Plant Reliability Improvement and Financial Gain: What's the Connection?

By Marcus B. Punch

As hydro plant owners modernize and replace generating equipment, they are considering how decisions about reliability will affect the plant's value in a competitive electricity market. A methodology is available for quantifying reliability and its economic benefits.

Most hydropower plants in the world have been in service for 40 years or more, an age at which reliability typically declines. As a result, preparation for life extension and modernization of assets has become a key business process in many hydroelectric utilities. Because a plant's reliability is a source of competitive advantage, hydropower business planners need to quantify the relationship between reliability improvement and financial gain. A methodology for accomplishing this analysis, described in this article, is easily within the reach of hydroelectric system planners and engineers.

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This article has been evaluated and edited in accordance with reviews conducted by two or more professionals who have relevant expertise. These peer reviewers judge manuscripts for technical accuracy, usefulness, and overall importance within the hydroelectric industry.

Does reliability equal profitability?

Researchers have found that 80 to 90 percent of plant life cycle costs can be attributed to decisions made in the design and planning stages.[1] Getting reliability right at the start of a new project or refurbishment is important, but high reliability does not always mean high profits. Generally, the higher the reliability target placed on a design, the greater the design effort and capital expense required to achieve it. A higher achieved reliability normally results in lower life costs associated with operations and maintenance. The total life cost is the sum of the design and capital costs and the lifetime operation and maintenance costs.

The relationship between a plant's reliability and the revenue it can earn follows a "law of diminishing returns." There is a limit to how much an asset can earn for a business, no matter how reliable it is. Therefore, extreme levels of reliability do not necessarily produce the best financial performance.

Figure 1 illustrates the net returns, or revenue less total costs, for a typical hydro plant. The net revenue curve shows a level of reliability at which financial returns are optimized. Improving reliability beyond this point will incur costs that exceed the revenue increase. Conversely, failing to allocate the necessary resources to maintain reliability also will hurt profitability through increased maintenance and operating costs and decreased revenues. Quantifying this relationship allows engineers and business planners to redefine reliability issues as profitability issues.

Table 1

Application of Weibull Analysis-to-Failure Data Set

Time at Failure (hours)	*Failure Order*	*Median Rank**
1,000	1	7.4
2,000	2	18.1
3,000	3	28.7
4,000	4	39.4
4,700	5	50.0
5,500	6	60.6
6,100	7	71.3
6,700	8	81.8
7,300	9	92.6

*The median rank is calculated as 100 x (rank order - 0.3)/(number of failures + 0.4)

Quantifying reliability: understanding the basics

There are three essential steps in determining whether a particular reliability improvement will lead to financial gain. First, the extent of the reliability improvement must be quantified. Second, the lost value associated with doing nothing about the reliability issue must be quantified. Third, the first two analyses must be combined to determine whether the change will create value.

When dealing with reliability, plant life can be divided into three characteristic periods: a period of early failures with a rapidly decreasing failure rate, a period when the failure rate is fairly constant, and a wear-out period when the failure rate rises rapidly. Because of the rapid increase in failure rate during the wear-out period, one cannot expect an aging plant to continue to provide the same levels of reliability that it has in the past. Quantifying future losses usually involves a statistical analysis of plant utilization, the plant's product mix, and market valuation of the products supplied.

Reliability engineers must project future failure trends and cost impacts when determining the optimal refurbishment or replacement option for the plant. A statistical technique known as Weibull analysis has proven to be a powerful tool for estimating future failure rates of plant equipment based on plant history.

Why Weibull?

Weibull analysis is a technique for discovering trends in data. It involves fitting a failure data set to the following cumulative distribution function:

Figure 1

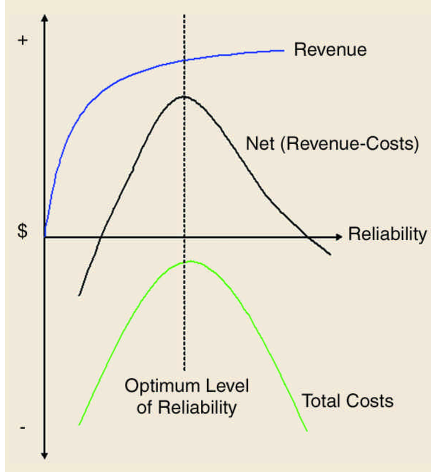

Figure 1: For a typical hydro plant, increased reliability yields improved revenues, but beyond a certain optimum point the costs of increasing reliability outweigh the revenue gains.

