ENERGY EFFICIENY OF WATER DISTRIBUTION SYSTEMS

A limited number of options exist to save energy in water distribution operation. Turning off lights in pump stations and using pickup trucks with small engines can only marginally affect energy use. Pumping stations are the water distribution system components that provide the greatest opportunity for cost savings due to improved operation. Optimal operation in these cases corresponds to minimizing pumping energy consumption while maintaining adequate service.

Most utility managers would deny that their pumping stations are operated inefficiently and they are generally justified in that assertion. However, while not being terribly inefficient, there is probably not a pump station in the world that is operated at lowest possible cost. The issue is really one of trying to get as close as possible to this theoretical least cost operation without spending excessive money on the required hardware and software to lower the costs or by taking any unnecessary risks. The best solution will depend on the utility. A small utility with energy costs of a few thousand dollars per year may be willing to settle for wasting a large fraction of energy while a large utility with millions of dollars per year in energy costs may be willing to spend a considerable amount of money trying to squeeze one or two percent from its energy bill.

Multi-objective Nature of the Problem

The objective of this monograph is to present various methodologies for minimizing the energy consumption associated with water distribution systems. It should be recognized, however, that the minimization of energy consumption should not be regarded as the sole goal in operating water distribution systems. Rather it is just one of many objectives, some of which are directly contrary to energy minimization. Some of the other objectives are described in the following paragraphs. Any proposed operating policy for a water distribution system should thus be evaluated with regard to its impact on these objectives as well.

Satisfying Demands

The goal meeting consumer demands is the number one goal of all water supply systems, and in no way should the goal of saving energy preclude satisfying demands.

Emergency Protection.

The primary purpose of storage in a water distribution system is to provide water to meet very high short-term demands (e.g. fires) and to provide uninterrupted water service during power outages when pumps cannot operate. Keeping the tanks less than full reduces energy requirements for pumping but also reduces the amount of water available for such emergencies. Most utilities deal with this problem by maintaining an arbitrary minimum water level for use in meeting emergency situations.

Water Quality.

If the water level in a tank remains constant and separate drain and fill lines were not installed with the tank, there is no way for water to be exchanged between the tank and the remainder of the distribution system. Eventually, the disinfectant residual will drop off and regrowth of microorganisms can occur. Strategies to minimize energy consumption must take into account the fact that some exchange of water between tanks and the distribution system is necessary from a water quality standpoint. Holding the tank water level at a constant optimal level can result in water quality deterioration.

Capital Cost Minimization.

Energy costs to overcome friction in pipes can be reduced by installing large pipes so that the head loss (and thus the energy needed to overcome the head loss) is minimized. Sizing such pipes based on energy sized to flow at less than 5 ft/sec at peak flow, the dead loss when carrying average flow will be reasonable. The marginal cost of upsizing such a pip will generally exceed the marginal energy reduction. However, it may be worthwhile in some cases, particularly long pipelines, to consider upsizing pipes for energy reduction.

Problems and Solutions

Causes of Inefficiency.

There is no single simple approach to minimizing pumping energy costs because there is no single reason that pumping systems are operated less than optimally. Instead, there are a myriad of reasons why pumping stations operate at a higher than optimal cost. Some of these reasons include:

1. pumps which were incorrectly selected,
2. pumps which have worn out,
3. limited capacity in the transmission/distribution system,
4. limited storage capacity,
5. inefficient operation of pressure (hydropneumatic) tanks,
6. inadequate or inaccurate telemetry equipment,
7. inability to automatically or remotely control pumps and valves,
8. penalty due to time-of- day or seasonal energy pricing,
9. lack of understanding of demand or capacity power charges,
10. operator error,
11. suboptimal control strategies.

Most of these problems will not be noticed without the utility actively looking for energy waste. Pumps operating efficiently look just like those which are wasting energy.

Factors That Effect Energy Use.

Energy consumption is directly proportional to the discharge and head and inversely proportional to the efficiency of the pumps. The problem is complicated, however, by the fact that the efficiency is itself a function of the discharge, the problem of minimizing energy costs can be stated mathematically in a fairly simplified form below as

$$\text{minimize} \sum_{i=1}^{n} k \; Q_i \; h_i \; p_i \,/\, e_i \tag{1.1}$$

$$\text{subject to} \sum_{i=1}^{n} Q_i \; dt_i = V$$

where Q_i = discharge at operating point i
h_i = head at operating point i
p_i = price of energy at operating point i
e_i = wire-to-water efficiency at operating point i
k = units conversion factor
n = number of operating points
dt_i = length of time at operating point i
V = volume of water to be pumped

From equation (1), it is clear that energy usage can be reduced by decreasing the volume of water pumped, the head against which it is pumped or the price of energy, and increasing the efficiency of the pumps. Each of those factors which impact energy usage is discussed in the following paragraphs.

