CHAPTER 5
PUMPING SYSTEM DESIGN

5-1. Force main hydraulics

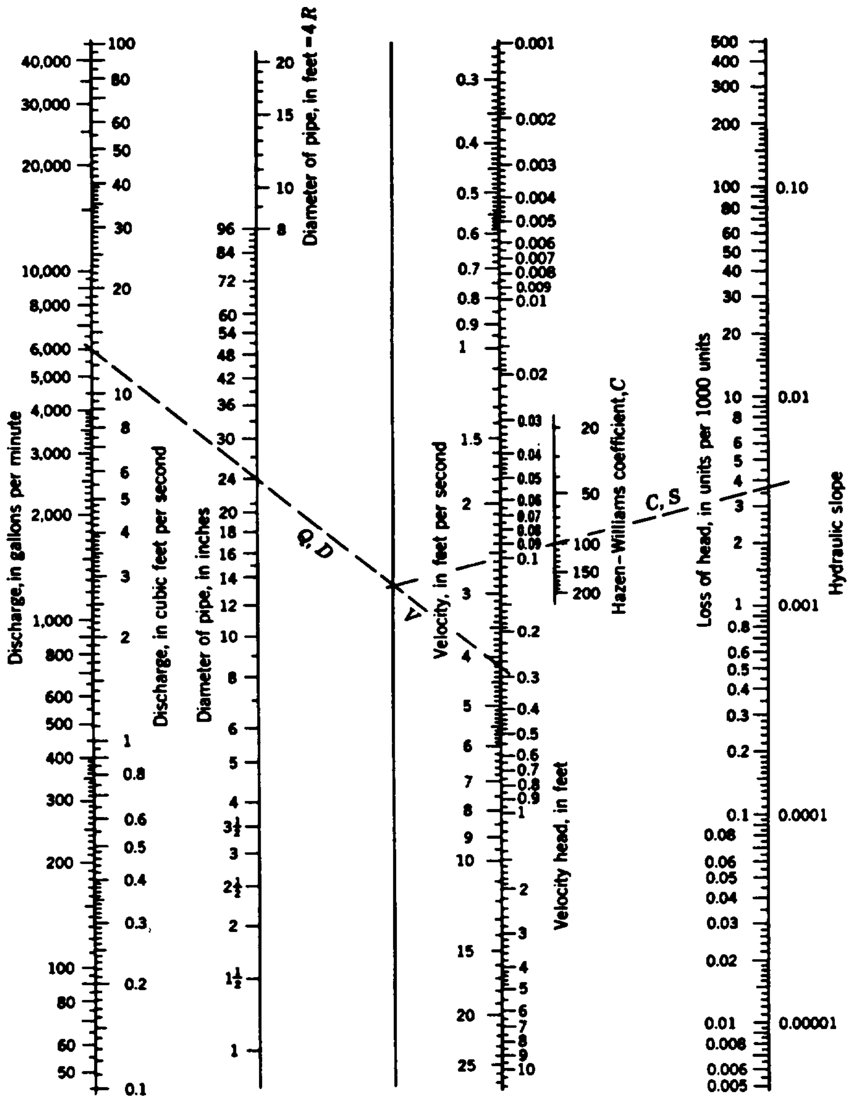
a. General. The pipeline which receives wastewater from a pumping station, and conveys it to the point of discharge, is called a force main. Force mains will be designed as pressure pipe, and must be adequate in strength to withstand an internal operating pressure equal to the pump discharge head, plus an allowance for transient pressures caused by water hammer. The internal operating pressure is maximum at the pumping station, and is reduced by friction to atmospheric, or near atmospheric, at the point of force main discharge. The primary consideration in the hydraulic design of force mains is to select a pipe size which will provide the required minimum velocities without creating excessive energy losses due to pipe friction. The most economical size of force main should be determined on the basis of power costs required for pumping, and capital investment costs of piping and equipment. In practice however, the size is usually governed by the need to maintain minimum velocities at low flows to prevent deposition of solids, and to develop sufficient velocity at least once a day to resuspend any solids which may have settled in the line. However, regardless of pipe sizes required for minimum velocities, the minimum diameters to be used are 1Y4-inch for pressure sewers at grinder pump installations, 4-inch for force mains serving small pump stations and pneumatic ejectors, and 6-inch for all other force mains.

