# HOW TO JUSTIFY MACHINERY IMPROVEMENTS USING RELIABILITY ENGINEERING PRINCIPLES

by
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## ABSTRACT

For the typical machinery engineer, the difficulties encountered with making reliability improvements lie not with the "mechanics" of improvements, but with justifying the cost of improvements. It is difficult to translate sound engineering principles into terms that the accounting community can understand.

The purpose of this paper is to equip machinery engineers with reliability engineering principles that translate "best practices" into net present value financial terms. Using the concepts of life-cycle costs, the effects of off-design conditions and poor installation practices will be shown to reduce the expected life of a pump by as much as 60 percent. A Monte Carlo simulation will be used to compare commercial practices, good practices, and best practices for a specific pump installation. Life-cycle costs will be summarized, for each case, in net present value, to select the best equipment choice.

## LIFE-CYCLE COST INTRODUCTION

Life-cycle costs (LCC) sum all total costs from inception to disposal for both equipment and projects (Barringer and Weber, 1996). The objective of LCC analysis is to choose the most cost-effective approach from a series of alternatives, so the least long-term cost of ownership is achieved.

LCC is strongly influenced by equipment grade, the grade of installation and use practices, and maintenance strategies. The typical problem of specifying and justifying equipment is producing the numbers and making them defensible in the face of numerous conflicts:

- Project engineers want to minimize capital expenditures,
- Maintenance engineers want to minimize repair hours,
- Production wants to maximize uptime hours,
- Reliability engineers want to maximize equipment reliability, and
- Accounting wants to maximize net present value of the project.

These conflicting issues, with no specific answers, result in a management edict to "buy cheap and complete the project quickly." This paper will show how to find the numbers so an average engineer has a working tool to "buy right rather than buying cheap," and finish the analysis quickly.

LCC analysis helps engineers justify equipment and process selection based on total costs rather than initial purchase price. The sum of operation, maintenance, and disposal costs far exceed procurement costs. Life-cycle costs are total costs estimated to be incurred in the design, development, production, operation, maintenance, support, and final disposition of a major system over its anticipated useful life span (DOE, 1995). The best balance among cost elements is achieved when total LCC is minimized (Landers, 1996). As with most engineering tools, LCC provides best results when both engineering art and science are merged with good judgment.

Procurement costs are widely used as the primary (and sometimes only) criteria for equipment or system selection—i.e., cheap is good. Procurement cost is a simple criterion. It is easy to use. It often results in bad financial decisions! Procurement costs tell only one part of the story. The major cost lies in the care and feeding of equipment during its life. Remember the adage attributed to John Ruston, “It's unwise to pay too much, but it's foolish to spend too little.”

Usually, procurement cost is the only value in life-cycle cost that is well known and clearly identified—but it is only the tip of the iceberg. Seeing the tip of an iceberg (similar to the obviousness of procurement cost) does not guarantee clear and safe passage around an iceberg. Hidden, underlying substructures of an iceberg (similar to the bulk of other costs associated with life-cycle costing for equipment and systems) contain the hazards.

Life-cycle cost was conceived in the mid 1960s, and many original works on LCC are now out of print. Publications by Blanchard, et al. (Blanchard and Fabrycky, 1990; Blanchard, 1992; Fabrycky and Blanchard, 1991), regarding life-cycle costs are now sources for a variety of LCC interests.

LCC emphasizes business issues by enhancing economic competitiveness to work for the lowest long-term cost of ownership. This requires engineers to worry about all cost details—they must 1) *think like MBAs*, and 2) *act like engineers* for profit making enterprises.

## WHAT GOES INTO LIFE-CYCLE COSTS?

The basic cost tree for LCC starts simply. The tree has two branches for acquisition costs and sustaining costs, as shown in Figure 1.

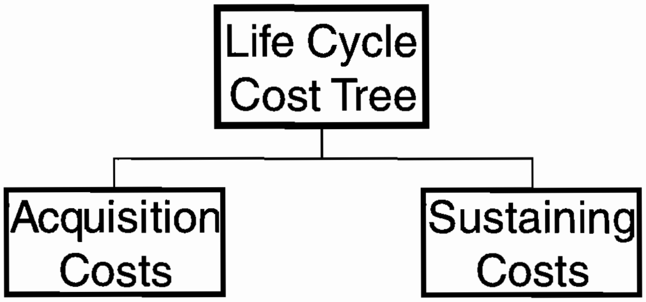


*Figure 1. Top Levels of Life-Cycle Cost Tree.*

Acquisition and sustaining costs are not mutually exclusive. If you acquire equipment or processes, they always require extra costs to sustain the acquisition, and you cannot sustain without someone having acquired the item. Acquisition and sustaining costs are found by gathering the correct inputs, building the input database, evaluating the LCC, and conducting sensitivity analyses to identify cost drivers. In general, cost details for the acquisition tree, shown in Figure 2, are usually identified and collected correctly. The collection of costs for the sustaining tree shown in Figure 3 is the major problem!

Frequently, the cost of sustaining equipment is two to 20 times the acquisition cost. The first obvious cost (hardware acquisition) is usually the smallest amount of cash that will be spent during the life of the acquisition, and most sustaining expenses are not obvious.

The cost details must go into the correct time buckets to make the life-cycle cost information useful. Cost details are important for 1) how much cost, and 2) when costs are incurred. These details are used for calculating net present value. Net present value is the single most important financial indicator for making decisions relating to capital issues.

For the sustaining tree, four items are difficult to collect:

- Replacement/renewal costs,
- Replacement/renewal transportation costs,
- Support/supply maintenance costs, and
- Operating costs.

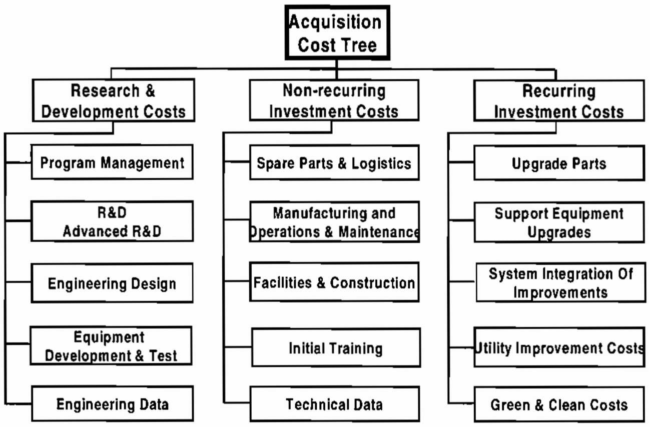


*Figure 2. Acquisition Cost Tree.*

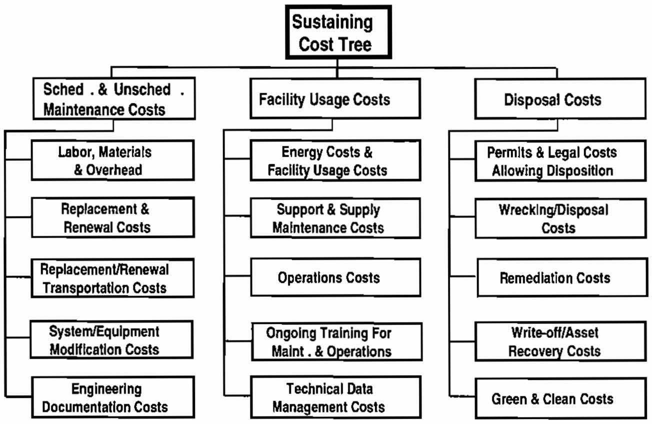


*Figure 3. Sustaining Cost Tree.*

Electrical costs are also particularly important because of high costs and varying loads on the equipment.

Most capital equipment authorizations ignore major portions of the sustaining cost tree as they lack details for the sustaining expenditures. Based on some “justifications,” equipment never fails and, surprisingly, some of the equipment never uses electricity!! When failure costs are included, they appear as a percentage of the initial costs, and are spread evenly through every year of the typical 20-year life for the project. For wear-out failure modes, the analysis is penalized by not including failures in the proper time span.

Complications arise in the sustaining tree that are driven by planned costs in the acquisition tree. About 65 percent to 75 percent of the total LCC is set when the equipment is specified—and most decisions are based on the acquisition tree, which is the smallest portion of the LCC!!

LCC is a process. The process provides for including appropriate costs, as shown in Figure 4. Appropriateness changes with each specific case as shown (Fabrycky and Blanchard, 1991, Appendix A).

## ENGINEERING FACTS

LCC requires facts driven by data. Most engineers say they lack data. However, data are widely available as a starting point for LCC (Bloch and Geitner, 1995). Often data reside in local computer files, but it has not been analyzed or put to effective use. Analysis can start with arithmetic and grow to more complicated statistical analysis (Barringer and Weber, 1995). Follow the guidelines for each step listed in Figure 4 to work out a typical engineering problem. Remember that a single right or wrong

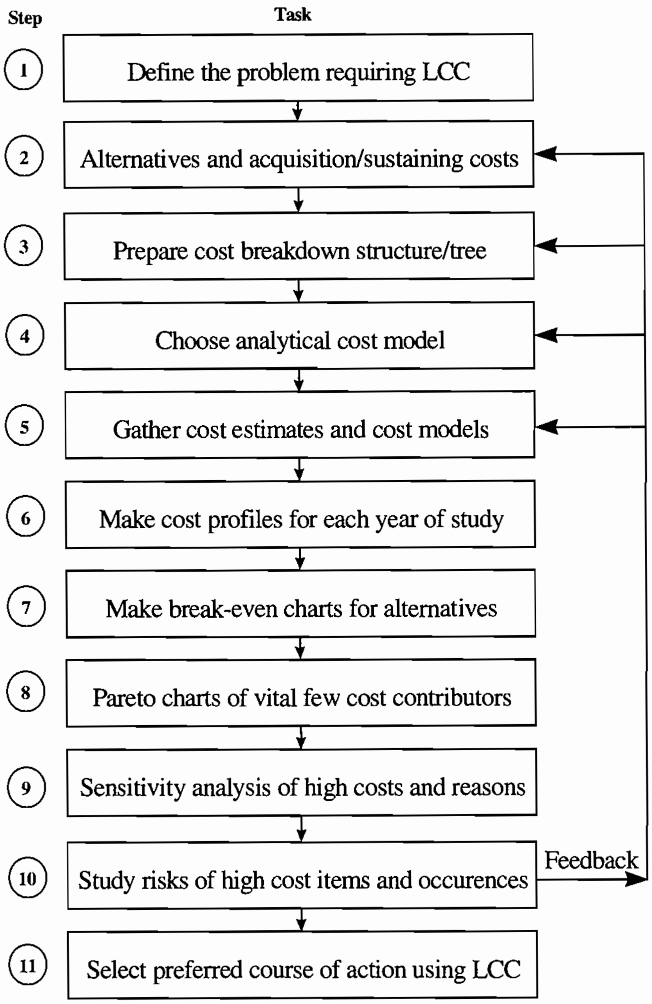


*Figure 4. Process Flow for LCC Calculations.*

method or solution does not exist—many methods and routes can be used to find LCC. If you disagree with the cost or life data, substitute your own values determined by local operating conditions, local costs, and local grades of equipment.

