Identifying Energy Savings Opportunities in Industrial Pumping Systems

D. A. Casada
K. L. McElhaney
Oak Ridge National Laboratory
Oak Ridge, Tennessee USA

1 Abstract

In most industrial settings, energy consumed by pumping systems is responsible for a major part of the overall electricity bill. In some cases, the energy is used quite efficiently; in others, it is not. Facility operators may be very familiar with pumping system equipment controllability, reliability, and availability, but only marginally aware of system efficiency. There are some good reasons to increase that awareness:

- As budgets shrink and the intensity of both domestic and international competition increases, the pressure to find additional methods to reduce operating costs will grow.

- The reliability of pumps correlates with their efficiency; that is, pumps operated near their design, or best efficiency point, will tend to perform more reliably and with greater availability.

- More frugal and efficient use of the earth's limited natural resources is essential.

The cost of energy consumed by pumps usually dominates the pump life cycle cost. Many end users, already strained to support day-to-day facility operations, lack the time and resources to perform a methodical engineering study of the many pumps within their facilities to understand their associated energy costs and the potential opportunities for energy savings.

Under the auspices of the United States Department of Energy's (USDOE) Motor Challenge Program, screening guidance documents and computer software have been developed to help end users, consultants, and equipment distributors recognize, both qualitatively and quantitatively, pumping system efficiency improvement opportunities.

A key element in the Motor Challenge optimization strategy is to encourage a systems approach to how motors, drives, and motor-driven equipment are engineered, specified, operated, and maintained by industry. Because pumps have been identified as the single largest end use application, accounting for 25% of motor systems' energy use in all manufacturing industries in the United States, they are a natural target in any effort to improve motor-driven systems' energy consumption. The general thesis of this approach is that it is more important to gain a measure of the overall system efficiency or effectiveness than to focus on individual components.

The elements that comprise the systems approach and their general order of review (in reverse sequence) are

- ultimate system goal or purpose
- piping system
- pump
- gear or coupling
- motor
- adjustable speed drive (if applicable)
- motor starter
- transformer

This paper describes the general methodologies employed and shows a case study example of the screening and software application.

2 Optimization Philosophy—A Systems Approach

There are several reasons for reviewing the system elements in reverse sequence. First, the greatest efficiency improvement opportunities are found in situations where the fluid system is doing more work (e.g., delivering a higher flow rate or head) than is needed to support the ultimate purpose of the system. Another important reason is that energy savings identified at the end of the energy transfer path are multiplied at the power line (the distribution point) because of the inefficiencies in the intermediate elements (e.g., pump, motor).

There are methods for estimating efficiencies for the individual components (such as the motor [1]) in the field; the systems approach, however, encourages looking at overall efficiency or effectiveness. Some elements, such as the motor starter and shaft-to-shaft coupling are important from a reliability standpoint, but are inconsequential from an energy efficiency perspective.

Because pumping systems consist of many of these interrelated components, understanding how the entire system operates and its purpose is important in optimizing overall system performance. A favorable adjustment to one component may result in another component in the system operating less efficiently, with a net loss in system efficiency and higher energy consumption. Thus, any effort toward reducing energy consumption should take into consideration the unique interrelationships of the system components.

3 Pumping System Fundamentals

3.1 Power and Efficiency Relationships

Some fundamental power and efficiency relationships may be defined for the principal active components in motor-driven pumping systems, in reverse sequence from the pumped fluid to the electrical power supply.[*]

Useful hydraulic power developed by a pump is proportional to the product of the volumetric flow rate, head, and fluid specific weight

$$P_f = QH\,\gamma. \qquad (1)$$

Pump efficiency is defined as the pump's fluid power divided by the input shaft power

$$\eta_p = \frac{P_f}{P_s}. \qquad (2)$$

Shaft input mechanical power is the product of the rotational speed and torque

$$P_s = \omega T. \qquad (3)$$

Motor efficiency is defined as the shaft mechanical power[†] divided by the motor electrical input power

$$\eta_m = \frac{P_s}{P_e}. \qquad (4)$$

The majority of electric motors used to drive pumps in industrial service are 3-phase, alternating current, induction motors. For a balanced[‡] 3-phase condition, the motor input power is

$$P_e = \sqrt{3}\ V\ I\cos\theta. \qquad (5)$$

Combining and rearranging terms, pump efficiency can then be expressed as

$$\eta_p = \frac{QH\,\gamma}{P_e \eta_m}. \qquad (6)$$

Finally, the wire-to-water efficiency, η_{ww}, which is a measure of the combined motor and pump efficiency is

$$\eta_{ww} = \frac{P_f}{P_e} = \frac{QH\gamma}{P_e}. \qquad (7)$$

The relationships defined by Eqs. 1–7 are generally applied to individual components, or in the case of the wire-to-water efficiency, the pump and motor combination.

The head and flow rate terms are based on hydraulic measurements performed in the immediate vicinity of the pump. The same relationships can also be applied to the system so that efficiencies include some or all of the system components.