Equation 1:

$$F(t) = 1 - e^{-\left[\frac{t}{\eta}\right]^{\beta}}$$

where F(t) is the probability of survival until time t.

The Weibull "characteristic life," η, is a measure of the spread in the data. It indicates the time at which approximately 63 percent of a population of identical items are expected to have failed. The Weibull "shape parameter," β, indicates whether the failure rate is increasing, constant, or decreasing. A β of 1.0 indicates that the failure rate is constant. If β is less than one, the item has a decreasing failure rate, typical of the early life failure period. If β is greater than one an increasing failure rate is present, which is typical of equipment that is wearing out.

The Weibull distribution was first described in 1949, and is now one of the most widely used distributions for failure data analysis.[2] An Internet website, www. weibull.com, contains detailed information on many of the procedures discussed in this article.[3] The main advantage of the Weibull distribution is its versatility. It is equally useful in detecting increasing, constant, and decreasing failure rates. It can approximate exponential, log-normal, and normal distributions, which also have been used to trend failure data. Weibull analysis also provides reasonably accurate reliability forecasts with very small data samples, and has been shown to adequately model mechanical, electrical, and electronic failures. It is a fundamental component of the reliability-centered maintenance process.[4]

Weibull analysis, step by step

The essence of Weibull analysis is to determine the parameters η and β for a given set of failure data. These parameters are obtained by plotting failure data and performing some simple calculations. Before the advent of statistical software packages, failure data were plotted on special Weibull plotting paper from which the parameters could easily be estimated. Today, several software packages are available that plot the data, estimate the Weibull parameters, and display the underlying failure rate trends. One such package, including the programs RCMCost and AvSim+, is available from Isograph Reliability Software of Warrington, United Kingdom. It is also possible to perform

Figure 2

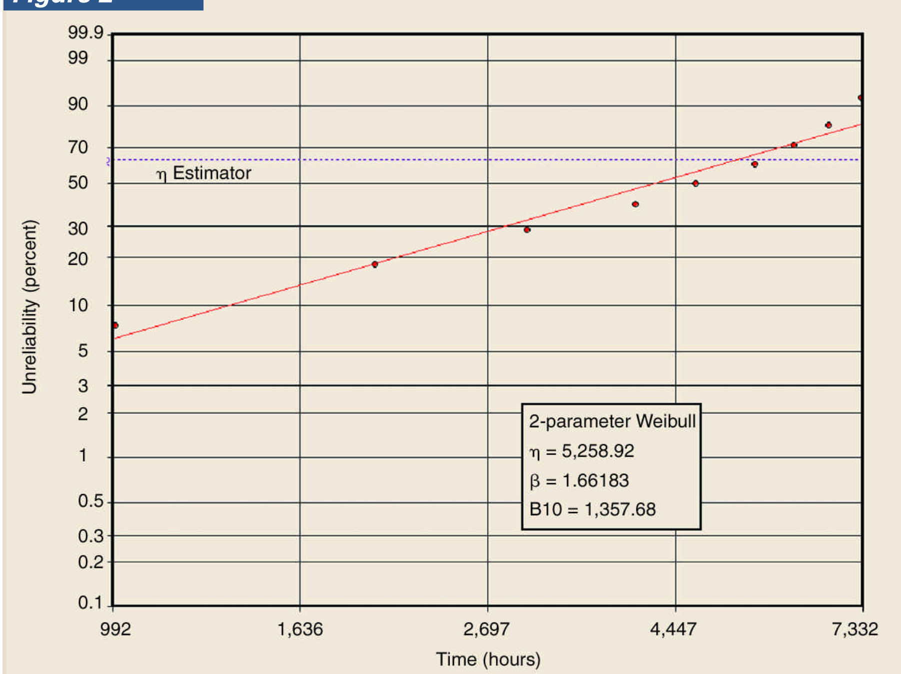

Figure 2: In Weibull analysis, the cumulative frequency of failure through time is computed and plotted on a specially scaled graph. The Weibull parameters η and β can be determined graphically or analytically from this procedure.