*Step 1: Define the Problem*

The process requires installation of a new pump for a forthcoming modification. It is a 30 hp pump: 3 inch inlet × 1.5 inch outlet × 10 inch volute, with an 8 inch impeller. The pump provides water for transporting 30,000 lb/hr of high-density polyethylene (HDPE) pellets. If the pumping system fails, it shuts down the process and penalizes the plant with gross margin losses of $3000 per hour of failure.

*Step 2: Alternatives and Acquisitions/Sustaining Costs*

Study two grades of pumps: ANSI, and ANSI enhanced with extra rigid baseplate. Note that API pumps are not a consideration, because no physical need exists for utilization of the high grade features such as high temperature, etc.

Study two physical installation alternates: solo pump, and dual pumps. The dual pumps will be run in sequence of one week online and one week offline.

Study two maintenance strategies: fix when broken, and good maintenance practices of replacing additional components when the pump has failed, so that reliability is improved and future failures delayed.

Study three grades of installation and use: commercial installation from quick/cheap installations and widely varying operating conditions, better installation and use practices with reasonable limits imposed, and best installation and best use practices imposed for precise installation and small variations allowed during operation of the equipment. Of course, each grade of installation/use is increasingly more expensive to implement and control.

The study options and conditions listed above require solving 24 separate problems, as shown in Table 1.

*Table 1. Solve 24 Problems to Find the Best Solution.*

**Solve Problems For:**
**Net Present Value, Availability, Reliability, Effectiveness, and Maintenance Hours**

| | Fix When Broken Maintenance | | | Good Maintenance Practices | | |
|---|---|---|---|---|---|---|
| | Installation/Use Practices | | | Installation/Use Practices | | |
| **ANSI Pump** | Commercial | Better | Best | Commercial | Better | Best |
| Solo NPV | $ | $ | $ | $ | $ | $ |
| Solo R*A | % | % | % | % | % | % |
| Maintenance Downtime | hrs. | hrs. | hrs. | hrs. | hrs. | hrs. |
| Dual NPV | $ | $ | $ | $ | $ | $ |
| Dual R*A | % | % | % | % | % | % |
| Maintenance Downtime | hrs. | hrs. | hrs. | hrs. | hrs. | hrs. |
| **ANSI EnhancedPump** | | | | | | |
| Solo NPV | $ | $ | $ | $ | $ | $ |
| Solo R*A | % | % | % | % | % | % |
| Maintenance Downtime | hrs. | hrs. | hrs. | hrs. | hrs. | hrs. |
| Dual NPV | $ | $ | $ | $ | $ | $ |
| Dual R*A | % | % | % | % | % | % |
| Maintenance Downtime | hrs. | hrs. | hrs. | hrs. | hrs. | hrs. |

*Step 3: Prepare Cost Breakdown Structure/Tree*

Each case for the cost breakdown structure will incur cost in the categories of Figure 5 (please refer to APPENDIX for Figure 5). This is a checklist for cost to be collected. Note that for this analysis, the obvious costs that are generally defined correctly in most projects for the acquisition costs, such as project management costs, etc., *are not* included because they are common to all the cases. This analysis pays particular attention to the sustaining cost tree items.

Capital costs for the acquisition trees are shown in Table 2. The costs in Table 2 are for solo pump configuration, and dual pumps will double these acquisition costs. Replacement costs for the sustaining tree concerning each item are shown in Table 3. Time required for making replacements for the sustaining tree is shown in Table 4. Time required for good maintenance practices are paced by the item that fails, and assume all other replacements are accomplished within the allotted time for repair of the failure.

*Table 2. Capital Costs Details.*

| | ANSI | | | ANSI Enhanced | | |
|---|---|---|---|---|---|---|
| | Commercial Practices Installation & Use | Better Practices Installation & Use | Best Practices Installation & Use | Commercial Practices Installation & Use | Better Practices Installation & Use | Best Practices Installation & Use |
| Base Purchase Price | $ 5,711 | $ 5,711 | $ 5,711 | $ 9,050 | $ 9,050 | $ 9,050 |
| Factory balance | $ - | $ 75 | $ 150 | $ - | $ 75 | $ 150 |
| Field align rotating components | $ 150 | $ 180 | $ 225 | $ 150 | $ 180 | $ 225 |
| Foundations | $ 500 | $ 1,000 | $ 1,500 | $ 833 | $ 1,650 | $ 2,500 |
| Mount pump to foundation | $ 400 | $ 600 | $ 800 | $ 400 | $ 600 | $ 800 |
| Grout | $ 250 | $ 500 | $ 750 | $ 250 | $ 500 | $ 750 |
| Valves/fittings | $ 750 | $ 825 | $ 1,000 | $ 750 | $ 825 | $ 1,000 |
| Straight run of pipe | $ 100 | $ 120 | $ 130 | $ 100 | $ 120 | $ 130 |
| Assembly of piping system | $ 500 | $ 625 | $ 750 | $ 500 | $ 625 | $ 750 |
| Field align piping systems | $ 100 | $ 150 | $ 200 | $ 100 | $ 150 | $ 200 |
| Electrical | $ 2,000 | $ 2,000 | $ 2,000 | $ 2,000 | $ 2,000 | $ 2,000 |
| Instrumentation | $ 500 | $ 500 | $ 500 | $ 500 | $ 500 | $ 500 |
| Modify Impeller For BEP | $ - | $ 125 | $ 150 | $ - | $ 125 | $ 150 |
| High efficiency motor | $ 1,318 | $ 1,318 | $ 1,318 | $ 1,318 | $ 1,318 | $ 1,318 |
| Total = | $ 12,279 | $ 13,729 | $ 15,184 | $ 15,951 | $ 17,718 | $ 19,523 |

*Table 3. Item Replacement Costs.*

| | ANSI | | | | ANSI Enhanced | | | |
|---|---|---|---|---|---|---|---|---|
| | Item Cost | Logistic Cost | Labor + Expense | Total | Item Cost | Logistic Cost | Labor + Expense | Total |
| Impeller | $ 700 | $ 300 | $ 800 | $ 1,800 | $ 700 | $ 300 | $ 800 | $ 1,800 |
| Housing | $ 500 | $ 300 | $ 1,000 | $ 1,800 | $ 500 | $ 300 | $ 1,000 | $ 1,800 |
| Pump Bearings | $ 175 | $ 75 | $ 800 | $ 1,050 | $ 300 | $ 75 | $ 800 | $ 1,175 |
| Mech. Seal | $ 350 | $ 100 | $ 800 | $ 1,250 | $ 1,000 | $ 100 | $ 800 | $ 1,900 |
| Bearing Seal | $ 50 | $ 75 | $ 800 | $ 925 | $ 300 | $ 75 | $ 800 | $ 1,175 |
| Shaft | $ 350 | $ 300 | $ 800 | $ 1,450 | $ 350 | $ 300 | $ 800 | $ 1,450 |
| Coupling | $ 100 | $ 75 | $ 800 | $ 975 | $ 700 | $ 75 | $ 800 | $ 1,575 |
| Motor Bearings | $ 150 | $ 200 | $ 800 | $ 1,150 | $ 150 | $ 200 | $ 800 | $ 1,150 |
| Replacement Mtr. | $ 1,000 | $ 200 | $ 800 | $ 2,000 | $ 1,000 | $ 200 | $ 800 | $ 2,000 |
| Motor Starter | $ 500 | $ 75 | $ 100 | $ 675 | $ 500 | $ 75 | $ 100 | $ 675 |

*Table 4. Replacement Times—Hours.*

Elapsed Repair Time (hours)

| | ANSI | ANSI Enhanced |
|---|---|---|
| Impeller | 6 | 7 |
| Housing | 12 | 13 |
| Pump Bearings | 6 | 7 |
| Mechanical Seal | 6 | 7 |
| Bearing Seal | 8 | 9 |
| Shaft | 6 | 7 |
| Coupling | 6 | 7 |
| Motor Bearings | 6 | 7 |
| Replacement Motor | 6 | 7 |
| Motor Starter | 1 | 1 |

System failure costs for the sustaining tree concerning solo and dual pumps are shown in Table 5. Pump performance details and electrical costs for the sustaining tree are summarized in Table 6. Details in Tables 2 through 6 provide cost information. They lack cost profiles in discrete time intervals for the sustaining cost tree that will be used in NPV calculations.

*Table 5. Risk Costs for System Failure—Solo and Dual Pumps.*

| | Solo Pump | Dual Pump |
|---|---|---|
| Probability of system failure | 100% | 0.1% |
| $/hr Consequences if failure occurs | $ 3,000 | $ 3,000 |
| $/hr Risks | $ 3,000 | $ 3 |

Probability of simultaneous failure of dual pumps = Pp * UAs
where: Pp = probability of primary device failure in one year
UAs = unavailability of the standby device in one year

*Table 6. Pump Performance Details and Electrical Costs.*

| | Commercial Practices | Better Practices | Best Practices |
|---|---|---|---|
| Practice allows flow of BEP -x% | -30% | -20% | -10% |
| Practice plans for aimpoint flow of % BEP | 100% | 100% | 100% |
| Practice allows flow of BEP +x% | 15% | 10% | 5% |
| Pump efficiency at lowest allowed flow | 52% | 54% | 55% |
| Pump efficiency at BEP | 55% | 55% | 55% |
| Pump efficiency at highest allowed flow | 55% | 55% | 55% |
| Lowest allowed flow (gpm) | 140 | 160 | 180 |
| Flow at BEP (gpm) | 200 | 200 | 200 |
| Highest allowed flow (gpm) | 230 | 220 | 210 |
| Total head at lowest allowed flow (ft) | 285 | 278 | 270 |
| Total head at BEP (ft) | 260 | 260 | 260 |
| Total head at highest allowed flow (ft) | 240 | 245 | 250 |
| Specific gravity of fluid | 1 | 1 | 1 |
| Horsepower for lowest allowed flow (hp) | 19.38 | 20.99 | 22.31 |
| Horsepower for BEP (hp) | 23.88 | 23.88 | 23.88 |
| Horsepower for highest allowed flow (hp) | 25.34 | 24.75 | 24.10 |
| Installed Motor Horsepower | 30 | 30 | 30 |
| Motor Efficiency | 95% | 98% | 98% |
| Electrical cost $/(yr-hp) | $ 350 | $ 350 | $ 350 |
| Electrical costs per year @ installed hp ($/yr) | $ 11,053 | $ 8,527 | $ 8,527 |
| Percent Of Time System Is Operating | 100% | 100% | 100% |

Reliability models are needed to find when end of component life occurs, as costly replacements follow death of the component. Details from the reliability models go into the sustaining costs.