b Design formula and chart. Force mains will be designed hydraulically with the use of the Hazen-Williams formula as follows:

$$V = 1.32\ C\ R^{0.63}\ S^{0.54}$$

where
V = velocity in feet per second
C = coefficient of pipe roughness
R = hydraulic radius in feet, and
S = slope of energy grade line in feet per foot

(1) Roughness coefficient. Values of C to be used in the formula range from 100 for older force mains which have been in service a number of years (usually over 10), to 140 for force mains which are newly constructed. Some manufacturers of plastic and asbestos-cement pipe report C values as high as 150. However, due to uncertainties in design and construction, plus a desire to provide a margin of safety, C values greater than 140 will not normally be permitted. At some installations, force mains may be very old (40 to 50 years) and in extremely bad condition, with offset joints broken pipe, or materials encrusted on pipe walls. For these cases, lower C values may be justified. However, values lower than 80 will not be allowed unless verified by flow and pressure tests. A solution to the Hazen-Williams formula is given in figure 5-1.



Source: Design and Construction of Sanitary and Storm Sewers WPCF Manual of Practice No. 9 by Water Pollution Control Federation, 1970, p. 83.

Figure 5-1. Chart for Hazen-Williams formula.

(2) Velocity. Velocity criteria for force mains are based on the fact that suspended organic solids do not settle out at a velocity of 2.0 foot per second or greater. Solids will settle at velocities less than 1.0 fps and when wastewater pumps are idle. However, a velocity of 2.5 to 3.5 fps is generally adequate to resuspend and flush the solids from the line. Force mains serving small pump stations, which are designed to operate on an intermittant basis, will be sized to provide a minimum velocity of 3.5 fps at the peak discharge rate. For small stations having flows too low to warrant a minimum velocity of 3.5 fps with one pump operating, the design may call for both pumps to be operated manually once a week for a sufficient period of time to flush out the line. Larger stations having three or more pumping units, which operate a major portion of the time, will require minimum force main velocities ranging from 2.0 fps with one pump operating, to 5.0 fps with several pumps operating. In these cases, it is only required

that a minimum velocity of 2.5 to 3.5 fps be provided once or twice daily. Large pumping stations which serve the entire installation or major portions thereof, and which are designed to pump continuously, will usually have a greater number of pumps operating over a wider range of flowrates. Since the pumping range may vary from 7 or 8 to 1, it will generally be sufficient to design for velocities of 0.5 up to 7.0 or 8.0 fps. Maximum velocity is set at 10.0 fps.

(3) Slope. The value of S in the formula is equivalent to the kinetic energy loss due to pipe friction divided by the length of conduit, or $S = H_f/L$. Minor energy losses from fittings and valves will be converted to equivalent lengths of conduit for use in the formula. Conversion tables for fittings and valves can be found in standard hydraulics textbooks. The total kinetic energy loss in a force main will be computed by multiplying the slope of the energy grade line by the total length of conduit including equivalent lengths, or $H_f = S \times L$.

5-2. Pump analysis and selection

a. Total dynamic head. The head in feet against which a pump must work when wastewater is being discharged is termed the total dynamic head (TDH). The two primary components of TDH in wastewater applications are the static discharge head and the kinetic losses due to pipe friction. Velocity and pressure heads are also present, but are usually insignificant. The TDH will be calculated with the use of the Bernoulli energy equation which can be written as follows:

$$TDH = (P_d/W + V^2_d/2g + Z_d) - (P_8/W + V^2_8/2g + Z_8) + H_f$$

where

P_d, P_8 = gage pressures in pounds per square foot

V_d, V_8 = velocities in feet per second

Z_d, Z_8 = static elevations in feet

H_f = kinetic energy loss from pipe friction, fittings, and valves, as calculated in paragraph 5-1b (3).

w = specific weight of fluid in pounds per cubic foot, and

g = acceleration due to gravity 32.2 ft/sec^2)

All head terms are in feet. Subscripts d and 8 represent force main discharge and pump suction, respectively. In order to determine hydraulic conditions at the pump suction, it will be necessary to write an energy equation from the liquid level in the wet well to the pump suction nozzle.