3.2 Defining System Boundaries

In the simple pumping system shown in Fig. 1, fluid is drawn from a tank and pumped through a piping system to an elevated tank. The system includes one flow control valve in the main line. A recirculation line with another control valve is also included. The pump is driven by an electric motor fed from a motor control center (MCC) that is fed by a station transformer. To measure efficiency in such a system, a series of boundaries or "boxes" may be drawn around the system. For each defined system boundary, the power input and useful output are measured, and the ratio defines the efficiency of the process inside the boundary.

[*] The Nomenclature section provides a listing of symbols used throughout this paper.

[†] The motor shaft power and the pump shaft power are implicitly assumed to be equal for a directly coupled motor and pump. If a gear or mechanical speed control is interposed between the motor and pump, however, the assumption is invalid. The balance of this paper and the current version of the Pumping Systems Assessment Tool (PSAT) software assume a directly coupled motor and pump.

[‡] While assuming balanced conditions may be the only practical approach, an accurate 3-phase measurement relies on either the two- or three-watt meter method.[2]

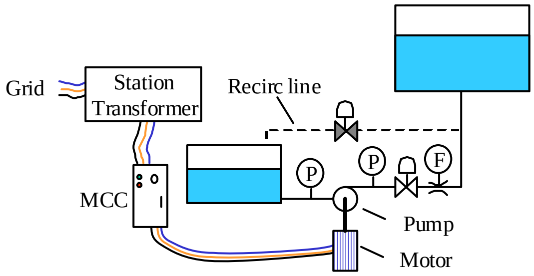

Figure 1. Simple motor-driven pumping system.

In Fig. 2, the boundary is drawn around the pump. The input power is the shaft mechanical power; the output power is the hydraulic power delivered to the system. The power ratio is the pump efficiency.

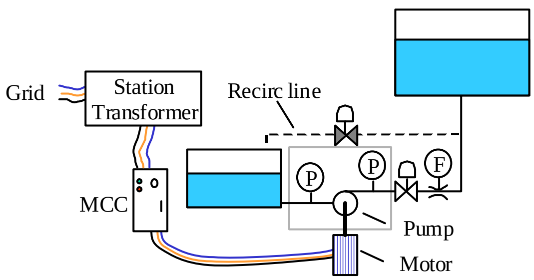

Figure 2. Pump efficiency.

In Fig. 3, the boundary is drawn around both the pump and the motor. The input power is the electrical power supplied to the motor; the useful output power is the hydraulic power delivered to the system. The ratio is the combined motor and pump, or wire-to-water efficiency.

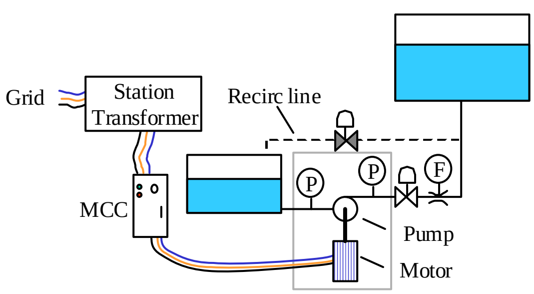

Figure 3. Combined motor and pump efficiency.

In Fig. 4, the boundary is drawn around the pump, the motor, and the entire normal delivery piping network, from the source to the discharge tank. The input power is the electrical power supplied to the motor; the useful output power is the net hydraulic power delivered across the fluid system.

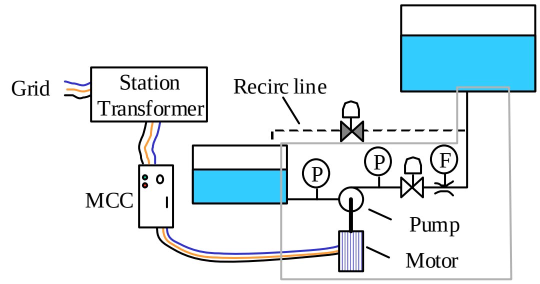

Figure 4. System efficiency.

The system efficiency, as defined by the power transfer in and out of the system boundary defined in Fig. 4 is, therefore, given by

$$\eta_{sys} = \frac{P_f}{P_e} = \frac{QH_s\gamma}{P_e}\,. \quad (8)$$

The flow rate used in Eq. 8 is the net flow between tanks (ignoring recirculation flow). The head is the elevation difference between the tanks, or static head (implicitly ignoring friction losses). This is a true overall *system* efficiency.

If all physical fluid systems were geometrically similar, the system efficiency value reflected by the boundary defined in Fig. 4 would clearly be the best single figure of merit, since it captures the overall useful work performed by the system relative to the input energy. In this case, however, the relationship defined in Eq. 8 shows that for a closed cycle circulating system with no static head, the overall system efficiency would be zero. This result does not mean that the overall systems approach is not useful. It does illustrate the importance of exercising caution when defining the system boundary, since most fluid systems are geometrically unique. The example analysis in Section 4.8 illustrates the process of defining an appropriate system boundary.