Every piece of equipment comprises components. Each component has an inherent reliability. Inherent (or intrinsic) reliability is the best theoretical capability of components that can be demonstrated in a laboratory environment.

Inherent component reliability is altered downward, as measured by age-to-failure, by grade of installation, and how the equipment is used. Grade is a rank indication of the degree of refinement, features, or capabilities for installation and operation. The grades of equipment installation/use practices (and thus the costs) in the acquisition tree are precursors of failure costs covered in the sustaining tree. LCC accuracy improves and benefits from quantification of grade issues, just as LCC analysis improves by use of probabilistic analysis rather than deterministic analysis. Most engineers know that nothing dies on schedule and nothing gets repaired on schedule—the problem is how to quantify the details.

Very high-grade installations and very high-grade practices for operation of the equipment demonstrate (by long ages-to-failure) most of the inherent equipment life is usable. However, low-grade installations and low-grade operations destroy inherent life of equipment. The key for LCC calculations is accurate reflection of effects of practices on inherent reliability. This is frequently accomplished by laboratory tests on low-cost electronic components, but seldom quantified on high-priced mechanical components. Thus, the effects of practices on inherent life must be obtained by surveys from experts in the field. Field surveys may not be the desired method of acquiring data, but it is the most practical method considering time and costs. This forms the art of engineering that is used with the science of engineering to derive practical answers in real time.

Engineering drawings specify the grade of installation (and frequently they specify the grade of operation). Often, the production department specifies the grade of operation. The grade of equipment installation and operation needs to be priced-out as part of the specification process. It cannot be ignored—it affects life-cycle costs.

Maintenance departments and operation departments, if total productive maintenance (TPM) oriented, specify the grade of maintenance. Most engineers, during their career, are accused of gold plating, over engineering, and wasting money on the grade of installation. Engineers are aware of how the installation grade strongly influences the number of failures for the sustaining tree, but lack details for quantifying their opinions.

Good LCC analysis responds to accusations of detractors by providing monetary results to refute charges of gold plating, over design, high cost, and other overstatements/exaggerations. The resulting life multipliers, from Table 7, alter the inherent reliability of equipment and change base failure rates (lower failure rates) to predict actual failure rates (higher failure rates).

The multipliers from Table 7 are used in Table 8 (please refer to APPENDIX for Table 8) to alter the inherent reliability model. Notice how the ANSI model and the ANSI enhanced models have different inherent life. For the best practices, only three percent of the inherent life is lost, compared with 44 percent loss of life for better practices, and 97 percent loss of inherent life for the lowest grade commercial practices.

Table 8 also shows taxonomy (the classification of equipment in an ordered system that indicates natural relationships) effects on life. Life of the mechanical portion of the system is different from the electrical system. When both are considered together, system life is much shorter. The taxonomy definitions demonstrate why different organizations talk about different numbers for the same device. Reciprocals of the mean time to failure (MTTF), in Table 8, give failure rates, which could be used for deterministic computations of net present value (NPV). Deterministic NPV calculations are simpler, but often give inaccurate results when components have wear-out failure modes as shown above.

Table 8 uses Weibull statistics to characterize component life (Abernethy, 1998). Weibull descriptors are tools of choice for reliability engineers. Beta value implies failure modes for the components. In Table 8, the beta values are greater than unity and imply wear-out failure modes.

*Table 7. Centrifugal Pump Practices, Life, and Costs.*

| | | Pump Curve % Off BEP | L/D Suction Straight Runs | Rotational Shaft Alignment | Piping Alignment | Rotational Belence | Foundation Design | Grouting |
|---|---|---|---|---|---|---|---|---|
| **Best Practices** | **Resulting eta Multiplier** | + 5% to -10% of BEP | L/D = 10 to 12 | ±0.001 inches/inch error | ±0.003 inch error | Smooth at 0.0198 ips | 5 Times Equipment Mass | Monolithic And Adhesive Epoxy |
| Impeller | 0.9726 | 98% | 100% | 100% | 100% | 100% | 100% | 100% |
| Housing | 0.8547 | 86% | 100% | 100% | 100% | 100% | 100% | 100% |
| Pump Bearings | 0.8719 | 98% | 100% | 100% | 100% | 99% | 100% | 100% |
| Mech. Seal | 0.9533 | 98% | 99% | 100% | 100% | 100% | 100% | 100% |
| Bearing Seal | 0.8719 | 98% | 99% | 100% | 100% | 100% | 100% | 100% |
| Shaft | 0.9801 | 98% | 100% | 100% | 100% | 99% | 100% | 100% |
| Coupling | 1.0000 | 99% | 100% | 99% | 100% | 100% | 100% | 100% |
| Motor Bearings | 1.0000 | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Replacement Mtr. | 1.0000 | 99% | 100% | 99% | 100% | 100% | 100% | 100% |
| Motor Starter | 1.0000 | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

| | | Pump Curve % Off BEP | L/D Suction Straight Runs | Rotational Shaft Alignment | Piping Alignment | Rotational Belance | Foundetion Design | Grouting |
|---|---|---|---|---|---|---|---|---|
| **Better Practices** | **Resulting eta Multiplier** | + 10% to -20% of BEP | L/D = 6 to 8 | ±0.003 inches/inch error | ±0.010 inch error | Good at 0.0448 ips | 3.5 Times Equipment Mass | Slightly Pourous But Adhesive |
| Impeller | 0.6583 | 88% | 95% | 95% | 94% | 95% | 95% | 98% |
| Housing | 0.5163 | 73% | 95% | 95% | 92% | 95% | 95% | 95% |
| Pump Bearings | 0.3950 | 79% | 90% | 88% | 88% | 90% | 90% | 90% |
| Mech. Seal | 0.4314 | 88% | 90% | 90% | 84% | 90% | 90% | 90% |
| Baaring Seal | 0.3950 | 88% | 90% | 90% | 84% | 90% | 90% | 90% |
| Shaft | 0.5705 | 79% | 90% | 88% | 88% | 90% | 90% | 90% |
| Coupling | 0.6036 | 92% | 95% | 90% | 94% | 95% | 90% | 91% |
| Motor Bearings | 0.9776 | 94% | 93% | 94% | 97% | 95% | 90% | 90% |
| Replacement Mtr. | 0.6036 | 100% | 100% | 100% | 100% | 100% | 99% | 99% |
| Motor Starter | 1.0000 | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

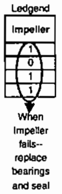
| | | Pump Curve % Off BEP | L/D Suction Streight Runs | Rotational Shsft Alignment | Piping Alignment | Rotational Balsnce | Foundstion Design | Grouting |
|---|---|---|---|---|---|---|---|---|
| **Commercial Practices** | **Resulting eta Multiplier** | +15% to -30% of BEP | L/D = 1 to 3 | ±0.009 inches/inch error | ±0.125 inches error | Rough at 0.248 ips | 0.5 Times Equipment Mass or Stilt-Mounted | Cementitous & Low Adhesion |
| Impeller | 0.1949 | 68% | 75% | 90% | 69% | 81% | 88% | 88% |
| Housing | 0.1438 | 70% | 80% | 83% | 64% | 79% | 78% | 80% |
| Pump Bearings | 0.0151 | 65% | 60% | 58% | 40% | 61% | 50% | 55% |
| Mech. Seal | 0.0095 | 65% | 60% | 58% | 40% | 61% | 50% | 55% |
| Bearing Seal | 0.0151 | 51% | 60% | 40% | 40% | 64% | 55% | 55% |
| Shaft | 0.1149 | 65% | 60% | 58% | 40% | 61% | 50% | 55% |
| Coupling | 0.0737 | 76% | 80% | 65% | 71% | 78% | 70% | 75% |
| Motor Bearings | 0.8625 | 78% | 80% | 55% | 80% | 75% | 60% | 60% |
| Replacement Mtr. | 0.0737 | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Motor Starter | 1.0000 | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

The cost data above must also include maintenance replacement strategies, as shown in Table 9. With the input data from Tables 2 through 9, the search can begin for minimizing the lowest long-term cost of ownership as found by LCC. Every LCC example has its own unique set of costs and problems to solve for minimizing LCC. Remember that minimizing LCC pushes up NPV and creates wealth for stockholders. Finding LCC requires finding details for both acquisition and sustaining costs with many details. The most difficult analysis lies in the sustaining cost tree.

*Table 9. Maintenance Replacement Strategies.*

**Good Maintenance Practices To Fix Each Component When Broken Strategy Plus Other Associated Components**

| | Impeller | Housing | Pump Bearings | Mech. Seal | Bearing Seal | Shaft | Coupling | Motor Bearings | Replacement Mtr. | Motor Starter |
|---|---|---|---|---|---|---|---|---|---|---|
| Impeller | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Housing | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pump Bearings | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Mech. Seal | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| Bearing Seal | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Shaft | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Coupling | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| Motor Bearings | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Replacement Mt | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Motor Starter | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |



**Fix When Broken Strategy: 1=Replace, 0=Do Not Replace**

| | Impeller | Housing | Pump Bearings | Mech. Seal | Bearing Seal | Shaft | Coupling | Motor Bearings | Replacement Mtr. | Motor Starter |
|---|---|---|---|---|---|---|---|---|---|---|
| Impeller | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Housing | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pump Bearings | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mech. Seal | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bearing Seal | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| Shaft | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Coupling | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Motor Bearings | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| Replacement Mt | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Motor Starter | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

### *Step 4: Choose Analytical Cost Model*

The cost model is an engineering spreadsheet for calculating NPV, using a discount rate of 12 percent. The spreadsheet merges cost details and failure details to prepare the NPV calculations. Failure costs are incurred by each year as they fail, using a Monte Carlo simulation of birth/death to cover the uncertainty. The Monte Carlo simulation is performed using an Excel® spreadsheet—every solution gives different answers.

