

Utah State University

DigitalCommons@USU

Reports

Utah Water Research Laboratory

January 1994

Selecting Controls for Water Distribution Systems

J. Paul Tullis

Follow this and additional works at: https://digitalcommons.usu.edu/water_rep



Part of the [Civil and Environmental Engineering Commons](#), and the [Water Resource Management Commons](#)

Recommended Citation

Tullis, J. Paul, "Selecting Controls for Water Distribution Systems" (1994). *Reports*. Paper 52.
https://digitalcommons.usu.edu/water_rep/52

This Report is brought to you for free and open access by the Utah Water Research Laboratory at DigitalCommons@USU. It has been accepted for inclusion in Reports by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.



ASCC - ...
1994

Selecting Controls for Water Distribution Systems
by
J. Paul Tullis¹

ABSTRACT

One of the key requirements for reliable operation of a water supply system is a thorough analysis and proper selection of the control valves and pumps. For valves, selection criteria includes capacity, pressure loss, controllability, torque, cavitation and transients. Pump selection requires matching the pump performance to varying system demands. Examples are given for single pump operation and use of pumps in series and parallel. When future demands exceed the original design conditions, or if significant changes are required in the operation of the system, each important control device should be analyzed to see if it can operate safely at the new conditions or determine if modifications or replacement is required.

INTRODUCTION

Properly selected and designed control devices for water transmission and distribution systems must have good hydraulic performance, reliable operation, reasonable initial cost and low maintenance cost. The key to achieving such a system is a thorough initial design. Six items needed to ensure good performance are:

1. THE DESIGN-- The design should include a thorough analysis of the critical factors that influence the ability of the control devices to perform their intended functions safely and reliably for the expected

¹Senior Research Scientist, Utah Water Research Laboratory, Utah State University Foundation, 1309 East 700 North, Logan, Utah 84322-9300.

119811

life of the system.

2. BID SPECIFICATIONS-- To ensure that the control devices meet the intended operational requirements, it is necessary to clearly specify the operational requirements for the equipment supplier.

3. OPERATING PROCEDURE-- As a part of the design, a written procedure should be developed to ensure that the system is operated safely, economically and within the design parameters.

4. TRAINING OPERATING PERSONNEL-- Give adequate training to the system operators so they understand the system, the sources of potential problems, proper maintenance practices and how important their role is. Obtain feed-back from them on problems as they arise and modify the design or operation as needed.

5. FOLLOW RECOMMENDED MAINTENANCE PROCEDURES-- Obtain maintenance procedures from the equipment suppliers. Use them to train the operating personnel. Keep them on file and readily available. Develop some type of quality assurance program to be sure that training is up to date and that the maintenance is being done properly.

6. MODIFY AS DEMANDS CHANGE-- Future demands on the system may exceed the range of conditions used during the design to select the control devices and develop the operating procedure. The control devices should be re-analyzed to see if they can operate safely at the new conditions. If not, consider what modifications are required.

This paper addresses how the analysis, selection and operation of the control devices influences the performance and life of the system. Control devices can be classified as either dynamic or static. Pumps and valves are the primary dynamic flow control components. Static controls include orifices, flow meters, storage tanks and surge tanks. Each must be analyzed thoroughly enough to be sure that it can perform its intended function safely with no adverse effects on other components in the system.

Reliable operation, low maintenance and long life of a piping

system are strongly dependent on the quality of the design. Careful operation and regular maintenance cannot compensate for mistakes or omissions in the design. During the design phase, all factors that have a significant influence on the performance of the control devices should be considered. This includes developing an operational plan for the system in parallel with the design. Without complete information on operational requirements and limitations, it is difficult to select the best equipment. This paper does not attempt to cover all aspects of a good design. But it does demonstrate the type of factors that should be considered to provide a good design. Examples of valve and pump selection are included that demonstrate how key factors not considered during the design, can lead to poor system performance and frequent repairs.

VALVE SELECTION

Valves serve a variety of functions in a pipe distribution system including:

1. Control flow
2. Control pressure or water level
3. Cause or control cavitation
4. Cause or control transients
5. Provide safe filling of pipeline
6. Release air during filling and operation
7. Vacuum relief during draining or pipe rupture
8. Isolation of control valves and pipe sections
9. Prevent reverse flow to protect pumps from reverse rotation and prevent pipe from draining

Each of these applications requires different considerations. Several of these will be discussed to demonstrate the effect of design choices on the operation and life of the system. The applications to be considered are: flow and transient control, cavitation control, prevention of reverse flow and automatic pressure regulation.

Flow Control Valve manufacturers frequently advertize the performance of their valves with a graph showing the percent flow versus valve opening. For most applications, it is desirable for control valves to have linear control characteristics. That means that the flow is reduced linearly as the valve moves from full open to closed. Such advertizing can

be misleading. The ability of valves to control flow depends as much on the system as it does on the design of the valve. The same valve can operate linearly in one system and not in another.

Selecting the proper flow control valves requires information on maximum and minimum flows and the pressure requirements for both the present and projected future demands. It also requires establishing criteria for valve selection. Typical criteria that can be used in selecting a good flow control valve are:

1. The valve should not produce excessive pressure drop when full open.
2. The valve should control over at least 50% of its movement. This definition of control means that when the valve is closed 50%, the flow should be reduced at least 10%. This is equivalent to specifying that the valve loss should be about 20% of the total system loss when it is closed 50% .
3. The maximum flow must be limited so the operating torque does not be exceed the capacity of the operator or valve shaft and connections.
4. The valve should not be subjected to excessive cavitation. Cavitation results in noise, vibrations, erosion damage and loss of capacity at extreme levels of cavitation.
5. Pressure transients should not exceed the safe limits of the system. This requires that the valve is sized so it controls the flow over most of its stroke and that the closure speed is controlled to limit the transients.
6. Most valves should not be operated at small openings. Most conventional valves will experience seat damage due to the high pressure drop and associated high velocity and cavitation near the seat.
7. Some valves should not be operated near full open. Quarter turn valves like butterfly and ball valves can experience torque reversals near the full open position. This can cause cyclic stresses in the valve shaft and operator that can lead to fatigue. Another reason

is that for some valves, the discharge coefficient does not vary much near full open, so the valve does not control the flow.