3.3 System Requirements

All pumping systems share certain characteristics, one of which is the nature of fluid flow. To produce fluid flow through a pipe or valve, a pressure differential must be created across the component. The greater the pressure differential, the greater the rate of flow. For a given system, a curve can be drawn to show the pressure differential required at any given flow rate. This is called the system curve. Figure 5 shows an example of a system curve where the pressure (head) is a function of flow.

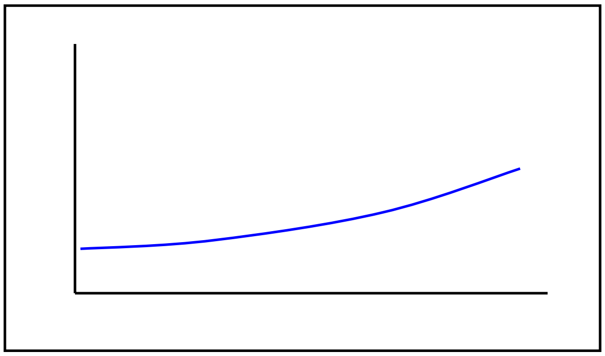

Figure 5. System curve.

System curves are made up of two fundamental components: the static head and the frictional head. Figure 6 shows a system curve and illustrates the static and frictional head comprising the total head. Static head is predominant in systems where the fluid changes elevation, such as cooling towers. Frictional head is associated with piping and piping components (e.g., valves, fittings), rather than gravity, such as in closed loop cooling systems. Most systems have a combination of static and frictional head.

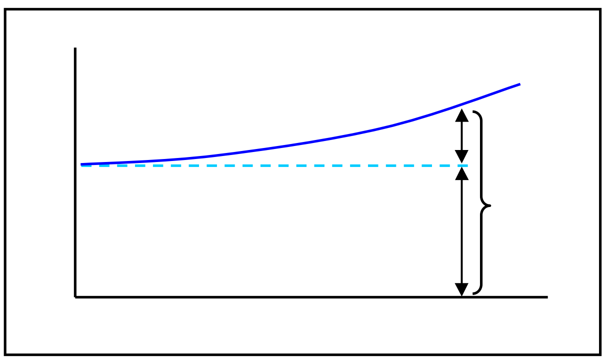

Figure 6. Frictional and static head comprise the total head on a system curve.

Similarly, performance curves showing the relationship between head and flow rate can be drawn for pumps. A typical curve for a centrifugal pump is shown in Fig. 7. Starting at some head (pressure) at zero flow, the curve shows a slight decreasing pressure as the flow initially increases and a steeper decline with further increases in flow.*

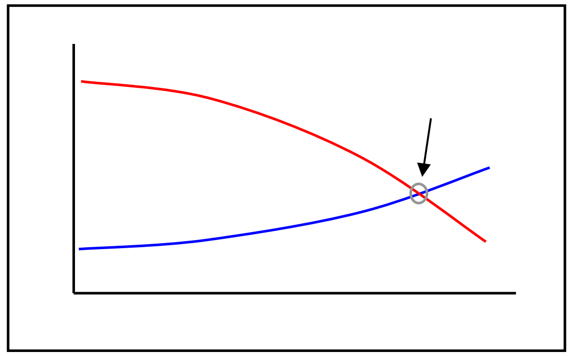

Figure 7. Pump and system curves showing the intersection or operating point.

A fundamental concept for analyzing fluid pumping systems is the operating point, which is the combination of pressure and flow at which a given system and pump operate. The operating point is determined by plotting the system and pump curves, as in Fig. 7. For centrifugal pumps, the operating point is the intersection of the pump and system curves and represents the equilibrium flow point where the pressure drop through the system equals the pressure added to the fluid by the pump.

There is another important consideration when attempting to optimize a pumping system: system requirements may vary with seasonal or time-of-day variations in loads. By tracking flow rates over time, a flow duration curve like that shown in Fig. 8 can be developed. Trending requirements in this fashion can aid in matching the output (work) with actual system needs.

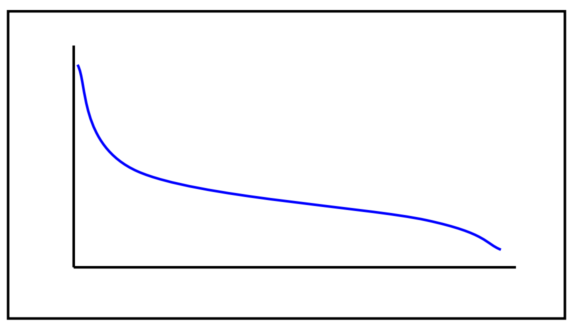

Figure 8. Flow duration curve.

4 The Pumping System Assessment Tool (PSAT) Software

4.1 Introduction

In some cases, pumping system end users recognize that there may be energy savings available, but they are frequently not prepared to work through the maze

* For some pumps, the curve may show a constant or slightly increasing pressure as flow increases, then decreasing pressure with further increases in flow.

of interrelated components to make an assessment of potential opportunities.