b. System head-capacity curve. To determine the head required of a pump, or group of pumps, that would discharge at various flowrates into a force main system, a head-capacity curve must be prepared. This curve is a graphic representation of the total dynamic head, and will be constructed by plotting the TDH over a range of flowrates from zero to the maximum expected value. Friction losses can be expected to increase with time, thus affecting the capacity of the pumping units and their operation. Therefore, system curves well reflect the maximum and minimum friction losses to be expected during the lifetime of the pumping units, as well as high and low wet well levels. The typical set of system curves will generally consist of two curves using a Hazen-Williams coefficient of C = 100 (one for maximum and one for minimum static head), and two curves using a Hazen-Williams co-efficient of C = 140 (for maximum and minimum static head). These coefficients represent the extremes normally found in wastewater applications.

c. Pump head-capacity curve. The head that a particular pump can produce at various flowrates is established in pump tests conducted by the pump manufacturer. The results of these tests are plotted on a graph to form the pump characteristic curve. Along with the discharge head developed, the pumps operating efficiency, required power input, and net positive suction head are generally included on the same diagram.

(1) Efficiency and power input. Pump efficiency is the ratio of the useful power output to the input, or brake horsepower, and is given by:

$$E = \frac{\underline{wQ\ TDH}}{(bhp)(550)}$$

where

E = pump efficiency (100 E = percent)

w = specific weight of fluid in pounds per cubic foot

Q = pump capacity in cubic feet per second

TDH = Total dynamic head, and

bhp = brake horsepower

Pump efficiencies usually range from 60 to 85 percent. Most characteristic curves will indicate a best efficiency point (BEP) at which pump operation is most efficient. Where possible, pumps will be selected to operate within a range of 60 to 120 percent of the BEP.

(2) Net positive suction head. When pumps operate at high speeds and at capacities greater than the BEP, the potential exists for pump cavitation. Cavitation can reduce pumping capacity and may in time damage the pump impeller. Cavitation occurs when

the absolute pressure at the pump inlet drops below the vapor pressure of the fluid being pumped. To determine if cavitation will be a problem, the net positive sunction head (NPSH) available will be computed, and compared with the NPSH required by the pump. The NPSH is not normally a problem when discharge heads are less than 60 feet. However, when heads are greater than 60 feet, or when the pump operates under a suction lift, or far out on its curve, the NPSH will be checked. The NPSH available at the eye of the impeller in feet will be calculated with the following formula:

$$NPSH_A = H_8 + P_a/w - P_a/w$$

where

H_8 = total energy head at pump suction nozzle
= P8/w + V2 /2g + Z,

P_a = atmospheric pressure in pounds per square foot absolute, and

P_V = vapor pressure of fluid being pumped in pounds per square foot absolute

All head terms are in feet.

(3) Affinity laws. A set of relationships derived from flow, head and power coefficients for centrifugal pumps, can be used to determine the effect of speed changes on a particular pump. These relationships are known as affinity laws and are as follows:

$$Q_1/Q_2 = N_1/N_2$$
$$H_1/H_2 = N^2{}_1/N^2{}_2$$
$$P_1/P_2 = N^3{}_1/N^3{}_2$$

where

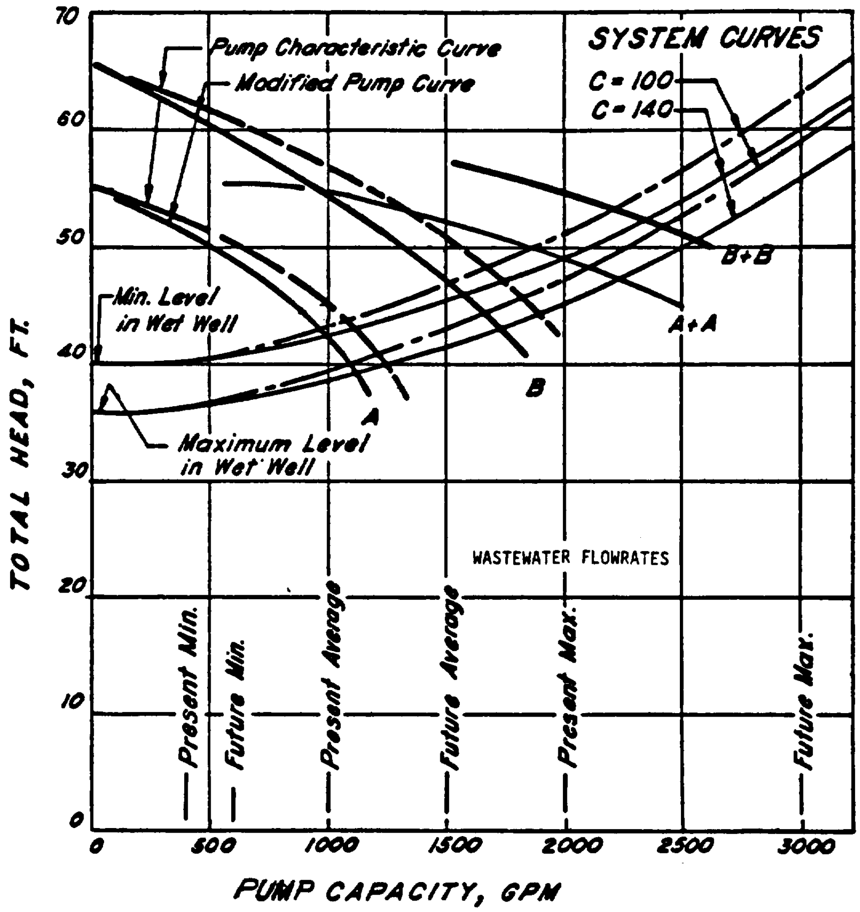
N_1, N_2 = pump speeds in revolutions per minute (rpm)