Weibull analysis using MS Excel spreadsheets.[5]

As an example of applying the Weibull distribution to failure data, consider a failure data set consisting of a series of times at which failures of a specific type, or "failure mode," occurred in a population of identical equipment. These times to failure are ranked by magnitude and a "median rank" is calculated for each, as shown in Table 1 on page 1. A probability graph is then constructed by plotting the median ranks against the times to failure. Figure 2 on page 2, a plot developed using the AvSim+ software, illustrates the procedure. In a manual analysis, a line of best fit is drawn through the data points plotted on Weibull paper, and the Weibull parameters η and β can be determined graphically.

The Weibull parameters in this example are η=5,259 hours and β=1.66. Therefore, this particular failure mode is exhibiting an increasing failure rate and approximately 63 percent of a population of items exhibiting this failure mode will fail within 5,259 hours of service life. The AvSim+ software also calculates that 10 percent of the items will have failed within 1,358 hours. This is known as the "B10" life, a measure that is often quoted on components such as bearings.

Weibull analysis is a highly versatile technique for evaluating the reliability of hydropower plant components. Figure 3 shows data collected on a particular type of hydraulic system failure experienced in a recently installed set of turbine governors. In this example, η=10,236 hours and β=0.81. This failure mode is exhibiting a decreasing failure rate. The relatively high initial failure rate may be related to the quality of the installation. However, the data predict that those items that have survived the initial period will continue to operate with a low constant failure rate. The problem is not getting worse.

Figure 3

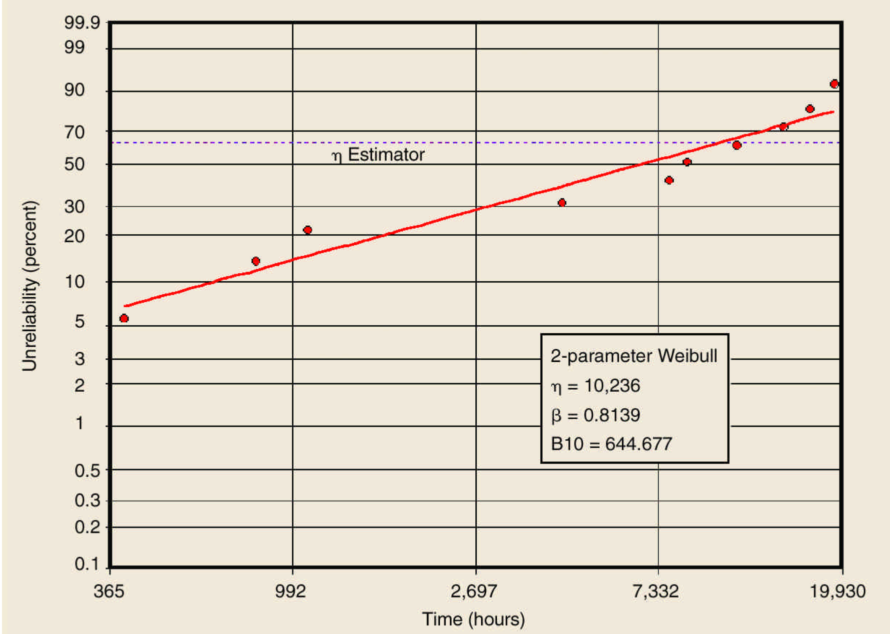

Figure 3: For this data set on failures of a recently installed hydraulic governor system, the β parameter of 0.81 suggests that the initial high rate of failure will not persist into the future.