Based on the overall systems optimization philosophy, the PSAT computer software was developed to assist end users in assessing the overall effectiveness of pumping systems.*

The PSAT software relies on three fundamental bases, each of which is discussed in detail in the following sections:

1. fundamental electrical, mechanical, and fluid power relationships,

2. typical performance characteristics from industry standards and databases, and

3. field measurements of fluid and electrical parameters.

PSAT estimates the existing (as-installed) motor and pump efficiency using field measurements and nameplate-type motor and pump information. It also estimates achievable efficiencies if the motor and pump were optimally selected to meet the specified system flow and head requirements. The *existing* and *optimal* results are compared, and potential power savings are calculated. Potential cost and energy savings are also estimated based on user-specified power rates and operating times.

4.2 Fundamental Power Relationships

The general relationships that describe power transfer from the motor's electrical input to the fluid system are identified in Eqs. 1–8, but may be discussed in more detail. Instead of proceeding from the fluid process backward as was done in Eqs. 1–5, this assessment begins with the input power to the motor.

Motor input power can usually be measured in the field on "low" voltage busses, such as 480-V. Motor efficiency measurements, however, cannot usually be conducted in the field. If it is assumed that a reasonably accurate estimate of motor efficiency can be made, Eq. 4 can be used to determine shaft power.

Assuming directly coupled equipment, the motor shaft power and the pump shaft power are approximately equal. Pump efficiency, per Eq. 3, is the ratio of fluid power to shaft power. If the parameters that define fluid power (flow rate, head, and fluid specific weight) are known, pump efficiency can also be determined.

* PSAT applies to centrifugal pumps directly coupled to 3-phase induction motors. The minimum size motor is 5 hp; there is no maximum. The PSAT software will be available through the USDOE Motor Challenge Program at no cost. A metric version is planned for release at a later date.

4.3 Motor Performance Characteristics Used by PSAT

The USDOE Motor Challenge Program distributes, free of charge, the MotorMaster+ (MM+) software.[3]† The NEMA (National Electrical Manufacturer's Association) design B subset of motors in this database was used to develop average performance characteristics (current, power factor, and efficiency vs load) used in PSAT. Using these average values, curve fits of the performance characteristics were developed.

Although there is variation in motor performance within a given power, speed, and efficiency class, relative to other uncertainties surrounding pumping system field measurements, the variability of the motor data is relatively small.

The curve fits developed from the average performance characteristics of the MM+ database allow motor efficiency to be estimated based on motor size, speed, and measurement of either motor input power or current. If power is measured, PSAT determines the shaft power and efficiency that is consistent with the specified motor size and speed. If current is measured, the power is estimated from the current vs load profiles in PSAT. A full set of motor characteristics (*shaft power*, *current*, *power factor*, and *electrical power*) can be established, regardless of whether current or power is measured.

Although the motor characteristics used in PSAT were derived exclusively from 460-V motors, other nominal voltages (*230-*, *2300-*, *4160-*, and *6900-V*) can also be selected. The current data is linearly adjusted for nominal voltage.

The motor efficiency class (*energy efficient*, *standard*, and *average*) is also selectable. The *average* selection calculates motor performance characteristics based on the average of the standard efficiency and the energy efficient motor values.

† Part of the bases for the MM+ package is an extensive database of motors. The database, constructed using motor manufacturer-supplied data, includes a comprehensive list of parameters such as motor rated power, efficiency, power factor, speed, full load current, enclosure style, NEMA design type, rated voltage, and cost.

4.4 Pump Capability Estimation Used by PSAT

Most motors used with pumps are manufactured to NEMA Design B standards; however, there are many different pump designs applied to the broad spectrum of industrial pumping applications. For certain applications such as sewage or stock pumping, service reliability considerations prevent the use of the more efficient pump designs used for clean water pumping.

The Hydraulic Institute (HI) publishes a standard that provides guidance on achievable efficiencies.[4] This standard addresses the effects of general pump style, capacity, specific speed, and variability on achievable efficiency from miscellaneous other factors such as surface roughness and internal clearances.

The PSAT software uses curve fits of the graphical data included in the HI standard to estimate achievable efficiency. Figure 9 shows a comparison of optimal efficiencies for two pump styles, based on PSAT calculations using the HI methodology. These curves reflect the HI standard's estimate of maximum achievable efficiency.

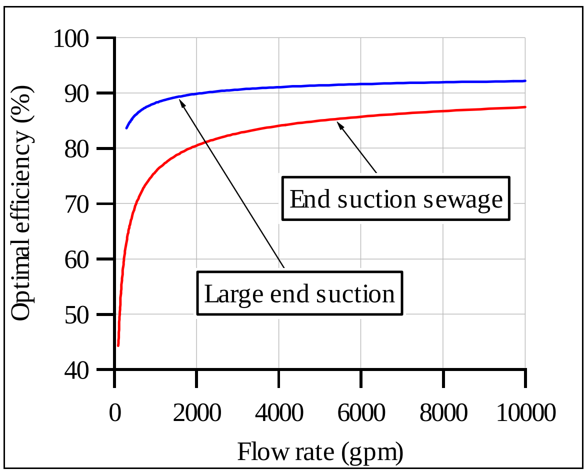

Figure 9. Optimal pump efficiency for two pump styles.