The following example focuses on criteria 2, 3 & 5: how to determine if a given valve will provide good flow control and what are the implications if it does not. The ability of a valve to control over most of its travel depends primarily on the ratio of the system friction losses to the valve loss.

Consider sizing a butterfly valve to control flow in a pipe connecting two reservoirs for two situations. a) a short pipe where pipe friction is small, (System A) and b) a long pipe with high friction (System B). Assume for both systems it is required to regulate flow down to 10% of Q_{max} . Initially assume that the control valve will be the same size as the pipe.

Figure 1 shows how the flow varies as the full line-size butterfly valve is closed in each system. For system A, the flow is reduced almost linearly as the valve closes. The range of control is between about 15% valve opening (where the flow is 10% Q_{max}) and full open. This shows that a full line-size butterfly valve is a good control valve in system A because it controls over the entire range of its usable travel.

For system B, Figure 1 shows that regulating the flow between 10% Q_{max} and Q_{max} will force the valve to operate between about 5% and 40% open. Butterfly valves should generally not be operated below about 15% open for extended time due to possible seat damage and poor flow control. If the valve is therefore limited to regulating the flow between 15% and 40% of its total travel, the flow range will only be from about 60% Q_{max} to Q_{max} . A line-size butterfly valve is obviously not a good choice for this application. If this type of analysis were not made as a part of the design and a line-size butterfly valve was selected for system B, it would not provide adequate flow control and the valve would wear faster than normal due to seat damage from operating at small openings.

A simple solution to the control problem in systems with high friction is to use a smaller valve. The data points plotted on Figure 1 are based on installing a butterfly valve in system B with the valve diameter half that of the pipe. With a smaller valve, the system capacity is reduced about 8% with the valve full open, but there is much wider range of flow control.

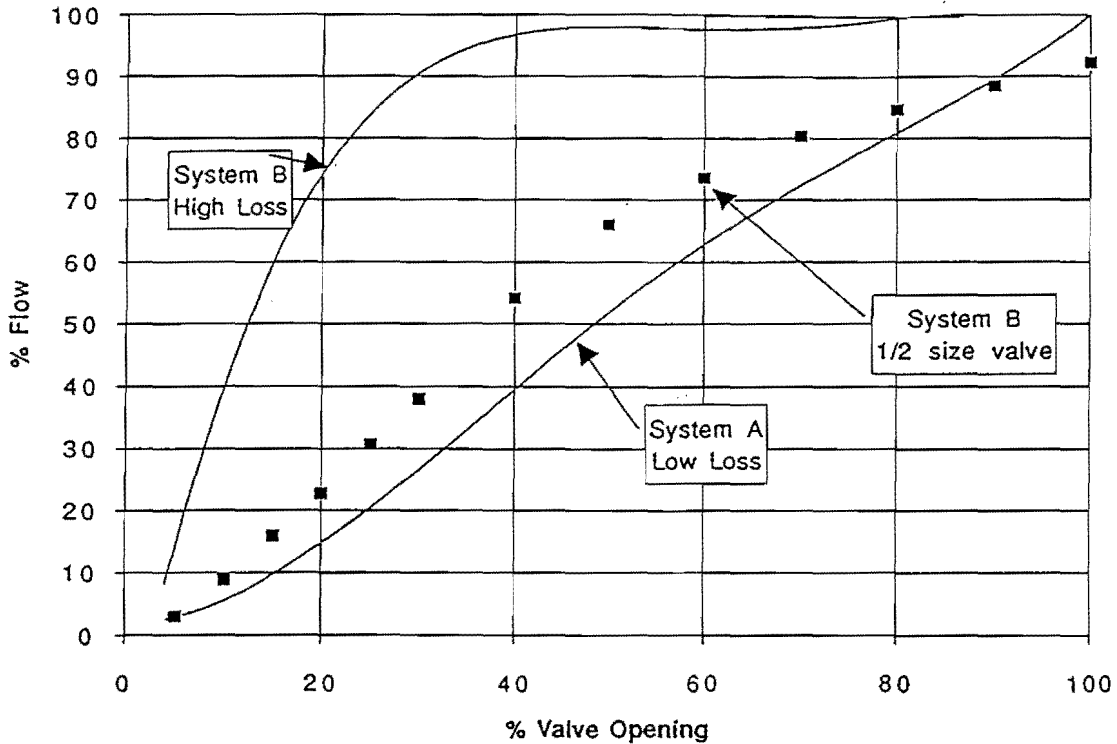


Figure 1 Flow Control in Systems With Low and High Friction Loss

The range of opening over which the valve controls the flow also has a significant effect on the safe closure time for control valves. Transient pressures are created when there is a sudden change in the flow. Most valve operators close the valve at a constant speed. For the line-size valve in system B, there is essentially no reduction in flow during the first 60% of the closure time and 75% of the flow change occurs in the last 20% of the closure time. The safe closing time must be based on the time the valve is actually controlling the flow. The smaller the range of flow control, the longer the required total valve closing time. If the valve closure time is not properly determined, excessive transients can be generated that can cause operational and maintenance problems.

