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HTGR PLANT AVAILABILITY AND RELIABILITY EVALUATIONS

VOLUME II: APPENDICES

by

G. J. Cadwallader, G. W. Hannaman, F. K. Jacobsen,
and R. J. Stokely

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APPENDIX A METHODOLOGY

A.1. INTRODUCTION

The objective of the methodology described in this appendix is to economically locate and correct areas that may contribute to unavailability of components and systems, including those that are new and uniquely designed. The detection and correction of problem areas can almost always be achieved to a very high confidence level for any system or component if there are effectively no limits on the resources (calendar time, facilities and money) that can be allocated to the task. When this is the case, the objective can usually be met by applying the reliability analysis techniques (Refs. 1-3) described in subsequent sections for locating and correcting the potential problem areas.

Usually, however, there are serious constraints on the resources available. Nevertheless, these constraints can frequently be relaxed and additional resources made available if sufficient justification can be presented to the decision makers (i.e., the persons in control of the resources). The general case therefore requires that a decision be made concerning the commitment of additional resources to discover or correct potential problem areas.

When considering options, it is usually the case that some or all of the consequences associated with a particular option will involve uncertainty. Therefore, the decision must often be made under uncertainty. Hence, the general problem with which this report deals is a problem for reliability analysis and decision under uncertainty analysis (Refs. 4,5), and that general methodology can be used to analyze every such problem that arises.

The general methodology requires listing each option to be considered. Then, for each option, the possible outcomes (i.e., events) worth considering must be determined along with the associated likelihoods and values (i.e., usually, losses). If the decision maker is not indifferent to chance situations having expected values of zero over the range of values of consequences associated with the options, then the values of consequences across all options must be normalized to the same base to permit a decision between options. In any case, the values must all be in the same units, for example, present value in terms of 1976 dollars.

The general methodology therefore requires these items to be determined: (1) options to be considered and the associated costs, (2) for each option, the possible outcomes worth considering, (3) the likelihoods of each possible outcome, (4) the value (e.g., loss) associated with each possible outcome, and (5) the decision maker's preference or aversion to risk over the range of values of the consequences associated with the options.

The first option considered is usually the existing or usual life cycle event (LCE) plans and controls for the system or component, and other options consist of the use of different sets of plans and controls. To determine the "possible outcomes worth considering" [Item (2) above] it is necessary to determine the sources of loss. This requires consideration of every LCE for every component that can cause a significant loss (i.e., unavailability). Formal tools most useful for this portion of the evaluation include failure modes and effects analyses (FMEAs) and fault tree analyses (FTAs). FMEAs are useful primarily for locating losses caused by single failures. The analysis commences with the failure mode and determines the effects. Table A-1 is an example FMEA table taken from IEEE Std-352 (Ref. 3). Determination of the failure modes of a component is accomplished by considering failure modes of each and every individual function the component performs. Hence, the analyst must know or determine all functions the component provides in order to perform a thorough FMEA.

The FTAs are particularly useful for discovering and displaying combinations of events (including failures and errors) that lead to the same

TABLE A-1
FMEA TABLE FORMAT FROM IEEE STD 352^(a)

Page ____ of ____

Functional Level	Diagram	Program Typical Plant
System Typical Reactor Trip Function		Report No IEEE Std 352-1975, Appendix A
Subsystem Sensor Circuit 1	See Fig A1	Prepared By _____
Equipment _____		Date _____ Rev _____

No.	Name	Failure Mode	Cause	Symptoms and Local Effects Including Dependent Failures	Method of Detection	Inherent Compensating Provision	Effect Upon RPS	Remarks and Other Effects
1	Pressure transmitter PT-1	Fail low	Corrosion wear, mechanical damage, heat effects	Low output to alarm unit, ac relays will remain energized for channel 1	Periodic test	Redundant channels, 2 and 3	Both trip paths 2/2 logic	Possible immediate detection
		Fail high	Misadjustment	High signal level to alarm unit, ac relays will deenergize for channel 1, with no trip	Periodic test	Redundant channels, 2 and 3	Both trip paths 1/2 logic	Partial trip alarm
2	DC power	Fail low or OFF	Transformer failure, diode failure	Removes operating power for transducer, alarm unit will sense low pressure, ac relay will open will open with no trip on channel 1	Periodic test, spurious trip alarm	Redundant channels, 2 and 3	Both trip paths 1/2 logic	Spurious trip if other channel failed 1/2
		Fail high	Heat effects, misadjustment	Transducer setpoint exceeds trip level, relays will remain energized for channel 1	Periodic test	Redundant channels, 2 and 3	Both trip paths 2/2 logic	
3	Alarm unit PC1	Fail OFF	Transformer failure open circuit in output section, setpoint drift	AC power to ac relays removed for channel 1, ac relay open when no trip on channel 1	Periodic test, spurious trip alarm light	Redundant channels, 2 and 3	Both trip paths 1/2 logic	Spurious trip if other channel failed 1/2
		Fail ON	Short in output, section, setpoint drift	Does not remove ac power to ac relay for channel 1 trip, ac relay remains energized. Both paths become 2/2 logic	Periodic test	Redundant channels, 2 and 3	Both trip paths 2/2 logic	
4	AC control relay, X1A	Fail closed	Contacts shorted or fused armature jammed wiring	Does not break circuit to dc relays on trip, dc relay remains energized for channel 1, trip path A becomes 2/2 instead of 2/3 logic	Periodic test	Redundant channels, 2 and 3	Degraded trip, trip path A, 2/2 logic	
		Fail open	Loss of ac power (instrument bus), coil failure broken wire or loose connection	DC relay opens when no trip on channel 1	Spurious trip on test	Redundant channels, 2 and 3	Both trip paths 1/2 trip logic	Spurious trip if other channel fails 1/2

(a) Reproduced with permission of IEEE Standards Committee

top event (i.e., effect). These analyses start with the effect (i.e., top event) and determine the failure modes of components and any other causes (e.g., operator error) that contribute to it. The top event in the fault tree is usually a major undesired event, for example, loss of availability of the entire system. Top effects of concern are sometimes determined from FMEAs, but usually they are simply the principal major event(s) it is desired to avoid. FTAs are also directly useful for quantitative analyses whereas FMEAs are most useful in qualitative evaluations involving single failures.

Examinations of the above descriptions reveals the similarities and differences of the two methods of determining potential problem areas. Both document failure modes and effects, but they derive and display them differently. The FTAs show only subevents which lead to the top event (this includes combinations of failures and human errors), and FTAs are directly useful in quantitative evaluations. In practice, the analyst usually cross checks the results of FMEA and fault tree analyses with each other so that an integrated determination of possible outcomes worth considering finally results.

The likelihood of each possible undesired outcome can be computed from the fault tree for that outcome (i.e., top effect in the fault tree). This requires the determination of likelihoods for all subevents in the tree. These are determined from existing data, or from the most expert judgment available when data do not exist.

The determination of the value associated with each possible consequence is, or can be reduced to, a deterministic problem of value estimation. In any case, the values must all be converted to the same base before combining or comparing values.

Finally, the decision maker's preference or aversion to risk must be determined over the range of values associated with the possible consequences of the various options. This is determined from the decision

maker, and depends on his financial position and general attitude (usually aversion) toward risk.*

A.2. LOSS AND ITS SOURCES

For decision analysis, values are usually expressed in terms of currency. When significant interest rates and inflation are involved, these values are usually expressed in terms of currency at some specific point in time (e.g., 1976 dollars on January 1, 1980). A loss is a value that is negative. The decision maker's role is to commit resources (i.e., accept known losses) to increase net value by increasing known or expected values, or by reducing known or expected losses.

The potential sources of loss are ubiquitous. Fortunately, the actual causes of loss due to a specific piece of equipment are usually few in number and can almost always be attributed to insufficient controls in one of several general areas (e.g., design, quality control, or operation and maintenance). Expected losses can be controlled by controlling the causes of failure or by controlling the consequences of failure. To control the causes of failure, each life cycle event of every component capable of being involved in a significant loss must be considered. Each aspect is discussed separately below.

A.3. COVERING ALL COMPONENTS

Every component capable of causing a significant loss must be considered if the expected losses are to be acceptably controlled. Lack of thoroughness in this matter (e.g., by analyzing only the principal components) will usually result in an ineffective control of losses. Program histories are replete with seemingly small oversights that lead to severe consequences. For example, failure to adequately consider all fasteners

*Analyses in this report assume the decision maker is indifferent to chance situations having expected values of zero, that is, that he has no preference or aversion toward risk.

has resulted in fasteners coming loose and destroying rotating equipment. Also, failure to adequately consider the possibility of high-purity oxygen producing spontaneous combustion of finely divided material with which it comes into contact resulted in a serious loss in the manned space program.

While every component must be considered, it is often not necessary to consider every part of the component. However, great caution and skill must be exercised in deleting parts from consideration. Consider, for example, a pressurized housing that has lockwired bolts securing the pressurized fluid. However, the environment of the lockwires is periodically a turbulent liquid which over a long period of time will cause failure of the lockwires, leading to release of the bolts and a severe loss. As another example, consider a vertically mounted circuit board, the malfunction of which would have no serious direct effect. However, if a particular component on the board shorts to ground, it melts solder, which then falls to a board below, possibly causing shorts which will result in a major loss. The two examples illustrate risks involved with failing to adequately consider every component, including parts. The large quantity of components that must generally be considered should make it obvious that the task requires analysts who are technically highly competent and capable of working meticulously and efficiently so that unnecessary analyses are minimized, and needed analyses are recognized and performed economically and on schedule.

A.4. COVERING ALL LIFE CYCLE EVENTS

Table A-2 is a typical list of life cycle events (LCEs) that will suffice for most components. The preceding section described the risk associated with failure to adequately consider every component. However, it is also necessary to adequately consider every LCE that could possibly result in a serious loss. These can be as subtle, and therefore as easily overlooked, as some parts. Consider, for example, the LCE procurement. A purchase order improperly typed could order a wrong part, material, etc.,

TABLE A-2
EXAMPLE GENERAL LIST OF LIFE CYCLE EVENTS

1. Design
2. Procurement
3. Materials
4. Fabrication, handling, and storage
5. Inspections
6. Shipping
7. Storage
8. Installation and checkout
9. Preoperation
10. Startup
11. Operation
12. Forced outages
13. Scheduled outages
14. Maintenance
15. Accidents

resulting in a serious loss in at least two ways. First, incoming inspection could catch the deficiency and reject the item, and a loss could result if reordering caused a lengthy schedule delay. Second, inspection could miss the deficiency (e.g., by inspecting to the purchase order), and if not otherwise detected (e.g., by the fact it would not fit), a serious loss could result through subsequent malfunction or failure.

For these reasons, every LCE should be considered with sufficient care to assure it is not a potential source of a significant expected loss. This task, because of its broad nature, requires the analysts be specially selected or thoroughly trained to be completely aware of the potential sources of loss for each LCE.

A.5. DETERMINING FAILURE MODES AND CONSEQUENCES

Having picked a particular component and one of its life cycle events (e.g., "bearing" and "installation"), attention is turned to modes (ways) by which things can go wrong and result in a loss. For example, during installation a bearing may be installed backward, resulting in a damaged housing and a four-day schedule slippage. The cause of the loss may have occurred in an earlier life cycle event, but the loss itself should occur during the life cycle event under consideration. The loss consists of direct costs (e.g., cost of failure analysis and corrective action) and indirect costs (e.g., schedule delays). This part of the analysis is principally qualitative with emphasis on possibilities and general consequences.

Two tools that are useful for these qualitative analyses are failure modes and effects analysis (FMEA) tables (Table A-1), and fault tree analyses (FTAs). The FMEAs concentrate on failures associated with individual components, and are therefore particularly useful for discovering single failure points in a system (i.e., single components, the failure of which will result in system failure or any other highly undesirable event or loss).

