device symbols to which they are appended. This distinction should be accomplished through the use of either color or positioning. Typical indications that can be provided by appended characters and annotations are the presence of tags, alarm conditions, or the control mode of a device.

Three different methods of presenting numerical data are typically provided. The first should allow the actual numerical value to be displayed with sign and units information. The second should allow numerical data to be presented in bar chart form. The third should allow numerical data to be presented in line graph (trend) form.

A multilevel hierarchical scheme is desirable for presenting information on displays. System level displays provide the operator with information from the entire system (i.e., data acquired from more than one RTU). RTU level displays should provide data acquired from one RTU. Additional levels of displays may be required.

Special display groups can be allocated for system-oriented displays such as menus, indices, summaries, and overviews. A typical display organization scheme is as follows:

- System level displays include alarm summaries, analog bar charts, analog line graphs (trends), analog limits, communication system status and activity, configuration control or indication, deactivated data summaries, deactivated RTU summaries, event summaries, index display, index display to provide selection of all major CRT displays in the system, maintenance (general), SCADA system maintenance logs, one-line displays menu, reports menu, RTU menus, substituted data summaries, system overview display menu, and tag summaries.
- RTU equipment level displays include alarm summaries, alarm lists, alarm inhibit summaries, alarm inhibit displays, annunciator list, deactivated data summary, one-line diagrams, outage summaries, tag summaries, and lists of all input and outputs. The display should list all applicable alarms and inhibits that are active. Alarm lists should display all alarms (acknowledged and unacknowledged) that have not returned to normal.

**ii. Invalid request, timeout, and control failure.**—An "Invalid Request" statement appears on the CRT whenever the operator performs a function incorrectly or out of sequence. Typical error statements are: page number is invalid, device under clearance, and no more than one control point may be selected at one time.

After occurrence of an invalid request, the "Invalid Request" statement disappears when the operator selects "CANCEL" or a new function. New control actions should be inhibited until the invalid request is inactive.

The "Timeout" statement should appear in flashing white on the CRT whenever one of the selection features has timed out. The window presently displayed and the flashing device should be cleared from the screen when the timeout occurs. Also, the "Control Failure" statement should appear in flashing white on the CRT whenever a controllable device has failed to operate after proper initiation of a control action by the operator.

**iii. Display request or access procedures.**—A SCADA system requires many different display screens. Overall screens show the entire system. Various other screens, including alarm lists, individual plants, and individual pieces of equipment show parts of the system in greater detail. The large number of screens in a SCADA system requires an organized system to make accessing the screens as simple as possible. A target may appear on the screen, or a function key on the keyboard may be used for selecting displays. Methods of selecting displays include the following:

- Direct.—These schemes directly request a specific CRT display:
  - Selection from an index list.—The cursor is placed on the desired screen on a list. The lists could be subdivided into smaller lists.
  - Selection from alphanumeric code.—Each display has a number which is typed in. This method can be difficult for a large system which would have a large number of displays, but can be useful as a secondary method of selecting screens.
  - Selection from targets.—Labeled targets may be selected by the cursor to access specific screens.
  - Selection by device.—Selecting a device with the cursor can bring up a display showing available commands and information.
- Indirect.—Requests for displays may also be the result of indirect actions. The following are types of indirect display requests:
  - Alarm lists.—A visual alarm indication can be provided in the display header area of all displays to request specific alarm list displays.

- Previous page requests.—Selection of the "previous page request" key causes the current display to be replaced by the last display.
- Page forward and backward requests.—Displays within a particular display group are sequentially accessible through use of these keys. "Page Forward" and "Page Backward" keys are often required for multiple-page listings, such as lists of alarms.

It is desirable to have more than one option available for selecting displays.

**iv. Data entry procedures.**—Text and numbers must be entered into the system at various times. Text includes entering free-form data into messages.

Numbers include:

- Entering numbers into predefined entry fields for use as operating/analog/setpoint limits and operating parameters
- Data to be entered to override a status or numerical data value which is known to be in error

**v. Deactivate or reactivate point or RTU equipment.**—Removal of input and output points from the system for testing purposes is sometimes desirable when doing maintenance on the system. Typical requirements are as follows:

- Deactivation.—Deactivated points should be displayed on the screens using a separate color and should retain the last known value. Any calculated values that use deactivated points should use the last known value and should also be displayed as deactivated. Deactivation of an RTU should deactivate all I/O points associated with the RTU. No control activities should be possible through a deactivated RTU. Deactivation of groups of points is also desirable. CRT displays summarizing all deactivated points or RTU's should be provided. Operators should be able to manually enter replacement values or states for deactivated points using either manual entry or manual-override procedures.
- Reactivation.—The operator should be able to reactivate deactivated points and RTU's. Reactivation should cause information from reactivated points or RTU's to be used by the master station to update the data base. Reactivation of an RTU should only reactivate those points which were deactivated as a group with the RTU. Points which were individually deactivated should remain deactivated until individually reactivated. Reactivation of an individual point from an RTU which has been deactivated should reactivate only that point.

**vi. Device tagging.**—The SCADA system must be updated when devices are taken out of service. Tagging is used to indicate restrictive operating conditions and prevent certain control operations. Complete records of tagging can be stored in the data base for report production. Tags are usually indicated by color-coded alphabetic characters displayed adjacent to the devices with which they are associated. Types of device tags should be determined by the people performing the maintenance.

After a tag is placed on a device, the system should prevent supervisory control of tagged devices. The ability to place multiple tags on a device is desirable. The indication of a device's highest precedence tag should be displayed in inverted video whenever more than one tag is active on a device.

**vii. Supervisory control procedures.**—Displayed graphic symbols can be used as the targets for associated controllable devices. Target selection, through either cursor or text select methods, should cause the graphic symbol to flash. Control-related information should be presented when a controllable device is selected. This information should include the special condition tag messages and valid "next-step" selections. "Next-step" choices should be identified during the control sequence process by displaying windows of all possible control commands. The "next-step" options presented should take into account the current condition of the controllable device. Each selection made during the control sequence should result in new indications of "next-step" choices. A selection should be rejected if:

- The device is not under supervisory control.
- The device's control is software inhibited because of the presence of a tag.
- The control point associated with the device is deactivated or the entire RTU serving the device is deactivated.
- The control selection requested is not valid.
- An excessive period of time (programmable parameter) has elapsed since the last selection took place during the control sequence.

The rejection of a selection should be accompanied by a message appearing on the CRT explaining the reason for the rejection. Rejected selections should also be logged on the event logger.

Several control types that can be controlled through supervisory control procedures are defined below:

- Two-state control, such as turning a pump on and off, can be performed simply by selecting the device and then selecting the control function desired.
- Incremental control is attained when a device such as a gate is opened a small amount at a time. This process can be performed by selecting the device and then selecting a jog function repeatedly (to jog the device to the desired position) or entering a value specifying the number of incremental control actions desired and then depressing an EXECUTE pushbutton.
- Setpoint control is attained when a result is desired, such as a certain waterflow. A gate can be raised and lowered to maintain the flow. The operation of the gate would be similar to two-state control, except that a setpoint entry field would be provided for entry of the desired flow. All setpoint entries must be subjected to reasonability and limit checks. Appropriate messages should be provided when entry errors are detected. If a new setpoint is not entered, the setpoints should retain their previous values.

Verification must take place upon each operator selection to check the validity of each selection step. When a control action has been selected and validated, an indication should be given to the operator to indicate that the selection was valid and the system is prepared to EXECUTE the command.

The EXECUTE function should cause the necessary control routines and confirmation software to be initiated.