TORQUE

Evaluating the third criteria for selecting and sizing control valves

requires adequate information on torque. To be sure that the valve shaft, connections and operator are properly sized, the torque or thrust must be known. The force required to operate a valve consists of seat friction, bearing friction, packing friction, hydrodynamic forces and inertial forces. These forces are best determined experimentally. The data can be generalized for a given valve by expressing the data in terms of torque coefficients. The flow torque coefficient C_{tdp} is defined as:

$$C_{tdp} = T/D^3 \Delta P \quad (1)$$

in which T is the hydrodynamic or flow torque, D the valve disc diameter and ΔP the net pressure drop across the valve. The value of C_{tdp} varies with valve type and valve opening. Since the torque coefficient defined by Equation 3 is dimensionless, it is valid for valves of different size, as long as geometric similarity is maintained.

One key step in properly applying torque information is the determination of the flow condition creating maximum torque. This requires that the system be analyzed for all possible operating conditions and valve openings. For a given size and type of valve, the torque depends on the torque coefficient and the pressure drop which, in turn, depends on the flow. In short systems with small heads and little friction, the valve will see maximum torques at large openings where the flow is high. In long systems with high reservoir heads, the valve will see maximum torque at small openings where the pressure drop is high.

For the system data used for the previous example, the calculated flow torque that the butterfly valve experiences as it closes for Systems A and B is shown in Figure 2. For the system with high friction (System B) the torque is maximum at 20°. For the low friction system, maximum torque occurs at 80°. The actual magnitude of the flow torque will vary with valve type, flow rate and pressure drop.

Another situation where it is easy to overlook the condition causing maximum torque is with parallel pumps. Each pump normally will have a discharge control valve. The maximum system flow occurs with all three pumps operating. However, the flow and the torque on the pump discharge valve is maximum for one pump operating. One specific example (Tullis, 1989) showed that the torque on a butterfly valve was three times higher when one pump was operating compared to three pumps operating.

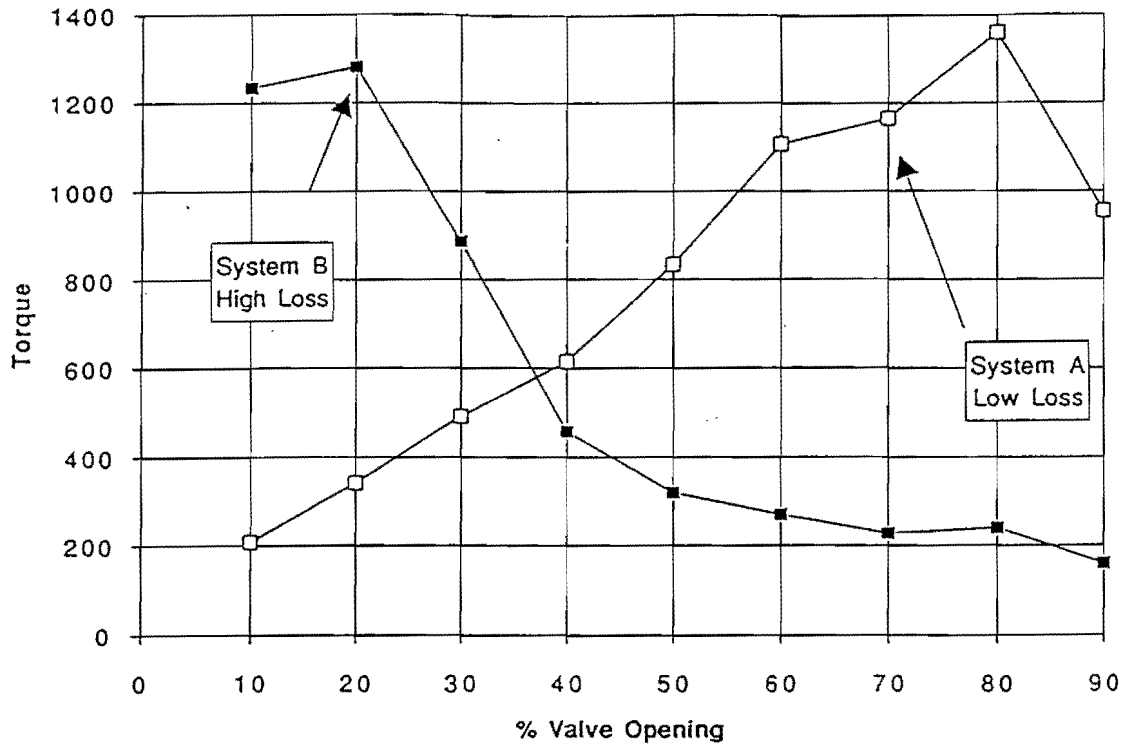


Figure 2 Flow Torque in Systems With Low and High Friction Loss

Cavitation Cavitation occurs when liquid at constant temperature is subjected to vapor pressure either by a static or a dynamic means. If the local pressure somewhere in the fluid drops to or below vapor pressure and nuclei are present, vapor cavities can form. They grow and collapse rapidly causing noise, vibrations, possible erosion damage to solid surfaces and reduce performance. A valve can be damaged by cavitation when operating at high flow rates, low pressures or large pressure drops. The loss of material will eventually require repair or replacement.

A cavitation analysis is necessary to determine if the valve will experience excessive noise, vibrations or erosion damage. Information for making a complete cavitation analysis for valves is contained in references 2 and 4 (Tullis, 1989; Tullis, 1993). If the analysis identifies problems for a particular valve, the designer should consider a different style of valve or several other available options. Another option would be to limit the range of operation to the non-cavitating conditions. The analysis must consider the full range of operation. Some valves cavitate worst at small openings and others will cavitate more near full open. It depends on both

the system and the valve design.

