RELIEF VALVE TESTING INTERVAL OPTIMIZATION PROGRAM FOR THE COST-EFFECTIVE CONTROL OF MAJOR HAZARDS

Steven T. Maher, Robert K. Rodibaugh, Dr. David R. Sharp, and Georges DeSaedeleer *

Quantitative risk assessment techniques are receiving increased application in companies whose facilities involve (or are perceived to involve) complex and/or hazardous processes. Although the technologies are readily available, often quantitative risk assessments do not follow through with cost-effective applications of the results of such an effort. This paper will explore a straightforward application of quantitative risk assessment which balances potential losses against the costs related to test and maintenance; and provide a basis for optimized valve testing intervals which result in improved safety and/or decreased testing/maintenance costs.

INTRODUCTION

Typically not the subject of an explicit quantitative evaluation, valve testing intervals are often based on a judgemental balancing of potential losses, which generally increase as the test interval is extended, versus the potential savings from less frequent testing. This applies to critical components which are subject to periodic testing such as instrumentation, valves (relief, turbine overspeed, etc.), structural components, and critical components such as pumps and electrical supplies. Test intervals are subject to industry standards, codes, and applicable regulations; however, there is typically some latitude, within those constraints, where a decision can be made regarding the test interval to be used for a particular application.

This paper describes an application of quantitative risk assessment techniques and plant specific and/or industry data pertaining to pressure safety and relief valves. The objective is to quantitatively determine potential loss (factoring in challenging frequencies, relief system availability, and potential consequences) and balance this loss against the potential savings in manpower and other costs associated with a testing/preventive maintenance (PM) program.

Such a program focuses energy on areas which are more critical from a loss prevention or availability improvement viewpoint, resulting in a reduction in maintenance costs or a cost-effective improvement in overall safety. Additional safety improvements can be realized if the current testing frequencies significantly contribute to relief system unavailability or if a maintenance staff has difficulty in accommodating existing inspection requirements.

* Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, USA 15230-0355 and Brussels, Belgium

RISK AND HAZARDS MANAGEMENT IN THE 80'S

In this decade, major industrial accidents have occurred which have been well publicized and have had significant impacts. Government legislation is rapidly evolving and is providing an incentive and impetus to facility owners to implement a risk management plan evaluating the safety aspects of proposed designs or validating the safety of an operating plant. Appropriately implemented, risk and hazards management provides distinct benefits to the facility owner by allowing for both cost-effective and safety-conscious decisions pertaining to design and operations.

These developments have prompted industry to scrutinize their operations for risks to the public, employees, and possible loss of capital investment and production. High capital costs of facilities and lower profit margins mandate high plant utilization factors and the avoidance of the widespread impact of accidents. Computerized, state-of-the-art quantitative risk and hazards management technologies are seeing increased use by industry to ensure financial viability of its operations. The sensible application of these techniques can provide tangible benefits for both society and industry:

- Identify corrective action to reduce the possibility or mitigate the effects of safety hazards and to minimize the possibility of financial loss and unscheduled downtime caused by system failures, accidents, inefficient maintenance procedures, and operability problems

- Create a "living" system model to facilitate rapid evaluations of the impact of proposed plant modifications or operational changes on safety or reliability

- Identify areas where increased operator awareness can increase safety or reduce financial risk, or where relaxed operating procedures would minimally affect risk or reliability

- Provide comprehensive quantitative risk statements to environmental, regulatory, and insurance agencies to provide a basis for decision making

- Improve public relations through plant safety management, community awareness of safety, and the development of concrete evacuation plans which demonstrate management concern

Quantitative risk assessment (QRA), itself, provides tangible benefits; however, too many projects focus on the technology and fall short of fully implementing practical applications of the QRA. Once the basic models are developed for a comprehensive QRA, relatively minor increases in effort (usually in the form of sensitivity studies) can greatly enhance the usability of QRA. There are too few qualified loss prevention and risk management professionals. These valuable resources should be used efficiently by applying QRA techniques in a controlled and focused manner to maximize the utility of QRA efforts. This paper will examine one practical application of QRA.