Upon the system's acknowledgment of the EXECUTE command, the operator may proceed to other displays and actions, prior to completion of the confirmation process, without affecting its execution. The results of the confirmation process should be displayed to the operator upon completion.

The operator should have the option to cancel the control sequence at any point in the selection sequence for device control. Depressing a "Cancel" key should abort the command sequence and return the display to the previous state.

A time delay is usually provided to cancel devices selected for control if the operator has not taken the next required step of control action. The time should be reset and restarted each time a valid device selection is made in the control sequence.

Some typical control modes for devices are as follows:

- Local manual mode.—All control is accomplished by an operator locally from the control board at the device. All supervisory control from the SCADA master is disabled when the equipment is in the local manual mode. When a device is in the local mode, a mode switch is used to physically inhibit RTU control. When the mode switch is in the "LOCAL MANUAL" position, a color coded "LM" is displayed adjacent to the device symbol on each appropriate display.
- Local automatic mode.—The process control is accomplished by local automatic control equipment (local relays or programmable controllers) located at the control board. All supervisory control from the SCADA should be disabled when the mode switch is in the "LOCAL AUTOMATIC" position. Whenever the mode switch is in the "LOCAL AUTOMATIC" position, a color coded "LA" is displayed adjacent to the device symbol on each appropriate display.
- Supervisory mode.—All control is accomplished by the RTU equipment in

conjunction with the SCADA master. Whenever the mode switch is in the "SUPERVISORY" position, a color coded "S" is displayed adjacent to the device symbol being controlled by the RTU on each appropriate display.
- Clearance mode.—All control is locked out for the purpose of maintenance, failed equipment, etc.

General types of control options for equipment devices are as follows:

- Pump units.—The following control options can be provided for pumping units: start, stop, lockout, and speed control.
- Gates and valves.—The following control options can be provided for gates and valves: raise, lower, open, close, setpoint, emergency close, and emergency raise.

**viii. Events or alarms.**—An event is a non-emergency condition, such as changing a mode switch from local to remote. An alarm is an abnormal condition that requires immediate attention from the operator. Events and alarms must be in the system so the operator has full knowledge of the condition of the system being controlled and monitored. Too many events and alarms slow down the system and overwhelm the operator with information that cannot be assimilated in a short period of time. Alarms should be grouped into different classes depending on the degree of urgency. System designers should classify alarms during system design.

- The occurrence of an alarm should cause audible and visual indications. Different audio tones can be used to differentiate between different types of alarms.
- Visual indication.—Visual indication of an alarm condition should be given in a reserved area of the display header. The indication area should include a target which, when selected, causes page 1 of the alarms list to be displayed. The alarms list displayed should be the list for the area from which the alarm was reported. If more than one alarm is reported at the same time, the alarm list for the area reporting the lowest numerical class of alarm should be displayed. If the target is selected again, the area alarms list for the area reporting the next lowest numerical class of alarm should be displayed. Repetitive selection of the target should step through all area alarms lists possessing active alarms in order of increasing class number.

Devices on CRT displays should visually indicate an alarm condition by flashing. The color of the device should continue to indicate the state of the device.

The word ALARM adjacent to the alarm target should indicate an alarm by flashing and changing color to inverted yellow. Selection of the alarm target should cause page 1 of the alarm list to be displayed.

Unacknowledged alarm conditions should be indicated on the alarm lists by flashing the alarm message. The message should be displayed with a color code to indicate the class of the status or analog/binary coded decimal (BCD) change as described in the subparagraph on color and flash standards.

Numerical data (limit information) that are displayed and are at or beyond limit settings should indicate the alarm condition by flashing and changing color.

The alarm list information should include date and time of occurrence, area identification, device designation, and alarm description

Alarm acknowledgment, acknowledgment indication, and silencing.—These functions should only be performed in the same workstation mode category as the workstation from which acknowledgment is permitted.

- Silencing.—A silence function should be furnished which causes the audible alarm indication of the lowest numerical class of existing alarms to silence each time the function is activated. To completely silence simultaneous alarms in differing classes, the silence function should require activation several successive times. The silence function should be activated through depression of a SILENCE key.
- Alarm acknowledgment.— Acknowledgment of an alarm should be possible from any single-line, tabular list, station

alarm list, or system alarm list CRT display on which the alarming point, numerical data item, or alarm message appears. Acknowledgment should be accomplished by positioning the cursor on the alarming point, numerical data item, or alarm message and depressing an ACK (acknowledge) key.

- Acknowledgment indication.—The CRT displays should be returned to their pre-alarm condition, and alarm bells should be silenced once alarms are acknowledged.
- Master-station equipment alarms.—Alarm and event status inputs are usually provided for all master-station equipment. These status inputs indicate alarm or event conditions for the following equipment: CPU's, disks, printers, and workstations. Alarms are also provided for master-station software errors (traps) and communication system failures.

**ix. Logging.**—Each event, alarm, and control action can be printed on a logger. Events and alarms can be assigned to separate loggers. Messages are usually one line in length and similar to the CRT displayed message. Each log message usually contains the designation of the point or device and the abbreviation of the site that pertains to the message. Date and time information is usually included in the message. The date and time reported should be the detection time (RTU time tagged time) for the alarm or event which initiated production of the message and the time the control was executed for control action messages.

- CRT printing or copying.—At the operator's option, a printout of any CRT display from any workstation can occur through use of a PRINT CRT function. Access to the function can be by selecting the PRINT CRT target on the CRT display. The display on the requesting workstation is output to the selected printer when the PRINT CRT function is requested. The CRT display in its entirety is printed (all static and dynamic information). Any notes or comments manually entered on the screen prior to the PRINT CRT request should also be printed. The CRT display as it exists when the PRINT CRT request is made should be printed. If a PRINT CRT request cannot be accomplished when requested, a "PRINT CRT busy" message should be output on the CRT of the requesting workstation. A busy message should not inhibit workstation operation.
- CRT line graphing (trending).—Features can be provided which allow operators to assign data base resident numerical points for line graph recording. Assignments should be made on line graph assignment CRT displays that allow duration and other line graphing parameters to be specified for each assigned point. Line graph selection CRT displays should be provided to permit an operator to specify up to six line graphs to be displayed on a selected workstation CRT. Points being line graph recorded should be stored in the historical data base. Scaling values and offsets should be automatically established from the limit and conversion data associated with the numerical points being recorded. Operators should be able to override automatic scaling and input their own values through use of line graph assignment displays.

  Line graph displays can be used to show the changes in values over time.

- Bar charting.—Features can be provided to allow operators to assign any numerical data base quantity to be a horizontal or vertical bar chart. Also, features should be provided to allow quantities to be plotted in stacked bar chart form. Assignments of quantities should be made on bar chart CRT selection displays that allow the bar chart parameters to be assigned to each charted quantity. Bar chart selection CRT displays should be provided to permit an operator to select up to 16 recorded numerical quantities to be bar charted on the selected workstation. Points being bar charted can be stored in the historical data base.

**x. Reports or logs.**—The report or log feature should be interactive and normally interface with users through any workstation.

Modifications to the data base(s) should not necessitate redefinition of existing reports or logs. When desired by the operator, changes made to one report should ripple through to other associated reports.

The operator should be able to produce both prescheduled and on-demand reports. Prescheduled reports are produced automatically at specific times such as hourly, daily, and monthly. On-demand reports are printed at the operator's request. Reports can be stored in memory, output to disk, or output to printers. A separate logging device is often used to print out alarms only so that it is not interrupted by noncritical reports.