Check Valves Selecting the wrong type or size of check valve can result in poor performance, severe transient pressures and frequent repairs (Tullis, 1992). Proper check valve selection requires understanding the characteristics of the various types of check valves and analyzing it as a part of the system in which it will be operated. A valve that operates satisfactorily in one system may be totally inadequate in another. Each valve type has unique characteristics that give it advantages or disadvantages compared to the others. The characteristics of check valves that describe their hydraulic performance and which should be considered in the selection process include:

1. Opening characteristics of the valve, ie. velocity versus disc position data.
2. The velocity required to fully open and firmly backseat the disc .
3. The pressure drop at maximum flow.
4. Stability of the disc at partial openings.
5. Sensitivity of the disc to respond to upstream disturbances.
6. Speed of valve closure compared to the rate of flow reversal of the system.

Disc stability varies with flow rate, disc position and upstream disturbances and is an important factor in determining the useful life of a check valve. For most applications it is preferable to size the check valve so that the disc is fully open and firmly backseated at normal flow rates. This may require selecting a valve that is smaller than the pipe size. One of the worst design errors is to oversize a check valve that will be located just downstream from a pump, elbow, or control valve. The disc will be subjected to severe vibrations that may cause accelerated wear. To avoid this problem, it is necessary to obtain information from the valve manufacturer defining the minimum velocity required to keep the valve fully open and select the size of valve so the system velocity is normally higher. If such data cannot be obtained from the manufacturer, analytical methods are available for swing check valves (Kalsi Eng., Tullis Eng., 1993).

The transient pressure rise generated at check valve closure is another important factor in determining if a system will operate properly and with minimal maintenance. The pressure rise is a function of how fast the valve disc closes compared to how fast the flow in the system

reverses. The speed that the flow in a system reverses depends on numerous factors including: the number of pumps, the specific speed of the pumps, pipe length, friction, pipe profile and elevation change, and the presence of surge protection devices such as air chambers and surge tanks. In systems where rapid flow reversals occur and cause a significant reverse velocity before the check valve closes, the disc will slam shut causing a pressure transient.

The closing speed of a valve is determined by the mass of the disc, the forces closing the disc and the distance of travel from full open to closed. Fast closing valves have the following properties:

1. The disc (including all moving parts) is light weight.
2. Closure is assisted by springs.
3. The full stroke of the disc is short.

Swing check valves are the slow closing valves because they violate all three of these criteria, i.e., they have heavy discs, no springs and long disc travel. The nozzle check valve is one of the fastest closing valves because the closing element is light, it is spring loaded, and has a short stroke. The silent, duo, double door, and lift check valves with springs are similar to nozzle valves in their closing times; mainly due to the closing force of the spring.

Systems where rapid flow reversals occur include parallel pumps where one pump is stopped while the others are still operating and systems that have air chambers or surge tanks close to the check valve. For these systems there is a high energy source downstream from the check valve to cause the flow to quickly reverse. As the disc nears its seat, it starts to restrict the reverse flow. This builds up the pressure, accelerates the disc and slams it into the seat. Results of laboratory experiments, field tests and computer simulations show that dramatic reductions in the transient pressures at disc closure can be achieved by replacing a slow closing swing check valve with a fast acting check valve. For example, in a system contained parallel pumps where the transient was generated by stopping one of the pumps, the peak transient pressure was reduced from 108 psi to 11 psi when a swing check was replaced with a nozzle check valve. Such a change improved performance and significantly reduced maintenance,

Pressure Regulating Valves There are numerous applications for

pressure regulating valves (PRV). They are used to maintain a constant upstream, downstream or differential pressure (sometimes called pressure reduction or sustaining valves), limit the maximum system pressure (pressure relief valves) and control transient pressure surges (surge anticipating valves). The basic difference in the valves is the operation of the pilot control system.

Misapplication of PRVs can result in lack of control, unstable operation, continuous valve movement and pressure transients. All of these increase maintenance costs and reduce the economic life of the system. Two of the most important principles in selecting the correct PRV is choosing the proper valve size and matching the response time of the valve to the system dynamics.

Sizing the PRV follows the same principles discussed for selecting a good control valve, since a PRV is a control valve that is usually automatically hydraulically actuated. Typically, globe style valves are used for this application because they can be hydraulically controlled using system pressure. If properly sized, the globe valve will control the flow over most of its stroke. This is especially important for globe valves since their stroke is usually relatively short. Good control is one of the key factors that will help optimize valve life and performance.

Another factor influencing performance and maintenance is the speed of operation of a PRV. The valve is usually activated by a pilot system that senses a local pressure or by the water level in a tank. The operating speed for a PRV that is pressure controlled is directly related to the length of the system. The valve must move slow enough that the pressure transients are small and adequately dampened. If not, the pressure variations caused by the valve may force the valve to continually "hunt" and never find a stable operating condition.

PUMP SELECTION

Optimizing the life of a water supply system requires proper selection, operation and maintenance of the pumps. During the selection process, the designer must be concerned about matching the pump performance to the system requirements, anticipate problems that will be encountered when the pumps are started or stopped and when the pipe is filled. The design should also consider the effect of variations in flow and pressure requirements, anticipate problems that will be encountered due

to increased future demands and details of the installation of the pumps.

Matching Pump and System Selecting a pump for a particular service requires matching the system requirements to the pump's capabilities. The process consists of developing a system equation by applying the energy equation to evaluate the pumping head required to overcome the elevation difference (static lift) and the friction plus minor losses. For a pump supplying water between two reservoirs, the pump head required to produce a given discharge can be expressed as:

$$H_p = \Delta z + H_f \quad (2)$$

or

$$H_p = \Delta z + CQ^2 \quad (3)$$

in which the constant $C = \Sigma(fL/2gdA^2 + K_i/2gA^2)$.