Volume Pumped.

The utility does not have a great deal of control over the volume of water pumped into a given pressure zone. Saving energy by not meeting demands is not considered acceptable practice. To the extent that water conservation reduces consumption, it also results in energy conservation. In distribution systems with multiple pressure zones, savings can be realized by minimizing the number of times water needs to be pumped. This is accomplished by eliminating instances where the utility pumps water into a high pressure zone only to have it flow back into a lower pressure zone through pressure reducing valves. Pressure zone boundaries can also be rearranged so that customers are served from the lowest zone feasible. This can cause problems if, for example, customers who had become accustomed to 115 psi water are switched to a pressure zone which provides them water at 45 psi while 45 psi is more than adequate for domestic purposes, the customers are likely to complain.

Head.

Reducing the total dynamic head against which the pump must work will reduce energy consumption. The easiest way to accomplish this is to keep storage tanks less than full provided that the efficiency of the new tanks full. Considering that most utilities let tanks float within a range of levels, energy savings can be realized by keeping the water level near the bottom of this range for as much of the day as possible, raising the level only for short periods to obtain some exchange of water between the tank and the distribution system. Of course, when tank levels are relatively low, the utility has less water in storage for the purpose of responding to an emergency.

Friction vs. Lift Head.

The head produced by a pump can go into either lifting water or overcoming friction. If most of the energy goes into lifting the water, the system head curve will be very flat. This the cases where the suction reservoir and discharge reservoir are very close to the pumping station. In these cases the energy consumption is the same, for example, when one pump is run for two hours or two pumps are run for one hour, and little saving can be realized by changing the scheduling of pumps. At the other extreme are situations in which most of the energy is used to overcome friction losses. This characterized by a very steep system head curve. This condition usually corresponds to an in- line booster pump station a great distance away from either the suction or discharge reservoir. In these situations, it is much better to run the pumps at as constant of a discharge as possible. That is, one pump running for two hours uses less energy than two pumps running for one hour.

Price of Energy.

While many electric utilities have a constant price for energy usage, others employ time-of-day pricing to discourage energy use during times of peak electrical demand. Water utilities can take advantage of this price structure by filling storage tanks during off- peak periods and letting the tank eater levels fall (within reasonable limits) during peak periods the existence of sufficient storage in the water distribution system is a necessity in order to take advantage of such price. In systems with less storage, it may be more advisable to use a standby generator or pumping equipment driven directly by internal combustion motors to meet peak demands.

Efficiency.

Utilities need to periodically check to insure that pumps are indeed operating near their best efficiency point. A pump can supply adequate pressure and flow to a given service area and from this a utility can mistakenly conclude that it is wording well. In reality, the pm may be robbing thousands of dollars from the utility each year in the form of unnecessarily high energy bills. There is no substitute for actual measurement of wire-to-water efficiency.

Studies to Improve Efficiency

Approaches to Cost Savings.

In addition to addressing different types of problems which result in a less than optimal system, utilities are faced with several levels at which they can address the problem. In order of increasing coat, these range from:

1. field testing of pumping equipment,
2. an engineering/economic evaluation of energy consumption,
3. use of computer hardware/software to assist pump operators.

The key to doing a good job in improving operation of a utility's pumping operation comes in identifying the problem(s) from the list of problems that is most significant for the utility and selecting the solution approach(es) from the list above that best addresses the problem. For a reasonably large utility, pump testing or an engineering/evaluation should cost tens of thousands of dollars, software development and training costs hundreds of thousands of dollars, and SCADA (Supervisory Control and Data Acquisition) hardware costs millions of dollars. A utility is wise to investigate the less expensive approaches first before turning to major investments in hardware or software.

Pump Testing.

Pump testing is a fairly standard practice and is documented in numerous places. If a utility has not had its pumps tested in several years, it may be worthwhile to have the pumps tested in place. The key to testing pumps is to make certain that all meters and gages used have been recently calibrated. Pump testing should include generation of the head characteristic curve and efficiency characteristic curve and comparison of these curves with curves from when the pump was new. Efforts should be made to test the pumps over as wide a range of flows as practicable. The tests can identify pumps which are inefficient due to mechanical problems.

Engineering/Economic Evaluation.

While pump testing is fairly standardized, an engineering/economic study of pumping operations can include a wide variety of analyses, including a report of pump testing results. While such a study is fairly utility specific, some of the possible components are described below.

Review of Historical Energy Bills.