FMEAs and FTAs are presently almost exclusively applied to the LCEs associated with component operation; however, with simple modifications the formats can be applied to any LCE with which the physical component is associated, such as fabrication or transportation. For example, a "failure mode" during these nonoperational LCEs might be "out-of-spec" or "damaged"; a "failure mechanism" might be "under cut" or "over torqued"; and an "effect" might be "order new material and remachine with 14 days schedule delay."

LCEs associated only with paper (e.g., some designs and procurements) appear best handled by the use of general or special checklists rather than FMEA tables or fault trees, although fault trees could be useful in developing the checklists. Table A-3 is an example general design review checklist (Ref. 6). Although the table is primarily designed to control losses of operating components and systems, failure to assure compliance with many of these questions (e.g., Question A.4.g: "Extremes of ambient temperature?") could result in schedule delay losses not associated with a hardware failure (e.g., due to customer refusal to approve the design). General checklists should be employed to develop special checklists for each unique situation.

The FTAs commence with an undesired top event and derive all possible subevents that lead to the top event. Hence, they include all items in the FMEA table having that undesired event as a consequence and, in addition, they include all combinatorial events that result in the same top event. The latter are generally not formally discovered by FMEAs. Figure A-1 lists the general symbols employed in fault-tree analysis; these are the same as those employed in WASH-1400 (Ref. 7). Figure A-2 is an example fault tree presented to illustrate the use of this tool for determining potential subevents that can lead to the top undesired event.

This phase of the evaluation is generally considered qualitative, because it determines possibilities and does not (formally, at least) consider probabilities or other numerical values. Technically, therefore, it is not possible to perform formal (numerical) decision analysis with this

TABLE A-3
EXAMPLE DESIGN REVIEW CHECKLIST

Questions	Functional Input	Yes	No	N/A
A Does the design meet optimum mix of customer requirements?				
1 Safety provisions				
Intended use and foreseeable misuse?				
b Free of sharp edges burrs corners etc?				
c Interlocks/safety devices?				
d Corporate/division/agency safety standards?				
e Complete instructions?				
f Warning hazard and severity signs?				
2 Operation and maintenance provisions				
a Clear concise instructions?				
b Simple operations?				
c Understandable and operable controls?				
d Differing physical characteristics of operators?				
e Ease of maintenance?				
f Lack of maintenance warning?				
g Spare parts availability?				
h Misuse non standard use?				
3 Cost provisions (to the customer)				
a Basic cost?				
b Total life cycle cost?				
c Spare parts cost?				
4 Customers' environment effect on product provisions				
a Extremes of service voltages?				
b Extremes of service water hardness?				
c Extremes of service pressure?				
d Extremes of service temperature?				
e Extremes of external vibration?				
f Extremes of external shock?				

Questions	Functional Input	Yes	No	N/A
g Extremes of ambient temperature?				
h Extremes of humidity?				
i Foreign material (sand, grit, oil lint, dirt etc)?				
j Corrosive ambients (salt air, sea water, acids, etc)?				
k Extremes of external magnetic fields?				
l Extremes of sound ambients?				
m Weather extremes?				
n Radio interference?				
o Nuclear radiation?				
p Supplementary products (detergents bleaches oils grease, etc)?				
5 Product effect on customer/societal environment provisions				
a Appearance?				
b Noise?				
c Odor?				
d Temperature?				
e Vibration?				
f Light?				
g Radiation?				
h Exhaust?				
i Space?				
j Packaging disposal/recycle?				
k Final product disposal/recycle?				
6 Reliability/Performance provisions				
a Advertised performance throughout load range and life?				
b Advertised life?				
B Does the design meet total cost specification?				
1 Value engineering analysis made?				
2 Competitive cost comparison made?				
3 Service warranty costs quantified and minimized?				
4 Manufacturing and producibility costs optimized?				
a Utilizing existing processes, equipment, and facilities?				
b Tool/price costs?				
c Maximum standardization?				
d Utilize more efficient new processes, equipment and facilities?				
e Minimal inspection and testing required?				
C Does the design meet reliability requirements?				
1 Maximum stresses within limits through full range of travel, load, voltage, etc?				
2 Derating utilized?				
3 Simplicity optimized?				

TABLE A-3 (Continued)

Questions	Functional Input	Yes	No	N/A	Questions	Functional Input	Yes	No	N/A
4 Failure modes of critical elements analyzed?					b. Vibration?				
5. Optimum use of standard proven parts?					c. Temperature extremes?				
6. Correct current factory and/or field/customer problems and complaints?					d. Humidity extremes?				
7. Similar design data considered?					e. Handling equipment?				
8 Design integrity tests successfully completed (life, safety simulated stress environments, etc.)?					f. Sand and dust?				
D. Does the design minimize manufacturing problems by:					5. Permitting shape and size of packaged product which would optimize rail car and truck loading (108" & 90" wide resp.).				
1 Utilizing existing equipment in fabrication, finishing, assembly, calibration, testing, packaging, etc.?					6. Providing clear handling instructions on outside of packaging?				
2 Utilizing more efficient new processes, equipment and facilities?					7 Considering disposal of used packaging material?				
3 Avoiding hazardous operations?					F. Does the design minimize service calls and service problems?				
4 Optimizing tool/piece costs?					1 Has serviceman safety been considered?				
5. Utilizing existing acceptable tooling and parts where possible?					2. Are installation instructions clear?				
6 Permitting maximum standardization?					3 Can product be satisfactorily installed in minimum time?				
7 Specifying tolerances consistent with acceptable processes and equipment?					4 Have previous and current service problems been corrected?				
8. Correcting or avoiding previous or current manufacturing problems?					5. Are items requiring frequent maintenance easily accessible?				
9 Minimizing operations requiring special skills or special attention?					6. Are new or non-standard items minimized?				
10 Clearly identifying critical parameters to be controlled during the procurement and manufacturing cycle?					7. Are servicing instructions clear? Are they adequate? Do they come from Fault Tree Analysis or Failure Mode and Effects Analysis? Do they verify performance after repair?				
11. Specifying materials conforming to Corporate standards?					G. Does the design comply with applicable laws and agency requirements?				
12. Specifying materials which minimize raw material inventory?					1. Does the product comply with applicable laws and agency requirements?				
13 Being clearly and completely described on drawings?					a. Local ordinances?				
E. Does the design minimize packaging, shipping, handling and warehousing problems by:					b. State laws?				
1 Utilizing standard packaging?					c. Federal laws?				
2 Minimizing offsets, projections, etc. which require additional packing material?					2. Does the product comply with applicable agency standards or guidelines?				
3. Withstanding applicable transportation tests?					a Underwriters' Lab?				
4 Considering shipping and warehousing environment?					b. American Gas Association?				
a Shock?					c. N.Y. Board of Standard & Appeals?				
					d. Chicago Plumbing Lab?				
					e. ANSI?				
					f. AHAM?				
					g. NEMA?				
					h. AEC?				
					H. Does the design take into consideration pertinent litigation involving personal injury, property damage, or environmental damage associated with the product or similar products?				

TABLE A-3 (Continued)

Questions	Functional Input	Yes	No	N/A
I. Patentability?				
1 Has an infringement search been conducted to avoid liability infringement of patents owned by others?				
2 Has a state-of-the art search been conducted to benefit from and be aware of development by others?				
3 Has prompt disclosure of inventions been made to assist in obtaining patent protection?				
J. Have human factors been considered in the design?				
1 Are controls well organized?				
2 Are controls located for efficient operation?				
3 Can monitoring devices be easily and accurately read?				
4 Are instructions clear, legible and complete?				
5 Can all operations be performed safely without danger to the user or the product?				
6 Have physiological and psychological characteristics (age, education, size, strength or handicap) of the user been considered?				
7 Can maintenance be performed easily?				
8 Have the human factors of competitive products been analyzed?				
K. Is the appearance of the product appropriate?				
1 Does the product relate to the environment in which it will be used?				

Questions	Functional Input	Yes	No	N/A
2 Must the design relate to other Westinghouse products?				
3 Does the color and finish relate to its environment and use?				
4 Does the appearance represent the technical quality and cost of the product?				
5 If the product is part of a product line, does the appearance relate to the rest of the line?				
6. Are components and hardware consistent with product quality?				
7. Has the appearance of competitive products been analyzed?				
8 Does the scale (size) of the product relate to the scale of its immediate surroundings?				
L. Have graphics for the product and for supportive materials been considered?				
1 Are rating and/or instruction plates clear, concise and complete?				
2 Are rating and/or instruction plates located for easy readability?				
3 Has the size, type and location of Corporate identification been specified?				
4. Are instruction books and repair manuals easy to read and understand?				
5. Does the graphic design of labels, packaging, shipping cartons, buying data, brochures and promotional literature meet Corporate standards?				

EVENT REPRESENTATIONS

The rectangle identifies an event that results from the combination of fault events through the input logic gate.

The circle describes a basic fault event that requires no further development. Frequency and mode of failure of items so identified are derived from empirical data.

The triangles are used as transfer symbols. A line from the apex of the triangle indicates a transfer in and a line from the side denotes a transfer out.

The diamond describes a fault event that is considered basic in a given fault tree. The possible causes of the event are not developed whether because the event is of insufficient consequence or the necessary information is unavailable.

The circle within a diamond indicates a subtree exists, but that subtree was evaluated separately and the quantitative results inserted as though a component.

The house is used as a switch to include or eliminate parts of the fault tree as those parts may or may not apply to certain situations.

LOGIC OPERATIONS

AND gate describes the logical operation whereby the coexistence of all input events is required to produce the output event.

OR gate defines the situation whereby the output event will exist if one or more of the input events exists.

INHIBIT gates describe a causal relationship between one fault and another. The input event directly produces the output event if the indicated condition is satisfied. The conditional input defines a state of the system that permits the fault sequence to occur, and may be either normal to the system or result from failures.

Fig. A-1. Standard fault tree logic and event symbolism
(from WASH-1400)

(a)

(b)

Fig. A-2. (a) Example of a system providing torque, and (b) fault tree for loss of torque

information alone. Many good decisions, however, can and have been made without formal decision analysis. For example, adding a redundant fastener in a critical location, and adding a final quality inspection and functional test prior to installation of a component that becomes very difficult to repair after installation, are the type of decisions regularly made by judgment rather than formal decision analysis. When the judgment is based on considerable experience and thought, and there is not a great assurance cost involved, judgment alone to increase or decrease controls may suffice if the potential loss is low, and judgment alone to increase controls may suffice if the potential loss is high. Otherwise, formal decision analysis is generally advisable. Such decisions can be based on inequalities rather than on actual values. This often simplifies the problem tremendously. For example, suppose the existing situation poses a potential loss of at least \$150,000 with a probability of at least 0.05, but an option that costs not more than \$1000 to implement will reduce this likelihood to less than 10^{-6} . Since the existing expected loss is $\geq \$7500$ (i.e., $\geq 0.05 \times \$150,000$) and the expected loss associated with the option is $\leq \$1000^+$ (i.e., $\leq \$1000 + 10^{-6} \times \$150,000$) the decision to select the option can be made without knowledge of the actual values. This simplified formal method is recommended for consideration in every situation where it may be applicable, because it can save a great deal of analysis time.

A.6. DETERMINATION OF LIKELIHOODS AND LOSS DISTRIBUTIONS

Likelihoods and loss distributions are probabilities associated with events. Estimates can be based on direct empirical evidence, and/or judgment. The latter should be based on some combination of related experience, established theory, and logical argument. Usually, direct empirical evidence is unavailable or insufficient. For example, determination of the failure rate of a common silicon diode from Mil-Hdbk-217 utilizing every appropriate application factor is not direct empirical evidence on a particular manufacturer and lot. Hence, strictly speaking, even when such data are employed it is usually due to judgment that the actual events of concern will have likelihoods of occurrence analogous to those for which data are available.