Typical daily reports are as follows:

- A report listing tag placements and removals
- Reports that summarize all analog or BCD limit violations which result in alarms
- Reports that summarize the communication errors to all remote sites, local sites, and external communication channels

A typical on-demand report might involve SCADA system equipment performance. This report should be a log of all detected SCADA system equipment failures and resource monitoring data collected during the time prior to the report request. Specific information to be presented on the report would include:

- CPU failures (local area network, Master, FEP)
- Workstation failures (CPU, disk, keyboard, trackball, mouse, etc.)
- Logger failures
- Disk failures
- Line-printer failures
- I/O equipment failures (RTU's, RTU cards, etc.)
- Communications equipment or processor failures (modems, network interface cards, etc.)
- System resources monitoring data such as daily peak, average, and minimum CPU, auxiliary memory, and I/O channel utilization

Each report entry should contain the following information:

- Time of report entry
- Device identification (or report entry identification)
- Failure information (if the report entry is for a failure)
- Monitored and calculated resource information (if the report entry is data from the resource monitoring function)
- Deactivated points report.—This report should list all status, analog, and BCD points which are deactivated at the time the report is requested. The report should additionally include data on those points which have been manually over-ridden. The report entries should be sorted by RTU abbreviation.

(i) **Workstation partitioning.**—A large system sometimes requires more than one operator at separate workstations. Each workstation is limited to certain functions depending on which mode it is currently in.

The partitioning scheme should allow control capabilities and information to be segregated and assigned to workstations only as necessary to allow personnel to perform their duties. The scheme should allow workstations in any partition access to all CRT displays but should restrict applications usage, control, tagging, data manipulation, alarming, and acknowledgement capabilities in accordance with partition definitions.

A CRT display that assigns partitions should be provided. Use of the display should only be possible from workstations partitioned for the configuration mode. All partitions should be assignable from this display except that for the configuration mode. A method should be provided which allows the automatic, preprogrammed reassignment of workstation partitions in cases of workstation failure.

Workstations should operate in only one partition at a time. Workstations should be assignable to more than one partition (i.e., given permission to operate in the partition). The workstation modes are: operations, configuration, observation, training, and programming and engineering.

(3) **Network management software.**—Each network should have its own network operating system (NOS). Each NOS must be compatible with each associated CPU operating system. Each NOS should supervise and monitor the allocation and utilization of the network resources. Each NOS should detect network malfunctions, support normal supervisory control and data acquisition operations,

and provide an efficient method for communications between the SCADA system components. Each NOS should support multiple users in a multiple programming environment. Each NOS should be furnished so it is 100-percent expandable without any modification; i.e., if 8 nodes are required for the SCADA system, the NOS should support 16 nodes. On-line diagnostic software should provide periodic analysis of the master-station hardware and should detect failures and faults in the master-station hardware. Master-station hardware that should be analyzed periodically includes the CPU, the solid-state memory, the disk memory, the controllers, the printers, and all the other peripheral devices. On-line periodic diagnostic software should be periodically executed without being requested by an operator.

Each NOS should protect all network parameters against inadvertent or unauthorized modification. A backup procedure should be provided to restore the system and ensure fast recovery in the event of hardware failures.

**(a) Network management.**—The NOS should include the functions of a network manager. The network manager should maintain information on every subscriber or node in the network and present this information in the form of reports to the operator for use in determining the condition of the network. The NOS should provide the necessary software to enable a programmer to use the operator's workstations to access reports. The reports generated by the NOS network manager should provide the following information as a minimum:

- Number of characters passing through a subscriber or group of subscribers in a predetermined timeframe
- Overloaded network trunks or nodes
- Underused network trunks or nodes
- Misconfigured network
- Remote configuration
- Installation and distribution of software
- Restoring and backing up files

**(b) Network control.**—Each NOS should support both menu-driven and command language control by the operator.

**(c) Network security.**—Each NOS should include the following network security functions:

- Error checking software
- Memory management software
- Parity checking
- Access restrictions giving subscribers access to only specific applications or systems
- Password safeguards requiring users to provide a password to access specific applications on a particular system.

**(d) Network diagnostics and maintenance.**—The diagnostic and maintenance software is required to maintain the reliability and availability of the network. Network operating system software should have the following diagnostic functions as a minimum:

**i. Periodic on-line diagnostics.**—This software is periodically executed without being requested by the operator. Errors encountered by the periodic on-line diagnostic software are usually output to the system administration console. The SCADA system operates more efficiently if these error messages are retrieved by the SCADA software and output to the operator's console and printed on the alarm or event logger, depending on the nature of the error.

**ii. On-demand on-line diagnostics.**—This category should be designed to run only upon request of the operator and should be initiated through an operator's workstation. On-demand diagnostics may temporarily suspend an on-line periodic diagnostic. The diagnostic software should provide the means to enter operational parameters required by the selected diagnostics. The software should provide hard-copy messages to be output on a logger during execution of the diagnostic program. The on-demand on-line diagnostic software should be designed to test every device in the network. This software should be used for detecting and isolating hardware device malfunctions. This software should be designed to execute on an individual basis to completion, unless it is aborted by the operator. Some of these diagnostics will necessitate that the system usage of a particular device be temporarily halted and its use rerouted to another device, if available. Errors detected while executing this software should output descriptive messages on the appropriate logger.

## 11-7. Remote Terminal Units

**a. Hardware.**—The RTU is located at the remote site and serves as the master station's eyes, ears, and hands with respect to interfacing to the RTU. Modern RTU equipment employs microprocessors to handle all of the functions of data collecting, equipment control, communication security encoding and decoding, communication protocol, self test, diagnostics, and closed-loop process control. Using microprocessor-based RTU's allows a high degree of flexibility and functional capability in the operation of the SCADA system.

The RTU should be furnished with more than one communication port to allow interfacing to RTU test sets and more than one SCADA system if multiple entities require access to the RTU.

Built-in diagnostics are one of the most important features of the microprocessor-based RTU. These test programs provide a convenient and economical method of performing RTU hardware maintenance. Another important feature of the microprocessor-based RTU design is the ability to store programs in a nonvolatile read-only memory (ROM) and allow the changing of parameters or limits using an additional memory that can be altered from the master station over the communication channels. The ability to modify parameters via the communication channel offers significant operational flexibility for the SCADA system.

The RTU software is usually referred to as "firmware." Firmware is simply software that has been committed to a ROM device. If the software was not located in a nonvolatile memory, such as ROM, then the program information would be lost each time the power was interrupted. Having the software reside in nonvolatile ROM (programmable read only memory [PROM] or erasable PROM provides nearly instant recovery and availability of the RTU after a power interruption. Peripheral devices that might be used for loading software into volatile read/write memory are not compatible for use in the harsh environment of a remote site and would add significant cost to each RTU. The alternative of downloading the software from the master station over the communication channel affords flexibility for changing program parameters, setpoints, etc., but can cause a significant delay in putting an RTU back in service after a power interruption. Therefore, the information that is downloaded and alterable at the RTU needs to be carefully considered so that system performance is enhanced and not degraded by downloading of software.

The RTU should be furnished with sufficient battery-backed random access memory to store time tagged RTU data in the event of an RTU-to-master-station communication failure. The backup memory should be of sufficient size to log data for a user-specified time period, commonly 24 to 72 hours.

Spare memory, I/O channels, and associated cards should be provided for future RTU expansion.

The RTU microprocessor hardware should have a fail-safe (watchdog) timer or other failure-detection feature which will assure that all control or output functions remain in their inactive state during hardware and software failures and that upon power fail or power up, control outputs do not generate impulses that result in unrequested control actions.

The RTU should be furnished with a disconnect switch that disables all discrete outputs so output signals from the RTU will not operate external devices during testing or maintenance procedures.