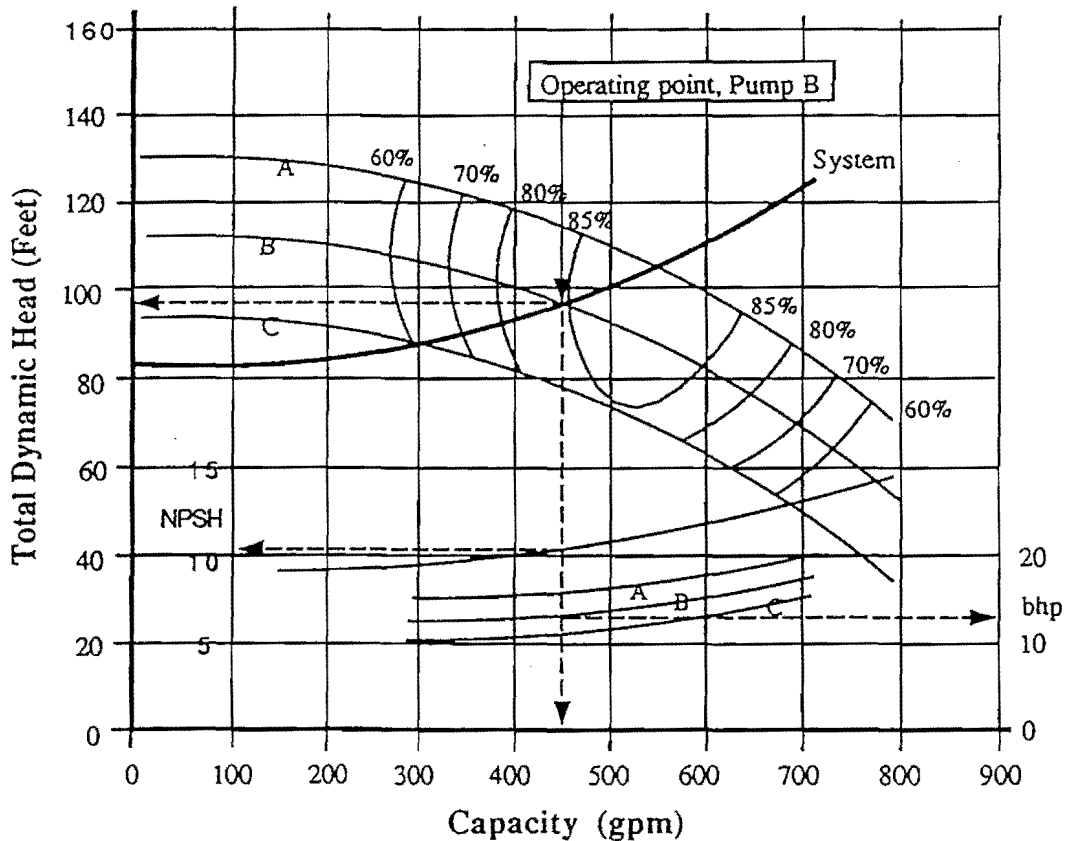


Figure 3 Pump Selection for Simple System

Figure 3 shows a system curve for a pipe having a 82-foot elevation lift and moderate friction losses. If the elevation of either reservoir is a variable, then there is not a single curve but a family of curves corresponding to the various differential reservoir elevations.

The three pump curves shown in Figure 3 represent different impeller diameters. The intersections of the system curve with the pump curves identify the flow that each pump will supply if installed in that system. Proper pump selection requires that it not only provide the required head and discharge but that it operate near its rated conditions and function free of cavitation, vibrations and any other undesirable characteristics. For this example both A and B pumps operate in their best efficiency range. A pump that does not operate near maximum efficiency not only consumes more power but can experience accelerated wear.

The selection process is more complex when the system demand varies, either due to variations in the water surface elevation or changing flow requirements. If the system must operate over a range of reservoir elevations, the pump should be selected so that the system curve, based on the mean (or the most frequently encountered) water level, intersects the pump curve near the mid-point of the best efficiency range. If the water level variation is not too great, the pump may be able to operate efficiently over the complete flow range.

The problem of pump selection is more difficult when planning for future demands or if the pumps are required to supply a varying flow. This problem is demonstrated in the next two examples. The purpose of the examples is to stress again how important the design phase is in optimizing the life of the system. Operation and maintenance procedures cannot compensate for improper pump selection, installation and operation.

Constant speed centrifugal pumps generally operate at one flow rate in a given system. The system resistance can be increased by throttling a valve to reduce the flow, but there is no simple way to reduce losses to increase flow. The alternative is to use multiple pumps. Selection of the pumps and the decision about installing them in parallel or in series depends on the amount friction in the system. It is generally most economical and simplifies maintenance if the pumps are identical.

However, such a choice may not provide the required flow and keep the pumps operating in an efficient range.

Parallel Pump Operation Figure 4 shows the system curve for a 12-inch diameter pipe that is about 4000-foot long with an elevation lift of 65-feet. For simplicity the Net Positive Suction Head (NPSH) and Brake Horse Power (BHP) data have been eliminated from the figure. For one C pump, the system will operate at a flow rate of about 475 gpm at best efficiency point (bep) of 85%. The intersection of the system curve with the curve labeled 2-pumps shows that two C pumps can provide a total flow of about 620 gpm. The two pump curve is constructed by adding the flow of each pump at each head. The pump efficiency of two pumps operating in parallel is determined by projecting horizontally to the left to intersect the single pump curve. For this example, each pump will supply 310 gpm and operate at just over 60% efficiency. One pump will operate at its bep but two pumps operate at significantly reduced efficiency. The loss of 25% efficiency at the higher flow may eliminate the choice of two identical pumps as the preferred choice. The choice partly depends on the percent of time that the pumps must operate at the high flow. If it is required only for peaking periods, identical pumps would be a good choice