BACKGROUND AND OBJECTIVES

Testing and preventive maintenance (PM) is necessary to help ensure the availability of critical equipment such as instrumentation, valves (e.g. relief), structural components, etc. Testing/PM is performed periodically. However, critical equipment which is susceptible to failure or mis-calibration may often be too infrequently tested, while other less critical components may be tested too frequently, diverting valuable corporate resources from real safety issues. Currently, the basis for testing/PM intervals is often a judgemental balancing of potential losses versus costs. Sometimes these have a firm basis in experience; however, by quantitatively balancing potential losses against potential savings from test interval relaxation, QRA techniques can be used to optimize these testing/PM intervals (see figure 1). This paper focuses on one application - pressure relief valves.

Pressure relief valves were chosen as the focus of this paper for the large spectrum of applications. There are many situations in the field where valves are exposed to severe service or are protecting highly toxic or explosive process streams and should be tested more frequently. This is contrasted with valves whose testing requirements could be relaxed without compromising plant safety and result in significant savings. Test intervals are subject to industry standards, codes, and applicable regulations; however, within those constraints, there is typically some latitude where a decision can be made regarding the test interval to be used for a particular application.

The objective of this paper is to correlate the relevant technical factors and provide a basis for such a decision. This paper will discuss two approaches for the evaluation of pressure relief valve testing/PM intervals: 1) a detailed QRA and 2) a simplified, practical approach focusing on the dominant factors in the problem. The objective for both approaches is to quantitatively determine potential loss (factoring in challenging frequencies, relief system availability, and potential consequences) and balance this loss against the potential savings in manpower and other associated costs for a testing/PM program. Some readily usable tools will be provided to make this a more workable problem.

TECHNICAL APPROACH

A detailed QRA which includes the testing of relief valves explicitly in the model is a valid approach, but is not always necessary or practical. This section contrasts a detailed with a more straightforward application of quantitative risk assessment techniques.

Detailed Quantitative Risk Assessment (QRA)

Hazards and availability problems which have been identified through any number of ways [e.g. history of known problems in a system, Hazard and Operability Studies (HAZOPS), Failure Modes, Effects, and Criticality Analysis (FMECA)] can be systematically analyzed, evaluated and documented using fault tree analysis (FTA), event tree analysis (ETA), and consequence analysis. Consequence analysis examines the impact of the identified problems on equipment, personnel, the environment, and the public. Representative phenomena investigated may include hazardous material dispersion, shock wave propagation, thermal radiation effects, health effects, environmental impact, financial impact, and unfavorable public image. Results of this analysis can be expressed in terms of facility downtime and related loss of production costs, capital equipment losses, cost of on-site and/or off-site clean-up, and estimates of health effects caused by hazardous material exposure.

The detailed QRA often involves fault trees that are constructed to model process hazards or system unavailability. Fault trees are logical structures which describe the causal relationship between the basic hardware, human, and environmental events resulting in system failure. The logical connections between the events are described by event statements and made by logic gates such as AND and OR. At the top of the fault tree is the undesired event. Lower levels, or branches, identify the successive fault combinations which may cause the undesired event. The failures may include random component failures, common cause failures, human errors, and test and maintenance unavailabilities. Boolean algebra techniques are used to quantify the probability of the occurrence of the top level undesired event, using the contributing probability of lower level events. FTA analyzes a specific undesired event for its contributing causes and probability of occurrence.

In contrast to FTA, event tree analysis uses forward logic in a decision tree-like diagram to define accident sequences that involve the complex interrelationships between systems and their likelihood of occurrence. Simple in form and easily-interpreted, event trees provide a powerful tool for depicting an event which involves multiple system failures, support system failures, and operator action. The tree begins with the initiating event on the left, and branches to the subsequent successes and/or failures of essential mitigation equipment.

These analytical techniques provide meaningful decision-making tools for risk management and loss prevention to assist in making educated decisions to optimize a system with respect to safety and cost. By weighing the probability of a given undesired event versus its safety and financial consequences, one can identify the largest contributors to the problem and recommend effective methods to reduce risk or improve reliability to acceptable levels. These recommendations may include changes to the plant/system design or operating procedures.