Q, H and P terms represent pump capacity, discharge head, and power output respectively, at speeds N_1 and N_2. These relationships will be used in analyzing variable speed pump operation in the absence of manufacturer's characteristic curves, or where characteristic curves do not show performance at the desired speeds.

d Pump selection. System analysis for a pumping station will be conducted to select the most suitable pumping units which will meet service requirements, and to determine their operating points, efficiencies, and required horsepower.

(1) Single pump operation. A system head-capacity curve will be prepared showing all conditions under which the pump is required to operate. The system curve will then be superimposed onto a pump head-capacity curve, or characteristic curve, to define the pump operating point. The point where the two curves intersect represents the head and capacity at which the pump will operate in the given piping system.

(2) Multiple pump operation. Where two or more pumps discharge into a common header, the head losses in individual suction and discharge lines will be omitted from the system head-capacity curve. This is because the pumping capacity of each unit will vary depending upon which units are in operation. In order to obtain a true picture of the output from a multiple pump installation, the individual suction and discharge losses are deducted from the pump characteristic curves. This provides a modified curve which represents pump performance at the point of connection to the discharge header. Multiple pump performance will be determined by adding the capacity for points of equal head from the modified curve. The intersection of the modified individual and combined pump curves with the system curves shows total discharge capacity for each of the several possible combinations. Pumps will be selected so that the total required capacity of the pump installation can be delivered with the minimum level in the wet well and maximum friction in the discharge line. Pump efficiency will be a maximum at average operating conditions. A typical set of system curves with pump characteristic curves is shown in figure 5-2.



U.S. Army Corps of Engineers

Figure 5-2. Typical pump-system curves.

5-3. Wet well design

a General. Wet wells will be constructed at pumping stations for the purpose of storing wastewater flows prior to pump operation. The storage volume required depends upon the method of pump operation, i.e., whether pumps are constant, adjustable or variable speed. In addition to providing adequate storage volume, wet wells will be designed to (1) allow for proper pump and level controls, (2) maintain sufficient submergence of the pump suction inlet, (3) prevent excessive deposition of solids, and (4) provide ventilation of incoming sewer gases. In smaller stations, bar racks or comminuting devices may be installed within the wet well in order to reduce costs. Overflows from wet wells are prohibited in all cases.

b Storage volume. If pumps are of constant or adjustable speed type, the wet well volume must be large enough to prevent short cycling of pump motors. For pumps driven by varible speed drives, the storage volume may be small provided pumping rates closely match the incoming flowrates. The volume required for the wet well will be computed with the following formula:

$$V = tq/4$$

where

V = required volume in gallons between start and stop elevations for a single pump, or a single speed step increase for adjustable or variable speed operation

t = minimum time in minutes of one pumping cycle (time between successive pump starts), or time required for a speed or capacity change, and

q = pumping capacity, or increment in capacity where one or more pumps are operating and an additional pump is started, or where pump speed is increased, in gallons per minute

Constant or adjustable speed pumps driven by squirrel-cage induction motors will be designed for minimum cycle times as shown in the following table.

Table 5-1. Minimum pump cycle times.