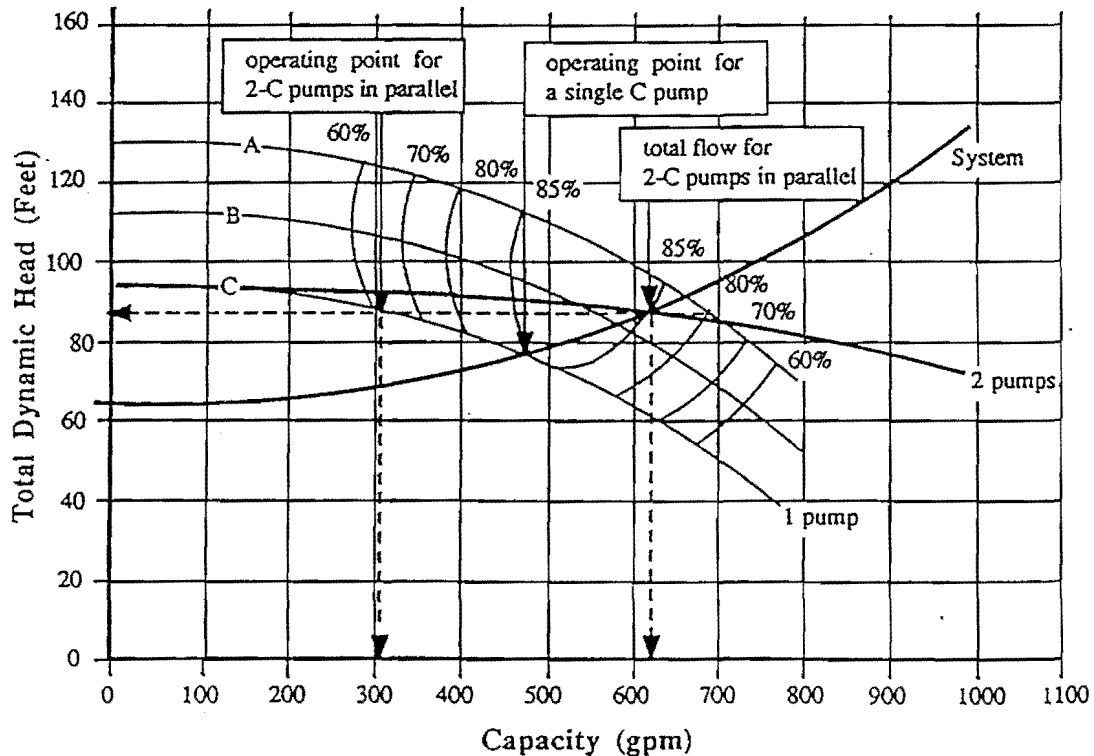


Figure 4 Poor Selection of Parallel Pumps

and the low efficiency would have little economic impact. If the higher flow is because of increased demand and the system must operate at the higher flow most of the time, then another choice would be better.

When a permanent flow increase is required due to increased demands, the additional pump should generally have greater capacity than the original pump. The advantage of this is demonstrated in Figure 5 which shows two pumps of different capacity operating in parallel. For one C and one B pump in parallel, the combined curve follows the B curve until the head drops the shutoff head of pump C (about 92-feet). Beyond that point, the flows from the two pumps add. For this design, assume that the initial flow required is 560 gpm so one C pump would be initially installed in the system.

Future demands should be anticipated during the design phase and the original pumps selected with future parallel operation in mind. This means selecting the first pump so it operates at a flow above its bep. This helps keep it in an acceptable efficiency range when the second pump is added. For this example, the C pump operating by itself, will operate at 80% efficiency. When the B pump is added, it will operate at its bep

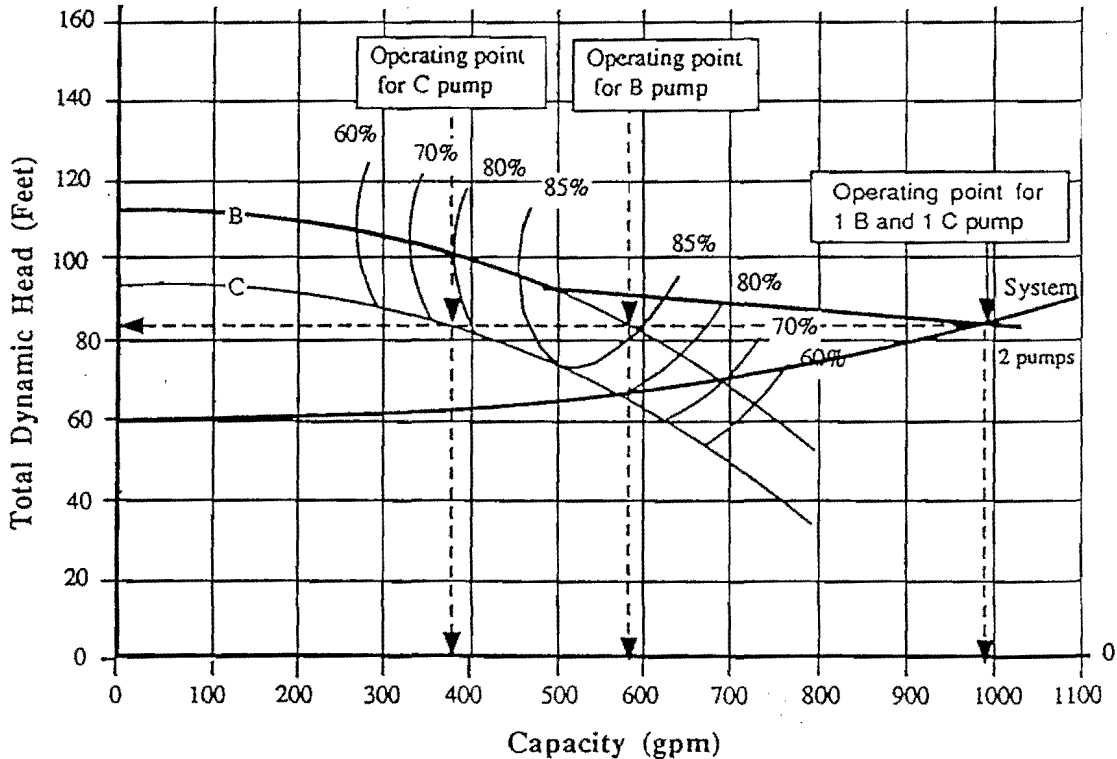


Figure 5 Parallel Pumps With Different Capacity

(85%) and the C pump will be at 75% efficiency. The B pump would operate at 71% efficiency, if operated alone. If the initial design did not anticipate the additional pump, the first pump would normally be selected to operate right at its bep and it would operate at a very low efficiency or would need to be replaced when the second pump was installed.