Models are typically constructed using interactive computer methods for fault and event tree development and solution to systematize and expedite the risk management and loss prevention effort substantially. These "living" computer models of the physical system can be readily changed to reflect the sensitivity of risk or reliability to design or operations changes. Fault tree models can be developed to a level of detail in which relief valve test intervals are specific parameters of the valves' failure probability or unavailability. This provides a workable vehicle for performing sensitivity studies of the effects of varying pressure relief valve test interval on the overall system hazard rate or unavailability.

Abbreviated Approach

Although a detailed QRA can provide a basis for defining test intervals; the cost of the analysis, if performed only for this purpose, may exceed the cost of any financial benefits which might be realized.

Since this is not a perfect world and significant uncertainties often exist in the likelihood of incidents which challenge the relief valve and in the resultant consequences should the relief valve fail, a more straightforward approach can usually be justified. The phenomena associated with the failure of a relief valve are fairly well characterized. If the analyst focuses his or her efforts on the dominant variables, a large number of valves can be meaningfully evaluated without investing huge resources. With a good understanding of its limitations, this abbreviated approach can adequately characterize the problem to determine outlier valves which are significantly

overtested or undertested. In some instances, prior to relaxing testing requirements, it may be prudent to perform more detailed analyses.

For this application, the primary potential loss calculations involve the challenging frequency of the relief valves (failures which require relief valves to actuate to relieve overpressure), the reliability of the overpressure relief system, and the potential consequences should the relief system be challenged and then fail. These losses are summed for all the failures associated with a particular relief system or system type (see "SYMBOL USED" section to define variables):

$$L = \sum (F_C * Q * C) \qquad (1)$$

For failures of relief valves which can directly result in undesirable consequences (e.g., leakage):

$$L = \sum (F * C) \qquad (2)$$

These potential losses can then be weighed against the cost of testing to provide a basis for a balancing of the testing/PM interval.

Pressure relief system unavailability can be evaluated using data pertaining to design, service conditions, testing, maintenance, environment, and size to develop application specific failure rates. The following failures can be considered in the evaluation of pressure relief valve unavailability; however, in most cases only a few of the failure modes listed will dominate loss:

- o failure to open on demand
- o failure to reseat
- o failures during standby which disable valve opening
- o wearout failures
- o failures resulting in valve leakage or premature opening
- o operator errors during PM
- o system unavailability due to test or PM
- o operator error resulting in block valve misalignment (modern systems usually do not have block valves in series with the relief valve)

Many facilities have a multitude of valves to consider and may find a program which includes even these abbreviated techniques fairly formidable. For these situations, the analyst may choose to categorize the pressure relief valves and evaluate a limiting case from within each category. Parametric sensitivity analyses can explore areas of interest within a particular subsystem or look at various extremes of service or environment.

APPLICATION AND ANALYTICAL CONSIDERATIONS

The previous section identified that primary interests might include:

- o situations where a valve is in fairly benign service and there is a reasonable potential for savings without significantly compromising the margin of safety

- o situations where the likelihood of potential challenges or resultant consequences are large and it is entirely possible that valves may not be tested frequently enough

The evaluation of pressure relief valve testing/PM intervals involves a balancing of the costs of potential losses with the costs associated with testing and preventive maintenance. This is determined by calculating the mathematical minimum of the sum of the two costs. If necessary, weighting factors can be included to emphasize management concerns about plant losses and public perception. For consistency, costs/impacts should be expressed in the same units and over the same time period.

This section will discuss the bases for individual contributors to loss and testing/PM costs.

Calculation of Testing and Preventive Maintenance Costs

The cost includes both the direct costs related to the manpower invested and any associated downtime, and also indirect costs which may be associated with health hazards to workers and equipment wearout or premature failure. The total cost of testing/PM is proportional to the testing frequency and should include the costs associated with all components in the relief system including any periodic verification of block valve positioning.

$$\text{Total Testing Cost/Unit Time} = \sum (C_r / T) \qquad (3)$$

Calculation of Potential Losses

See equations 1 and 2 on previous page.