More size, bhp	t, minutes
Less than 20	10 to 15
20 to 100	15 to 20
100 to 250	20 to 30
Over 250	as recommended by manufacturer

The storage volume calculated for small stations (capacities less than 700 gpm) which utilize two identical constant speed pumps, may be reduced one half by providing a control circuit to automatically alternate the pumps. The storage volume required for variable speed pumps will be based on providing sufficient time for a change in capacity when a pump is started or stopped. When a pump is started, the motor must be ramped to the desired speed, and the pumps already in operation must be reduced in speed. The time required for this is usually less than 1 minute. A considerable amount of storage is normally available in large sewers which serve stations utilizing variable speed pumps. This volume may be considered in design by calculating backwater curves for the various operating levels. The maximum retention time in the wet well will not exceed 30 minutes to prevent septicity.

c. Suction pipe connections. Pump suction piping will be selected to provide a velocity of 4 to 6 feet per second. Pipe should be one or two sizes larger than the pump suction nozzle. Vertical pumps installed in a dry well which is adjacent to the wet well, will be fitted with a 90 degree suction elbow, followed by an eccentric reducer and a gate valve. The suction line will be extended through the wall into the wet well, and terminated with either a 90 or 45 degree flared elbow, or an elbow with a flared fitting. The most commonly used piping arrangements are illustrated in figure 5-3, where D is the diameter of the flared inlet, and S is the submergence depth.

Adequate submergence of the suction inlet is critical to prevent air from being drawn in by vortexing. Minimum required submergence depths are given in table 5-2 as a function of velocity. The net positive suction head (NPSH) will also be considered when determining S. See paragraph 5-2c (2).

Table 5-2. Required submergence depth to prevent vortexing.

Velocity at diameter D, fps	S, feet
2	1.0
4	2.6
5	3.4
6	4.5
7	5.7
8	7.1

Larger, conventional type pump stations will normally be constructed with wet wells divided into two or more sections, or compartments, so that a portion of the station can be taken out of service for inspection or maintenance. Each compartment will have individual suction pipes, and will be interconnected with slide or sluice gates. The floor of the wet well will be level from the wall to a point 12 to 18 inches beyond the outer edge of the suction bell, and then will be sloped upward at a minimum 1:1 slope.