**b. Data acquisition and control.**—The RTU equipment must be capable of interfacing to the various site equipment in order to collect status, alarm, and telemetry data and to be able to control the equipment. The accuracy, resolution, and throughput should meet or exceed the accuracy, update times, and control requirements necessary to satisfactorily operate and meet the overall SCADA system requirements. Each input and output should be individually fused and optically isolated. The external equipment interfaces are basically the same for any RTU application and include the following:

- Control inputs
- Control outputs
- Analog inputs
- Analog outputs
- Digital inputs
- Digital outputs
- Pulsed inputs

**(1) Control inputs.**—Control inputs provide information on the "state" of the equipment (open/closed, on/off, etc.), the position of switches (backup/normal, manual/supervisory, etc.), and alarm conditions (power failure, high limit, etc.). These major types of control inputs can be categorized as follows:

**(a) Electrically separate binary input (ESBI) type.—** The ESBI type is a dry contact input with two states. The states are either "open" or "closed."

**(b) Voltage supplied binary input (VSBI) type.—** The VSBI type is a contact operation that supplies a voltage indication of the state of the contact. The states are "no-voltage/open" or "voltage/closed."

**(2) Control outputs.—**Control outputs are designed to withstand the high-energy electrical transients associated with the switching of high-inductance loads. Control outputs are normally momentary operation type with typical operation times of 250 milliseconds to 10 seconds. Applications that require a "maintained" type of output or latching type output are performed by special applications programs within the RTU.

Operation of critical equipment requires select-before-operate (SBO) security operation, and the output types must be designed to ensure that only the correct control output is operated. In addition, some RTU's will allow only one control output to operate at any one time to further enhance operation security. The SBO security scheme provides for an end-to-end system check whereby the master station sends a control output select message and receives a check-back message from the RTU before an execute command is accepted or issued.

An additional safeguard to prevent incorrect control output commands would be a timer that only allows the control output to be selected for a few seconds. In some applications, such as closed-loop process control, the SBO operation may not be desirable, so some control outputs may be used as direct operate types. In applications such as automatic generation control, the required raise and lower pulse outputs are of the direct control type.

The control outputs provide the interface between the RTU equipment and the site facility equipment to allow the site facility equipment to be controlled from the master station. The type of control outputs will vary depending on the type of device that requires control. The major types of control outputs can be categorized as follows:

- Solid-state discrete output (SSDO) type.— The SSDO type consists of compatible signal "contact closure" developed by a solid-state device (either a silicon controlled rectifier, triac, or transistor). These devices are used to operate the equipment directly without using "interposing electromechanical relays" and are suitable for card or printed wire board mounting for high-density packaging. Many control outputs and no-maintenance requirements dictate the use of SSDO type control outputs.
- Electrically separate discrete output (ESDO) type.—The ESDO type consists of electromechanical relay contacts. These outputs are used to operate control equipment when few control outputs are available and space is available for mounting the individual relays. Also, these outputs are well suited when multiple contacts are required to operate the equipment or are required to switch high inductance loads.
- Electrically separate discrete output dual (ESDOD) type.—The ESDOD type consists of two electromechanical relays and associated contacts. These outputs provide dual contact outputs for the control of two-state devices that are inherently self-latching. Devices that require two-state type outputs are power circuit breakers (trip/close), motors (start/stop), and electrical set/reset types of devices.

**(3) Analog inputs.—**The analog input (ANI) type will accept a variable direct-current signal. The direct-current signal represents a telemetry value such as volts, flow, position, etc., and is derived from instruments equipped with an electrical transducer. The input quantity can be either a voltage or current. The analog signal inputs are multiplexed within the RTU and each is sampled using one common analog-to-digital converter. The design of these inputs must be carefully considered to prevent unwanted electrical noise and transients from causing incorrect instrument readings.

**(4) Analog outputs.—**The analog output type will produce a variable direct-current signal. The signal produced is either a voltage or current and is proportional to a digital quantity. These outputs are usually used to operate direct-current recorders, and the variable direct-current voltage output can be used to control variable speed motor controllers.

(5) **Digital inputs.**—The binary coded decimal input (BCDI) type will accept parallel digital binary coded decimal data (8421 code). The binary coded decimal data is usually derived from absolute digital encoding equipment. The BCD data is usually used to indicate equipment positions or water levels when resolution to the hundredth of a foot is required. The BCD data is in the form of 3-digit, 4-digit, 5-digit, or 6-digit decimal data.

(6) **Digital outputs.**—The binary coded decimal output type is represented as BCD data. This type of output is rarely used but could be used to drive local digital displays, providing an indication of setpoint values or process variables.

(7) **Pulsed inputs.**—A pulsed input circuit will accept a momentary pulsed contact closure. Pulsed signals can be derived from wattmeters and flowmeters. The pulsed signals are input into the RTU and are totalized or accumulated.

c. **Operator interface requirements.**—The RTU should provide an operator's panel to allow: control of local devices, the entry of setpoints and schedules, indication of RTU analog and BCDI variables, checking or changing the RTU data base, checking RTU operating conditions (battery voltage, RTU temperature, system time, etc.), and input algorithm parameters. The operator's panel should be provided with coded access to the RTU to prevent unauthorized access to the operator's panel functions.

d. **Power supply requirements.**—The power supply should supply power to all of the RTU components, including analog transducers and ESBI and SSDO wetting voltages if required. The power supply primary power input should be transient protected to limit input peak voltage to a 200-V maximum within 5 nanoseconds. Over-voltage protection to open the primary power circuit if the input voltage exceeds 135 V root mean square within 5 nanoseconds should also be provided. The protection circuit minimum power dissipation should be sized according to the total RTU load; 8,000 watts for 1 millisecond is typical for a 15-ampere, 120-V, alternating-current circuit.

A battery charger with batteries should be provided to allow the RTU to function for a user specified time period during the loss of normal alternating-current power. The RTU battery should provide power for all RTU functions, including analog transducer and wetting voltage power supplies. The charger should have a current rating sufficient to supply the full rated load in addition to providing the required current to fully charge a completely discharged battery within 12 hours. Batteries should be of the sealed celluloid type to minimize battery maintenance and ventilation requirements. Separate power supplies or separate isolated outputs from each power supply should be available to provide voltages to meet RTU optical isolation and power requirements. Voltage divider networks should not be used. Battery voltages and equipment operating voltage requirements should be matched as closely as possible to minimize the use of direct-current-to-direct-current converters.

e. **Enclosures.**—RTU enclosures should provide a separate compartment for data acquisition microprocessors and associated equipment, communications equipment, and battery chargers with batteries. The enclosure should be of the required National Electrical Manufacturers Association rating suitable for the enclosure dust and moisture environment. Ventilation should be provided to dissipate equipment-generated heat and minimize condensation while preventing the entrance of rodents, insects, dust, and moisture. In extremely cold or damp environments, internal thermostatically controlled enclosure heaters should be used. The enclosure should be designed to minimize transfer of battery charger and power supply generated heat to microprocessor enclosure compartments. For outdoor installations, sun shields should be provided to limit solar heat buildup within the enclosure. Openings in the enclosure tops should be avoided to prevent the entrance of moisture. The enclosure mechanical design should make use of hinged, latched, exterior doors, hinged swing-out panels, and standard size rack mount panels arranged in a manner to allow ease of access to the rear as well as the front of equipment. A grounding bar with a single-point grounding system, including a ground lug for a ground cable, should be provided.

f. **Software requirements.**—The RTU software provides real-time interfacing between the associated master station and the RTU, monitors site conditions, executes closed-loop control commands, and reports site conditions to the master station. RTU software may provide some or all of the following functions:

- **RTU primary power failure.**—Alarm the master-station operator concerning the power loss and other user predetermined site conditions occurring after the power loss. Shutdown before the RTU battery level causes erratic RTU operation. The RTU should be designed so that primary power loss to the RTU or an RTU failure does not cause inadvertent operation of external equipment. This design requires that, during a failure, each output should remain in a user selectable, predetermined state, usually its current state.