Reliability and competitive advantage

To understand how reliability affects profit, some investigation of market

Figure 4

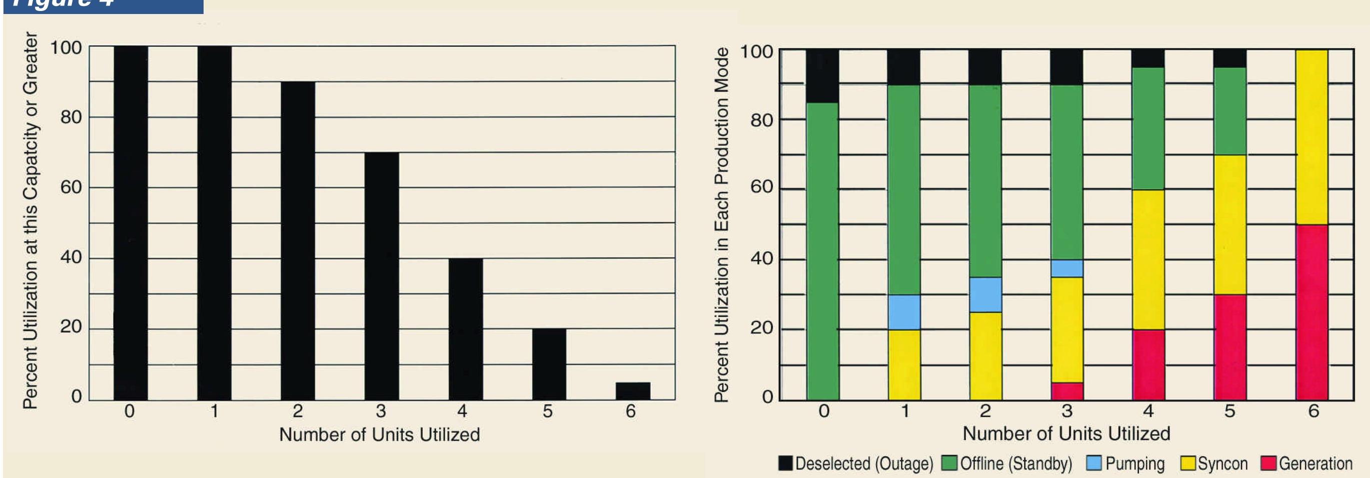

Figure 4: This production profile for a pumped-storage hydro station illustrates how often a given number of units are dispatched (left), and what the product mix is for each dispatch scenario (right).

Table 2

Probability of Being Unable to Deliver Multiple-Unit Capacity over a Ten-Year Period

Number of Units Needed	Percent Probability That Not All Units Will Be Available: Year 1	Year 2	Year 3	Year 5	Year 10
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.03
5	0.00	0.00	0.01	0.04	0.88
6	0.12	0.60	1.19	2.96	14.09

supply-demand interaction is necessary. Revenue earned by electricity suppliers in deregulated markets is largely determined by the timing and placement of production with respect to market demands. A production profile effectively expresses how equipment is used to gain profit. The profile describes how often various dispatching unit capacities are utilized, and the product-mix of different operating modes for each level of capacity utilization.

For example, consider a typical pumped-storage power station, comprising six generating units. The station is capable of providing generation, frequency control, and voltage control products to the market, using pumped storage to take advantage of energy market price differentials and trading its standby capacity with other generators.

Figure 4 shows that almost 40 percent of production scenarios involve utilizing four units or more, and almost 20 percent involve utilizing five units or more. At low capacities, the units are mainly in standby with some voltage control and pumped storage, whereas at high capacities production is dominated by generation and voltage control. Next, the value that the market places on the products from this station during the various capacity utilization scenarios must be determined. Trading records can be correlated with production records to determine the average price paid for the station's products in each of the capacity utilization levels.

By combining capacity utilization, product mix, and market values for all markets and products, a station utilization-to-earnings relationship can be determined. Figure 5 shows that earnings are nonlinear in relation to capacity utilization. Most of the station revenue is earned during high capacity utilizations, even though the proportion of time spent in high capacity utilization is small.

For this station, unavailability of one generating unit when the market demands six units results in a much greater loss of revenue opportunity than it would during a lower-demand period. This is why reliability is such an important source of competitive advantage for hydropower businesses, which often seek to obtain revenues from peak generation, rapid generator unit loading, or underwriting the generation contracts of other producers.