Monte Carlo models use random numbers to simulate the probability of failure. This, in turn, is used to calculate the age-to-failure for each component. The age-to-failure (t) for each component in Table 8 is driven by the Weibull equation. The characteristic age at failure, *eta*, and the Weibull shape factor, *beta*, are found from actual or hypothesized ages to failure, and, in turn, describe the cumulative distribution function (CDF), which is a statistical term. The CDF varies from zero (no deaths) to one (all are dead), and the characteristic life, *eta*, occurs when the CDF = 63.2 percent.

The Weibull equation, written in age-to-failure, is t = eta*(ln(1/(1−CDF)))^(1/beta). Fortunately, Excel® has a random number function, RAND(), which produces numbers between zero and one. The random number generator simplifies calculations by substituting RAND() for the CDF values.

Here is an example of how the Weibull equation will work in the Monte Carlo model. Find the age-to-failure in Table 7 for an ANSI pump seal, where beta = 1.4, eta = 150,000 hours, using a random number of 0.303: thus, t = 150,000*(ln(1/(1−0.303)))^(1/1.4) = 72,443 hours. Each time a new random number is selected, the age-to-failure will be different, but driven by the statistical parameters beta and eta, which characterize the ages-to-failure for the component. This method represents the real life situation, as you never know how long a specific component will last! The Monte Carlo model starts with an initial complement of equipment whose life is randomly selected for each component, and the model will wind-down the simulated life numbers until end of useful life occurs.

Table 10 (please refer to APPENDIX for Table 10) shows an example of the Monte Carlo results for the first 10 years of life. Notice how the failure rates change by year and other useful information provided in the spreadsheet model.

As an alternative to Monte Carlo solutions, the simple case of using a constant failure rate for each component makes cost calculations easy, for a first cut. However, constant failure rates lack NPV accuracy, because NPV calculations are sensitive to what year the failures occur. Higher penalties are incurred for early failures, and advantages go to later failures with delayed costs. Constant failure rates dismiss the advantages of when failures occur.

*For the purpose of this paper only, many of the cost items identified in Figure 2 are not included, so that only the direct acquisition costs and direct sustaining costs are included to provide an unadulterated calculation of NPV. Remember that you would not ignore this issue for authorization for expenditure (AFE) submissions.*

### *Step 5: Gather Cost Estimates and Cost Models*

This is the complicated section where all the details are assembled.

- Alternative #1-ANSI pump—Use the following details:

  - Start with the inherent life for the ANSI pump from Table 8. Alter the life by the factors in Table 7 for three different installation/use practices.

  - Allow installation of a solo pump or a dual pump with the risk cost consequences of failure, as described in Table 5.

  - Use two maintenance practices of fix when broken or good maintenance practices, as described in Table 9.

  - Draw maintenance costs from Table 3 for the ANSI pump. Use capital costs from Table 2 for the ANSI pump.

  - Use power consumption costs from Table 6, allowing random variation in the costs depending upon the practices employed. Add the acquisition/sustaining costs from Step 3.

This requires six models (six NPV values) for the ANSI solo pump case, plus six models for the dual pump case, for a total of 12 models, and produces 12 NPV values. Because only costs (no profits) are considered, the NPV with the least negative number is the initial winner. This information will complete the top half of Table 1.

NPVs along with the product of availability and reliability (as a limited subset of the effectiveness equation) will be used for the tradeoff calculations. This will be described later.

- *Alternative #2-ANSI enhanced pump*—Use the following details:

The same as for alternative #1, but using ANSI enhanced details. The NPV details will complete the bottom half of Table 1.

*Step 6: Make Cost Profiles for Each Year of Study*

This step will take into account the annualized charges shown, plus the lumped charges at the front and rear end of the project. Table 10 gives spreadsheet details of the Monte Carlo simulation, by year, for only a portion of the 20-year study cycle. Each iteration is a 20-year "snapshot" of the birth and death of components. Many iterations are required to obtain a consistent result (1000 iterations). Table 10 also shows the suspended component usage for unfailed items replaced as part of good maintenance practices. Notice how maintenance hours required for the equipment grow with time, and since failures are increasing, reliability declines even though availability remains high.

The grand total of costs in Table 10 is replicated five times and averaged to reduce the errors that randomly occur, and with replication an estimate is available for the error in the results. Averaged costs for each period go into the net present value calculation. Table 10 shows power costs are 92 percent of total cost in the early years, and power as a percentage of total costs declines as maintenance costs increase with time for the condition explained in the spreadsheet heading. Of course the ratio of (electrical costs)/(total annual costs) is substantially different for lower grade equipment, lower grade installation/use, and solo pumps.

Since the pump in Table 10 is a dual pump and the availability is reported for a single unit, the system availability must be calculated. Two pumps in parallel with 99.97 percent availability and short repair times, as observed in Table 10, are: $A_0$ ~1 (1−0.9997)^2 ~ 0.999,999,9. In short, the dual pumping system is highly available, as the unavailability for the system is 0.00001 percent!

The probability of system failure in Table 10 for year five can be found from the calculated reliability numbers. Probability of failure for a pump is: POF ~ 1–65.70 percent = 0.343, and the unavailability of a pump is 1–99.97 percent = 0.0003. Then, the probability of simultaneous pump failures = 0.343*0.0003 = 0.0001. Thus, the consequences of failure, shown in Table 5, are too harsh a penalty at $3/hour of downtime for this case—but this error is a trivial matter.

Each case described in step 5 produces a cost profile for each year, by means of Monte Carlo simulation. The cost profiles are put into a net present value spreadsheet, shown in Table 11 (please refer to APPENDIX for Table 11)—only 10 years are shown from a 20-year spreadsheet. Table 12 summarizes all NPV cost profiles.

*Table 12. NPV Summary.*

**Monte Carlo Solution Results**

Best
Worst

| | Fix When Broken Maintenance | | | Good Maintenance Practices | | |
|---|---|---|---|---|---|---|
| | Installation/Use Practices | | | Installation/Use Practices | | |
| **ANSI Pump** | Commercial | Better | Best | Commercial | Better | Best |
| Solo NPV | $ (2,836,915) | $ (153,350) | $ (98,949) | $(2,562,066) | $ (144,673) | $ (96,047) |
| Solo R*A | 0% | 39% | 62% | 0% | 42% | 64% |
| Maintenance Time/yr | 156 hrs | 7 hrs | 3 hrs | 144 hrs | 6 hrs | 3 hrs |
| Dual NPV | $ (198,187) | $ (67,901) | $ (67,728) | $ (233,641) | $ (68,913) | $ (68,225) |
| Dual R*A | 0% | 39% | 62% | 0% | 42% | 64% |
| Maintenance Time/yr | 156 hrs | 7 hrs | 3 hrs | 144 hrs | 6 hrs | 3 hrs |
| **ANSI Enhanced Pump** | | | | | | |
| Solo NPV | $(1,230,029) | $ (109,767) | $ (82,655) | $(1,115,875) | $ (107,368) | $ (82,732) |
| Solo R*A | 0% | 58% | 75% | 0% | 60% | 75% |
| Maintenance Time/yr | 67 hrs | 4 hrs | 2 hrs | 62 hrs | 4 hrs | 2 hrs |
| Dual NPV | $ (142,075) | $ (72,611) | $ (74,253) | $ (162,592) | $ (72,864) | $ (74,994) |
| Dual R*A | 0% | 58% | 75% | 0% | 60% | 75% |
| Maintenance Time/yr | 67 hrs | 4 hrs | 2 hrs | 62 hrs | 4 hrs | 2 hrs |

Remember that the *most favorable* NPV values in Table 12 are the winners, with the *smallest negative values*. This is because no profits are considered. The most cost-effective winning combination is the ANSI dual pump, using best installation/use practices and fix when broken maintenance replacement practices, with an NPV = −$67,728.

Table 12, when viewed only from a financial viewpoint, developed by combining financial data, installation practices, use practices, and maintenance practices, can answer the questions asked at the beginning:

- *Project engineers want to minimize capital expenditures*—The least capital cost spent is for a solo ANSI pump with commercial installation practices, and this will result in the worst financial results with an NPV = ($2,836,915). This is a very bad bargain and is number 24 on the list of alternatives. It is not affordable for achieving the lowest long term cost of ownership!
- *Maintenance engineers want to minimize repair hours*—The least maintenance hours are achieved with an ANSI enhanced pump and the NPV = ($74,253), which is number seven on the top 10 list for NPV.
- *Production wants to maximize uptime hours*—The maximum uptime hours are achieved with a dual ANSI enhanced pump using good maintenance practices. The NPV = ($74,994), which is number eight on the top 10 list for NPV.
- *Reliability engineers want to maximize equipment reliability*—The best equipment reliability is achieved with a dual ANSI enhanced pump using good maintenance practices. The NPV = ($74,994), which is number eight on the top 10 list for NPV, and
- *Accounting wants to maximize net present value of the project*—This is obtained with a dual ANSI pump using best practices and a fix when broken strategy. This is number one on the top 10 list and the NPV = ($67,728).

Be careful of overgeneralizing results from Tables 12 and 13 (please refer to APPENDIX for Table 13). Each case has its own special conditions concerning performance and costs, although some tendencies prevail.

In Table 12, the figures for maintenance hours, availability, and reliability are averages for the 20-year time period. Availability does not change much during the 20 years. However, substantial changes occur for maintenance downtime hours, as shown in Figure 6, and reliability changes substantially, as shown in Figure 7. Both cases illustrate the case for the top item in Table 13, which is a ranking of the top 10 NPV values.