Potential Consequences

Three primary undesirable failures and resultant consequences are associated with pressure relief valves - failures of the relief valve to open and potential overpressure situations, spurious openings of relief valves and potential releases of toxic materials, and leakage resulting in inoperable equipment or system downtime. To characterize the problem using the abbreviated approach, it is often sufficient to estimate the impacts of these consequences using simplified analyses to obtain an accuracy consistent with this level of analysis. These system specific impacts should be normalized to the same units and consider:

- impact on employees
- impact on public
- impact on environment
- public perception
- plant or system downtime
- loss of capital equipment
- cleanup requirements

Challenging Frequencies

To characterize the problem, an estimate of the challenging frequency of the pressure relief system is needed. This frequency could be estimated using operating records, industry data sources, existing analyses of similar systems, or expert opinion of facility personnel. Hazards identification techniques such as Hazops could be used to identify dominant failures or sequences of failures which can be quantified on a very simplistic basis. If the system has had some challenges, "close calls", or a failure history of certain critical components is available, it may be possible to use this information in the calculation of system specific challenging frequencies.

Pressure Relief System Failure

Pressure relief system failure frequencies can be calculated using information pertaining to design, materials handled, service, testing, maintenance, environment, and size to develop application-specific failure rates. Design characteristics such as multiple relief valves should be directly factored into the calculation of system failure rate.

Many of the parameters which affect relief system failure have a dependence on testing interval. For some failure modes, relief system failure frequencies are improved with increased testing. For failures such as operator error, wearout, and inoperability during the testing or PM period, relief system failure rate may be compromised.

Some of the more important contributors to relief system failure are described below and summarized in table 1:

Inadvertent Valve Leakage

These failures can directly contribute to losses or to a challenge of available mitigation systems; therefore, the challenging frequency of the relief system does not factor into these failure modes.

Random Mechanical Failures - these are typically available in literature as hourly failure rates which can be converted to an annual failure rate, if desired.

Wearout Failures - Although more complex equipment wearout models can be used, a reasonable approximation can be used assuming that failures are random and are normally distributed about a mean valve lifetime (note that other distributions may be applicable):

$$f(t) = (2 * \pi)^{-\frac{1}{2}} * e^{-\frac{1}{2}t^2} \qquad (4)$$

This can be characterized by estimating a mean time between wearout failures for a certain valve group and the time for the failure of one-tenth of the valve population.

Valves Failing to Reseat or Spurious Opening

Random Mechanical Failure Resulting in Premature Opening - typically available as hourly failure rates - normalize to annual.

Failure to Reseat - Demand failure rates are available in literature. These demand failure rates are combined with the challenging frequency of the relief system, the failure of available mitigation systems, and the postulated consequences to determine potential loss.

Operator Error During Preventive Maintenance - either an industry or plant specific estimate for operator error is combined with the annual frequency of PM. Although this failure mode is typically not dominant, this is one case where the potential loss may increase with the testing frequency.

Failure to Function on Overpressure

Failure to Open on Demand - these are active failures typically available in literature as demand failure probabilities. In the abbreviated model, this may be assumed constant and not a function of the test interval.

Failures During Standby which Disable the Relief Valve or the Integral Block Valve - The failure probability is directly proportional to the product of the failure rate and the mean time interval between tests. In the abbreviated model, the failure rate is assumed to be constant. In reality, the failure rate may deviate slightly or even decrease for longer surveillance intervals, but this would not be expected to significantly impact the results.

Unavailability due to Test or Maintenance - For some design configurations, an increase in testing/PM frequency can increase the unavailability of the relief system (proportional to test duration and frequency), especially if a valve is removed for testing without replacement.

Operator Error During Preventive Maintenance - Increased testing frequency provides more opportunities for operator error during valve removal, installation, or calibration. This contribution is proportional to the frequency of testing/PM. The failure of the maintenance personnel to restore block valves to their correct position following test and maintenance is considered in the abbreviated model. Human error failure rates can be obtained from references 4 and 12. A typical human error probability for failure to restore a valve with failure of recovery is included in Table 1.

Wearout Failures - High testing frequencies can lead to premature wearout under extreme circumstances. However, for the purposes of an analytical characterization of this sort, failure of the valve to open on overpressure due to this wearout failure mode may be neglected since it is likely to be implicit in the standby and demand failure probabilities which are part of the data base. Cumulative wearout failures such as corrosion, plugging, or polymer buildup can be directly incorporated into this abbreviated model. See table 1.