When direct empirical evidence ϵ accrues on an event E_1 following a prior-established probability of the event $P(E_1)$, then Bayes' theorem can be employed to incorporate the new information into the prior, yielding an updated estimate of the likelihood of the event $P(E_1|\epsilon)$. The formulation is

$$P(E_1|\epsilon) = \left[\frac{P(\epsilon|E_1)P(E_1)}{\sum_j P(\epsilon|E_j)P(E_j)} \right]$$

where E_j is a set of mutually exclusive and exhaustive events including E_1 . This process can be repeated as new evidence accrues. The relation is readily extended to cover a continuous random variable x by letting $j \rightarrow \infty$, $E_j \rightarrow x$, and $P(E_j) \rightarrow P_{DF}(x)$:

$$P_{DF}(x|\epsilon) = \frac{P(\epsilon|x)P_{DF}(x)}{\int_x P(\epsilon|x)P_{DF}(x)dx} \quad .$$

Judgment concerning likelihoods of events can be quantized in a number of ways. For continuous variables this is frequently most conveniently performed by having the most knowledgeable persons available concerning the subject estimate the likelihood F_1 that the variable $x \leq x_1$ for $i = 1, 2, \dots, n$, and drawing a smooth curve through the points, thus estimating the cumulative function $F(x)$ for the variable. The probability density function of x is the first derivative of $F(x)$.

If n independent estimates of the probability of a variable are generated, then the results can be combined into a single relation:

$$P_{DF}(x) = \frac{P_{DF}(x|\epsilon_1)P_{DF}(x|\epsilon_2)\dots P_{DF}(x|\epsilon_n)}{\int_x P_{DF}(x|\epsilon_1)P_{DF}(x|\epsilon_2)\dots P_{DF}(x|\epsilon_n)dx} \quad .$$

Caution must be exercised that the basis of the estimates is different evidence, not just different sources employing some or all of the same evidence. Discrete random variables can be handled in similar fashion with minor modification to the formulations.

A.7. INTEGRATING THE ANALYSES

The problem of concern is to reduce expected losses on an economic basis by reducing likelihood of loss, loss itself, or both. The swiftest and simplest analyses and options are often the most economic and should therefore be given first consideration. The use of inequalities, the determination of expected losses without evaluating the contributions by cause, and the discovery of options that reduce the expected losses regardless of cause should be attempted prior to commencing a detailed analysis and solution by evaluation of controls.

If the simpler attempts fail, it may become necessary to evaluate existing controls. This is because all losses are caused, and all causes are the result of imperfections in controls. An imperfect control can generally cause losses in LCEs other than the one during which it is applied. Losses attributable to a control must therefore include expected loss contributions due to that control summed over all components and LCEs affected. Thus, when analysis of controls becomes necessary, the analysis must integrate all the loss contributions attributable to a particular control, thereby focusing appropriate attention on the root causes of the expected losses and increasing the chances of finding a direct solution to problem areas by simply improving the effectiveness of the control.

All controls affecting a particular component sometimes affect no other components. In these cases, the expected losses can be integrated under the component itself. However, it may not prove particularly helpful to do so once the contributions by controls are known, and it is not often that such independent components exist. Therefore, when analysis of controls becomes necessary, it is recommended that expected losses be integrated under controls for all affected components and LCEs, and that the expected losses also be summed under components where such information may be found helpful.

A.8. DETERMINATION OF ECONOMIC OPTIONS

This task requires determination of options and demonstration that they reduce expected losses. The two most obvious general avenues of discovering such options are, first, ways to reduce the loss itself and, second, ways to reduce the likelihood through modification of the controls making the greatest contributions. These are areas where great benefits can be derived from the ingenuity of the analysts. For example, consider a principal component the possible failure of which has been determined to present a large expected loss. An option to modify the design of an interfacing component may avoid the need to implement a costly process control during fabrication of the principal component to reduce the expected loss. Neither is there a unique "best solution," because the cost of an evaluation must be considered. Hence, although Option A may be cheaper to implement than Option B, nevertheless, if Option B is analyzed first its implementation may be able to reduce the expected loss sufficiently that evaluation of Option A is not economic.

The recommended procedure to obtain economic options is therefore to first assign analysts with demonstrated ingenuity and enthusiasm to the task, and to provide them with a few simple guidelines which they should consider as a minimum. For example, avenues and approaches in Table A-4 should be considered.

TABLE A-4
PROCEDURE TO OBTAIN ECONOMIC OPTIONS

Approach	Avenues
1. Reduce loss itself	1.1 Design: (1) Principal component (2) Other components 1.2 Maintainability
2. Reduce likelihoods	2.1 Design: (1) Principal component (2) Other components 2.2 Controls: (1) Existing: (a) Principal component (b) Other components (2) Additional: (a) Principal component (b) Other components

Options, of course, must be evaluated using the same (decision under uncertainty) principles as for the existing design, and should include all costs associated with implementation. Subsequently, the analysts should be encouraged to use and challenged to demonstrate their ingenuity at determining economic options, and their performance should be monitored.

A.9. PRIORITIES

To set evaluation priorities, the procedure is first to determine need dates by schedule, and to estimate evaluation times and consequential required latest acceptable start dates. If any start date is significantly passed, then a preliminary estimate of the associated expected loss distribution and analysis (or other) options should be furnished the decision maker as quickly as practicable. A preliminary evaluation should be made to determine the equipment for which a full evaluation is expected to be economically justified. The manpower loading required for these evaluations should be determined and adjusted (by advancing start dates) to agree with available manpower loading as much as possible. The decision maker should be advised of discrepancies. If manpower requirements cannot be met, then schedule uncertainties and alternatives should be evaluated, such as completion after the need date, performing less thorough analyses for some equipment, or completely deleting evaluations having the minimum expected values per manhour of evaluation time. It should be noted that due to the usual inclination of decision makers to have strong aversion to chance situations involving large losses for which they would be responsible (e.g., chance situations with expected values of zero, but involving large potential losses), it is unlikely that available resources will not be allocated to evaluate and improve controls in such situations once the decision maker is properly informed.

A.10. EVALUATION INITIATION AND TERMINATION CRITERIA

Initiation and termination of an evaluation require directives by the decision maker. Both decisions must usually be made under uncertainty. The initiation decision often appears most difficult because of lack of information concerning the likelihood of potential losses. If the associated losses are large, however, the very lack of information itself means the decision maker faces significant expected losses, and therefore it is probably advisable to at least authorize an evaluation to reduce these uncertainties. This can be accomplished for any system or component by

sample evaluations selected primarily from the areas that appear to pose the largest expected losses. These evaluations should also estimate the expected loss reductions which the decision maker can use to decide if further analyses are expected to be justified.

The initial controls on some systems and components are completely adequate, and application of the methodology to such situations should result in no additional controls. However, the application of the methodology should be considered worthwhile at the end of such an evaluation if, including the cost of the evaluation, the associated expected loss has been reduced, albeit only by adding information.

Continued evaluations of any system or component would eventually become uneconomic regardless of how poor the initial controls were. Therefore, regardless of whether the evaluations were initiated on a small initial sample basis or as an extensive effort, a criterion is needed to flag the decision maker to consider terminating evaluations in each area. Although no single criterion would probably be considered best by all decision makers for the wide variety of possible applications of the methodology, an economic criterion appears appropriate for situations where considerations of consequences, evaluations, and additional controls are principally economic.

Assuming the decision maker is indifferent to chance situations with zero expected loss, the termination flag criterion could be based on the expected loss reductions of completed evaluations, including the costs of the evaluations. This information could be presented and displayed graphically by a number of control chart techniques (Ref. 8) to provide the decision maker a simple indication of the value of the analyses as well as to flag him to consider termination of analyses in particular areas. The actual decision on whether to terminate evaluations should employ all available information to determine whether evaluation of any subset of remaining potential problem areas can be expected to result in a reduction in the expected losses. Prior costs should not be included in this determination except through their indirect influence on the estimates of likelihoods.

A.11. CONCLUSIONS

Proper application of the above-described methodology to a system or component having significant expected losses which can be economically reduced should result in an effort of systematic detection and correction of potential problem areas that is reliable, timely, and effective in reducing expected losses. The reliability and timeliness of the effort will be limited primarily by the natures and abilities of the personnel assigned to the task, and by the time available. The cost effectiveness depends inversely on how thoroughly the existing LCE controls have been implemented, and directly on the efficiency of the effort. The efficiency of the effort can be expected to rise rapidly as team experience accumulates and the processing of information becomes routine or automated. Application of the methodology described herein should prove particularly effective for new and uniquely designed components and systems because considerable uncertainty often exists in these situations due to absence of or limited experience. However, application of the methodology should prove to be effective in reducing expected losses for almost any project that faces large individual or cumulative potential losses and that has gathered insufficient evidence to assure the expected losses are acceptably small.

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APPENDIX B

DETAILED DISCUSSION OF FAILURE MODES AND EFFECTS ANALYSES (FMEAs)

B.1. ORIENTATION

The following sections contain detailed discussions of the FMEAs performed for each major component analyzed in this evaluation. The components are listed in Section 3.1 of Volume I. Volume I also summarizes the detailed discussions given here and includes the FMEA tables (Table 3-2), which are therefore not repeated here.

Each discussion includes a description of the component, its function, and the environment (if it is significant). Each also discusses the FMEA more fully, describes the controls and qualitatively estimates their expected adequacy, and suggests actions that appear worth consideration for Fort St. Vrain (FSV) or future plants.

The following comments concern the general controls applied for each of the components included in this investigation.

The Fort St. Vrain helium circulators were designed and manufactured in accordance with General Atomic engineering standards, drawings, and specifications and were inspected and tested in compliance with quality assurance plans and procedures prepared expressly for these units. Applicable portions of these documents were written to assure that this equipment would meet the intent of Section III of the ASME Boiler and Pressure Vessel Code. ASME survey teams conducted audits of General Atomic for compliance with Code requirements during the period in which the circulators were manufactured (i.e., in 1968 and 1971). As a result of these surveys, General Atomic was given Certificates of Authorization to manufacture equipment in accordance with the ASME Code.

The discussion of these general controls will therefore not be repeated in the FMEA discussions for each component which follow.

B.2. HELIUM COMPRESSOR INLET FMEA

B.2.1. Function of the Helium Compressor Inlet

The function of the compressor inlet is to direct the flow of primary coolant into the compressor blades. Primary coolant discharges from the steam generator modules into the circulator inlet plenum at the bottom of the PCRV cavity. From the upper part of the plenum, the primary coolant is drawn through a large, coarse, cylindrical screen and downward (see Fig. B.2-1). At the bottom, the flow is turned inward and upward with a reduction in flow area, causing an increase of the flow velocity into the compressor blades.

B.2.2. Physical Description

The complete compressor inlet is comprised of three separate assemblies. The first assembly into which the primary coolant flows from the inlet plenum is the circulator inlet fairing, the second is the helium inlet assembly, and the third is the helium ducting. Detailed descriptions of each are presented later in this section (Sections B.2.5 through B.2.7).

B.2.3. Environment

The basis for the environment of the assemblies which comprise the compressor inlet is the primary coolant. It effectively sets the temperature of the parts and would be the vehicle for spreading of contaminants. The temperature of the helium entering the inlet is about 755°F at 100% power and 570°F at 25% power. Aerodynamic loads on the inlet fairing and the inlet assembly are relatively small. Aerodynamic loads on the helium ducting are relatively large because it must withstand the torque that results when the stator straightens the helical flow of the primary coolant

Fig. B.2-1. Primary coolant compressor-related hardware

from the compressor rotor. The inlet assembly serves as the physical support for the flapper valve and for the diffuser assembly, thereby incurring some weight loads.

B.2.4. Discussion of the FMEA

Impacts

The possible impacts resulting from failure of one of these three hardware items vary widely. Impacts include (1) simple removal and replacement of the helium ducting (with the circulator), and (2) removal of the inlet fairing by cutting it apart in place, removing and replacing parts through the center PCRV penetration, and reassembling it in place. Although this event would have an impact level of II (or possibly I), its likelihood appears to be extremely low. More detail is provided in the discussion of each component in Sections B.2.5 through B.2.7.