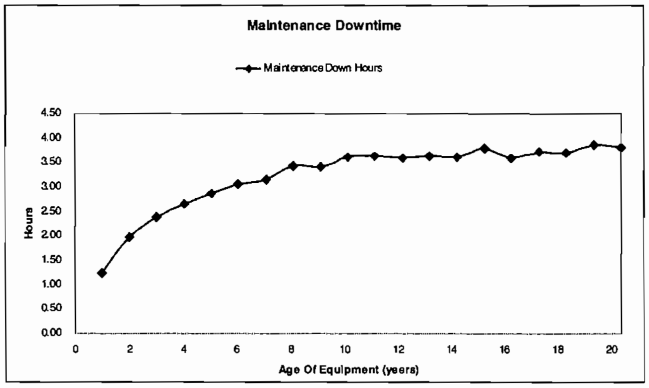


*Figure 6. Maintenance Downtime: ANSI, Dual, Best Practices, Fix When Broken.*

*Step 7: Make Break-Even Charts for Alternatives*

Break-even charts are generally useful tools for showing a quick grasp of details from the simulations. However, Figure 8 does not produce any break-even choices.

Another technique useful for studying alternatives involves effectiveness. The effectiveness equation is a helpful tool for use as

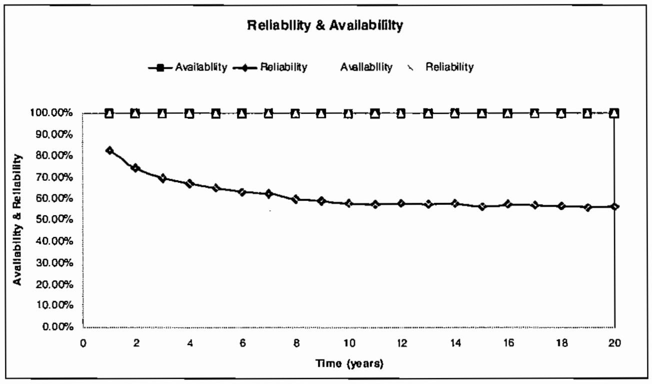


*Figure 7. Reliability and Availability: ANSI, Dual, Best Practices, Fix When Broken.*

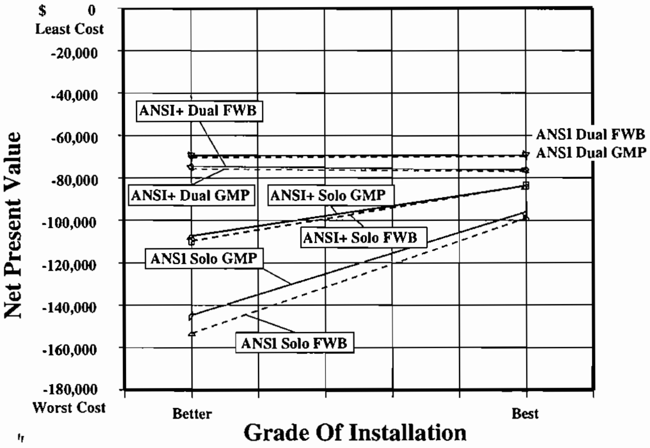


*Figure 8. NPV Versus Installation/Use Grades.*

a sales tool for presenting LCC calculations involving probabilities. It gives a figure-of-merit. It measures chances of producing the intended results. The effectiveness equation is described in several different formats (Blanchard, et al., 1995; Kececioglu, 1995; Landers, 1996; Pecht, 1995; Raheja, 1991). Each element is a probability. The issue is finding a system effectiveness value that gives lowest long-term cost of ownership with tradeoff considerations:

$$\text{System effectiveness} = \text{Effectiveness/LCC} \tag{1}$$

Cost is a measure of resource usage. It never includes all possible elements but must include the most important. Effectiveness is a measure of value received (effectiveness rarely includes all value elements, as many are too difficult to quantify). Effectiveness varies from zero to one:

$$\text{Effectiveness} = \text{availability} * \text{reliability} * \text{maintainability} * \text{capability} \tag{2}$$

Each element of the effectiveness equation must have a firm datum, which changes with nameplate ratings to obtain a true value that lies between zero and one. You need these measures to help sell LCC.

- *Availability*—deals with the duration of uptime for operations and is a measure of *how often* the system is alive and well. It is often expressed as:

$$A = (\text{uptime})/(\text{uptime} + \text{downtime}) \tag{3}$$

Uptime and downtime refer to dichotomized conditions. Uptime refers to a capability to perform the task, and downtime refers to not being able to perform the task. As availability grows, the capacity for making money increases, because the equipment is in service a larger percent of time. Watch out for self-serving definitions of convenience not in the best interest of stockholders such as (uptime + downtime) < 8760 hours per year, as the lack of making money is an LCC issue.

- *Reliability*—deals with reducing the frequency of failures over a time interval. Reliability is a measure of *the probability for failure-free operation* during a given interval, i.e., it is a measure of success for a failure free operation. It is often expressed in simple exponential terms as:

$$\begin{aligned} &R(t) = \exp(-t/\text{MTBF}) = \exp(-\lambda t) \\ &\text{or, expressed in Weibull terms, as} = \exp(-t/\text{eta})\hat{\ }\text{beta} \end{aligned} \tag{4}$$

where $\lambda$ is constant failure rate and MTBF is mean time between failure. MTBF (a yardstick for reliability) measures the time between system failures and is easier to understand than a probability number. For exponentially distributed failure modes, MTBF is a basic figure-of-merit for reliability (and failure rate, $\lambda$, is the reciprocal of MTBF). For a given mission time, high reliability requires a long MTBF. To the user of a product, reliability is measured by a long, failure free, operation. Long periods of failure free interruptions result in increased productive capability, while requiring fewer spare parts and less manpower for maintenance activities, which results in lower costs. To the supplier of a product, reliability is measured by completing a failure free warranty period under specified operating conditions, with few failures during the design life of the product.

Improving reliability often occurs by reducing errors from people or improving processes/procedures, and these changes can usually be made at small costs. Or reliability is improved by equipment, which increases capital cost. Reliability improvements bring expectations for improving availability, decreasing downtime and smaller maintenance costs, improved secondary failure costs, and results in better chances for making money because the equipment is free from failures for longer periods of time.

- *Maintainability*—deals with duration of maintenance outages or *how long* it takes to complete (ease and speed) maintenance actions compared with a datum. The datum includes maintenance (all actions necessary for retaining an item in, or restoring an item to, a specified, good condition) performed by personnel having specified skill levels, using prescribed procedures and resources at each prescribed level of maintenance. Maintainability characteristics are usually determined by equipment design, which then sets maintenance procedures and determines the length of repair times.

A key maintainability figure-of-merit is the mean time to repair (MTTR) and a limit for the *maximum* repair time. Qualitatively, it refers to the ease with which hardware or software is restored to a functioning state. Quantitatively, it has probabilities and is measured based on the total downtime for maintenance, including all time for: diagnosis, troubleshooting, tear-down, removal/replacement, active repair time, verification testing that the repair is adequate, delays for logistic movements, and administrative maintenance delays. It is often expressed as:

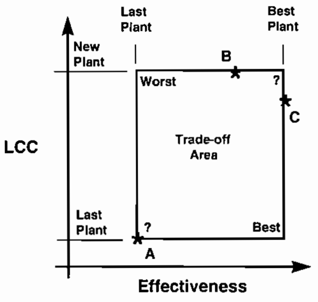
$$M(t) = 1-\exp(-t/\text{MTTR}) = 1-\exp(-\mu t) \tag{5}$$

where $\mu$ is constant maintenance rate and MTTR is mean time to repair. The arithmetic average of repair time, which is easier visualized than probability values. This simple, easy to use repair time criteria is often expressed in exponential repair times rather than more accurate, but cumbersome, log-normal distributions of repair times, which are skewed to the right by unusual and lengthy repairs. The maintainability issue is to achieve short repair times for keeping availability high, so that downtime of productive equipment is minimized for cost control when availability is critical.

- *Capability*—deals with productive output compared with inherent productive output. This index measures the systems capability to perform the intended function on a system basis. Often the term is synonymous with productivity, which is the product of efficiency multiplied by utilization. Efficiency measures the productive work output versus the work input. Utilization is the ratio of time spent on productive efforts to the total time consumed. For example, suppose efficiency is 80 percent because of wasted labor/scrap generated, and utilization is 82.19 percent because the operation is operated 300 days per year out of 365 days. The capability is 0.8*0.8219 = 65.75 percent. Capability measures *how well* the production activity is performed compared with the datum.

- *System effectiveness*—equations quantify important elements and associated costs, to find areas for improvement to increase overall effectiveness and reduce losses. For example, if availability is 98 percent and capability is 65 percent, the opportunity for improving capability is usually much greater than for improving availability. System effectiveness equations are helpful for understanding benchmarks, past, present, and future status, as shown in Figure 6, for understanding tradeoff information.

Engineers need graphics to provide a fundamental understanding of the problem. Figure 9 provides a graphical sales tool to display facts for effectiveness and life-cycle costs. It helps explain details, and shows why certain actions are preferred. Each engineer wants to select equipment or projects that have low life-cycle costs and high effectiveness—but often this is not accomplished in real life because the ideas are not sold effectively. Figure 9 is a presentation and sales tool using the system effectiveness elements described above.



| Parameter | A<br>Last Plant | B<br>New Plant | C<br>Best Plant |
|---|---|---|---|
| Availability | 0.95 | 0.95 | 0.98 |
| Reliability | 0.3 | 0.4 | 0.6 |
| Maintainability | 0.7 | 0.7 | 0.7 |
| Capability | 0.7 | 0.8 | 0.6 |
| Effectiveness | 0.14 | 0.22 | 0.25 |
| LCC | 80 | 100 | 95 |

*Figure 9. Benchmark Data Shown in Tradeoff Format.*

The lower right-hand corner of Figure 9 brings much joy and happiness, often described as "bang for the buck" (Weisz, 1996). The upper left-hand corner brings much grief. The remaining two corners raise questions about worth and value. The system effectiveness equation is useful for tradeoff studies (Brennan, et al., 1985), as shown in the outcomes in Figure 10.

System effectiveness equations have great impact on the LCC, because so many decisions made in the early periods of a project carve LCC values into stone. About 2/3 of the total LCC is fixed during project conception (Followell, 1995; Yates, 1995). Expenditure of funds flows at a later time (Brennan, et al., 1985). The chance to influence LCC cost reductions (Blanchard, 1991) grows smaller when projects are converted into bricks and mortar, as shown in Figure 11.

Figure 12 does not consider the results of capability or maintainability, since they are about the same value for each configuration. Also, the effectiveness value is strongly driven by the reliability value. Notice that adding good maintenance practices to the ANSI dual pump, for best practices of installation and use, adds #5 to the effectiveness for a one percent increase in cost. The question each end user must ask, "Is the extra cost worth the extra reliability?" Figure 12 provides a tool for selling the features. Details for this figure come from Table 12.