Operator Error Resulting in Block Valve Misalignment - Increased testing frequency provides more opportunities for the operator to also fail to realign the block valves properly upon restoration of the system to service. This contribution to unavailability is also proportional to the frequency of testing/PM. Block valves on the pressure relief device often have their position verified on a periodic basis. Although typically not a dominant contributor, this may also be factored into the analysis.

Failure Rate Data

Table 1 lists some example failure rate data compiled from public literature for relatively clean service. Several of the more useful sources are identified in the reference section. If plant specific data is available, this can be used explicitly or in combination with industry data using statistical techniques such as Bayesian updating (ref. 1). However, industry data may be all that is available for certain applications. Use of this data must be made with the understanding of the basis for this information and the limitations of its use.

There will always be limitations and inaccuracies in the use of available failure data. A greater number of relevant reported failures reduces, but does not eliminate uncertainty. With the continuous development of new and improved equipment, the information compiled from the field or from testing may not exactly match information required for equipment being considered for a new system design. Corrections made to new equipment designs to correct previous weaknesses may improve component reliability but may also allow new

TABLE 1 - SUMMARY OF FAILURE MODES AND UNAVAILABILITIES FOR PRESSURE RELIEF VALVES

FAILURE MODES	ANALYTICAL CHARACTERIZATION		REPRESENTATIVE MEDIAN FAILURE RATES OR DEMAND FAILURE PROBABILITIES
Loss due to Inadvertent Valve Leakage - $L = \sum (F * C)$:			
Random Mechanical Failures	$F = \lambda$	(5)	5×10^{-5}/hr
Wearout Failures	Distribution of failure: $f(t) = (2 * \pi)^{-\frac{1}{2}} * e^{-\frac{1}{2}t^2}$	(4)	-----
Loss due to Valves Failing to Reseat or Spurious Opening - $L = \sum (F * C)$:			
Random Mechanical Failures	$F = \lambda$	(5)	5×10^{-6}/hr
Failure to Reseat on Demand	$F = F_c * P$	(6)	$P = 2 \times 10^{-5}$/ demand
Operator Error During Preventive Maintenance	$F = F_c * H_e/T$	(7)	$H_e = 0.01$/ activity
Loss due to Failure to Function on Overpressure - $L = \sum (F_c * Q * C)$:			
Failure to Open on Demand	---		$Q = 2 \times 10^{-4}$ / demand
Failures during Standby which *Disable Relief Valve or the* Integral Block Valve	$Q = \frac{1}{2} \lambda T$	(8)	5×10^{-6}/hr
Unavailability due to Test or Maintenance	$Q = (DT + P_m*DM)/T$	(9)	-----
Operator Error on Preventive Maintenance	$Q = H_e/T$	(10)	$H_e = 0.01$ / activity
Wearout Failures	Distribution of failure: $f(t) = (2 * \pi)^{-\frac{1}{2}} * e^{-\frac{1}{2}t^2}$	(4)	-----
Operator Error Resulting in Block Valve Misalignment	$Q = H_e/T$	(10)	$H_e = 0.001$ / activity

NOTE - H_e/T is the probability of human error normalized to an annual value

types of equipment failures to occur. The analyst or the designer will never have as much information as desired and must always choose from existing information while considering influencing factors such as service, testing, maintenance, environment, size, and manufacturer.

The judicious use of available failure rate data is a challenge for a loss prevention analyst. Clouding the issue, setpoint drift or specifications out of tolerance are often counted as failures even though they may not be direct contributors to disabling the safety function of equipment. These factors can result in the industry data not being directly applicable and may necessitate an evaluation of the types of failure included in the data and a massaging of information prior to use. The loss prevention practitioner may also have to make compensations for failure mechanisms specific to the process stream (e.g., plugging due to process material solidification).