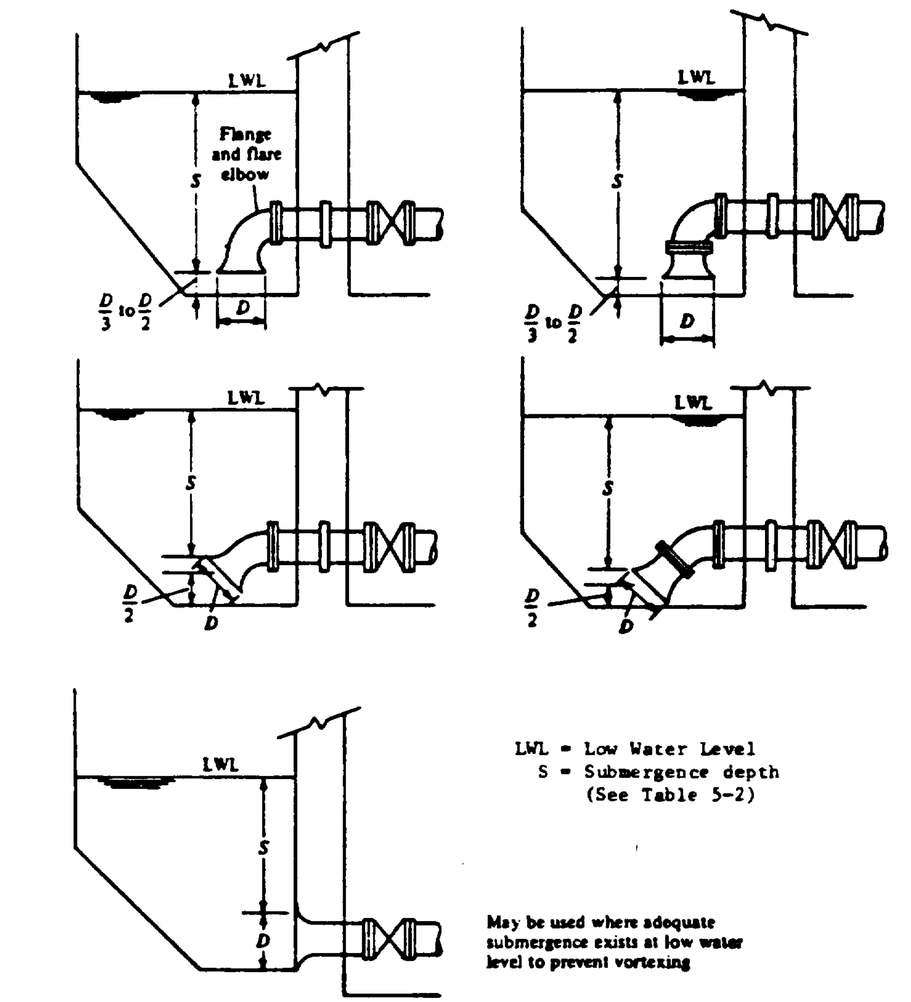
5-4. Pump controls and instrumentation

a. General. Instrumentation at a pumping station includes automatic and manual controls used to sequence the operation of pumps, and alarms for indicating malfunctions in the pumping system. Automatic control of pumps will usually be based on the liquid level in the wet well. Paragraph 4-4 contains a discussion of the various modes of pump operation, pump control systems, and a description of level detection devices. Manual control of pumps is always required in order to operate the pumps during emergencies, for maintenance purposes, or when automatic systems fail. Manual override will be set to bypass the low level cut-off, but not the low level alarm.

b. Selection of control points. A control range of at least 3.0 feet is required between maximum and minimum liquid levels in the wet well. A minimum of 6 inches will be required between pump control points used to start and stop successive pumps, or to change pump speeds. For small stations, the control range may be less, however control points will not be set closer than 3 inches.

(1) Constant or adjustable speed pumps require simple on-off switches to start or stop pumps, or to change from one speed step to the next.

(2) Variable speed pumps require a more complex control arrangement. The two basic types of level control for variable speed operation are (a) variable level, and (b) constant level. For variable level control, a narrow band of control points is established in the wet well. Pump speed is then adjusted in steps by the level detection system (usually a bubbler tube) as the level varies. Pumps operate at maximum



Source: Wastewater Engineering: Collection and Pumping of Wastewater by Metcalf & Eddy, Inc., 1981, p. 360.

Figure 5-3. Pump suction connections to wet well.

speeds near the HWL, and at minimum speeds near the LWL. However, pumps are started and stopped by level switches. Constant level control is seldom used, but may be required where a very narrow band of operation is necessary. In a constant level system, one level is set as the control point, and pump speed is adjusted in a stepless fashion as the liquid level rises above, or falls below this point.

c. Alarms. Alarms will be provided to signal high and low liquid levels in the wet well, pump failure, or a malfunctioning speed control system. The high level alarm will be set above the start point of the last pump in the operational sequence, but below the start point of the standby pump, if used. The low level alarm will be set below the shutoff point of the lead pump. An emergency, low level pump cutoff will be set below the low level alarm.

5-5. Surge phenomena

a. Water hammer. Sudden changes in flow and velocity in force mains can occur as a result of pump startup, pump shutdown, power failure, or rapid closing of a valve. These velocity changes can produce large pressure increases or surge phenomena known as water hammer. The most severe water hammer conditions are usually caused by a pump shutdown or power failure. An analysis of water hammer will include calculating the critical time, determining the maximum pressure increase, and selecting a method of control.

b. Critical time. When flow is suddenly changed in a force main, a pressure wave is generated which rapidly travels the entire length of conduit, and back to the point of change. The time required for this roundtrip is given by:

$T_c = 2L/a$

where

T_c = critical time in seconds
L = length of force main between point of flow change and point of discharge in feet, and
a = velocity of pressure wave in feet per second

When flow is completely stopped (Q = O) in a time interval greater than Tc, the maximum theoretical pressure increase is not fully developed. However, when flow is stopped in a time interval less than or equal to Tc, the change is said to be instantaneous, and the maximum pressure increase is developed as given below.

c. Maximum pressure increase. The maximum theoretical pressure increase or surge caused by water hammer is calculated from the following:

$h_w = aV/g$

where

h_w = pressure increase in feet
V = velocity of fluid in the pipeline prior to flow change in feet per second
g = acceleration due to gravity, or 32.2 ft/sec2 at sea level, and
a = velocity of pressure wave in feet per second

Some typical values of a are given in table 5-3 below.

Table 5-3. Water hammer wave velocities.