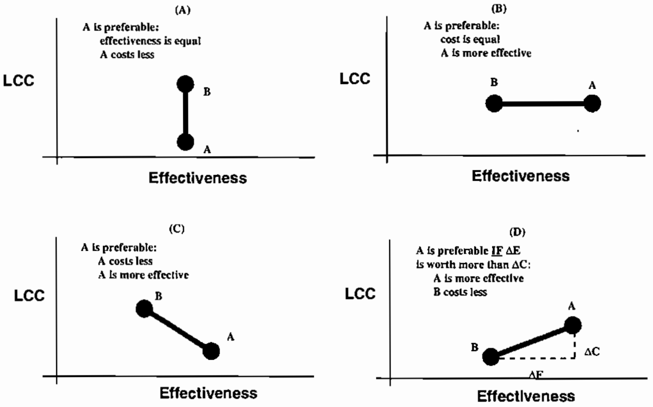


*Figure 10. Some Possible Outcomes from Tradeoff Studies.*

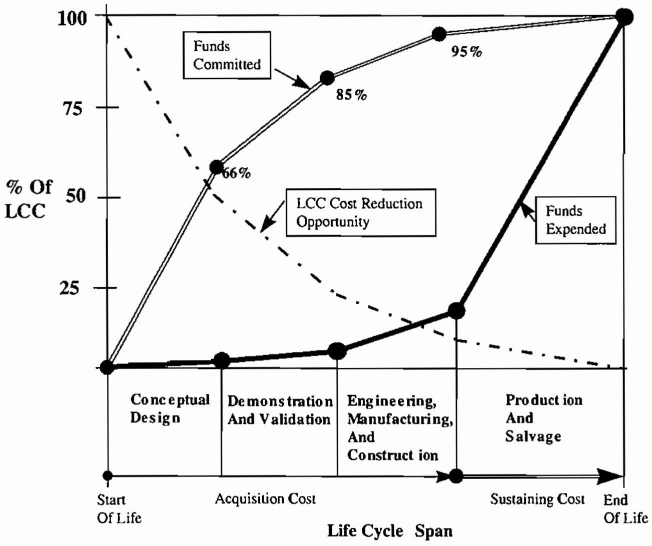


*Figure 11. Funding Trends by Commitment and Expenditure.*

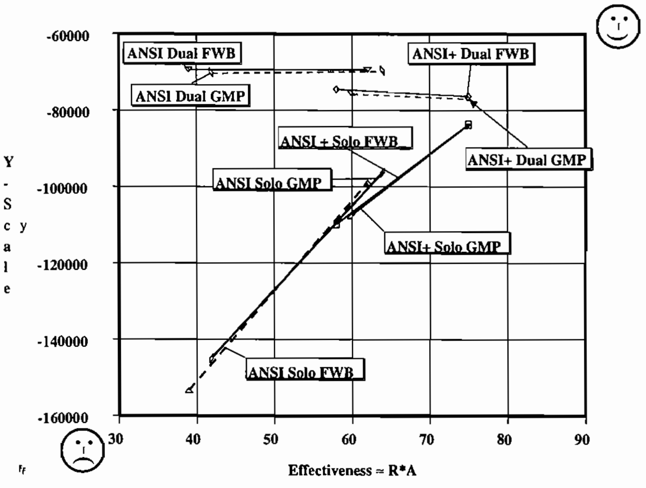


*Figure 12. Tradeoff Chart for NPV and Effectiveness.*

### *Step 8: Pareto Charts of Vital Few Cost Contributors*

The purpose of Pareto charts is to identify the vital few cost contributors, so the details can be itemized for sensitivity analysis and ignore the trivial many issues. Pareto rules say that 10 percent to 20 percent of the elements of a cost analysis will identify 60 percent to 80 percent of the total cost—these items are the vital few items of concern and need to be carefully considered.

The NPV for investment, failure costs, and power costs is −$67,728. The NPV for only investment cost is −$26,058, and the NPV for investment plus power costs is −$64,995. The effect of power results in an NPV of −($64,995−$26,058) = −$38,937. The NPV effects of failure costs are the balance, or −$2,733. An approximate Pareto distribution of NPV costs is:

- Electrical power 38,937/67,728 = 57.4%
- Capital costs 26,058/67,728 = 38.5%
- Failure costs 2733/67,728 = 4.0%

This Pareto distribution of costs for ANSI enhanced dual pumps installed/used with best practices and fix when broken maintenance strategies are informative! One item consists of the vital few—electrical power! The Pareto distribution is shown in NPV terms to see the financial effects, with consideration for time value of expenditures. The main issue is power consumption. For this scenario, maintenance costs fall into the trivial portion of NPV considerations.

### *Step 9: Prepare Sensitivity Analysis of High Costs and Reasons for High Cost*

Sensitivity analysis allows study of key parameters on LCC—power consumption. Power consumed is a direct result of work performed, energy lost in inefficient motors/bearing, and energy lost in pump dynamics. High efficiency components can reduce power consumption.

For the pump and motor in the preferred configuration, the highest efficiency components have been selected and thus no other practical devices exist for making a sensitivity analysis, except for acquisition costs.

Table 8 shows the inherent reliability of the ANSI enhanced pump has a superior life (2.62 years) compared with the ANSI pump (1.57) years, by a factor of 2.62/1.57 = 1.67 times. Unfortunately, the high acquisition cost makes this equipment uneconomical. Perhaps the purchasing department can negotiate a better price for the equipment, which is attached to a very heavy baseplate. What is the largest purchase price we can afford to pay for the better equipment and arrive at the lowest NPV? This requires altering NPVs in Table 14 (please refer to APPENDIX for Table 14) and solving for the lower acquisition cost.

Remember, some of the extra costs for alternates 5, 6, 7, and 8 result from heavier equipment, larger foundations, and, thus, extra installation costs. Achieving lower purchase prices to get the better grade of equipment will be difficult (if not impossible) for the supplier of pumping equipment.

Start the sensitivity analysis for alternatives 5 through 8 in Table 14, using the NPV results similar to the details shown in Table 11, as each alternative has different acquisition costs and different yearly costs. Then decrease acquisition costs by increments and find the resulting NPV for each alternative in Table 14. Results of the sensitivity studies are shown in Figure 13.

Figure 13 shows a need for major cost reductions (most likely greater than can be achieved in a competitive environment for commodity equipment) if ANSI enhanced equipment is selected. Acquisition cost reductions greater than $5,000 are required to achieve break-even, shown by the solid horizontal line at ($67,728) in Figure 10 for alternative 1.

### *Step 10: Select Preferred Course of Action Using LCC*

The selection of a dual pump strategy using ANSI pumps with the best installation and use practices is the most cost effective Alternative 1. The use of good maintenance practices when components fail will increase the equipment reliability at only modest increases and cost, and may be the preferred tradeoff alternative—Alternative 3. The ANSI enhanced pump with its extra rigid baseplate is not affordable for this condition. The price is too high for value received—our "wants" carry an excessive price greater than our "needs." Note that Alternate 2 and 4 would be significant setbacks in both NPV and effectiveness, as costs would be higher and effectiveness would be lower. If you succumb to the cry of "gold plating for the best installation/use" and step down to the lower grade (and less expensive first cost) installation, poorer results will occur.

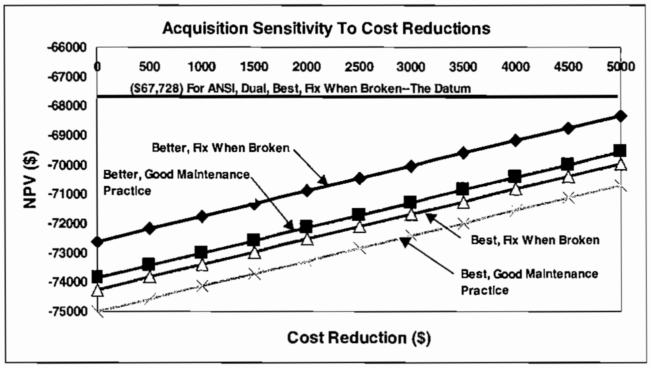


*Figure 13. Break-Even Chart for ANSI Enhanced Pumps—Alternatives 5, 6, 7, and 8.*

It is important to remember that each case is specific. Do not reach out too far in generalizing about equipment and installations. Situations that are "bad" in one case can be "good" in another when the facts are studied.

## SUMMARY

Life-cycle costs include cradle to grave costs. When failure costs are included, the quantity of manpower required could be engineered to avoid rules of thumb about how maintenance budgets are established. Adding installation and operating practices and their cost consequences to LCC add reality to equipment selection. Performing a Monte Carlo simulation to find costs incurred in each year for wear-out failure modes defers expenditures to later years (compared with constant failure rate models), and this provides advantages for NPV calculations when time effects of money are considered.

LCC techniques provide methods to consider tradeoff ideas. The LCC tradeoff visualization techniques are helpful for engineers. Likewise, LCC analysis provides NPV techniques of importance for financial organizations. LCC details give engineering and financial groups common ground for communication.

The same physical equipment can produce different LCC results in different organizations from use of different cost numbers, discount rates, and a host of other details. It is important to make local calculations to find the correct solution for the specific requirement.

All equipment has an inherent reliability, which results in a base failure rate. The installation and use practice alters the base failure rate to produce the expected failure rate for a particular operation. The examples show techniques for addressing a series of engineering alternatives and finding the results through use of financial techniques. This method "prices out" the costs of practices in a manner that is helpful to engineers.

Clearly, it is the responsibility of engineering departments to define equipment failure rates and the consequences of engineering practices on the life of equipment. Also, it is the responsibility of engineers to convert the results of equipment life and failures into a financial format for clearly communicating the financial results within the organization. In commercial enterprises, it is not helpful for the engineering department to be technical smart but business ignorant, since the reason for most commercial organizations is to make money. LCC is simply a way-stop on the never ending journey for reducing costs. LCC is clearly not a destination. LCC provides the tools to engineer maintenance budgets and costs.

Remember that the LCC calculations shown were shortened to provide only the direct acquisition costs and direct sustaining cost.

A limited subset of the LCC program written in Excel® for calculation of the above details is posted for free download from the World Wide Web (Barringer, 1998) at http://www.barringer1.com.

## APPENDIX

Some of the tables in this paper were too detailed to show up well if reduced to fit the two column format. For that reason, they are placed here in the APPENDIX.