The curves shown in Fig. 9 (and similar ones for other pump styles) form the reference points against which PSAT compares the existing (as-installed) pump estimated efficiency.

4.5 Field Measurements of Fluid and Electrical Parameters

It is beyond the scope of this paper to discuss the details of alternative methods for measuring and estimating system fluid and electrical parameters, but a brief discussion of the general availability and difficulty in measuring each parameter is useful.

Motor input power is usually not monitored by permanently installed instruments. Motor current is sometimes monitored and displayed remotely or at the MCC (typically only for larger motors). Motor input power and/or current can usually be measured on low voltage busses with portable test equipment.

Fluid viscosity and specific gravity are either essentially constant or can be readily determined by either direct measurement or from relationship to some other easily measured parameter (such as temperature).

Most pump applications include suction and discharge connections for pressure measurement, the parameters of primary importance in pump head calculation.*

Flow rate can be measured via permanent instrumentation in some applications but is less commonly available than pressure data. When permanently installed flow rate instrumentation is not available, temporary test devices can be employed. Alternatively, flow rate can be estimated using the measured differential pressure and pump performance curves. Estimating flow rate from measured differential pressure and the pump performance curve is not the preferred approach, but, in some cases, it is the only available means. In many cases, there are other sources of data that can help corroborate or refine flow rate estimates. When using pump performance curves, actual pump rotational speed should be measured. If rotational speed is significantly different than the speed at which the pump curve was developed, the pump curve should be adjusted by applying the pump affinity laws.

4.6 PSAT Display Layout

The primary screen of the PSAT software is shown in Fig. 10. The inputs are all located in the three regions that cover the left one-third of the panel.

The *Pump, motor, system information* in the upper left corner of the screen is general design information:

* In many pump applications, pressure gauges and/or transducers are permanently installed; however, unless they are included in a regular calibration program, data obtained using a temporary test gauge is preferred.

- pump style, nameplate speed, and number of stages
- fluid viscosity, specific gravity
- motor class, nameplate hp, rpm, and voltage.

The *Operating parameters* for the system are at the center left of the screen:

- operating fraction (fraction of time the pump is operated at the specified conditions)
- cost of electricity (cents/kWh).

The *Measured or required conditions*, at the center to lower left of the screen, are:

- measured (or required) flow rate and head
- measured motor power or current (depending on the selected load estimation method)
- measured bus voltage.

The *Calculated Results* are displayed in the upper right two-thirds portion of the screen.

Finally, *Log, summary file controls* are just below the *Calculated Results*. The log controls enable storage and retrieval of data for subsequent display and comparison. Data can be stored by plant, process, or any other structure the user elects. Tab-delimited text summary files that save the essential inputs and results can be created or existing summary files appended. The summary files can also be opened and manipulated in other software applications. For example, a summary file with the analysis results for all of a particular facility's pumps can be created, allowing further analysis in a spreadsheet program.

4.7 Combining the Elements

Based on the input data, PSAT first estimates the existing shaft power from the motor data measurements. It then calculates fluid power from the specified flow rate, head, and specific gravity. At this point, the motor input power, the shaft power, and the fluid power are known, as are the existing motor and pump efficiencies. Given the fraction of time the pump is operated and the electricity costs, the annual energy use and energy costs are also calculated.

Two actions are considered for comparison:

1. Replacement of an existing motor with an energy efficient model. The center *results* column shows the potential savings associated with motor replacement only.

2. An optimal pump selected for the application, combined with an energy efficient motor.

In either case, if the existing motor is energy efficient, no improvement in motor efficiency would be gained.

4.8 Example Application of PSAT

The example display data in Fig. 10 is based on a combination of measurements and estimates for a pumping application at USDOE's Y-12 plant in Oak Ridge, Tennessee. As the *Notes* section of Fig. 10 explains, motor current and voltage were measured on the secondary sides of permanently installed current (CT) and potential transformers (PT), because direct measurements could not be made on the 2300-V bus that fed the motor. The data was scaled by the CT and PT ratios to determine input power and voltage.* Pump suction and discharge pressures were read from temporarily installed test gauges. Because there was no reliable flow measurement in this system, the flow rate was estimated from the pump performance curve using the pressure data.

Nominal motor efficiency was not specified on the ~20-year-old nameplate; it was assumed that the motor belonged in the standard efficiency class.

The *Calculated Results* section of Fig. 10 shows that the existing pump and motor efficiency were estimated to be 57% and 94%, respectively (first column). If the standard efficiency motor were replaced with an energy efficient motor, a slight improvement in motor efficiency and corresponding reduction in power would result (Fig. 10, second column). With the specified continuous operation and 5.4 cent/kWh energy cost rate, the energy efficient motor would save around $1,200 annually. Alternatively, with a pump optimally matched to the measured system head and flow rate (Fig. 10, third column), annual savings of almost $22,000 would result. The principal reason for the large potential savings is that the pump was operating well below its best efficiency point flow rate—it had been previously sized for a significantly larger system requirement that was no longer needed.