- **RTU primary power restoration.**—The RTU should boot from dead start and be fully operational within a user specified time. Upon power restoration, the RTU should not perform any control operations until the RTU has received a new schedule or command sequence from the master station. Analog output points should not change state until positions are verified to ensure that, if a device has been manually controlled during an RTU power down, the RTU does not issue erroneous commands on powering up.
- **Communication failure.**—The RTU should failover to a user predetermined failure mode such as executing the last control setpoints or schedule that it had received from the master station and continue to archive data as required.
- Time tagging should be accurate to within a user-specified time period. For powerplant sites, this period is typically 1 millisecond. For other sites, a 1-second period is acceptable.
- User selectable, independently adjustable deadbands should be provided for each analog controlled variable such as a gate or valve. The deadband defines how far the analog controlled variable may deviate from the setpoint value before the RTU will take corrective action to readjust the controlled variable. The deadbands should prevent excessive gate or valve operation caused by minor changes in the water surface elevation or flow.
- User selectable, independently adjustable analog value scaling should be provided by the RTU software.
- The RTU should provide analog and BCD checks for sensor failures and out of limit conditions, alarming the master-station operator upon their presence.
- The RTU should provide error detection and diagnostic software to detect control software failure in interrelated simultaneous RTU control processes as well as in single processes. The control software should failover to a user predefined state and notify the master-station operator upon error or failure detection.
- The software can automatically update the master station if an alarm occurs at the RTU and the next scheduled master-station pole is not within the RTU interrupt update time.
- Analog sensor digital filtering software should be provided to aid in the elimination of spikes, surges, and ripple caused by problems in the analog transducer, converting, or telemetering hardware. Analog data received by the system should be optionally assignable to digital filter processing. Typical filters are rectangular integration, trapezoidal integration, multistage averaging, and smoothing filters.
- The RTU software should provide setpoint routines for control of all controllable devices such as gates, valves, pumps, and generators. The routines should include the necessary algorithms for closed-loop control, commonly proportional integral differential algorithms, or equivalent. The setpoint routines should operate within a user selectable time interval, during which time the RTU scans the sensors included in the setpoint control loop, performs the necessary calculations and data base accesses, and makes decisions whether the controlled device should be controlled (raise/lower, open/close, stop, etc.). Control loops should be implemented within the individual RTU's with no loops closed back through the master station. Changes in control algorithm parameters should be made at the master station or at the RTU operator panel if present. The changes should modify a table of values associated with each algorithm stored in the RTU. Changes made at the operator's panel should cause an alarm signal to be sent to the master station along with the value, or values, of the changed parameters.
- Arithmetic operations should be clamped to avoid overflow and prevent reverse control action. Control loops should be designed to ensure that no device movement occurs when changing from one control mode to another. An operator selectable control interval for each RTU algorithm and control

loop should be provided. An internal RTU scan interval that is significantly faster than the control interval should be provided (100 times faster is typical). The scan interval is the interval at which the RTU is scanning the I/O points to provide values to RTU microprocessor-based control algorithms.

# GLOSSARY

| TERM | DEFINITION |
|---|---|
| **A** | |
| Accumulator | Device used to store hydraulic pressure. |
| Acoustic transducer | Transducer that measures sound pressure in the auditory range. |
| Actuator | Converts the output of the control element to a mechanical operation that affects the process operation. |
| Algorithm | A prescribed set of well-defined rules or processes for the solution of a problem in a finite number of steps, usually expressed in the form of Boolean logic and mathematical equations. |
| Analog | A continuously variable electrical signal representing a measured quantity. For example, electrical signals such as current, voltage, frequency, or phase used to represent physical quantities such as water level, flow, and gate position. |
| Antihunt control | A stabilizing or equalizing system used to modify the response of a controller to prevent self-oscillations that would cause excessive operations of the controlled device. |
| Automatic control | A procedure or method used to regulate mechanical or electrical equipment without human observation, effort, or decision. |
| Automation | A procedure or method used to regulate a water system by mechanical or electronic equipment that takes the place of human observation, effort, and decision; the condition of being automatically controlled. |
| Availability | Uptime divided by total time as a decimal percent. |
| **B** | |
| Balanced operation | Operation of a canal system where the water supply exactly matches the total flow demand. |
| Bandwidth | Range of input frequencies over which peak amplitude differs by no more than –3 decibels from its value at a specified frequency. |
| Binary Coded Decimal (BCD) | Binary representation using four binary bits to represent a decimal number 0 through 9. Remaining combinations are discarded and a new set of four is used for the next decimal number. |
| Block diagram | Pictorial representation of the relationship between the input and output of elements in a control system. |
| Boundary conditions | Flow conditions imposed at the ends of a pipeline or canal reach by various physical structures, which must be described mathematically to solve the general equation of flow for hydraulic transient computer models. |

| TERM | DEFINITION |
|---|---|
| **C** | |
| Canal automation | The implementation of a control system that upgrades the conventional method of canal system operation. |
| Canal check gate structure | A structure designed to control the water surface level and flow in a canal, maintaining a specified water depth or head on outlets or turnout structures. Most canal check structures have movable gates. |
| Canal freeboard | The amount of canal lining available above maximum design water depth. |
| Canal pool | Canal section between check structures. |
| Canal prism | The cross-sectional shape of a typical canal. |
| Canal reach | Segment of main canal system consisting of a series of canal pools between major flow control structures. |
| Canal system control concepts | Downstream control and upstream control. |
| Canal system control methods | Local manual, local automatic, supervisory. |
| Canal system operation | Water transfer from its source to points of diversion for irrigation, municipal and industrial, fish and wildlife, and drainage purposes. |
| Canal system operation concepts | Downstream operation and upstream operation. |
| Canal system operation methods | Constant downstream depth, constant upstream depth, constant volume, controlled volume. |
| Cascade control | A method of automation using control units arranged in sequence such that a given unit is controlled by the preceding unit and controls the following unit. |
| Cascade flow | Regulated flow through a series of flow control structures. |
| Centralized control | Control of a canal project from a central location generally by a master station, communications network, and one or more remote terminal units (RTU's). |
| Centralized headquarters | Control of a canal project from a central location by the watermaster. |
| Central processing unit (CPU) | The portion of a computer that controls the interpretation of instructions and their execution. |
| Check gate | A gate located at a check structure used to control flow. |
| Closed conduit system | A conveyance system where the flow of water is confined on all boundaries (i.e., pipe systems). |