Failure Mode

Failure seems least likely to occur in the inlet fairing because it supports no external loads and only small aerodynamic loads. Additional discussion is presented in subsequent sections for each component.

B.2.5. Inlet Fairing (PN 90-R1105-211) FMEA

B.2.5.1. Function of the Inlet Fairing. Each of two inlet fairings, in each of the two primary coolant loops, collects half the primary coolant (helium) flowing out of the loop's six steam generators. The outflow from each steam generator directly enters the compressor inlet plenum. Each circulator draws primary coolant from this inlet plenum through its own inlet fairing. The flow velocities in the plenum are relatively low so that dense debris in the primary coolant settles to the floor. Primary coolant is drawn into the fairing primarily through the upper side wall, which is perforated to form a coarse screen. There is also space at the

top of the fairing for primary coolant to enter. The flow is then directed downward and inward to the inlet assembly.

B.2.5.2. Physical Description. The inlet fairing is installed in the compressor inlet plenum (see Fig. B.2-1). The plenum is a cylinder having the diameter of the PCRV cavity, about 31 ft, and about 51 in. high. The plenum is divided into halves, one for each loop, by a steel wall and is separated from the upper PCRV chambers by the lower floor. The fairing is shaped like a round-bottomed cylindrical tub with the center of the bottom removed. It is about 60 in. in diameter and about 43 in. high overall. It is made of 9/32-in.-thick steel plate. The upper 22 in. of the cylindrical portion is perforated with 3/8-in.-diameter holes staggered on 9/16-in. centers, and the top of the cylinder is open. The cylinder reaches up to within about 8-1/2 in. of the top of the plenum. The fairing is fastened to the plenum floor by four 1-in.-diameter studs, which are welded to both the fairing and the plenum floor.

B.2.5.3. Environments. The fairing has primary coolant on all sides at normal temperatures ranging from 742°F at 100% power to 570°F at 25% power. No other parts are mounted on the fairing. Heat transfer through the support studs is expected to be very small.

B.2.5.4. Discussion of the FMEA

Impacts

If the inlet fairing should fail, it would have to be cut into pieces to be removed. This is because it is installed beneath the lower floor in the circulator inlet plenum, and it is too large to be raised through the opening for the diffuser in the lower floor (see Fig. B.2-1). There is no opening from the circulator inlet plenum directly into the central penetration. The method of repair would be determined on the basis of the particular damage sustained.

Failure Modes

The most likely failure mode for the inlet fairing is judged to be breaking loose of one or more of its mounting studs. It would take unexpectedly high aerodynamic forces or vibration to make this failure mode likely. Hence, if a failure occurs it is expected to be due to a nondesign cause and therefore to be an isolated single failure.

B.2.5.5. Product Assurance Controls

Design Controls

The helium flow through each circulator of 871,000 lb per hr at 742°F and 686 psia is equal to a volume flow of 68,250 cfm. The total of the flow area for the perforations in the fairing (about 20 sq ft) and the area above the fairing (about 4 sq ft) is about 24 sq ft. The flow velocity through these paths is about 47 ft per sec. This low velocity together with the low density of the helium (about 0.21 lb per cu ft) keeps the pressure differential across the fairing very low (estimated velocity head about 0.05 psi). The fairing's 9/32-in.-thick wall and 1/2-in. by 1-in. stiffening rings have proved adequately strong during all testing.

Quality Assurance Controls

Provisions are described in Section B.1.

Operational Controls

The inlet fairing has no moving parts. It is inaccessible for and does not require maintenance. Only highly abnormal plateout on it of unexpected contaminants from the primary coolant appear able to degrade its performance. Provision has been made for removing contaminants from the primary coolant. Therefore, present operational controls are judged adequate.

B.2.6. Helium Inlet Assembly (PN 90-C2101-270) FMEA

B.2.6.1. Function of the Helium Inlet Assembly. The inlet assembly provides a continuation of the flow path initiated in the inlet fairing (see Fig. B.2-1). It takes the downward incoming flow and turns it past the horizontal and upward. The inlet assembly also transmits the weight of the flapper valve and the diffuser assembly down to the circulator penetration.

B.2.6.2. Physical Description. The overall shape of the inlet assembly is a large cylinder having an inside diameter as small as 29 in., an outside diameter as large as 42-1/2 in., and a height of about 32 in. It consists of a lower ring and an upper ring separated by 12 aerodynamically shaped columns (see Fig. B.2-2). The lower ring is comprised of a flange, which mates with the PCRV circulator penetration, and an aerodynamic fairing, separated by an insulating blanket. The upper ring is comprised of an upper flange (on which the diffuser is supported) and an aerodynamic fairing, and the disc catcher is held between these two components. Each of the aerodynamically shaped columns is comprised of a 1-1/16-in.-diameter stud (which is the load bearing member) and an airfoil-shaped column which is clamped between the upper and lower aerodynamic fairings by a separate bolt. The inlet assembly also includes pressure pickups from which the helium flow through the inlet can be determined.

B.2.6.3. Environment. The environment for the inlet assembly is provided principally by the primary coolant passing through it. The primary coolant is normally pure helium at temperatures of 742°F and 570°F for operation at 100% and 25% power, respectively. Because the bottom flange of the inlet mates with the circulator penetration, it will be cooled below the helium temperature. The primary coolant pressure varies from 686 to 589 psia at 100% and 25% power, respectively. There are no significant loads on the inlet assembly resulting from static or dynamic pressure. The assembly does support a vertical load from the weight of the diffuser assembly.

Fig. B.2-2. Inlet/diffuser assembly

B.2.6.4. Discussion of the FMEA.

Impacts

If an inlet assembly should fail, corrective action requires that the circulator machine assembly and flapper valve be removed first. Then the inlet and diffuser assembly must be removed for repair through the PCRV center penetration because they are too large to pass through the circulator penetration. After repair, they must be replaced via the same path.

Failure Modes

It is difficult to envision a failure mode for the inlet assembly that is both credible and significant. Perhaps the most likely mode is a significant leak in a pressure-sensing tube. Next most likely is perhaps failure of one of the tension fasteners such as the bolts clamping the three fairing members together. The effect of such a failure appears to be insignificant because the broken bolt pieces could not escape, and the fairings are also held in place by dowel pins and the support column. All the basic stresses in the structural parts are compressive and low.

B.2.6.5. Product Assurance Controls.

Design Controls

Testing has demonstrated that the aerodynamic analysis was adequate. Consistent results have been obtained from calibration of the flow-measuring pressure ports. The total weight of the inlet and diffuser is estimated to be 8573 lb. This weight is divided between the 12 support column studs, each of which is greater than 1 in. diameter. The resulting compression stress is less than 1000 psi. Hence, the inlet assembly design appears to have been adequately controlled by analysis as verified by test data.

Quality Assurance Controls

See Section B.1.

Operational Controls

This unit is inaccessible to maintenance other than operational action except during removal of a circulator or related components, during which on-site quality controls are required. Hence, the controls over operation and maintenance appear adequate.

B.2.6.6. Conclusions and Recommendations. The design of the helium inlet assembly appears to satisfactorily minimize potential failures. Quality assurance comparable to 10CFR50, Appendix B, was in effect for the design and should provide adequate assurance over manufacturing, materials, shipping, etc. No operational or maintenance conditions that could jeopardize this assembly are known. No additional action is recommended, but existing controls should be continued.

B.2.7. Helium Ducting (PN 90-C2101-340) FMEA

B.2.7.1. Function of the Helium Ducting. The helium ducting forms the continuation of the primary coolant flow path from the helium inlet assembly to the compressor rotor blades (see Fig. B.2-3). It provides insulation to retard heat flow into the circulator bearing assembly from the primary coolant. In addition, it provides a mounting place for the compressor stator, which includes the shroud for the rotor blades.

B.2.7.2. Physical Description. The helium ducting forms a curved annulus of decreasing diameter between its inner and outer shells. The smaller end of the inner shell is bolted to the compressor end of the circulator bearing assembly. The larger end is adjacent to the support cone. The outer shell is supported by and connected to the inner shell by 12 airfoil-shaped struts and extends up beyond the plane of the rotor to provide support for the compressor stator assembly.

Fig. B.2-3. Helium circulator assembly

B.2.7.3. Environment. The environment of the helium ducting is provided by the primary coolant, which flows through at normal temperatures ranging from 742°F to 570°F at 100% and 25% power, respectively. Although there are no large pressure loads on the assembly, a significant torsional load is transferred to the outer shell from the stator. This load results from the function of the stator blades to change the flow from the compressor rotor from helical to axial. The load is transmitted from the outer shell through the airfoil-shaped struts to the inner shell and then to the bearing housing.

B.2.7.4. Discussion of the FMEA.

Impacts

Failure of the helium ducting appears unlikely. However, if it occurred, the most likely failure would appear to be breaking at the support struts. There are 12 struts and they are lightly stressed so that breaking of just one will probably go unnoticed unless it breaks free of the other structure. If it breaks free, it will be blown upward in the flow stream and cause breaking of the compressor rotor blades. If breaking of all support struts is postulated, then the outer ring of the ducting will drop down and bring the compressor stator assembly in contact with the rotor and initiate breaking of the rotor.

Blades broken from the rotor could be contained by the metal of the helium ducting assembly. In that case, repair could be effected by removing the circulator and replacing it with a serviceable unit. However, if the blades or rotor fragments pierced the helium ducting, they could damage the disc catcher, which is part of the inlet assembly. This could make removal of the circulator much more difficult and require repair of the disc catcher. If damage to the disc catcher is slight, it may be repaired in place. If damage is great, the disc catcher must be removed with the inlet and diffuser assembly through the center PCRV penetration for repair.

Failure Modes

The support struts for the outer ring of the helium ducting appear to be the most likely parts to break. The circulator stress report, however, indicates even the struts encounter relatively low stresses during normal operations.

B.2.7.5. Product Assurance Controls.

Design Controls

A thorough stress analysis was performed on the ability of the support struts to resist the torque load generated by the compressor stator. The analysis indicates that the stresses for normal operation are less than half the yield strength of the material. Stresses are lower in all other portions of the ducting. The unit is chromium-molybdenum steel with an electrolytic nickel plating on all surfaces. This selection seems suitable for the application. Testing that has been accomplished demonstrates that this design will function properly under normal conditions.

Quality Assurance Controls

See Section B.1.

Operational Controls

Because the helium ducting is an inaccessible static component, it is not directly affected by plant operational controls. However, it has mating surfaces that are susceptible to damage during installation or removal of a circulator. Therefore, caution should be assured during such operations.

B.2.7.6. Conclusions and Recommendations. It is concluded that the helium ducting has been carefully designed with appropriate safety margins on

stress. It is further concluded that the existing controls, coupled with the acceptance testing, provide adequate quality assurance. Operation and maintenance controls are necessary during circulator installation. It is recommended that present controls be continued.

B.3. SUPPORT CONE (PN 90-C2101-301) FMEA

B.3.1. Function of the Support Cone

The support cone is the structural member that mounts the circulator bearing assembly to the PCR/V penetration. Therefore, it supports the weight and thrust loads of the circulator machine assembly and positions it relative to the compressor inlet and flapper valve assemblies. The support cone also forms part of the primary coolant boundary (see Fig. B.2-3).

B.3.2. Physical Description

The support cone is 38-7/8 in. outside diameter by 13.12 in. high overall. The outer flange is roughly 6-1/2 in. high by 3-1/2 in. thick, and the inner flange is 3-in. high by 2-1/2 in. thick and is joined by a 1-3/4-in.-thick conical section. The entire cone is machined from a single piece of steel. The steel is procured to specification ASME 3A-182 GR-F1-F8Q. The support cone is designed to comply with the ASME Boiler and Pressure Vessel Code, Section III, Class A.