Figure 5

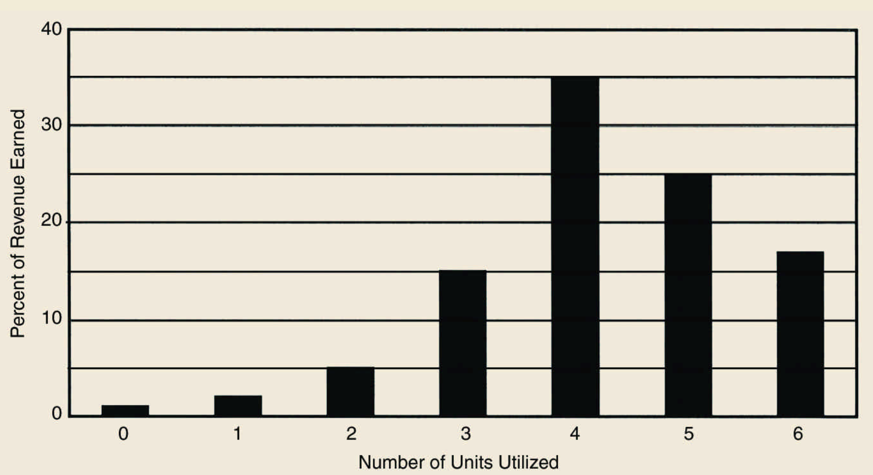

Figure 5: Revenues from a pumped-storage plant's six units are not proportional to the level of utilization. The simultaneous use of five or six units accounts for about 40 percent of plant revenue, although this mode of operation occurs only about 25 percent of the time.

Bringing it all together: a case study

Quantifying the financial benefits of sustaining or improving reliability is essential to gaining management support for reliability initiatives. A case study of an aging generator excitation control system illustrates how quantitative analysis can support a proposal for reliability improvements. The production profile used in this case study is the same as that in the previous example.

Maintenance staff had reported an increasing rate of failure in a set of excitation system circuit boards. As the boards were no longer supported by the manufacturer, on-board repairs were required each time a failure occurred. The reliability engineer obtained failure data for the past 25 years and plotted them according to the Weibull formula. The plotted data formed a "kink" that could not be well represented by a straight line fit. Further investigations showed why: the failure data actually represented multiple underlying failure modes. For a lengthy period of time the failure rate was almost random (β=1.15), apparently due to failures of various components on the circuit boards. Then, the failure rate suddenly increased rapidly (β=5), which maintenance engineers attributed to component aging and degradation of the circuit board materials and solder joints.

The "Bi-Weibull" distribution, a variant on the Weibull distribution, was applied to this data set using AvSim+ software. Then, using the Weibull parameters for the recent wear-out trend, the failure rate curve for the past four years and a prediction for the next ten years was plotted (Figure 6).

If the duration of each failure outage is known, it is possible to predict the unavailability of single generating units using the relationship shown in the following Equation 2:

$$\text{Unavailability} = 1 - \text{MTBF}/(\text{MTBF}+\text{MTTR})$$

where:

- MTBF is the mean time between failures; and
- MTTR is the mean time to repair (in this case, the MTTR was eight hours).

The probability that multiple units will be simultaneously unavailable can be calculated from the single unit unavailability using a standard equation for standby redundant systems.[3] Table 2 shows the predicted probability that the station will be unable to utilize various levels of capacity over the next ten years.

Over time, the rapidly increasing failure rate substantially reduces the ability of the station to utilize six units and also affects its ability to utilize five units. This is significant because utilization of five or six units accounts for more than 40 percent of the station's revenue. Annual revenue losses can be calculated using the percentages from Table 2 and the utilization-revenue chart. In this example, the revenue lost due to excitation system failures would rise from 0.02 percent in the first year to 2.6 percent by year ten.

Figure 6

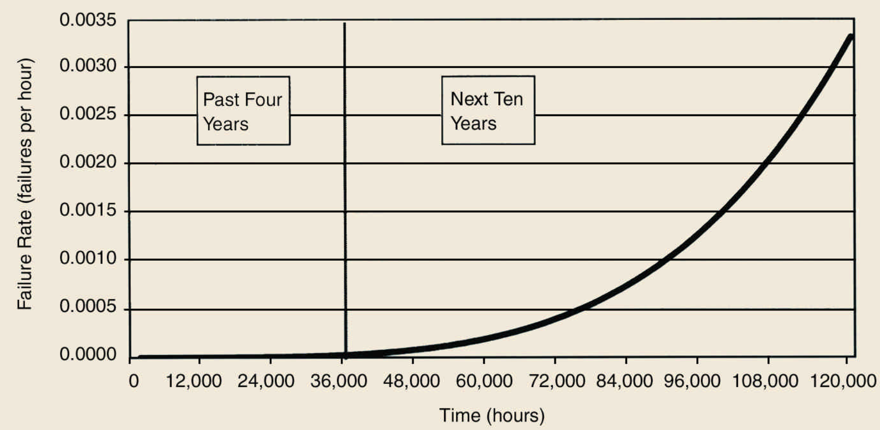

Figure 6: The single-unit failure rate for the next ten years has been projected using Weibull analysis and based on the last four years of record.