Series Pump Operation Not only should the original design consider the need for future pumps, but it must decide if the pumps should be installed in series or parallel. This choice has a significant impact on the pump selection. For parallel pump operation, the original pump should be selected so it operates at a flow above its bep. This example shows that for series installation, the original pump should be selected so it operates at a flow less than the bep. Figures 6 and 7 demonstrate the reason. Figure 6 shows a system where the C pump is selected because it will operate right at its bep. When a second identical pump is added in series, both pumps will operate below 60% efficiency. This would not be a good operating condition.

Figure 7 shows the same pumps selected for a system where a single C pump will operate at 380 gpm and 75% efficiency. Two C pumps in series will operate at about 73% efficiency. The choice of how far it is reasonable for the first pump to operate below its bep depends on how long it will be used before the second pump is added. Another option is to select the first pump so it operates at its bep and simply replace it when added capacity is needed. The decision would depend on the economics of operation cost versus replacement cost and the length of time before the pump must be replaced. The purpose of this discussion is not to consider all options for good pump selection but to demonstrate the importance of long-range planning and pump selection on operation of the system.

Starting and Stopping Pumps Starting or stopping the pumps and filling the pipeline can generate pressure transients that can damage the pipe and controls. If the design process does not consider these potential problems, the system may not function trouble free. Down-time and maintenance costs may be high. Not all systems will experience start-up and shut-down problems, but the design should at least consider the possibility.

Starting a pump with the pipeline empty will result in filling at a very rapid rate because there is little pressure or friction initially in the system.

As a result, the pump will operate at a flow well above the design flow. This can cause the pump to cavitate, but the more serious problem is the possibility of high pressures generated by the rapid filling of the pipe. It is possible for a pipe to rupture during filling if adequate precautions are not taken. Provisions should be made to control the rate of filling to a safe rate, provide adequate air release valves and develop a safe filling procedure. Start-up transients are often controlled by starting the pump against a closed or partially open discharge valve located near the pump and using a bypass line around the pump. This allows the system to be filled slowly and safely. If the pipe remains full, after the initial filling, subsequent start-up of the pumps generally does not create any serious problem.

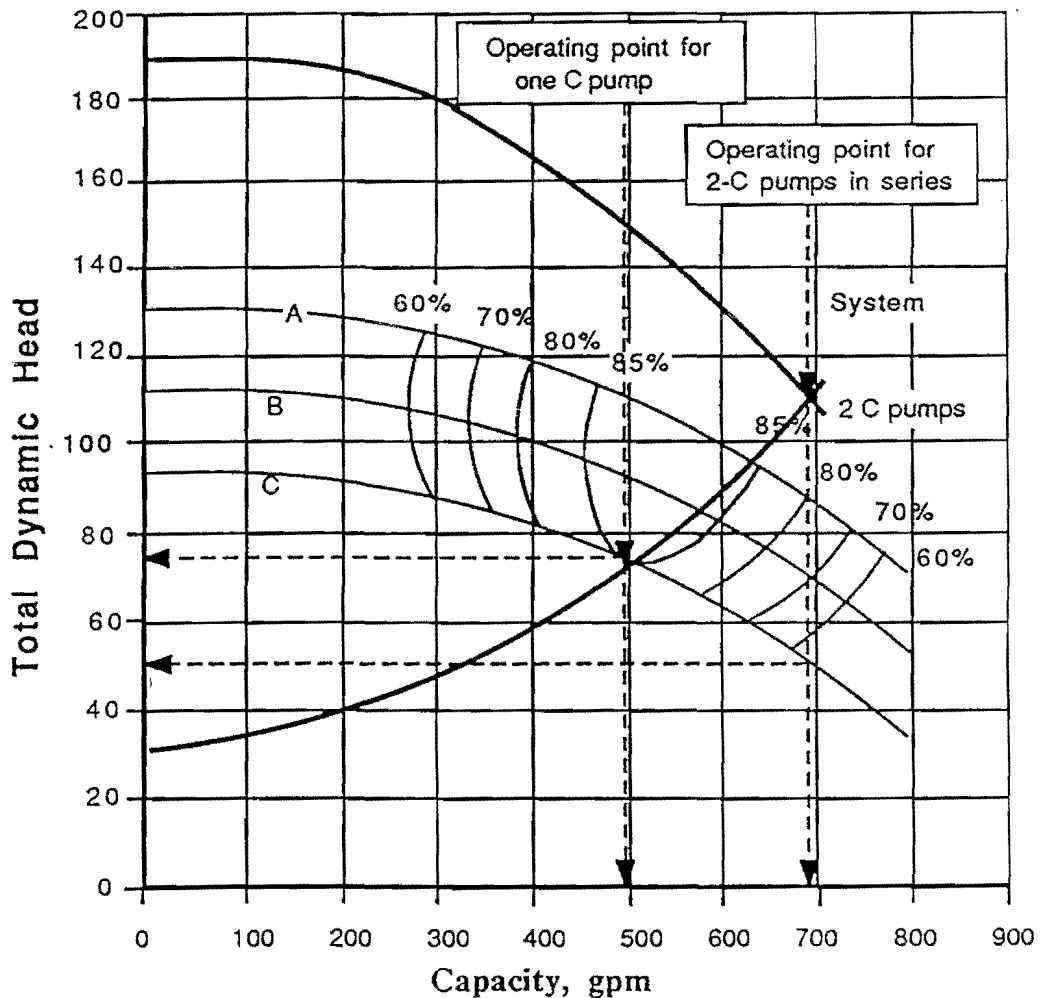


Figure 6 Poor Pump Selection for Series Pumps

For some systems, stopping the pump, either intentionally or accidentally, generates high pressures. The problem is most severe for pipelines that have a high elevation change and multiple high points. The magnitude of the transient is related to the length and profile of the pipeline, the pump characteristics and the magnitude of the elevation change versus the friction head. The downsurge caused by stopping the pump can cause column separation and high pressures due to closure of the check valves. Surge protection equipment should be added to such systems to prevent damage and excessive maintenance.