Pipe Material	a, ft/sec
Asbestos-cement	2700--400
Ductile iron	3100--4200
Steel	2700--3900
Concrete	3300--3800
Plastic	1100--1500
Fiberglass	1200--1600

d. Methods of control. Whenever a pump is shut down, or power to the station fails, the pump motor is suddenly cut off. Pump speed along with flow and velocity in the force main are quickly decelerated by pressure waves, which travel up the pipeline and back in accordance with Newton's second law of motion. When the velocity is reduced to zero, reverse flow through the pump would occur if a gravity operated check valve or an automatic control valve were not installed on the pump discharge line, and did not close properly. Reverse flow fully accelerated through the pump could cause transient flows and pressures well above maximum design conditions. A swing check valve which stuck open temporarily, and then slammed shut under these conditions, would re5-8 suit in a large pressure surge as given by paragraph c above. In order to control and limit these surge phenomena, the following practices will be followed.

(1) Gravity check valves. For simple cases involving small to medium sized pump stations with gradually rising force mains (no intermediate high points) of less than 1000 feet in length, and with static discharge heads of less than 50 feet, a gravity operated check valve will usually be sufficient. Gravity type check valves may be either swing checks utilizing outside lever and weight (or spring) set to assist closure, or then may be ball checks. Swing check valves are usually installed horizontally, while ball check valves may be either vertical or horizontal. For additional protection, a pressure relief valve may be installed in conjunction with check valves to allow reversing flow to reenter the wet wall. Pressure relief valves must be specially designed for sewage applications. As an alternative to relief valves, a hydro-pneumatic tank may be utilized.

(2) Automatic control valves. In situations where long force mains are required, pipe profiles must conform to existing ground elevations for economic reasons. This normally will result in high points in the force main, with the possibility of water column separation at the high points in the force main, with the possibility of water column separation at the high points during pump shutdown or power failure. The pressures generated when these separated columns come to rest against closed valves or against stagnant columns may be large, and are again determined by paragraph c above. In general, where force mains are greater than 1000 feet in length or contain intermediate high points, and where pumping stations are large in capacity, or static discharge heads are greater than 50 feet, control valves will be automatically operated (1) cone, (2) plug, (3) ball, or (4) butterfly valves. Normal operation of these valves upon pump shutdown, is to slowly close the valve while the pump continues to run. When the valve is closed, a limit switch then stops the pump motor. On power failure, an emergency hydraulic or other type operator closes the valve slowly. The time of valve closure is of utmost importance. Valves should be half closed when the velocity in the force main has dropped to zero. The time required to reach zero velocity can be calculated with the following formula:

$t = LV/g\ H_{av}$

where

t = time in seconds
L = length of force main in feet
V = velocity of fluid in pipeline in feet per second, and
H_{av} = average decelerating head including pipe friction in feet

The types of valve operators most often utilized are hydraulic, electric and pneumatic. Valves and operators specified for use will be fully adjustable for closure times ranging from t to 4t minimum. In some large pumping stations, the use of automatically controlled valves alone will not be sufficient. Extremely long force mains (over 1 mile) may require very long valve closing times, and thus result in excessive backflow to the wet well and reverse rotation of the pump and motor. To solve these problems, a pump bypass with surge relief valve will generally be required. Valves used for surge relief will be automatically controlled cone or butterfly valves, similar to the pump discharge valves. Normal operation upon pump shutdown now will require the pump discharge valve to be fully closed when the velocity has dropped to zero. The surge relief valve will be fully open allowing backflow to enter the wet well at a reduced rate. As before, the relief valve must close slowly to avoid water hammer. Most cases involving large pump stations with long force mains, which contain several intermediate high points, will be too complex to solve by hand using conventional methods such as graphical solutions, arithmetic integration, or water hammer charts. Many computer programs are now available for water hammer analysis, and are recommended for use in those instances.

5-6. Screening and comminuting devices. Centrifugal pumps are susceptible to clogging by rags, trash, and other debris normally found in wastewater. To protect pumps from clogging, equipment will be installed to screen or cut up these materials prior to pumping. Small pump stations with capacities of less than 200 gpm, including grinder pumps and pneumatic ejectors, are exempt from this requirement. The types of equipment to be used include bar racks, screens, and comminutors which are installed in the wet well, or in a separate influent channel. The design of these facilities is covered in TM 5-814-3/AFM 88-11, Vol. 3. At most medium to large sized pump stations, the use of mechanically cleaned bar screens or comminutors will be required. However, at smaller stations in remote areas, manually cleaned racks may be more feasible. The smallest clear opening between bars is normally 1 inch, and spacings of less than 3/4 inch will not be permitted. All electrically operated equipment in wet wells will have explosion proof motors.