ILLUSTRATIVE EXAMPLE - RELIEF VALVE TESTING INTERVAL BALANCING

This paper discussed methods for determining optimal relief valve testing/PM intervals which involve minimizing the sum of the costs of testing and potential losses associated with a specific testing interval. Some illustrative examples are provided to clarify this application which are based on the following:

- A simple pressure relief system containing two relief valves in parallel, each with two manual block valves in series
- The failure modes of the valves modeled are the following:
  - Failure of the Valve to Relieve Pressure (Standby and Demand)
  - Failure to Reseat or a Spurious Opening (Standby and Demand)
  - Mechanical Failure of the Block Valve
  - Human Error
    - Restoration of Valves to Operable Status
    - Inadvertent Misalignment
  - Wearout
  - Leakage
    - Random Mechanical Failure
    - Degenerative Failure Modes Fit to a Normal Distribution
  - System Unavailability due to Test or Maintenance

Three cases were evaluated, and the results are summarized in Figures 2 and 3:

1) System 1 is representative of a typical process stream. The optimum test interval calculated is 15 months based on a direct balance and 14 months based on a weighting of the potential losses. The results of this particular example are generally consistent with a typical testing/PM interval and might serve only to validate the testing/PM program currently in place.

   The curves provided for this case (figure 2) illustrate the various failure mechanisms associated with this example. The leakage loss curve shows the impact of human errors (causing a failure of the relief valve to reseat) which increase with decreasing testing interval, the relatively constant random leakage failure mechanisms, and the time dependent, degraded failure mechanisms (e.g., corrosion) which become important as the testing interval increases. Overpressure losses illustrate human errors predominant at smaller testing intervals and the time dependent, standby failures which become important as intervals are lengthened.

2) System 2, shown in figure 3, is representative of a process stream dealing with more toxic/explosive materials with related higher consequences. For this case, a better balance is reached at shorter testing/PM intervals illustrating the importance of testing/PM of critical equipment. The risk of financial loss is such that the sum of the annual testing/PM and potential loss costs is decreased with increased testing.

3) System 3 reflects a system with an inaccessible relief device on a process stream which is fairly benign. Lower challenging frequencies and consequences might provide a justification for a relaxation of the current testing/PM interval. For this example, a relaxation to 48 months from an existing testing interval of 12 months could provide an average annual savings of $3500 per valve.

CONCLUSION

The objective of this paper was to identify risk-based methods that can provide a rational basis for the selection of testing/PM intervals for critical components such as:

- pressure relief valves
- instrumentation
- large rotating machinery
- critical structural components

The application of quantitative risk assessment (QRA) concepts to balance potential losses against testing/PM costs can provide a sound basis for test and preventive maintenance intervals. One approach is to model the failure of critical components within a larger QRA. However, by sensibly considering dominant analytical contributors, the abbreviated method discussed in this paper can be applied on an as-needed, case-by-case basis.

The streamlined approach is a fairly straightforward but effective application of QRA techniques which provides tangible benefits and insights and, in many cases, as good a basis for decision making as the more complex modeling techniques. However, the streamlined approach is structured to be efficiently expanded as necessary to be compatible with or become part of a more comprehensive risk management program. Situations will probably occur where there is uncertainty about the optimal testing/PM interval determined by the abbreviated method. For these situations, a reasonable limiting case could be evaluated to provide a basis for decision making; or more complex models using more of the tools associated with QRA could be applied.

Future efforts which might be performed to reflect design or operations changes can also directly build on even these streamlined analyses. This quantitative assessment of potential losses and potential savings in testing costs provides a basis for the analysis of future operations, maintenance, and design changes associated with pressure relief valves or other critical component subsystems.

Applying even the abbreviated tools discussed above typically provides

- o a resultant optimal testing/PM interval
- o the testing costs and potential losses for a variety of intervals
- o the bases for the determination of relief system unavailabilities
- o identification of plant hazards
- o the basis for determining the consequences of plant hazards

- o an understanding of the level of confidence of the results and the identification of critical areas which might warrant further investigation
- o valuable insights into safety and risk
- o an appreciation for the availability of plant failure rates

One significant result of the various problems to which these techniques have been applied is that the optimal testing/PM interval of pressure relief valves agrees well with the range commonly used in industry and accepted as consistent with prudent engineering and maintenance. This reinforces the applicability of the technique and also of current operations practices.