As a first step the engineer should obtain energy bills paid by the utility and determine the fraction used by each pumping facility. The engineer should identify the location of all meters and the equipment served by each meter. The engineer should prepare plots of energy use vs. time and, after obtaining pumpage volumes, should plot energy cost per gallon pumped vs. time for each pumping facility. This will indicate the unit pumping costs (in cents per thousand gallons) and will correspond to the theoretical pumping cost if pumps are operating at their best efficiency points(s). If there is a significant difference, additional testing may be warranted. Such a review of energy bills can detect if the unit cost for pumping changes with the time of year or if a particular pump station has higher unit costs. This analysis may even identify billing errors on the part of the electrical utility or an inequitable energy rate when compared with other large customers. This analysis may give the water utility ammunition to negotiate a better rate from the electric utility. Finally, the review of energy bills should give the utility an idea of the magnitude of savings possible using more sophisticated techniques to reduce energy costs.

Review of Demand/Capacity Charges.

Many utilities are charged not only for the actual energy consumed but for the energy capacity required. This is often called "demand charges' and is based on the energy consumption rate during the peak use period. The engineer needs to determine what time period established the demand charge during each billing period. Was it a hot day during a dry period? Was it during a fire? Was it while the pumps were being tested? Was it due to an operator error? Once the cause of the peak demand has been determined, it is possible to identify ways of lowering the peak demand. Such measures as off-peak pumping during peak water use days, exercising standby pumping equipment (powered by internal combustion engine) during peak periods, distributing the load better between pump stations, or better operator training can all help reduce peak period energy usage. In some cases, this analysis may indicate that additional storage is required before savings can be realized.

Determine Operating Points.

A pump station can operate at a wide range of operating points over the course of a year. The engineer should identify the entire range of operating points and their efficiencies. The head and overall efficiency curves should be available from pump testing. The system head curve encountered by each pumping station is not a single curve but actually a family of curves depending on tank levels, consumption rates and operation of other facilities. For each pump combination and a range of system head curves, the efficiency and unit operating cost (in cents per thousand gallons) should be determined. This analysis can help identify the most desirable pump combinations. More importantly, it can point out undesirable pump combinations which operators should avoid. On a different level, the problems may not be due to operator decisions but rather with the pumping and distribution system itself. This analysis will help the engineer identify if the inefficiencies are due to poorly selected pumps, inadequate (or excessive) distribution system capacity or inadequate (or excessive) storage.

Interview Operators.

It is helpful to understand the logic operators use to make decisions on pump operation. Do they base decisions on tank levels? How are these decisions modified based on weather? Are there pump combinations that do not produce the rated capacity (e.g. two 1000gpm pumps that produce 1200 gpm when run together)? Are there hydropneumatic tanks that cycle every two minutes? Are the operators and their supervisors giving you the same answers? The answers to these questions will give the engineer an appreciation of the problems with the system but more importantly they give the engineer an understanding of the operators' points of view. The recommendations of the study need to be made in a way that is consistent with the operators' terminology and viewpoint. Introducing terms like "state variables" and "nonlinear programming" in a presentation to operators is a guaranteed way to limit communication.

Identifying Efficient Pump Combinations

Energy consumption and costs can be reduced significantly by identifying and using the most efficient pump combinations. Guidance on how to determine efficient pump combinations can be found here:

Ormsbee, L., and Walski, T., (1989) "Identifying Efficient Pump Combinations." Journal of the AWWA, pp. 20-34

Chase, D., and Ormsbee, L., (1993) Computer Generated Pumping Schedules for Satisfying Operational Objectives, Journal of the AWWA, pp. 54-61.

Optimization Studies.

There is a limit to what can be accomplished with pump testing and an engineering/economic evaluation. For utilities with significant energy costs, optimization may provide additional savings. In many cases, the existing rules for operating the system, which are usually couched in terms of maintaining tank water levels within a specified range, may be preventing the utility from realizing efficiencies. It may be more desirable to maintain water levels within one range during morning hours and another range during evening hours. And these ranges themselves may change with the weather and the time of year. Training operators to understand such flexible rules may be difficult. At this point it may be necessary to shift to some form of computer aided operation in which the operator provides information to a computer which describes the state of the system (e.g. tank levels, pumps currently operating) along with some additional information which may include the season, time of day, day of week. Previous day's demand and weather forecast. The computer would then identify the desired tank levels or which pumps should running at any time. The computer could then change pump operation at a time it selects, or recommend pump operation to the operator.

Any such optimal operation environment for a water distribution system will normally consist of three basic components. These include: (1) remote control units, (2) a supervisory control and data acquisition system (SCADA), and (3) an optimal control system (OSC). A more indepth discussion of optimal control strategies for water distribution systems can be found here:

Ormsbee, L., and Lansey, K., (1994) "Optimal Control of Water Supply Pumping Systems", ASCE Journal of Water Resources Planning and Management, Vol 120 (2).