This analysis was done with the system boundary drawn around the pump and motor, as previously shown in Fig. 3. An analysis of the system showed that a significant amount of the head being developed was unnecessary— it was being lost across a heavily throttled pump discharge valve. A conservative estimate indicated that a pump head of only 140 ft at 1200 gpm should satisfy the system needs.

* If voltage cannot be measured, nominal bus voltage can be used with minimal error. The measured voltage is used to adjust the MM+ estimates.

Reviewing the system and searching for waste is, in essence, a natural part of moving the boundary out to cover more of the system, as was done in Fig. 4. This system is a closed-cycle system (i.e., it has no static head). The 140 ft of head used is a conservatively high estimate of the frictional losses in the system if most of the artificially imposed friction (e.g., throttled valves) were eliminated.

PSAT can also be used in a hypothetical mode. With a flow rate of 1200 gpm and a *Required* head of 140 ft, the input power can be adjusted until an *Optimization rating* (large dial indicator at the right of the PSAT screen) of 100 is achieved. This rating indicates the adjusted power consumption that could be expected if the pump and motor were optimal for the application. As shown in Fig. 11, the annual cost associated with this operation would be less than $20,000, compared with almost $73,000 for the existing cost of operation (Fig. 10).

In this typical situation, there were nontechnical issues that prevented the optimal condition from being reached. The optimal system would have required pump and motor replacement as well as concomitant changes in the adjacent suction and discharge piping. Moreover, capital fund requirements would need to be estimated, budgeted, and approved—a nontechnical but significant problem.

Most of the potential savings were ultimately achieved through an alternative change which left the original pump and piping in place, and perhaps most significantly, were accomplished with already available maintenance funds. The scenario went as follows: the motor on a parallel pump had failed because of a broken foot and was scheduled for replacement. Instead of replacing it with another 4-pole motor, a 125-hp, 6-pole, 460-V motor was chosen to be used with the existing pump. By slowing the pump down, about 82% of the identified potential savings were realized (Fig. 12). Additional savings were achieved by isolating flow to a chiller that had been removed from service. The net annual savings were almost $50,000.

From this example it is evident that considering only the component (pump and motor) data, PSAT can identify potential savings. By focusing on the entire system, however, more significant energy savings opportunities can be uncovered.

5 Maximizing Fluid System Effectiveness

The PSAT software by itself cannot identify specific resolutions to system problems. In fact, as illustrated by Figs. 1–4, individual component efficiencies assessed by PSAT (using a small boundary) may be very good, while the overall system efficiency (using a larger boundary) can be poor. Defining system boundaries in the most optimal manner for each system is, therefore, important, and individual system optimization requires careful analysis on a case-by-case basis. Some general guidelines for system optimization can be identified, however, and are briefly discussed in this section.

The overall effectiveness of any operation is the product of the efficiencies of each individual energy component along the way. Optimizing one or another of the individual components may improve the overall efficiency—or it may reduce it because it causes another component to operate in a less efficient mode. Any effort to improve energy efficiency should consider the entire energy flow train.

Maximizing fluid system effectiveness is the equivalent of minimizing fluid system energy requirements. Energy requirements can be reduced by decreasing run time, flow rate, and/or head. These three objectives may be achieved by following some straightforward pumping system optimization measures.

- Large components that accumulate significant operating hours (run times) should be the primary focus of most optimization efforts.
- System operation should be commensurate with actual needs. Because a system has *always* been operated in a certain way does not imply the most *efficient* operation.
- Excessive piping and component frictional losses (including valve throttling) should be avoided or minimized.
- Pumps should be properly sized for the true system requirements.
- Piping systems should be flushed and cleaned regularly.