| TERM | DEFINITION |
|---|---|
| Closed-loop control | A classification of control that corrects errors in the system being controlled by monitoring the controlled value and comparing it with a standard representing the desired performance. |
| Collector system | Conveys water from several individual sources such as ground-water wells and drains and surface inlet drains for rainstorm and snowmelt runoff to a single point of diversion. The collector system is associated with projects that increase water supply and decrease flood damage. |
| Colvin algorithm | A canal flow control structure technique that operates the gates based on the rate of deviation of the water surface level from the setpoint. |
| Communication channel type | Simplex (one direction), half duplex (both directions but only one at a time [switchable]), and full duplex (both directions concurrently). |
| Comparator | A circuit or device that compares two electrical signals and provides an indication of agreement or disagreement. |
| Computer directed mode | Canal operating mode in which a computer monitors and directs operation of a canal. |
| Connector system | Conveys water from a single source to a different location typically without intermediate collection or diversions. The connector system is associated with regulation reservoirs and intakes to pumping plants or powerplants. |
| Constant head orifice turnout | A calibrated structure containing an adjustable orifice gate and a gate downstream to control a constant head differential across the orifice gate to divert and measure water from a main irrigation canal to a distributing canal. |
| Constant volume operation method | A canal operation that maintains a relatively constant water volume in each canal pool. |
| Control | To exercise restraining or directing influence over; a mechanism used to regulate or govern operation of a system. |
| Control element | A part of a control system through which the system's process is regulated. |
| Control scheme | The collection of methods and algorithms brought together to accomplish control of a canal system |
| Control system | An arrangement of electronic, electrical, and mechanical components that commands or directs the regulation of a canal system. |
| Controlled variable | The quantity or condition of a system that is measured and controlled. |

| TERM | DEFINITION |
| --- | --- |
| Controlled volume operation method | An operation in which the volume of water within a canal reach between two check structures is controlled in a prescribed manner for time variable inflows and outflows such as off-peak pumping or canal-side deliveries. |
| Conventional method | Where operations personnel (ditchrider and watermaster) control the canal system onsite. Labor-saving devices and machinery may be used to assist in the control of the canal facilities. |
| Cutoff frequency | Frequency that defines the limits of the bandwidth. |
| Cutoff rate | Rate at which the amplitude decreases with frequency beyond the cutoff frequency. |

## D

| TERM | DEFINITION |
| --- | --- |
| Deadband | The range through which the measured signal can vary without initiating a control action. |
| Dead time | The time required for the response to a change of input to a system to reach the location of a sensor (i.e., the time for a control initiated surge wave to travel from an upstream control check gate to a downstream sensor in a canal). |
| Delay time | Retardation of the time of arrival of a signal or impulse after transmission through equipment or a system; the time a circuit introduces between the input and output terminals. |
| Delivery | Release of water from turnouts to water users. |
| Delivery concept | Mode of making deliveries with respect to time; types are rotation, scheduled, or demand delivery concepts. |
| Delivery flexibility | The flexibility that water users have in requesting delivery changes and the ability of the canal system to accommodate the request. |
| Delivery system | Conveys water from a single source, such as a storage reservoir, to a number of individual points of use. The delivery system is a common classification. It is associated with irrigation, municipal and industrial, and fish and wildlife canal systems. |
| Demand delivery | Unrestricted use of the available water supply with limitations only on maximum flow rate and total allotment. |
| Demultiplexor | Device to convert a multiplexed signal to the original multiplexor input signal. |
| Derivative (rate) control | A mode of control that proportions the control device setting to the rate of change of the controlled variable. Derivative control is usually used with proportional or proportional plus integral control. |

| TERM | DEFINITION |
|---|---|
| Digital | Representation of a quantity by an arrangement of digits, each of which represents a portion or weighted portion of the quantity. In communications, transmission of quantities by a series of pulses. |
| Distortion penalty | A measurement of the distortion in an electronic signal over distance. |
| Distribution system | Delivers water from the main canal-side turnout to individual water users or to other smaller distribution systems. |
| Ditchrider | Canal system operations personnel. The person responsible for controlling the canal system on site based on the flow schedule established by the watermaster. |
| Diversion dam | The diversion dam is commonly constructed on a natural river channel and is designed to check or elevate the water level for diversion into a main canal system. |
| Downstream control | Control structure adjustments are based on information from downstream. The required information is measured by a sensor located downstream or based on the downstream water schedule established by the watermaster. |

**E**

| | |
|---|---|
| ELFLO controller | The Electronic Filter Level Offset (ELFLO) controller is a proportional and integral controller that uses an electronically filtered (delayed and smoothed) water level signal from the downstream end of a canal reach. ELFLO controllers are used for control of multiple reach canals and require communications circuits between check structures. |
| Encoder | Device to convert a value of a desired parameter, such as water depth, to another form, usually to an electronic equivalent such as volts. |

**F**

| | |
|---|---|
| Fade margin | Amount of radio or microwave signal exceeding the minimum required for reliable communication. |
| Feedback | The application of a portion of a signal or a function of a signal to a preceding stage of a control system. |
| Feed forward | The application of a portion of a signal or a function of a signal to a forward stage of a control system. |
| Filter | A device used to remove specific unwanted frequencies from electrical, mechanical, or hydraulic systems. |

| TERM | DEFINITION |
|---|---|
| Firmware | Software that has been committed to a read only memory (ROM) device. |
| Floating control | See three-position control. |
| Four-wire system | Typical wiring configuration used for voice circuits transmitting full or half duplex signals. |
| Frequency response analysis | A method of studying systems in which sine wave disturbances are input to the system, and the corresponding amplitudes and phases of these sine waves in the output signal are determined. |
| Full duplex | Communication channel type in which data flow in both directions simultaneously. |

## G

| | |
|---|---|
| Gain | The ratio of the output to the input signal of a control system. Gain is used to describe the proportionality factor of a proportional control system. |
| Gain crossover frequency | Frequency at which the gain is unity. |
| Gain margin | Magnitude of the reciprocal of the open-loop transfer function, evaluated at the frequency where the phase angle is equal to −180 degrees. |
| Gas discharge tube | Device that provides lightning protection by conducting lightning-induced transients to the ground. |
| Gate hoist | Portion of gate system used to raise and lower gate. |
| Gate lift | Same as gate hoist. |
| Gate position sensor | A device such as an analog or digital sensor that can measure the mechanical position of a gate and provide a signal representing the position. |
| Gate stroking | A global gate adjustment technique (state estimation algorithm) that produces a predetermined water surface variation in a canal. |

## H

| | |
|---|---|
| Half duplex | Communication channel type in which data flow in both directions, one direction at a time. |
| Hardware | Physical components of control systems (e.g., relays, switches, lights, integrated circuits, transistors, and capacitors). |

| TERM | DEFINITION |
|---|---|
| Hydraulic gradient pivot point | A location along the water surface in a canal reach where the water level remains essentially constant during changes in flow. |
| Hydraulic transient | A wave or pressure change propagated through a canal or pipeline during unsteady flow. |
| **I** | |
| In-channel storage | Water storage volume in a canal above the minimum water level required for conveyance. |
| Inclinometer | Instrument to measure the angle of an item; also called an angle transducer. |
| Inline reservoir | A reservoir constructed in line with the canal used to regulate flow for balanced operation. |
| Input/Output (I/O) | The input and output signals to computer-based control system or SCADA. |
| Instability | A condition of a system in which the state of equilibrium between elements is not restored. |
| Instrumentation system | Instruments, equipment, and electronic components used to convert actual data into a form useable by a control and communication system. |
| Integral (reset) control | A mode of control in which the output is proportional to the time integral of the error. Integral control is used in conjunction with proportional control in a hydraulic system. |
| Interface | A combination of electrical, mechanical, or other components interconnecting elements of a control system. |
| Inverted siphon | A closed pipe used to convey canal flow under drainage channels, depressions, roadways, or other structures. Also referred to as a sag pipe. |
| **L** | |
| Lateral | A branch canal or pipeline that diverges from the main canal or other branches. |
| Limit switch | Device to prevent overloading of gates and valves by limiting operation or travel to restricted specifications. |
| Linear Displacement Transducer (LDT) | Device used to measure and transmit gate position. |
| Linearization | Replacement of a nonlinear equation by an approximate linear equation. |

| TERM | DEFINITION |
|---|---|
| Little-Man controller | A variety of canal controllers of the floating control type that uses a set operating time and a set rest time mode of control and usually includes an antihunt device. |
| Loading | Application of signal conditioning frequency compensation to a twisted pair cable system. |
| Local automatic control | Onsite control by control equipment without human intervention. |
| Local manual control | Onsite control by a human operator (ditchrider). |
| Logarithmic decrement | Logarithm of the ratio of two successive maxima (or minima) of the oscillations. |