B.3.3. Environment

The outer flange of the circulator support cone is bolted to the PCR/V penetration flange, and the inner flange is bolted to the circulator bearing assembly. The support cone forms part of the primary coolant boundary. On its upper side it is insulated from the primary coolant flow stream; its lower side is exposed to the penetration purge helium. During full-load steady-state circulator operation, the maximum local temperature in the support cone is estimated to be about 190°F.

B.3.4. Discussion of the FMEA

Impacts

The support cone is a static part and its performance is not measured directly. If the support cone permits the bearing housing to move significantly in excess of normal, it will most likely result in the compressor or turbine rotors contacting adjacent static hardware and breaking. Breaking blades off the rotor would result in shaft unbalance, and possibly in bearing seizure or overspeed and automatic circulator trip. If this occurred at low circulator speed, the damage would likely be limited to the circulator machine assembly. Operating time lost would be that required to remove the failed circulator and replace it with a servicable unit. If the blades broke off at normal full-load circulator speed, there is a significant probability that one or more blades would penetrate the disc catcher. In this case, additional down time would be required to remove and repair the disc catcher in addition to the circulator.

Leakage past the support cone would normally pass purge helium into the primary coolant since the buffer helium is at a higher pressure than the primary coolant. However, a major leak would have to be repaired, probably on a nonpriority basis, because pressure transients could reverse the pressure differential which would cause primary coolant to leak out. The primary coolant contains some radioactive materials which would cause problems by contaminating the penetration and steam piping exterior. It would not present a direct safety hazard to the public.

Failure Modes

The most likely failure mode is expected to be leakage. Because the O-ring seals are metal, they have limited resilience and are thus more susceptible to leakage caused by relative motion between parts and to contamination. Most leakage failures are expected to occur and be detected early in the operational life.

B.3.5. Product Assurance Controls

Design Controls

Design analyses predicted that the maximum stress in the support cone is about 42% of the yield strength of the material from which it is made. The maximum stress in the inner flange bolts is about 40% of the minimum yield strength of the material. All evidence indicates that the design controls were adequate.

Quality Assurance Controls

The support cone is part of the primary coolant boundary. As such, it is designed and controlled in accordance with requirements of the ASME Boiler and Pressure Vessel Code. Therefore, the quality assurance controls appear adequate. Additional discussion of quality assurance controls is presented in Section B.1.

Operational Controls

The support cone is a static part inside the PCR; it requires no maintenance, and no other operational action affects it unless the circulator is removed. All removal, repair, and replacement actions require controls commensurate with 10CFR50 for safety-related equipment. Hence, operational controls should be adequate.

B.3.6. Conclusions and Recommendations

The support cone is conservatively designed and its nondesign aspects (including in-service operation) appear adequately controlled. It is recommended that the existing controls be continued.

B.4. COMPRESSOR ROTOR (PN 90-C2101-360) FMEA

B.4.1. Function of the Compressor Rotor

When the compressor rotor is rotated, it imparts an increase in energy to the primary coolant (helium) to cause it to circulate. The rotor is comprised of three types of parts (i.e., the disc, the blades, and the mounting bolts). The compressor rotor disc supports and rotates the compressor rotor blades. The rotor blades contact the primary coolant and increase its energy by accelerating it. The compressor rotor (mounting) bolts hold the rotor curvic coupling in contact with the mating surface on the shaft. Torque loads are transmitted from the shaft to the rotor by the curvic coupling. Therefore, only tensile loads in the rotor bolts are significant.

B.4.2. Physical Description

The helium circulator utilizes a single-stage, axial-flow compressor (see Fig. B.2-3). The rotor diameter is 18 in. to the periphery of the disc and 27.06 in. to the tips of the 31 blades. At 100% reactor power, each compressor rotates at 9550 rpm to circulate 871,000 lb per hour of helium at 686 psia and 742°F. The helium leaves the diffuser at 700 psia and 755°F.

The compressor rotor disc is machined from a one-piece forging of Type 422 stainless steel. It attaches to the shaft through a curvic coupling to which it is held by 8 bolts. The disc has a solid center and the rim is dovetailed for installation of the blades.

Each of the 31 blades is a precise, twisted airfoil made of Type 422 stainless steel. The blade height is 5.07 in. including the dovetail-shaped base. (The height is trimmed slightly after assembly into the complete rotor.) The blade chord varies from about 3.7 in. at the base to about 2.3 in. at the tip.

The bolts are made of Inconel 718 refined by the consumable electrode vacuum arc remelt process. Each bolt is 4.9 in. long from the bottom of the head to the end of the bolt. One inch of the end of the bolt is threaded 1.2 in.-20 UNF-2A. At the lead end, there is a 0.499-in.-diameter by 0.38-in.-long shoulder. The remainder of the bolt shank length is smaller (0.406 in.) than the minor diameter of the thread to reduce stresses in the threads. The bolt has a hexagonal head with a conical projection at its top to facilitate remote wrenching.

B.4.3. Environment

The compressor rotor is completely immersed in primary coolant. Only the periphery of the rotor disc and the rotor blades are in the flow stream. During 100% plant power operation, the primary coolant that passes through the rotor blades is at about 740°F and 700 psia. At 25% plant power, the helium conditions are about 569°F and 589 psia. The rotor disc and the rotor bolts are cooler where they mate with the circulator shaft, which is at a temperature of about 175°F at 100% power.

All the compressor rotor parts rotate at about 9550 rpm at 100% power. Buffer helium is supplied to the circulator bearing assembly to prevent bearing water from leaking into the compressor. A continuous flow of buffer helium from the shaft seal is normal. Abnormally, bearing water can flow out this same path and wet the underside of the compressor disc and the insulation and encounter the moving circulator blades.

B.4.4. Discussion of the FMEA

See Volume I, Table 3-2, Items 3.1, 3.2, and 3.3, for the compressor rotor blades, disc, and bolts, respectively.

Impact

A compressor rotor failure would result in removal and replacement of at least one circulator because a circulator cannot operate with a failed rotor. The corrective action would be limited to replacement of the circulator if the failure was not from a common cause and did not result in part of the disc, or a blade, penetrating the disc catcher. If the failure cause could not be isolated to the failed circulator, then one or more of the other circulators might have to be removed for inspection and possible repair.

If a failure results in a fragment of the disc or a blade penetrating the disc catcher, then the repair could become much more difficult. It is possible that a disc or blade fragment might penetrate part way into the disc catcher without completely leaving the helium ducting. This would tend to key the stator and disc catcher together, which could make circulator removal more difficult. Also, the disc catcher would probably require repair. The disc catcher is a continuous strip of Inconel 625 which is 0.050 in. thick by 8 in. wide by over 500 ft long. It is wound into a coil about 3 ft in diameter and 3 in. thick. Minor damage to the disc catcher might possibly be repaired in place by welding, but major damage would require removal for repair. Removal of the disc catcher requires disassembly of the inlet assembly, which in turn requires that the inlet and diffuser assembly be removed from the PCRV. The disc catcher, inlet, and diffuser are each too large to be removed through the circulator penetration. Thus, they must be removed through the larger central penetration in the bottom of the PCRV. Removal and reinstallation would be accomplished remotely because of high radiation levels in the lower PCRV plenum, adding considerably to the plant unavailability.

If one compressor blade should fracture from a defect within itself, it could cause the fracture of many more blades. Loss of even one blade, at normal speed, produces rotor unbalance that would cause rubbing of the shaft bearings. The worst possible result of severe rubbing would be

sudden seizure of the rotor shaft. This could possibly cause the compressor rotor to tear free from the shaft and penetrate the shroud, helium ducting, and disc catcher. It is more likely, however, that the rubbing would be detected and the circulator tripped without damage outside the circulator machine assembly. A fracture of the rotor disc would provide a greater probability of damage outside the circulator machine assembly.

Any bolt failure would be expected to require immediate circulator shutdown and removal from the PCRV for repair because of the resulting unbalance. However, it is believed that only an unexpected external event could cause simultaneous failure of all the bolts on one circulator rotor and thus allow damage by the rotor. Such an external event might be sudden seizing of a circulator shaft. Responsibility for failure due to such an external event would not be assigned to the bolt.

Fractures of a single bolt would probably result in a portion of that bolt being located differently and causing unbalance of the circulator rotor. The worst unbalance appears to result from a bolt breaking off adjacent to its threaded portion, followed by migration of the free portion to a position just inside the rotor rim diametrically opposite from where it originated. It is estimated that the resulting unbalance would not cause rubbing of the bearings. However, it would require circulator shutdown and repair. It is judged that the entire length of the bolt, if it were to unscrew from the shaft, would not be likely to escape because a portion of its hole through the disc is also threaded. It is judged highly improbable that the bolt threads would get "started" in the disc threads.

It is also conceivable that the broken bolt would become wedged between the rotating disc and the end cone. The bolt would likely be driven through the end cone, but, in the process, the rotor could be bent, fractured, or broken loose from the shaft with the consequences previously described.

The compressor blades may fail by becoming inefficient. This could conceivably result from unexpected contaminants in the primary coolant

depositing on the blades and significantly changing their shape or surface finish. The natures and likelihoods of such contaminants could be determined utilizing fault tree methods. Since the contaminant would most likely be carried in the primary coolant, all the circulators would probably be affected. To remove such deposited contaminants it is conceivable that a vapor or gaseous solvent might be used. However, it is more likely that no effective solvent could be found that would be acceptable for circulation through the reactor. Therefore, it is believed that corrective action would require removal of all circulators for cleaning.

Inefficient blade operation might also result from erosion of the blade. Erosion would probably also be caused by contaminants in the primary coolant and would therefore affect all circulators. Corrective action for significant erosion would probably require removal of all circulators.

Failure Mode

Failures of the compressor rotor parts appear to be unlikely. For each of the part types (disc, blades, and bolt) fracture is judged the most likely failure mode.

B.4.5. Product Assurance Controls

Design Controls

The blade aerodynamic design and mechanical design of the compressor rotor (exclusive of the blade root) were analyzed through use of the AXCOMP computer code. The mechanical analyses indicate that the combined bending and radial stress is less than 50% of the material yield strength at 150% of normal speed, and that the most severe oscillatory stress that is expected results from operation at 100% speed with flow blocked. Analysis indicates that the blades can endure this condition for many thousands of hours without experiencing fatigue failures. All development and qualification testing accomplished supports the conclusions of the analytical effort.

The compressor disc design was analyzed using two different computer codes (i.e., DISC and SAC). The DISC code does not consider axial loads and temperature distributions, but models the outer portions of the disc more appropriately. The results from the DISC code indicate a large margin of strength over load.

The SAC code was used in the stress analysis of the compressor disc. The disc modeling for the SAC code is coarse, consisting of a limited number of plates, cylinders, and rings. When run for input conditions including bolt loads and normal buffer flow, the SAC code predicted stresses of 85% of yield at 100% speed and 113% of yield of 150% speed at a point on the disc mounting cylinder. Further examination of the evaluation indicated that the high stress was very localized and resulted primarily from bending and thermal loads. Consideration of the effects of the coarse modeling and the nature of the major loads led to the engineering judgment that the design was acceptable.

The maximum credible overspeed for the circulator has been estimated to be about 147% and results from a sudden offset rupture of the circulator steam turbine discharge pipe. Maximum allowable continuous operating speed is about 113%. Rated speed (100%) is 9550 rpm. Each circulator rotor was spin-tested to about 146% speed without damage. Two of the production circulators were operated to 133% speed without damage. The successful high-speed testing indicates that the above predicted high stresses result from an overly conservative model and do not indicate an unsafe condition. Testing conducted at speeds up to 146% of rated circulator speed indicate that the compressor rotor design is satisfactory.