Evaluating costs, benefits of reliability improvements

Revenue loss is not the only cost of decreasing reliability. There are also increased maintenance costs due to higher failure rates, and there may be costs related to the increased risk of consequential damage to the plant, safety concerns, and environmental effects. For simplicity, only revenue is considered in this case study.

To understand how reliability underwrites financial gain or wealth creation, we can compute the financial benefit-cost ratio achieved if a refurbishment program were implemented in each of the next ten years. Expenditures may include replacement of plant equipment, improved maintenance plans and compliance, logistics systems, training, and increased component reliabilities.

For simplicity, "cost" is the capital expenditure on the program, and is assumed to be $1 million. "Benefit" is the revenue losses averted and cost savings in the years preceding the reliability improvement, less the opportunity cost of capital for the remainder of the ten years. It is assumed that reliability is returned to Year 1 levels. The results of this analysis suggest that despite recent failure rate trends, the most prudent time for project implementation is not immediately (Figure 7). The optimal intervention would be in two to four years' time. Indeed, capital expenditure can be delayed for six years without a

Figure 7

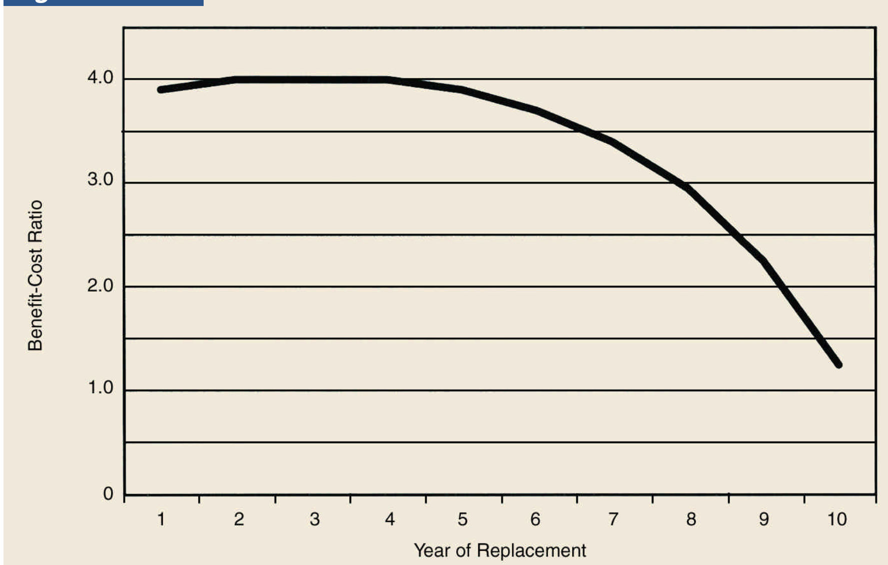

Figure 7: The benefit-cost ratio for generating unit refurbishment has been computed from the projected future reliability of the units and the production profile for the plant. The graph suggests that the benefit-cost ratio would be maximized by delaying refurbishment for two to four years.

substantial threat to the calculated financial benefits.

Conclusion

Engineers and managers need to understand the importance of reliability and its relationship to profitability. Although the qualitative value of reliability is widely recognized, hydropower plant owners typically have not applied the necessary level of resources nor empowered their staff to develop a quantitative understanding of the financial implications of reliability.

Many engineers complain that business decision-making is dominated by short-term, cost-cutting agendas to the detriment of long-term sustainability. This gap between engineers and business planners might be bridged if engineers and technical staff found a new paradigm — that, in the final analysis, despite the technical intricacies of their jobs, they are still managers of risk and creators of value. ▲

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Notes

[1]Gatenby, D., and G. Foo, "Designing for X: Key to Competitive, Profitable Markets," *AT&T Technical Journal*, Volume 69, No. 3, 1990, pages 2-13.

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