## M

| | |
|---|---|
| Magnitude ratio | Ratio of the input to the output or the ratio of the actual value to the setpoint value. |
| Main canal system | Delivers water from a primary source of supply to several points of diversion or canal-side turnouts to smaller distribution systems. |
| Manual control | Control of equipment requiring direct intervention of a human operator. |
| Master station | The centralized facility with communications to RTU's for the purpose of information retrieval, control of apparatus, system control, and operation optimization. |
| Mathematical model | A representation of physical laws or processes expressed in terms of mathematical symbols and expressions. The model is used as a basis for computer programs for examining the effect of changing certain variables in the analysis of the effect of flow changes in a water delivery system. |
| Measurement uncertainty | The estimated amount by which the measured quantity may depart from the true value. |
| Messenger cable | A steel or high-strength aluminum cable strung with metallic or fiber communication cables to physically support the entire cable between poles or towers. |
| Message security | Process of attaching a security code to all transmitted messages. |
| Microwave radio | A method of point-to-point radio transmission using the frequency spectrum above 890 megahertz (MHz). Microwave frequency characteristics limit transmission to line of sight distances. |
| Mismatch | A condition in which water supplied to a given point in a conveyance or distribution system does not equal the demand for water at that point. |

| TERM | DEFINITION |
|---|---|
| Mode selector switch | Device to switch the operating mode of a controlled item such as a gate; typical settings are manual, automatic, and off. |
| Multiplexor | Device that converts multiple measured analog or status signals into a single analog or digital signal. |

## O

| TERM | DEFINITION |
|---|---|
| Off-line reservoir | Constructed to the side of the main canal, usually in a natural drainage channel. In canal systems, used to store surplus water runoff during the winter season for use during the irrigation season. |
| Offset | The difference between the controlled variable and the referenced input (i.e., the difference between the water level in a canal system and the water level at design flow). |
| On-Off control | See two-position control. |
| Open channel system | A system of conveyance channels where the top flow boundary is a free surface (e.g., canal systems). |
| Open-loop control | A classification of control that initiates a control action with no comparisons to actual process conditions. |
| Operating criteria | Design and institutional criteria that determine the operating limits of a water system. |
| Operational concept | Mode of operating a canal with respect to location of priorities; usually supply oriented (upstream concept) or demand oriented (downstream concept). |
| Operational spill | A loss or waste of water in an irrigation system caused by operation of the system. |
| Optimization mode | Canal operating mode which is monitored and directed by computer with algorithms to optimize performance. |
| Overshoot | The maximum difference between the transient and steady-state controlled variable (water level or discharge). A measure of relative stability represented as a percentage of the final value of the output (steady-state condition). |

## P

| TERM | DEFINITION |
|---|---|
| P+PR | Proportional plus Proportional Reset (P+PR) algorithm is similar to the ELFLO + Reset algorithm except that the P+PR algorithm is applied to the automatic upstream control of canal systems. |
| Peak time | Time interval between the step change and the time at which the response reaches its maximum value. |

| TERM | DEFINITION |
|---|---|
| Phase margin | 180 degrees plus the phase angle of the open-loop transfer function at unity gain. |
| PID controller | A controller that combines proportional, integral, and derivative modes of control. |
| Potentiometer | A resistance element where a third connection is moved along the resistance element to provide a resistance proportional to the rotation (e.g., a voltage divider). |
| Predominant time constant | Time interval between the step change and the time for the envelope of the response to decay to 37 percent of its initial value. |
| Pressure transducer | Device used to convert measured pressure differences to an electrical signal. |
| Program | A set of coded instructions that directs a computer to perform some specific function or yield the solution to some specific problem. |
| Proportional control | A mode of control that moves a controlled element to a position proportional to the difference (offset) between the actual value of the controlled variable and the target. |
| Proportional plus reset control | A combination of proportional and integral control in which the difference or offset caused by the proportional mode of control is eliminated by the reset action. |
| Pumped storage | A reservoir that has a pumping plant as the main source of water supply. Often, outflow from pumped storage reservoirs is used to generate hydroelectric power. |

## R

| TERM | DEFINITION |
|---|---|
| Radio Frequency Interference (RFI) filters | A resistor-capacitor-inductor circuit used to reduce high frequency transients in electrical circuits. |
| Regulation reservoir | A reservoir used in canal systems to reduce the mismatch between downstream demands and upstream water supplies to maintain a balanced operation. |
| Remote monitoring | Periodic or continuous measuring of quantities at remote sites for transmission and dissemination at another location. |
| Remote terminal unit (RTU) | Supervisory control equipment at the remote site that performs data collection, executes control commands, performs automatic control functions, and communicates with a master station. |
| Repeatability | The ability of an instrument to read the same value of a data parameter consistently. |
| Repeater | Device used to amplify and retransmit a radio signal. |

| TERM | DEFINITION |
|---|---|
| Resolution | The smallest distinguishable increment into which a measured quantity is divided. |
| Resolver | An electromechanical device for resolving a mechanical position into two perpendicular electrical components. |
| Resonant frequency | Frequency at which the resonant peak amplitude occurs. |
| Resonant peak amplitude | Maximum value of the magnitude of the closed-loop frequency response. |
| Response time | The time required for the depth, pressure, or flow to reach and remain within a certain percentage of its steady-state value after a control correction has been initiated. |
| Rise time | Time interval for the response to change from 10 percent to 90 percent of its steady-state value. Sometimes other percentages are used. |
| Rotation delivery | Water delivery where a relatively constant supply flow is rotated to different users at varying times. |

## S

| TERM | DEFINITION |
|---|---|
| Sag pipe | See inverted siphon. |
| Scheduled delivery | Operation of a water delivery system to meet predetermined needs, generally based on user water orders; also called arranged delivery. |
| Self-regulation | A controlled system requiring virtually no operation intervention (see automatic control). |
| Selsyns | Acronym for self-synchronous generator motor in which the motor stays in sync with the generator. |
| Sensor | A device for measuring water level, flow, gate position, etc., for input to a local automatic controller or remote terminal unit (RTU). |
| Sequential control | Similar to setpoint positioning, except allows a single operator command to execute a control sequence involving several steps. |
| Setpoint | A value of water level, flow, etc., that the control system maintains; also called the target. |
| Setpoint positioning | A control operation that compares an existing value, such as gate position, with a desired value and uses the difference (error) to initiate a corrective action (raise or lower gate). |
| Settling time | Time interval between the step change and the time for the response to be within the allowable tolerance. |

| TERM | DEFINITION |
|---|---|
| Signal conditioning | Method of improving the quality of an electronic signal over distance. |
| Simplex | Communication type in which data flow in only one direction. |
| Soft start controller | Device to gradually ramp up the voltage to a motor during starting to reduce current and wear on the motor. |
| Software | Coded instructions that direct the operation of a computer. A set of such instructions for accomplishing a certain task is called a program. |
| Spark gap | A device with an air gap used to protect antenna leads and other electrical circuitry from lightning-induced transients. |
| Stable canal system | A canal system in which flow disturbances are attenuated. |
| State estimation algorithm | Method of predicting the motions of the control structures for a predetermined water demand or water surface profile. |
| Steady flow | Flow which is constant with respect to time. |
| Storage reservoir | Collects and stores water from storm runoff and snowmelt. It is the primary source of supply to the water project and main canal system. |
| Supervisory control | The control of a canal system from a centralized location (master station) over a communication system; uses RTU's at the canal structure sites. |
| Supervisory Control and Data Acquisition (SCADA) | Centralized monitoring and control from a master station using a two-way communication system and remote data collection and control equipment. |
| Surge wave | A translatory wave in an open channel resulting from a sudden change in flow of water, such as that caused by opening or closing a gate. |