Eight bolts hold the rotor to the shaft. Each of the bolts is stressed only to about one-half its yield strength by torquing. The loads on the compressor blades caused by acceleration of the primary coolant and on the disc caused by the difference in pressures on each face press the rotor toward the shaft and do not contribute additional bolt loads. The axial loading reaction to torque at 100% power, transmitted through the 30-degree pressure angle of the curvic coupling teeth assuming no friction, is

only about two-thirds of the bolt torquing loads. The bolt load is therefore restricted to the torquing load plus any loads from thermal expansion. Thermal expansion effects will be small because the disc and bolt are made of similar materials and should encounter similar temperatures.

Evaluation of the design indicates that the bolts are very modestly stressed and that rigid manufacturing controls are specified. Testing has been performed which simulates normal operating experience. No failures were encountered.

Quality Assurance Controls

Quality assurance features are described in Section B.1.

Operational Controls

Operational conditions controlled to enhance the reliability of compressor rotor operation include primary coolant temperature and contamination and circulator speed. The operational condition most likely to result in blade contamination or erosion is unexpected contamination circulating with the helium. The helium purification system is intended to minimize contamination in the helium. There is no indication of a problem with coating or eroding the blades. However, it was not practicable to demonstrate long-term effects.

Circulator speed is measured and controlled, and circulator overspeed results in circulator trip. Certain accidents, such as the major rupture of the steam pipe from the circulator to the reheater, may cause significant overspeed (not greater than 147% of rated speed) but those LCEs are not considered in this analysis.

B.4.6. Conclusions and Recommendations

It appears that required measures have been taken to provide reliable compressor rotors, and to mitigate consequences if a failure should occur.

There is an area of uncertainty in a calculated stress level in the rotor disc (at 150% speed) that was found to be high by analysis. Testing appears to have demonstrated that there is no failure problem associated with this indicated high stress.

B.5. BEARING ASSEMBLY FMEA

B.5.1. Introduction

The FMEA for the bearing assembly is comprised of seven functional subdivisions, which are listed with section references in Table B.5-1 and shown schematically in Fig. B.5-1. The bearing assembly subdivisions were based on the particular functions that each large component within the bearing assembly accomplishes with regard to the overall function basis for this analysis (i.e., helium circulation). Each subassembly failure analysis includes the failure contributions of items such as O-rings, bolts, and locking devices that hold the subassembly in position. This section presents a general description of the FMEA for the bearing assembly, followed by descriptions of the FMEAs for each of the subdivisions listed in Table B.5-1.

B.5.2. Function of the Bearing Assembly

The main functions of the bearing assembly are: (1) support and location of the compressor rotor and stator with respect to the support cone, (2) transmission of torque from the drives to the compressor, and (3) maintenance of the primary coolant seal along the shaft. In addition to these functions, several requirements were deemed essential to the bearing assembly design, for example, long bearing life, and low friction to reduce losses of the machine.

B.5.3. Physical Description

B.5.3.1. Bearing System. The bearing arrangement is schematically illustrated in Fig. B.5-2. The rotor is vertically mounted on two outboard

TABLE B.5-1
BEARING ASSEMBLY FMEA SUBDIVISIONS

Ref. No. on Fig. B.5-1 and in FMEA Table 3-2	Component Name	Ref. Section
4.1	Circulator shaft	B.5.7
4.2	Main bearing housing	B.5.8
4.3	Lower bearing and high-pressure feed housing assembly	B.5.9
4.4	Lower labyrinth and seal assembly	B.5.10
4.5	Upper thrust bearing assembly	B.5.11
4.6	Upper journal bearing assembly	B.5.12
4.7	Upper dynamic seal assembly	B.5.13

Fig. B.5-1. Bearing assembly component analysis divisions

Fig. B.5-2. Simplified circulator bearing and seal flow arrangement

journal bearings and two central thrust bearings. The size and flow requirements of the journal bearings are determined by rotor dynamics considerations. The shaft and bearing combination are selected so that the unit operates well below the first critical speed.

The thrust bearing is required to carry the rotor weight plus aerodynamic and pressure loads developed by the turbine and compressor discs. The net thrust may be in either direction, depending on operating conditions. The turbine and compressor flow paths are such that their forces tend to balance each other and reduce the net thrust on the shaft. The greatest thrust load occurs on a startup with full helium pressure.

Although the shaft and the bearings do not touch or rub at any time during operation, it is desirable that they be able to stand momentary rubbing without destruction of the bearing geometry due to friction welding or galling. To achieve this end, the shaft and bearing lands are flame-sprayed with chromium oxide (Cr_2O_3). The base metal for the shaft and bearings is 400 series martensitic stainless steel.

The thrust bearing is composed of six shallow pockets surrounded by relatively wide lands. The water lubricant is introduced into the pockets from external pressure sources which supply water to the main bearing housing of each machine. At zero shaft speed the bearing water pressure in the pocket is sufficient to float the shaft and provide hydrostatic lubrication. As shaft speed is increased, the shaft thrust face drags the lubricant along the shallow pocket until it reaches the land or step. At this point the flow channel is contracted, and this resistance to flow manifests itself in the form of increased pressure resulting in increased bearing stiffness. The pressure distribution along the pocket is shown in Fig. B.5-3.

B.5.3.2. Seal Systems. Figure B.5-2 illustrates the seal system arrangement. The function of this system is to prevent bearing water from leaking into the reactor or the drive turbine cavity and also to prevent reactor

Fig. B.5-3. Normal bearing water pressure distribution on thrust pad

coolant and steam from entering the bearings. Sealing is based on the control of leakage through narrow clearance passages along the shaft. The reactor coolant is separated from the bearing water of the compressor-side bearing by a double labyrinth and a narrow-clearance annular water seal. With a scavenge chamber interposed between the labyrinths of the water seal, the bearing drain is controllable at a pressure slightly above that of the primary coolant, while the scavenge chamber is held at substantially the same pressure as the primary coolant. Purified helium buffer gas is introduced between the two labyrinths at a pressure slightly higher than that of the primary coolant. Approximately 100 lb/hr of this buffer flows through one labyrinth into the primary coolant system, while approximately the same amount flows through the other labyrinth into the scavenge chamber. Here it mixes with water flowing from the adjacent journal bearing through the water seal. Thus, a combination of buffer and scavenging is employed to ensure zero leakage of bearing water into the primary coolant.

At the drive turbine end of the shaft, the bearing drain water is separated from the steam turbine cavity by a narrow-clearance annular water seal and a labyrinth. A scavenge chamber, interposed between the water seal and the labyrinth, is held at a pressure lower than both the steam pressure and the bearing drain pressure. Steam leaks into this scavenge chamber via the steam labyrinth, and bearing drain water via the water seal. The mixture is condensed and then piped from the circulator bearing system to the power plant condensate system.

The narrow-clearance annular seals used to control water leakage at both ends of the shaft have a diametral clearance just slightly larger than that of the journal bearings. The seal surfaces are precision-ground and flame-sprayed with chromium oxide in a manner similar to that for the bearings.

B.5.4. Environment

B.5.4.1. Pressure. Figure B.5-4 shows the expected environments around each subassembly. Actual values, of course, can vary considerably,

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Fig. B.5-4. Fort St. Vrain helium circulator bearing and seal flow arrangement

depending on the phase of plant operation or the occurrence of plant disturbances. For example, when the plant is shut down for refueling, the primary coolant absolute pressure is about 1 atm compared to the operating pressure of 700 psia. Similarly, the steam turbine pressure can be reduced from its normal 650 psia to about 1 atm if a circulator is shut down. The combination of these conditions can result in a variation in the pressure differential between the top and bottom of the bearing from 10 psid to 440 psid with the reactor helium pressure higher. Several prototype tests have demonstrated that the seal can be maintained even when this pressure differential becomes negative (i.e., steam pressure greater than reactor coolant pressure).

In the event that the bearing assembly environment experiences unexpected transients such as high or low absolute bearing water pressure, a circulator protective trip is initiated. The circulator is taken to the secured shutdown state automatically. The circulator is also tripped and secured when the buffer helium seal is upset. This shutdown is initiated by a negative buffer helium supply pressure to mid-buffer ΔP . After the first circulator is tripped, operator intervention is required to shut down the second circulator in that loop; this procedure prevents automatic loss of helium flow to the steam generators in one loop. Automatic circulator trip is also initiated if a drain malfunction occurs which decreases the pressure differential between the main bearing water drain and the steam water drain to less than 5 psia. Thus, several protective circulator trips are initiated if the variations from normal operating pressures in the bearing assembly exceed limiting setpoint values. These trips protect the circulator from damage, and require a reduction in plant output while the problem is corrected. Without these protective trips, simple disturbances to the bearing assembly environment could lead to circulator damage that would result in an extended plant shutdown.

B.5.4.2. Temperatures. Temperature and stress distributions within the bearing assembly were studied with computer models. Postulated events

resulting in rapid temperature changes were used to define boundary conditions for the computer simulation of transient conditions. For example, rapid steam-side temperature transients were investigated, and local stress calculations indicated that the maximum expected loads on the components in the bearing assembly are less than 50% of the material yield strength. Except for the labyrinth seal components (see Fig. B.5-4), the operating temperatures of the bearing assembly components were less than 200°F. The insulation in these seal assemblies provides the thermal resistance necessary to minimize heat loss from the primary coolant into the bearing water. Thus, the largest thermal gradient in the bearing assembly appears across the seals where the insulation is located. This arrangement limits the increase in bearing water temperature to about 10°F, which represents a thermal equivalent loss to the bearing water system of about 0.03% of the core power per circulator.

B.5.5. Discussion of the FMEA

The most likely failure modes of the bearing assembly in order of likelihood appear to be (1) instrument drift or loss of signal, (2) leakage of fluids past seals, and (3) binding of the shaft. Instrument failures appear to have little impact on plant availability; loss of one signal does not require shutdown of a circulator because backup signals can be used by the operator to infer the lost readings. The next most likely failure mode category appears to be leakage (internal or external) by loss of seal effectiveness. Separate FMEAs for each O-ring seal are investigated in Section B.10. The impact for the failure mode of leakage can range from degraded circulator performance to removal of a circulator for repair. The next most likely failure mode for consideration is binding, which can occur by failure of any part or fluid which contacts the shaft. The impact of this failure mode would most likely be an extended plant shutdown for circulator repair, if the shaft could not be jarred loose by the water turbine jets ("bumping").

B.5.6. Conclusions and Recommendations

The components analyzed in the bearing assembly FMEAs were initially designed using standard calculational models backed up by extensive prototype testing. The behavior of the bearing assembly was well monitored during these tests, and provided support to the original design calculations. As operating experience is gained, it is important to feed this experience back into the design of future units by devising improvements that can be economically implemented to avoid common operating problems.

As the plant operators also gain experience, they will be able to deal more rapidly with unusual conditions that appear during routine operation. Operator sensitivity to these anomalous conditions can prevent minor problems from developing into major ones. The operator must learn to rapidly and reliably secure a circulator when necessary to avoid a potential extended shutdown.

It is thus recommended that economic options such as improved training within the guidelines set forth in 10CFR55, Appendix A, bearing assembly redesign, or improved quality assurance procedures be reviewed in light of the operating problems encountered during the plant startup phase. The objective of this examination would be to evaluate the various options available,* and implement the option which minimizes the net expected loss associated with the bearing assembly.

B.5.7. Circulator Shaft FMEA

B.5.7.1. Function of the Circulator Shaft. The major functions of the shaft are (1) transmission of torque from the drive end to the compressor end, and (2) support and location of the rotating components with respect to the bearing assembly. The shaft operating with other parts of the

*This recommendation was the basis for selection of the water ingress failure mode for the economic evaluation summarized in Volume I, Section 3.3.4, and presented in more detail in Appendix C, Section C.4 of this volume.

bearing assembly fulfills other requirements in support of the main functions. For example, the shaft surface acting with the upper labyrinths restricts buffer helium flow through the machine and helps establish the lubricant drain pressure. The lower labyrinth and shaft limit the leakage of steam, and the water seal and shaft limit the leakage of bearing water into the steam/water drain cavity. When the shaft is not rotating, the (static) shutdown seal is pressed against the shaft to isolate the reactor helium from the bearing water systems. Thus, the shaft surfaces act with various seal assemblies to minimize transfer of fluids to undesired locations. Special features are also included in the shaft design to aid in circulator operation. These provisions include a braking surface to stop circulator rotation, and slots machined in the shaft to induce electrical signals for speed and displacement information.