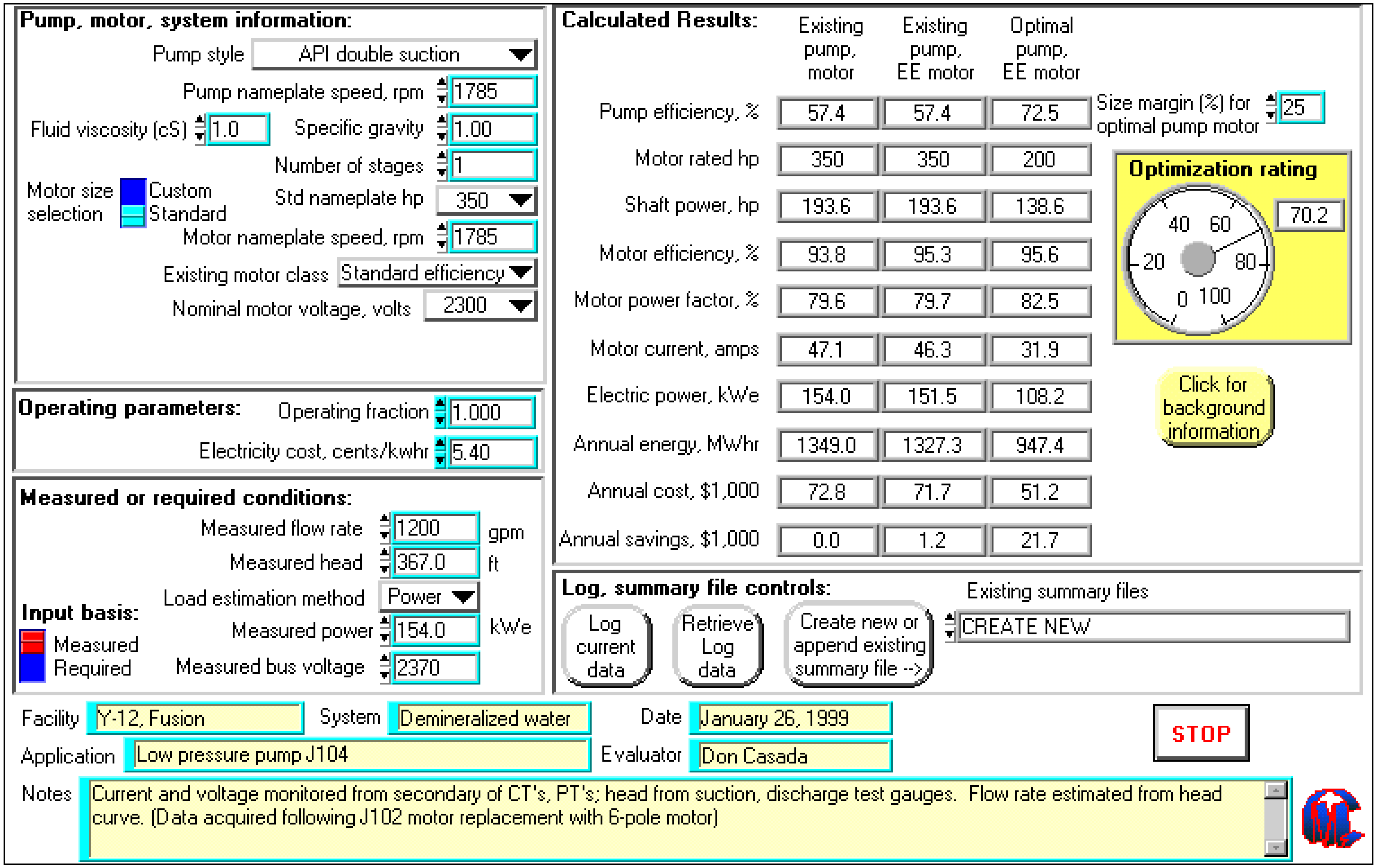

Figure 10. PSAT software primary screen.