Although the general testing/PM interval range used by industry seems appropriate, there is a significant amount of flexibility within this range and an opportunity for significant improvements from either a cost or safety perspective. This can apply not only to pressure relief valves, but also to instrumentation and other critical equipment which impacts the safety and economics of a plant. The challenge of providing a scientific basis for testing/PM interval optimization involves many variables; however, the streamlined techniques can provide a useful analysis performed in a cost-effective manner. In general, both quantitative risk assessment and these abbreviated techniques should be performed by someone knowledgable in the phenomena and limitations of the analysis.

Within this paper a specific application of quantitative risk assessment focused on testing/PM interval optimization was developed from basic concepts to generate several specific examples representative of a spectrum of process systems. Due to the limitations of a single publications, future efforts will have to include the following:

- o prioritization of analytical efforts
- o an abbreviated survey of intervals currently used in industry for testing/PM of critical components
- o quantification of the effectiveness of testing/PM
- o additional case studies which further illustrate the application of this technique and resultant reduced costs or improved safety
- o equating costs to safety and use of industry safety acceptance criteria such as the Fatal Accident Rate (FAR)

SYMBOLS USED

C_r = total cost per inspection, test, or preventive maintenance activity
T = test/maintenance interval
L = potential loss
F = failure frequency
Q = relief system unavailability
F_c = the frequency that the relief valve is challenged
C = cost of the potential consequences
λ = failure rate per unit time
DT/DM = duration of test/maintenance
P_m = probability of maintenance being performed after a test
H_e = likelihood of human error
P = probability of failure
f(t) = fraction of failures at time t

REFERENCES

1) Henley, Ernest J., Hiromitsu Kumamoto, Reliability Engineering and Risk Assessment, Prentice Hall, Inc., 1981.

2) OREDA - Offshore Reliability Data, OREDA Participants, PennWell Publishing Co. 1984.

3) NUREG/CR-2815, "National Reliability Evaluation Program (NREP) Procedures Guide", 1982.

4) "Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications" (NUREG/CR-1278), prepared for the Nuclear Regulatory Commission by Swain, A.D. and Guttman, H.E., Aug. 1983.

5) "Military Standardization Handbook, Reliability Prediction of Electronic Equipment, 217B&D" (MIL-HDBKs-217B&D), United States Department of Defense, 1974 (B) and 1982 (D).

6) NCSR Reliability Data Bank, National Centre of Systems Reliability, United Kingdom Atomic Energy Authority.

7) Loss Prevention in the Process Industries, Vol. 1 & 2, Frank P. Lees, Butterworth & Co. Ltd., 1980.

8) "Common Cause Fault Rates for Pumps" (NUREG/CR-2098) Nuclear Regulatory Commission, Feb. 1983. Also for Diesel Generators" (NUREG/CR-2099) and for Valves" (NUREG/CR-2770).

9) "Reliability Technology", A.E. Green & A.J. Bourne, 1972.

10) "Nonelectric Reliability Notebook", Rome Air Development Center, Griffiss Air Force Base, NY, RADC-TR-75-22, January 1985.

11) IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear - Power Generating Stations, (IEEE Std. 500 - 1984), Institute of Electrical and Electronics Engineers, Inc. John Wiley & Sons, Inc., 1983.

12) Kletz, T.A., "An Engineer's View on Human Error," Institution of Chemical Engineers, 1985.

13) Maher, S.T. and F.D. Stevenson, "Risk Management of a Fuel Gas Conditioning Facility Using Fault Tree Analysis," Canadian Journal of Chemical Engineering, volume 64, pgs 848-853, October 1986.

14) Maher, S.T. and D.R. Sharp, "Reliability and Hazards Assessment of a Central Cooling Water Supply System," October 1986.

15) Maher, S.T. and D.R. Sharp, "Risk Management of a Petroleum Refining Facility Using Fault Tree Analysis," March 1987.

16) Rodibaugh, R.K., G.F. Wandell, and J.A. Martin, "Extending the Testing Interval of Turbine Valves Through Probabilistic Analysis of Turbine Missile Ejection, July 1987.