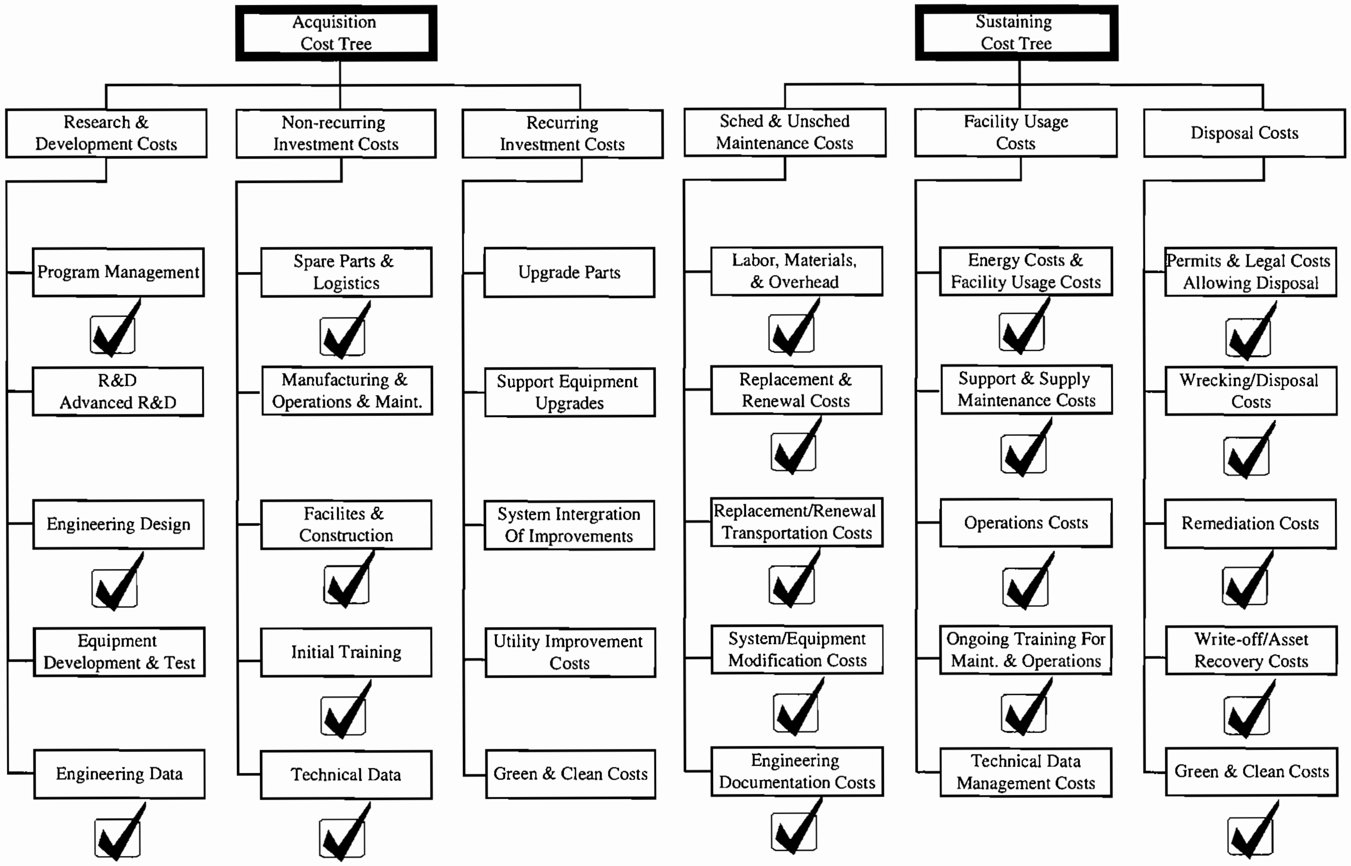


*Figure 5. Cost Components for Each Grade of Pump.*

*Table 8. Reliability Model Altered by Effects of Practices.*

| **Inherent Component Reliability** | **30 hp pump: 3"x1.5"x10" with 8" impeller pellet water pump for a 30,000 lb./hr. HDPE unit** | | | **Best Practices Installation & Use** | | **Effects Of Practices on Component Life** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **beta** | **eta** | | **Multiplier** | **beta** | **eta** | | | |
| **ANSI** | shape factor (no dimensions) | location factor (hrs) | **MTTF (yrs)= η∗Γ(1+ 1/β)** | Eta Life Multiplier From Practices | shape factor (no dimensions) | location factor (hrs) | **MTTF (yrs)= η∗Γ(1+ 1/β)** | | |
| Impeller | 2.5 | 300,000 | 30.39 | 0.9726 | 2.50 | 291,784 | 29.55 | | |
| Housing | 1.3 | 300,000 | 31.63 | 0.8547 | 1.30 | 256,412 | 27.03 | MTBF | |
| Pump Bearings | 1.3 | 100,000 | 10.54 | 0.9712 | 1.30 | 97,119 | 10.24 | For All | MTBF |
| Mech. Seal | 1.4 | 150,000 | 15.61 | 0.9677 | 1.40 | 145,159 | 15.10 | **Mech.-->** | **2.00** |
| Bearing Seal | 1.4 | 75,000 | 7.80 | 0.9677 | 1.40 | 72,579 | 7.55 | Items | |
| Shaft | 1.2 | 300,000 | 32.21 | 0.9712 | 1.20 | 291,357 | 31.29 | | |
| Coupling | 2 | 100,000 | 10.12 | 0.9801 | 2.00 | 98,010 | 9.92 | | |
| Motor Bearings | 1.3 | 150,000 | 15.81 | 1.0000 | 1.30 | 150,000 | 15.81 | For All | MTBF |
| Replacement Mtr. | 1.1 | 150,000 | 16.52 | 0.9801 | 1.10 | 147,015 | 16.19 | **Elect.-->** | **6.41** |
| Motor Starter | 1.2 | 300,000 | 32.21 | 1.0000 | 1.20 | 300,000 | 32.21 | Items | |
| | | | **1.57** | =~Mean time between system failures= | | | **1.52** | | |
| | | | 13,767 | hours | **Δ = Loss** | or= | **13,354** | hours | |
| | | | | | **3%** | loss= | **413** | hours | |

| **Inherent Component Reliability** | **30 hp pump: 3"x1.5"x10" with 8" impeller pellet water pump for a 30,000 lb./hr. HDPE unit** | | | **Best Practices Installation & Use** | | **Effects Of Practices on Component Life** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **beta** | **eta** | | **Multiplier** | **beta** | **eta** | | | |
| **ANSI Enhanced** | shape factor (no dimensions) | location factor (hrs) | **MTTF (yrs)= η∗Γ(1+ 1/β)** | Life Multiplier * eta From Practices | shape factor (no dimensions) | location factor (hrs) | **MTTF (yrs)= η∗Γ(1+ 1/β)** | | |
| Impeller | 2.5 | 300,000 | 30.39 | 0.9726 | 2.50 | 291,784 | 29.55 | | |
| Housing | 1.3 | 300,000 | 31.63 | 0.8547 | 1.30 | 256,412 | 27.03 | MTBF | |
| Pump Bearings | 1.3 | 300,000 | 31.63 | 0.9712 | 1.30 | 291,357 | 30.72 | For All | MTBF |
| Mech. Seal | 1.4 | 200,000 | 20.81 | 0.9677 | 1.40 | 193,545 | 20.14 | **Mech.-->** | **4.19** |
| Bearing Seal | 1.4 | 500,000 | 52.02 | 0.9677 | 1.40 | 483,863 | 50.34 | Items | |
| Shaft | 1.2 | 300,000 | 32.21 | 0.9712 | 1.20 | 291,357 | 31.29 | | |
| Coupling | 2 | 300,000 | 30.35 | 0.9801 | 2.00 | 294,030 | 29.75 | | |
| Motor Bearings | 1.3 | 150,000 | 15.81 | 1.0000 | 1.30 | 150,000 | 15.81 | For All | MTBF |
| Replacement Mtr. | 1.1 | 150,000 | 16.52 | 0.9801 | 1.10 | 147,015 | 16.19 | **Elect.-->** | **6.41** |
| Motor Starter | 1.2 | 300,000 | 32.21 | 1.0000 | 1.20 | 300,000 | 32.21 | Items | |
| | | | **2.62** | =~Mean time between system failures= | | | **2.53** | | |
| | | | 22,919 | hours | **Δ = Loss** | or= | **22,205** | hours | |
| | | | | | **3%** | loss= | **715** | hours | |