## T

| TERM | DEFINITION |
|---|---|
| Target | A value of water level, flow, etc., that a control system maintains; also called the setpoint. |
| Telemeter | To sense, encode, and transmit data to a distant point. |
| Three-position control | A mode of control that responds to the deviation from the setpoint by operating the controlled device for a predetermined amount of time. The corrective signal has three discrete values: no correction, increase the output correction, and decrease the output correction. |

| TERM | DEFINITION |
|---|---|
| Time lag | The time required for a change in the input to a system to cause a change in the output. Time lag is a result of dead time, measurement delay between sensing point and controller, or delay in signal transmission between controller and process. |
| Transducer | A device that converts one form of energy to another, such as hydraulic to pneumatic or mechanical to electrical. |
| Transient flow | Unsteady flow during a change from a steady-flow state to another steady-flow state. |
| Transient response analysis | A method of analysis in which a system is subjected to a pulse input, and the output of the system is recorded and analyzed with respect to fluctuations in flow with time. |
| Translatory wave | A gravity wave that propagates in an open channel and results in displacement of water particles in a direction parallel to the flow. |
| Turnout | A structure that diverts water from an irrigation canal to a distribution system or farm delivery point. Turnouts are used at the head of laterals. |
| Twisted pair | Typical type of metallic cable in which two conductors are twisted over their entire length. |
| Two-position control | A mode of control that responds to the deviation from setpoint by operating the controlled device to either of two extreme positions. Also referred to as On-Off control. |

## U

| TERM | DEFINITION |
|---|---|
| Ultra high frequency (UHF) | Ultra-high frequency type of radio system (300 to 3,000 megahertz). |
| Ultrasonic transducer | Transducer that measures sound pressure in the ultrasonic range. |
| Uninterruptible power supply (UPS) | A battery-powered device to provide alternating current power to a system through power interruptions and eliminate the transients resulting from these interruptions. |
| Unsteady flow | Flow that is changing with respect to time. |
| Upgrade | Provides a better match between the canal system delivery capabilities and the water users' demands. As a result, improved response and efficiency of a system is achieved beyond what could be accomplished by the conventional method of operation. |
| Upstream control | Control structure adjustments based on information from upstream. The required information is measured by a sensor located upstream or based on the upstream water schedule established by the watermaster. |
| Uptime | The total time that a system is available for service. |

| TERM | DEFINITION |
|---|---|
| **V** | |
| Variable target | A control technique that uses a changing setpoint value or target to compensate for changes in demand or storage. |
| Very high frequency (VHF) | Very high frequency type of radio system (30 to 300 megahertz). |
| **W** | |
| Wasteway | Structure used to divert surplus flow from the main canal into a natural or constructed drainage channel. |
| Water level pivot point | A location along the water surface in a canal reach where the water level remains essentially constant during changes in flow. |
| Watermaster | The person responsible for operation of the entire canal project. |
| Wave celerity | The velocity of propagation of a wave through a liquid, relative to the rate of movement of the liquid through which the disturbance is propagated. |
| Wedge storage | The volume of water contained between two different water surface profiles within a canal pool. |

# NOMENCLATURE

## Flow

$Q$ = flow, pool flow
$Q_1$ = flow at point 1 (different numbers for different locations)
$Q_i$ = initial flow
$Q_f$ = final flow
$QC$ = flow through a check structure
$QC_1$ = flow through check structure 1
$QT$ = flow through a turnout structure
$QT_i$ = initial turnout flow
$Q_{max}$ = maximum pool flow
$Q_{min}$ = minimum pool flow
$\Delta Q$ = flow change

## Depth

$Y$ = water depth
$Y_1$ = depth at point 1
$Y_i$ = initial depth
$Y_f$ = final depth
$Y_{max}$ = maximum depth
$Y_{min}$ = minimum depth
$\Delta Y$ = depth change
$YT$ = target depth
$YF$ = filtered depth
$Y_n$ = normal depth

## Pool Properties

$A$ = cross-sectional flow area
$B$ = canal bottom width
$c$ = wave celerity
$D$ = hydraulic depth
$L$ = pool length
$s$ = longitudinal slope of canal invert
$T$ = top width
$Z$ = side slope (run/rise)

## Velocity

$V$ = instantaneous velocity
$V_l$ = velocity of leading edge of wave
$V_m$ = mean flow velocity
$V_n$ = average velocity at normal depth
$V_w$ = translatory wave velocity

## Electrical and Mechanical

$B$ = gate width
$G$ = gate opening
$GR$ = gear ratio
$I$ = current
$kW$ = kilowatt
$L$ = acoustic path length
$P$ = vertical height of gate
$PC$ = pulley circumference
$PT$ = potentiometer turns
$r$ = radius of gyration
$V$ = volt
$W$ = total water load on gate
$w$ = wedge force
$\Delta G$ = change in gate opening
$\mu$ = coefficient of friction

# ALPHABETICAL LISTING

$A$ = area
$A$ = cross-sectional flow area
$B$ = canal bottom width; gate width
$c$ = wave celerity
$C$ = column end condition constant
$C_d$ = gate coefficient of discharge
$D$ = hydraulic depth
$d$ = diameter
$E$ = modulus of elasticity
$F$ = Froude number
$f$ = Darcy-Weisbach friction factor
$G$ = gate opening
$g$ = gravitational acceleration
$GR$ = gear ratio
$H$ = instantaneous piezometric head
$K$ = slope of pin block
$K$ = a constant
$L$ = pool length; load on lift; acoustic path length
$n$ = Manning's roughness coefficient, miscellaneous location
$P$ = wetted perimeter; vertical height of gate
$P$ = operating pressure
$PC$ = pulley circumference
$P_c$ = critical buckling load
$PT$ = potentiometer turns
$Q$ = flow; pool flow (discharge)
$Q_1$ = flow at point 1 (different numbers for different locations)
$QC$ = flow through a check structure
$QC_1$ = flow through check structure 1
$Q_f$ = final flow
$Q_i$ = initial flow
$Q_{max}$ = maximum pool flow
$Q_{min}$ = minimum pool flow

$QT$ = flow through a turnout structure
$QT_i$ = initial turnout flow
$R$ = radius
$R$ = hydraulic radius
$r$ = radius of gyration
$S$ = Laplace variable
$S$ = pin height
$s$ = longitudinal slope of canal invert
$T$ = top width
$t$ = time
$V$ = instantaneous velocity
$V_l$ = velocity of leading edge of wave
$V_m$ = mean flow velocity
$V_n$ = average velocity at normal depth
$V_w$ = translatory wave velocity
$v$ = volume (or better, $\forall$)
$W$ = weight; wedge force; total water load on gate
$x$ = distance
$Y$ = water depth
$Y_1$ = depth at point 1
$YF$ = filtered depth
$Y_f$ = final depth
$Y_i$ = initial depth
$Y_{max}$ = maximum depth
$Y_{min}$ = minimum depth
$Y_n$ = normal depth
$YT$ = target depth
$Z$ = side slope (run/rise)
$\Delta G$ = change in gate opening
$\Delta Q$ = flow change
$\Delta Y$ = depth change
$\mu$ = coefficient of friction
$\gamma$ = density of water

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