B.5.7.2. Physical Description. The shaft is machined from wrought Type 422 stainless steel and has a chromium oxide (Cr_2O_3) coating flame-sprayed on the bearing surfaces. The journal bearing diameter is 6.5 in., the thrust bearing faces extend out to a 10-in. diameter, and the smallest outside shaft diameter is 4 in., which occurs at the lower steam turbine (curvic) coupling. The shaft portions of the upper and lower curvic couplings are teeth machined in the end of the shaft which mate with matching teeth in the compressor and turbine discs. The environmental conditions for the shaft are described in Section B.5.4).

B.5.7.3. Discussion of the FMEA. For FMEA purposes, failure modes of the shaft were divided into two broad classes: those arising from failure of the shaft to perform a function, and failures that inhibit other parts of the machine from operating. Most failure modes of the shaft could result from external, internal, or a combination of causes, and result in the need for circulator removal for replacement of the shaft and other damaged components. After a failure analysis was completed it could be determined necessary or deemed advisable to replace other circulator shafts. This would be the case if the potential for common-mode failure were high.

Existing evidence, however, indicates that the internal causes of such shaft failure have a very low occurrence likelihood. Other failure modes such as "vibrates" and "leaks" can possibly be controlled by external operating procedures (e.g., operating away from critical speeds). Thus, the expected impact on plant availability from these failure modes would be much less significant than that from failure modes that require circulator removal for repair.

B.5.7.4. Product Assurance Controls. In addition to the assurance procedures described in Section B.1, several inherent design features of the shaft tend to reduce both the likelihood and impact of failures considered in the FMEA Table 3-2, item 4.1, of Volume I. For example, the shaft/bearing combination was selected so that the unit operates well below the first critical speed. Another feature is that the steady thrusts of the turbine and compressor tend to balance each other, reducing the net end thrust on the shaft and therefore the likelihood of momentary rubbing. Both shaft and bearings have been flame-sprayed with chromium oxide (Cr_2O_3) to allow a limited amount of momentary rubbing without binding.

In the event that binding does occur due to material in the bearing clearance gap, bearing water pressure and water turbine "bumping" may be used to flush out the debris and restore the circulator to normal operation without a lengthy plant shutdown. The product assurance aspects of the shaft failure mode "leaks" is discussed in Sections B.5.10.4 and B.5.13.4 in conjunction with the seals.

Maintenance procedures related to the shaft as well as all the components in the bearing assembly must be performed in accordance with approved procedures and independently verified by the site quality assurance personnel. Hence, adequate controls appear to exist on this potential source of failures.

B.5.7.5. Conclusions and Recommendations. It appears that adequate measures have been taken to ensure that the shaft will have a low failure

probability. General recommendations for the entire bearing assembly are discussed in Section B.5.6.

B.5.8. Main Bearing Housing FMEA

B.5.8.1. Function of the Main Bearing Housing. The functions of the bearing housing are (1) to support and locate the bearing assembly with respect to the support cone, and (2) to provide both channels and external connections for fluids necessary for circulator operation. In addition to these main functions, several features have been designed into the housing to aid in circulator operation. These features include the active elements of the speed sensors, thermocouple sensors, and pressure taps which aid the operator in ascertaining circulator operating conditions.

B.5.8.2. Physical Description. The main bearing housing is machined from Type 420 stainless steel and is 14.79 in. high with a maximum outside diameter of 20-7/8 in. The center is bored out to a 6.7-in. diameter near the shaft and to a 12-in. diameter where the upper thrust bearing assembly is housed. Eight major and 23 smaller holes drilled into the housing act as channels for fluids, sensor leads, etc. The expected operating inlet water pressure is 1320 psia with outlets in the 650-psia to 700-psia range. The bearing housing directs this high-pressure water to the required bearing surfaces, and returns the lower-pressure water to the bearing water drains. The environmental conditions are described for the bearing assembly in Section B.5.4.

B.5.8.3. Discussion of the FMEA. The failure modes considered for the housing result from the failure of principal functions and secondary functions (e.g., incidental requirements or engineered features). The likelihood of the main bearing housing causing damage to other components is expected to be small since the housing is a static component with no kinetic energy. Some failure modes are those which affect the flow of fluids through the housing such as a change in flow path, blockage, or leakage. In general, the failures would require circulator replacement.

However, some failure modes would allow the circulator to continue operation with degraded performance, as long as careful operator attention is maintained. For example, blockage of a bearing water inlet supply port may not require an immediate circulator shutdown since a redundant path for inlet water is provided. On the other hand, if the buffer helium line became plugged, the upper labyrinth seal would lose effectiveness, and moisture could enter the core. Shutdown of the circulator would be required until the helium path could be cleared. This could possibly be done without circulator removal if the operator could open the blocked passage by external variation of the buffer helium pressure while the circulator is secured.

B.5.8.4. Product Assurance Controls. In addition to the controls described in Section B.1, several unique features of the bearing housing help reduce the likelihood and impact of some failure modes. For example, the redundant water inlets protect against flow blockage whether initiated internally or externally. Protection from other failure modes is afforded by extremely thorough inspections during each manufacturing step and assembly procedure, thus reducing the likelihood of failure.

B.5.8.5. Conclusions and Recommendations. It appears that adequate measures have been taken to ensure that the bearing housing will have a low failure probability. General recommendations for the entire bearing assembly are discussed in Section B.5.6.

B.5.9. Lower Bearing and High-Pressure Feed Housing Assembly FMEA

B.5.9.1. Function of the Lower Bearing and High-Pressure Feed Housing.

The lower bearing directs high-pressure bearing water lubricant from channels in the main housing to the high-pressure feed housing and back to the lower thrust bearing face and the lowest journal bearing. These stationary bearing surfaces also locate the lower thrust face and journal of the shaft with respect to the main bearing housing, as can be seen in Fig. B.5-4. An additional function is the restriction of bearing water flow

toward the steam inlet by the high-pressure housing inside shaft clearance. The lower thrust bearing is held in position by 16 bolts in the main housing. The high-pressure housing is pressed against O-ring seals in the lower bearing by the water seal, which is in turn compressed by bolts through the steam turbine stator. (The assembly is described in Section B.5.10.)

B.5.9.2. Physical Description. The lower bearing assembly is 7.57 in. long, with an outside diameter of 16.375 in. and a minimum bore of 4.5 in. Both the bearing and high-pressure housing are made from Type 420 stainless steel. The environment for the entire bearing assembly is described in Section B.5.4.

B.5.9.3. Discussion of the FMEA. Most failure modes of this assembly require circulator removal for repair. For example, if the bearing surface becomes damaged and causes binding, circulator removal would be required unless debris in the gap could be flushed out. Also, if the high-pressure housing cracks, or the O-ring leaks, insufficient water supply to the bearing could lead to machine damage. The leaking bypass water would exit the machine through the steam/water drain, which would cause a protective circulator trip on a drain pressure malfunction. Finally, if excessive wear on the lower bearing occurs, resulting in increased vibration, circulator removal for repair may be required. The most likely causes of such failures in this bearing subassembly appear to be loss of normal environment, O-ring leakage, and excessive shaft vibrations. Variation of operating pressures outside the limiting values will initiate protective trips as described in Section B.5.4.1. In addition, operator observation of excessive bearing temperatures may result in a manually initiated protective trip, while the problem is evaluated and corrective action taken. O-ring leakage generally arises from poor machine assembly or fabrication problems and is thus controlled best by thorough quality control during all phases of manufacturing. In some cases shaft vibrations can be minimized by operational procedures. This bearing could also be exposed to excessive shock or vibrations during shipping. However, impact or shock meters are

used to monitor shock and vibration levels, and the machine is shipped in a container engineered to prevent damage.

B.5.9.4. Product Assurance Controls. Coatings of chromium oxide on the various surfaces were used to reduce the likelihood of failure due to occasional rubbing. The bearing design was based on considerable analysis and prototype testing and confirmed by startup experience. The most likely type of component failure appears to be leakage past O-ring seals, which should be adequately controlled by the thorough inspection and assembly procedures outlined in Section B.1.

Adherence to the planned operational procedures during startup, shutdown, and other operating phases can reduce the likelihood of bearing failure. Operator sensitivity and timely corrective action at the onset of anomalous conditions as detected by variations in the bearing assembly instrumentation could prevent a simply repairable component failure from progressing to extensive circulator damage or other condition requiring a lengthy plant shutdown for repair.

B.5.9.5. Conclusions and Recommendations. It appears that adequate measures have been taken to ensure that the lower thrust bearing assembly will have a low failure probability, provided the comprehensive operator training and controls are followed (10CFR55). General recommendations for the entire bearing assembly are discussed in Section B.5.6.

B.5.10. Lower Labyrinth and Seal Assembly FMEA

B.5.10.1. Function of the Lower Labyrinth and Seal Assembly. The primary function of this subassembly of the bearing assembly, which is shown in Fig. B.5-4, is to prevent the transfer of steam from the turbine into the bearings, and to control the flow of bearing water into the steam water drain. This assembly also holds the high-pressure housing in position, and houses the turbine rotor insulation.

B.5.10.2. Physical Description. The outside diameter of the assembly is about 8 in., the length is 3.8 in., and the inside diameter is 4.1 in. The base material for the assembly components is Type 442 stainless steel. Thermal insulation is placed inside the hollow regions of the components to reduce heat loss from the turbine drive steam to the bearing water. During assembly of the machine, the seal assembly is held in place by four bolts and lockwashers. However, the final positioning force on the assembly comes from fifteen 3/4-in. bolts torqued to 400 ft-lb, squeezing it between the lower bearing assembly and the steam turbine support. The seal components then transmit the force necessary to hold the high-pressure housing against the O-ring seals in the lower bearing.

B.5.10.3. Environment. The bearing water drain pressure can range from 45 to 530 psid higher than the steam water drain pressure as a result of plant load changes. The thermal gradient from the turbine to the bearing water system is large since the exit steam temperature is 670°F and the steam water drain is about 160°F. A more detailed description of the environment is given in Section B.5.4.

B.5.10.4. Discussion of the FMEA. Failures of this assembly can result in a wide range of impacts on plant availability from as small as "insignificant" to as large as a shutdown for circulator removal. For example, wear or increased leakage may not require a machine shutdown, since it may be more economic to operate the circulator with somewhat off-normal performance. The failure mode "leakage" might result in excessive steam flow into the steam water drain, which could cause a reduction in the plant thermal efficiency. A small leak, whether known or unknown to the operator, would probably have an insignificant effect on the plant availability. On the other hand, if the assembly loosens, separates, or causes shaft binding, removal of the circulator may become necessary to restore the machine to normal operation. Two failure modes listed in Volume I, Table 3-2, item 4.4, (i.e., binds, and leaks along the shaft) have possible self-correcting provisions. The onset of binding due to dimensional growth may be cleared

by the normal shaft vibrations flattening the protruding labyrinths in such a manner as to clear the binding before seizure occurs. Also, if excessive leakage of steam into the steam water drain occurs at lower shaft speeds, increasing the shaft speed might improve the seal characteristic sufficiently to reduce the leakage rate to an acceptable level. If, on the other hand, loose material jams between the shaft and seals and could not be cleared by "bumping," circulator removal would be required. The greatest damage arising from a seal assembly failure appears to occur if an insulation locking lip breaks off and causes damage to the steam turbine. Fortunately, this mode of failure appears to be in the highly improbable category.