*Table 10. Monte Carlo Failure Rate and Cost Profiles by Year.*

| **Summary** | **Failure Rate and Cost Summary By Year--Dual ANSI, Best Installation and Use, Good Maintenance Practices** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1000 <--# Iteration | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Average Of Cumulative Failures Per Year | Impeller | 0.000 | 0.000 | 0.002 | 0.003 | 0.002 | 0.003 | 0.007 | 0.007 | 0.013 | 0.012 |
| | Housing | 0.006 | 0.008 | 0.025 | 0.032 | 0.023 | 0.023 | 0.029 | 0.028 | 0.027 | 0.020 |
| | Pump Bearings | 0.006 | 0.008 | 0.025 | 0.032 | 0.023 | 0.023 | 0.029 | 0.028 | 0.027 | 0.020 |
| | Mech. Seal | 0.025 | 0.030 | 0.038 | 0.038 | 0.033 | 0.036 | 0.048 | 0.048 | 0.033 | 0.032 |
| | Bearing Seal | 0.049 | 0.072 | 0.090 | 0.105 | 0.137 | 0.116 | 0.112 | 0.135 | 0.115 | 0.120 |
| | Shaft | 0.020 | 0.016 | 0.014 | 0.017 | 0.020 | 0.030 | 0.020 | 0.024 | 0.030 | 0.026 |
| | Coupling | 0.004 | 0.034 | 0.040 | 0.034 | 0.045 | 0.052 | 0.071 | 0.062 | 0.067 | 0.076 |
| | Motor Bearings | 0.028 | 0.034 | 0.044 | 0.057 | 0.054 | 0.049 | 0.067 | 0.049 | 0.063 | 0.059 |
| | Replacement Mtr. | 0.046 | 0.049 | 0.066 | 0.058 | 0.058 | 0.051 | 0.065 | 0.063 | 0.052 | 0.052 |
| | Motor Starter | 0.018 | 0.017 | 0.026 | 0.023 | 0.025 | 0.031 | 0.018 | 0.023 | 0.031 | 0.030 |
| | Totals | 0.202 | 0.268 | 0.370 | 0.399 | 0.420 | 0.414 | 0.466 | 0.467 | 0.458 | 0.447 |
| | Mt'ce Down Hrs | 1.256 | 1.715 | 2.420 | 2.681 | 2.807 | 2.699 | 3.104 | 3.125 | 2.985 | 2.892 |
| Average Of Cumulative Suspensions Per Year | Impeller | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Housing | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Pump Bearings | 0.080 | 0.110 | 0.155 | 0.178 | 0.195 | 0.178 | 0.196 | 0.218 | 0.188 | 0.184 |
| | Mech. Seal | 0.090 | 0.148 | 0.173 | 0.206 | 0.227 | 0.206 | 0.246 | 0.224 | 0.223 | 0.212 |
| | Bearing Seal | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Shaft | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Coupling | 0.074 | 0.083 | 0.110 | 0.115 | 0.112 | 0.100 | 0.132 | 0.112 | 0.115 | 0.111 |
| | Motor Bearings | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Replacement Mtr. | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Motor Starter | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Totals | 0.244 | 0.341 | 0.438 | 0.499 | 0.534 | 0.484 | 0.574 | 0.554 | 0.526 | 0.507 |
| Average Of Cumulative Costs Per Year | Impeller | $ - | $ - | $ 4 | $ 5 | $ 4 | $ 5 | $ 13 | $ 13 | $ 24 | $ 22 |
| | Housing | $ 11 | $ 15 | $ 46 | $ 59 | $ 42 | $ 42 | $ 53 | $ 51 | $ 50 | $ 37 |
| | Pump Bearings | $ 57 | $ 100 | $ 99 | $ 115 | $ 118 | $ 113 | $ 154 | $ 112 | $ 120 | $ 110 |
| | Mech. Seal | $ 72 | $ 105 | $ 126 | $ 141 | $ 144 | $ 138 | $ 172 | $ 162 | $ 142 | $ 136 |
| | Bearing Seal | $ 47 | $ 68 | $ 85 | $ 100 | $ 130 | $ 110 | $ 106 | $ 128 | $ 109 | $ 114 |
| | Shaft | $ 29 | $ 23 | $ 21 | $ 25 | $ 29 | $ 44 | $ 29 | $ 35 | $ 44 | $ 38 |
| | Coupling | $ 17 | $ 48 | $ 59 | $ 54 | $ 64 | $ 69 | $ 94 | $ 81 | $ 87 | $ 95 |
| | Motor Bearings | $ 33 | $ 40 | $ 51 | $ 67 | $ 63 | $ 57 | $ 78 | $ 57 | $ 74 | $ 69 |
| | Replacement Mtr. | $ 93 | $ 99 | $ 133 | $ 117 | $ 117 | $ 103 | $ 131 | $ 127 | $ 105 | $ 105 |
| | Motor Starter | $ 12 | $ 12 | $ 18 | $ 16 | $ 17 | $ 21 | $ 12 | $ 16 | $ 21 | $ 20 |
| | Failure Cost $s | $ 371 | $ 510 | $ 641 | $ 698 | $ 729 | $ 703 | $ 842 | $ 782 | $ 774 | $ 746 |
| | Power Cost $s | $ 8,406 | $ 8,417 | $ 8,402 | $ 8,401 | $ 8,412 | $ 8,411 | $ 8,399 | $ 8,399 | $ 8,415 | $ 8,408 |
| | Grand Total Cost $s | $ 8,777 | $ 8,926 | $ 9,043 | $ 9,099 | $ 9,141 | $ 9,114 | $ 9,241 | $ 9,181 | $ 9,189 | $ 9,154 |
| | 1 Yr. Reliability | 81.71% | 76.49% | 69.07% | 67.10% | 65.70% | 66.10% | 62.75% | 62.69% | 63.25% | 63.95% |
| | 1 Yr. Availability | 99.99% | 99.98% | 99.97% | 99.97% | 99.97% | 99.97% | 99.96% | 99.96% | 99.97% | 99.97% |
| | Mt'ce Down Hrs | 1.256 | 1.715 | 2.420 | 2.681 | 2.807 | 2.699 | 3.104 | 3.125 | 2.985 | 2.892 |

| Maximum Spreadsheet Validity (yrs) | Number Of Iterations |
|---|---|
| 141 | 1000 |

*Table 11. Cost Profiles with Net Present Value Calculations.*

**Net Present Value Calculations:**

20 <--Project Life In Years

| **Cost Elements** | Year--> | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Capital | | $ 30,368 | | | | | | | | | | | |
| Costs | | $ - | $ 8,693 | $ 8,824 | $ 8,917 | $ 8,968 | $ 9,001 | $ 9,036 | $ 9,055 | $ 9,104 | $ 9,115 | $ 9,147 | $ 9,162 |
| Savings (enter as a positive number) | | | | | | | | | | | | | |
| Depreciation (straight line) | | ▨ | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 |
| Profit b/4 Taxes | | ▨ | $ (10,212) | $ (10,343) | $ (10,435) | $ (10,487) | $ (10,519) | $ (10,555) | $ (10,574) | $ (10,622) | $ (10,633) | $ (10,665) | $ (10,681) |
| Tax Provision @ 38% of Pb/4T | | ▨ | $ 3,880 | $ 3,930 | $ 3,965 | $ 3,985 | $ 3,997 | $ 4,011 | $ 4,018 | $ 4,036 | $ 4,041 | $ 4,053 | $ 4,059 |
| Net Income | | ▨ | $ (6,331) | $ (6,413) | $ (6,470) | $ (6,502) | $ (6,522) | $ (6,544) | $ (6,556) | $ (6,586) | $ (6,593) | $ (6,612) | $ (6,622) |
| Add Back Depreciation | | ▨ | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 | $ 1,518 |
| Cash Flow | | $ (30,368) | $ (4,813) | $ (4,894) | $ (4,951) | $ (4,983) | $ (5,004) | $ (5,026) | $ (5,037) | $ (5,067) | $ (5,074) | $ (5,094) | $ (5,104) |
| Discount Factors @ Rate Above | | 1.00 | 0.89 | 0.80 | 0.71 | 0.64 | 0.57 | 0.51 | 0.45 | 0.40 | 0.36 | 0.32 | 0.29 |
| Present Value | | $ (30,368) | $ (4,297) | $ (3,902) | $ (3,524) | $ (3,167) | $ (2,839) | $ (2,546) | $ (2,279) | $ (2,047) | $ (1,830) | $ (1,640) | $ (1,467) |
| Net Present Value | $ (67,728) | #DIV/0! | <--Internal Rate Of Return (requires at least one positive number and one negative number in row 43 to make a calculation--may also re | | | | | | | | | | |
| @ Discount Rate = | 12% | | | | | | | | | | | | |

*Table 13. Top 10 Alternatives.*

| Top Ten Alternatives From Monte Carlo Simulation | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Alternative Rank** | **Pump Grade** | **Dual Or Solo** | **Installation & Use Practice** | **Maintenance Practice** | **Capital Cost** | **NPV** | **Effectiveness ~ R * A** | **Δ % For NPV** | **Δ % For NPV** |
| 1 | ANSI | Dual | Best | Fix When Broken | $ 30,368 | **$ (67,728)** | 62% | - | - |
| 2 | ANSI | Dual | Better | Fix When Broken | $ 27,458 | $ (67,901) | 39% | -0.3% | -36.9% |
| 3 | ANSI | Dual | Best | Good Practices | $ 30,368 | $ (68,225) | 64% | -0.7% | 4.6% |
| 4 | ANSI | Dual | Better | Good Practices | $ 27,458 | $ (68,913) | 42% | -1.7% | -31.0% |
| 5 | ANSI + | Dual | Better | Fix When Broken | $ 35,436 | $ (72,611) | 58% | -7.2% | -6.1% |
| 6 | ANSI + | Dual | Better | Good Practices | $ 35,436 | $ (73,864) | 60% | -9.1% | -2.3% |
| 7 | ANSI + | Dual | Best | Fix When Broken | $ 39,046 | $ (74,253) | 75% | -9.6% | 21.2% |
| 8 | ANSI + | Dual | Best | Good Practices | $ 39,046 | $ (74,994) | 75% | -10.7% | 22.2% |
| 9 | ANSI + | Solo | Best | Fix When Broken | $ 19,523 | $ (82,655) | 75% | -22.0% | 21.1% |
| 10 | ANSI + | Solo | Best | Good Practices | $ 19,523 | $ (82,732) | 75% | -22.2% | 22.4% |

*Table 14. Changes Required for Alternatives.*

| Top Ten Alternatives From Monte Carlo Simulations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Alternative Rank** | **Pump Grade** | **Dual Or Solo** | **Installation & Use Practice** | **Maintenance Practice** | **Capital Cost** | **NPV** | **Effectiveness ~ R * A** | **Δ % For NPV** | **Δ % For NPV** |
| 1 | ANSI | Dual | Best | Fix When Broken | $30,368 | **$(67,728)** | 62% | - | - |
| 2 | ANSI | Dual | Better | Fix When Broken | $ 27,458 | $(67,901) | 39% | -0.3% | -36.9% |
| 3 | ANSI | Dual | Best | Good Practices | $30,368 | $(68,225) | 64% | -0.7% | 4.6% |
| 4 | ANSI | Dual | Better | Good Practices | $27,458 | $(68,913) | 42% | -1.7% | -31.0% |
| 5 | ANSI + | Dual | Better | Fix When Broken | $ 35,436 | ~~$(72,611)~~ | 58% | -7.2% | -6.1% |
| 6 | ANSI + | Dual | Better | Good Practices | $35,436 | ~~$(73,864)~~ | 60% | -9.1% | -2.3% |
| 7 | ANSI + | Dual | Best | Fix When Broken | $39,046 | ~~$(74,253)~~ | 75% | -9.6% | 21.2% |
| 8 | ANSI + | Dual | Best | Good Practices | $39,046 | ~~$(74,994)~~ | 75% | -10.7% | 22.2% |
| 9 | ANSI + | Solo | Best | Fix When Broken | $19,523 | $(82,655) | 75% | -22.0% | 21.1% |
| 10 | ANSI + | Solo | Best | Good Practices | $19,523 | $(82,732) | 75% | -22.2% | 22.4% |

**Force To ($67,728) And Find Required Cost Reduction**

**Trade-up**

**Trade-down**

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