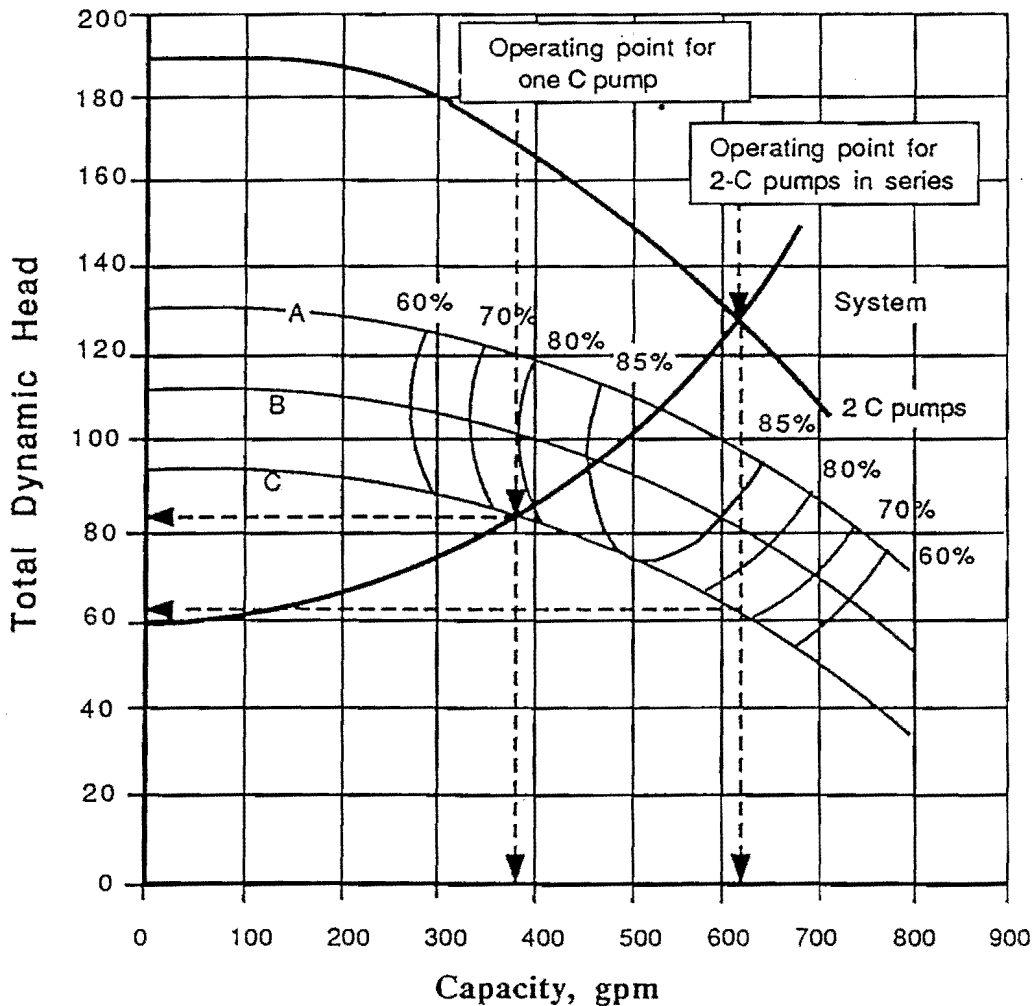


Figure 7 Good Pump Selection for Series Pumps

Another operational problem occurs with parallel pumps. Each line must have a check valve to prevent reverse flow. When a pump is turned off, the flow reversed almost immediately because of the high manifold

pressure supplied by the operating pumps. This causes the check valve to rapidly close. If a slow closing check valve is installed, the flow can reverse before the valve closes, generating high pressure transients. This problem was discussed in the section on check valves.

Numerous mechanical devices and techniques have been used to suppress pump shut-down transients. These include increasing the rotational inertia of the pump, use of surge tanks or air chambers near the pump, pressure relief valves, vacuum breaking valves, and surge anticipating valves. Selection of the proper transient control device will improve reliability, extend the economic life of the system and reduce maintenance. Failure to complete a transient analysis and include the required controls will have the opposite effect. A system is only as good as it is designed to be.

REFERENCES

1. Kalsi Engineering, and Tullis Engineering Consultants, (1993) "Application Guide for Check Valves in Nuclear Power Plants, Revision 1", NP-5479. Prepared for Nuclear Maintenance Applications Center.
2. Tullis, J. P., (1989) "Hydraulics of Pipelines-Pumps, Valves, Cavitation, Transients," John Wiley and Sons, New York, Copyright 1989.
3. Tullis, J. P., (1992) "Selection and Use of Control Devices in Water Distribution Networks," Presented at the International Course on Water Supply Systems. "State of the Art and Future Trends"; Valencia, Spain; October 19-23, 1992.
4. Tullis, J. P., (1993) "Cavitation Guide for Control Valves," Prepared for the U.S. Nuclear Regulatory Commission, NUREG/CR-6031.