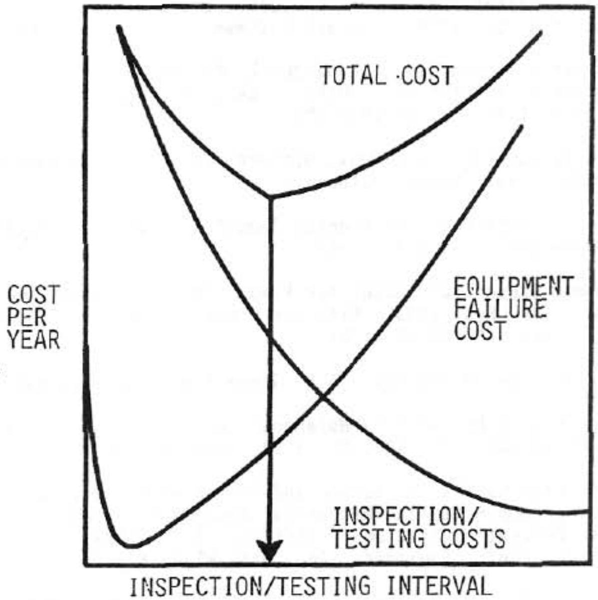

FIGURE 1 - OPTIMIZED INSPECTION/TESTING INTERVALS

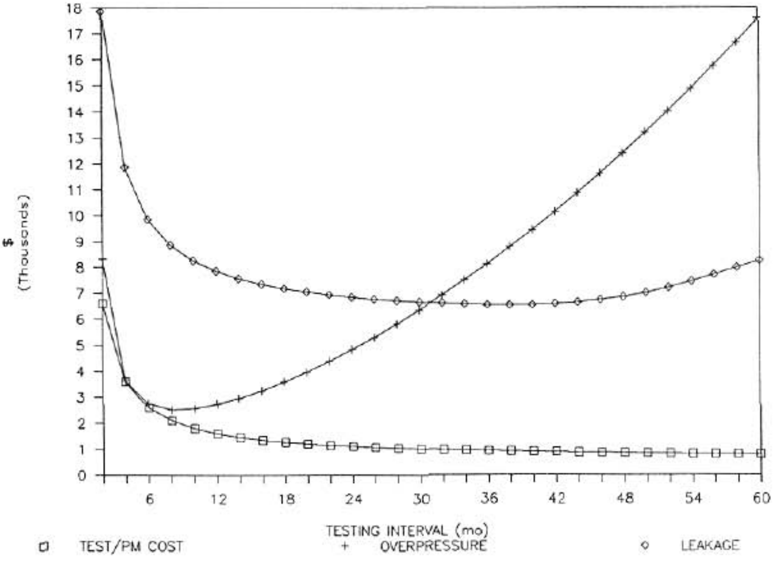

FIGURE 2 - ILLUSTRATION OF ANALYSIS OF SYSTEM 1

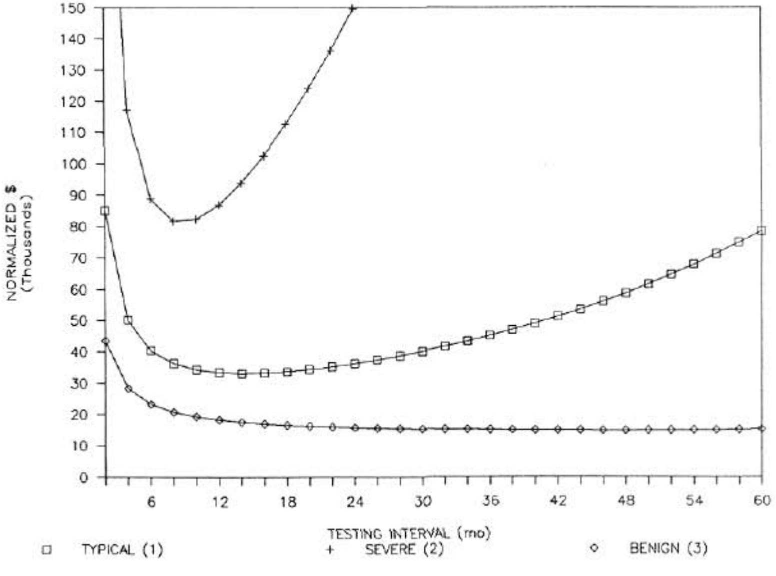

FIGURE 3 - WEIGHTED SUM OF LOSSES AND TESTING COSTS