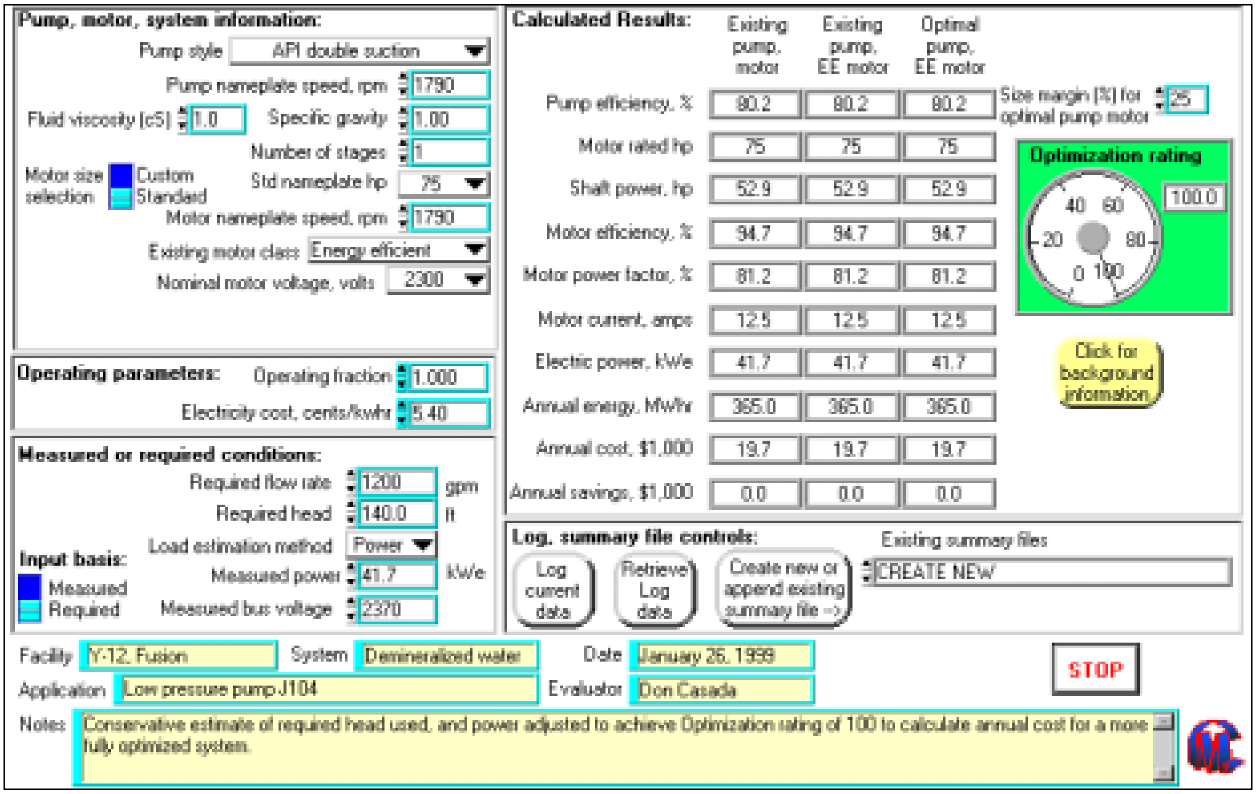

Figure 11. An optimized system, with a reduced pump head (allowing valve throttling losses to be liminated).

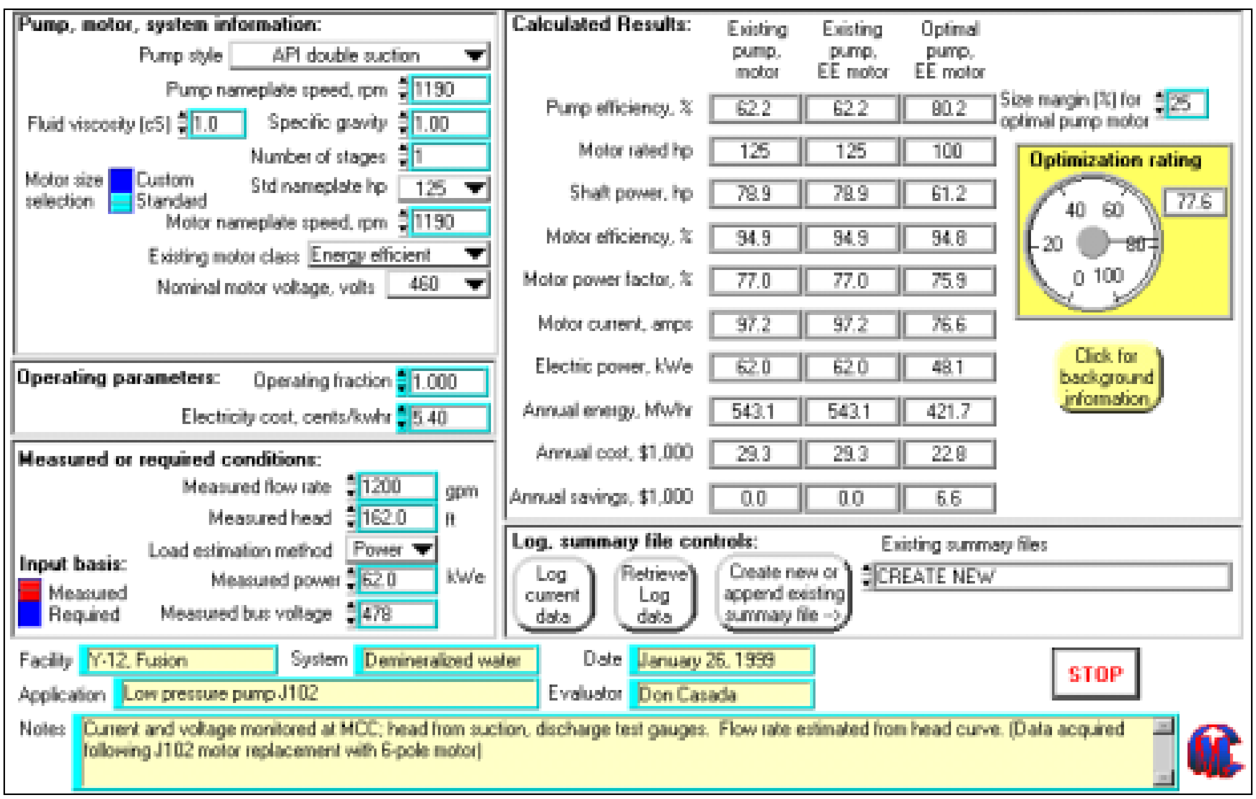

Figure 12. Results after actual changes were made (parallel pump's motor replaced). About 82% of the potential savings identified by PSAT were accrued. Achieving additional savings would require unavailable capital funds.

Nomenclature

H	total head
H_s	static head
I	current (rms)
P_e	motor input power
P_f	fluid power
P_s	shaft power
Q	volumetric flow rate
T	torque
V	voltage (rms)
η_p	pump efficiency
η_m	motor efficiency
η_{sys}	overall system efficiency
η_{ww}	wire-to-water efficiency
θ	voltage-to-current phase angle ($\cos \theta$ = power factor)
ω	rotational speed
γ	fluid specific weight

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