B.5.10.5. Product Assurance. In addition to the thorough quality control measures described in Section B.1, the design adequacy of this seal assembly is supported by careful analysis and considerable prototype testing evidence. Some additional features which reduce the impact or likelihood of failure are (1) the fact that steam and water are compatible fluids, and (2) careful control of the water chemistry during operation to reduce the likelihood of failure due to corrosion, wear, etc.

B.5.10.6. Conclusions and Recommendations. It appears that adequate measures have been taken to ensure that the lower labyrinth and seal assembly will have a low failure probability. General recommendations for the entire bearing assembly are discussed in Section B.5.6.

B.5.11. Upper Thrust Bearing Assembly FMEA

B.5.11.1. Function of the Upper Thrust Bearing Assembly. The main functions of the upper thrust bearing assembly are to provide (1) lubricant to the shaft thrust face from the main housing, (2) drain passage for the bearing water to the main housing, (3) location and support for the brake assemblies (Appendix B.6), and (4) both radial and axial support for the shaft.

B.5.11.2. Physical Description. The thrust bearing is made from Type 410 stainless steel with a maximum outside diameter of 12 in., minimum inside diameter of 6.57 in., and a length of 4.12 in. Numerous holes and passages are drilled for bearing water inlet and exhaust ports. The bearing surfaces are flame-sprayed with chromium oxide. This assembly is held inside the main bearing housing by four bolts, which extend into the main bearing housing. These bolts are held in place with an internal set screw drilled and staked from the bearing side. The environment around the assembly is expected to be turbulent bearing water, as described in Section B.5.4.

When the machine is shut down, gravity brings the lower thrust face of the shaft into contact with the lower thrust bearing face. Thus, rubbing occurs on the upper thrust faces only if excessive upward thrust occurs from a combination of steam, helium, or the bearing water supply conditions which result in such upward force on the thrust bearing.

B.5.11.3. Discussion of the FMEA. Most failure modes of this assembly result in the requirement for circulator removal for repair. If unusual operating conditions are ignored by the plant operators, most of the failure modes result in binding, and a plant shutdown is required to restore the circulator to normal operation. The most likely causes of such a condition appear to be ring stake material jamming the bearings, and water leakage through the O-ring seals bypassing the normal bearing water flow path. These conditions are listed in the FMEA Table 3-2, item 4.5, Volume I.

B.5.11.4. Product Assurance Controls. In addition to the quality control plan described in Section B.1, the bearing design is supported by careful analysis and prototype testing. The bearing surfaces have also been coated with chromium oxide (Cr_2O_3) to provide additional damage resistance to occasional rubbing which may occur (e.g., with problems on startup, shutdown, or loss of bearing water supply). During the operational phase, operator adherence to the circulator operating, test, and maintenance

procedures will also reduce the likelihood of failures, e.g., limiting speed, startup rates, etc., to recommended levels, performing scheduled testing on backup systems to show that inadvertent closure of valves has not occurred, and maintaining bearing water chemistry.

B.5.11.5. Conclusions and Recommendations. Because of the extreme care by quality control and the use of the most experienced craftsmen in assembling the first units, the ring stake locking method will probably prove to be sufficient for this plant. However, if a higher-volume circulator production is established, other fastener locking devices should be investigated to reduce the dependence on the workman's skill in critical locations (e.g., next to the rotating shaft in an area of turbulent water flow). Outside of the locking method, it appears that adequate measures have been taken to ensure that the upper thrust bearing will have a low failure probability. General recommendations are discussed in Section B.5.6.

B.5.12. Upper Journal Bearing Assembly FMEA

B.5.12.1. Function of the Upper Journal Bearing. The major function of the upper journal bearing is to provide radial support and lubrication for the shaft. In addition, this component provides ducts for helium to the shutdown seal, the buffer helium supply duct to the upper labyrinth seal drain passage, high-pressure water supply to the bearing water drain, pressure taps, and instrument paths for thermocouples. The upper journal bearing is held in position by 12 bolts and a machine fit in the main housing. The upper journal, in turn, provides location and support to the upper seal assembly. O-ring seals are located on the top and bottom of the bearing to prevent water, water/helium, or helium leakage between the bearing assembly components.

B.5.12.2. Physical Description. The bearing is made from Type 410 stainless steel; it is 9.18 in. long, with an inside diameter of 6.5 in. and an outside diameter of 12.75 in. Numerous holes, passages, and fits are machined in this component to accomplish the necessary functions. The bearing surfaces are flame-sprayed with chromium oxide.

B.5.12.3. Environments. In addition to the description in Section B.5.4, pressures around the journal bearing range from about 1300 psia at the entrance ports, to about 697 psia at the main drain, and 684 psia where the bearing water is mixed with the buffer helium and is drawn into the high-pressure separators.

B.5.12.4. Discussion of the FMEA. The most severe impact for this component arises from failures which damage the circulator and require an extended plant shutdown (i.e., circulator removal) to make repairs. For example, if the oxide coating flakes off the journal bearing, it could cause the shaft to bind. If this should occur, the operator would probably first attempt to break the shaft loose by "bumping" with the water turbine. In the event that this technique failed to restore the circulator to normal operation, eventual plant shutdown for circulator removal and repair would be required.

The leak failure modes may result in a condition which allows for continued operation with degraded performance. For example, if wear in the bearing results in a change in the pressure profile along the shaft, an increase in water leakage into the upper seal could occur. External adjustments to the buffer helium pressure, or operation at high shaft speed on the affected circulator, may negate the need for circulator removal. If the instrumentation signals are degraded, the operator may rely on other signals to be aware of operating conditions. Thus, shutdowns can be avoided for certain failure modes.

B.5.12.5. Product Assurance Controls. The entire bearing system has been tested in the prototype circulator and during startup testing, and no indication of inadequacy has been observed. The addition of the chromium oxide on the bearing surface reduces the likelihood of bearing failure arising from occasional rubbing by the shaft (e.g., as a result of external causes).

The quality assurance controls described in Section B.1 were employed for the FSV circulators. Detailed design calculations were supported by

the prototype tests. The bearing is expected to give excellent service for the life of the plant if the operating and maintenance procedures are carefully followed.

B.5.12.6. Conclusions and Recommendations. It appears that adequate measures have been taken to ensure that the upper journal bearing will have a low failure probability. General recommendations for the entire bearing assembly are discussed in Section B.5.6.

B.5.13. Upper Dynamic Seal Assembly FMEA

B.5.13.1. Function of the Upper Dynamic Seal. The primary function of this assembly is to prevent the transfer of helium coolant into the bearing assembly, and of bearing water into the helium coolant loop. The assembly also provides support and location for the helium ducting and thermal insulation. The sealing function is accomplished with the support of an external buffer helium supply of 200 lb/hr. During the circulator shutdown phase, a stationary shutdown seal (Section B.7) is pressed against the shaft, thus providing an alternate seal when lack of shaft rotation diminishes the effectiveness of the dynamic seal, making it more sensitive to buffer helium. In this section, only the dynamic seal failure modes and effects are discussed.

B.5.13.2. Physical Description. The dynamic seal assembly consists of four major components: (1) the shaft, (2) slinger ring, (3) upper journal labyrinth, and (4) upper labyrinth. The flow of buffer helium along the upper shaft prevents other fluids from leaking through the tortuous path set up by the seal assembly. A 3/16-in.-wide, 1/2-in.-deep groove is machined into the shaft where the slinger is positioned, which limits bearing water flow to the helium/water scavenge chamber to about 1 gpm. The two slinger halves are made from Type 410 stainless steel with an inside diameter of 6.25 in., outside diameter of 9 in., and thickness of 0.0625 in. Shaft clearance is about 1/8 in. on the diameter and 1/16 in.

on each side. The two slinger pieces are mounted on the top of the upper journal bearing in a machined groove. This arrangement of the slinger end shaft groove then adds flow resistance to the path between the upper journal labyrinth (scavenge chamber) and the bearing water.

The next barrier between the reactor helium and bearing water is the upper journal labyrinth seal, which is an annular component made from Type 420 stainless steel with an outside diameter of 12.75 in., inside diameter of 6.5 in., and thickness of 1.5 in. The labyrinth seal has a nominal shaft clearance of 0.005 in. It provides the scavenge chamber cavity for the helium water drain on the bottom, and the buffer helium supply port on top.

The uppermost component in this assembly is the upper labyrinth seal, which is also an annular piece made from Type 420 stainless steel. It has an outside diameter of 13.25 in., an inside diameter of 6 in., and thickness of 3 in. The nominal shaft clearance is 0.005 in. for this seal, which helps establish the steady-state buffer helium flow balance between the two labyrinths.

B.5.13.3. Environment. The normal environment around the labyrinths act to form a controlled helium flow seal. Buffer helium, nominally 200 lb/hr at 687 psia, enters the seal assembly between the two labyrinths. The scavenge chamber is maintained at 684 psia by the external helium recirculators and bearing water surge tank pressure. Thus, water (1 gpm) and helium (100 lb/hr) flow into the helium/water drain from this chamber. The remainder of the buffer helium flows into the reactor coolant at about 686 psia. A flow of 100 lb/hr is more than sufficient to prevent back diffusion of reactor helium into the bearing water system. The buffer helium flows into the reactor coolant at about 160°F (shown in Fig. B.5-2).

Variations in the pressure differential across the seal could occur as a result of external events which upset the nominal operating environments

(e.g., transfer from normal to backup bearing water, circulator startup, or shutdown transients). Normally the bearing water inlet pressure is maintained about 620 psid above the reactor pressure by the surge tank equalization lines and bearing water pumping system. Thus, the conditions around the seal itself are sensitive to several external systems (i.e., buffer helium, reactor pressure, and bearing water) such that nonroutine conditions could possibly upset the dynamic seal. A description of the protective circulator trips which result is given in Section B.5.4.1.

B.5.13.4. Discussion of the FMEA. The main function of the upper dynamic seal assembly is to provide a barrier between the bearing water and reactor coolant. The effectiveness of this barrier can be degraded by several conditions such as excessive wear on the seals, insufficient buffer helium, unusual environmental conditions, low shaft speed, or combinations of the above. The impact on plant availability can range from insignificant to requiring an extended plant shutdown for circulator repair.

The most likely failure mode of this system appears to be a leak along the shaft of one circulator, which would lead to a reduction in power level or possibly a plant shutdown. The most likely cause for dynamic seal leakage appears to be external system problems combined with a lack of operator attention. After a leak occurs, normal operating conditions can be restored with a brief shutdown for moisture removal from the reactor coolant, or a power reduction while one water supply loop for the bearing water system is cleaned up by the radioactive removal systems, depending on the direction of the leakage.

If the seal system prevents operation (e.g., by causing shaft binding), the circulator would have to be removed for repair. The other failure modes considered in the FMEA table (Table 3-2, Volume I) appear less likely; however, they would result in the need for circulator removal and repair if the problem could not be cleared externally.

B.5.13.5. Product Assurance Controls. In addition to the general quality assurance controls described in Section B.1, several special design features help reduce the likelihood of seal system failure as well as the impact on plant availability. For example, the seal gaps are greater than bearing clearance; thus, bearing rubbing would occur before seal rubbing. However, if misalignment occurred and a portion of the seal contacted the shaft, the seal teeth would wear away faster than the shaft until a sufficient clearance existed. In this case, an excessive gap would be expected on the opposite side. However, as long as external leakage can be inhibited, no action affecting plant availability would be required.

The objective of the operational controls is to maintain the seal effectiveness through external control of the variables which affect seal performance, such as buffer helium, shaft rotation, and bearing water/reactor coolant pressure conditions. Lights, alarms, and continuous information are fed to the operator so that timely actions may be taken to prevent the leakage of fluids from or to the reactor. Rapidly responding operators can prevent minor seal problems with insignificant impacts from developing into major problems that require longer shutdowns to reestablish normal operating conditions.

B.5.13.6. Conclusions and Recommendations. In this section the most likely mode of failure and impact on plant availability arises from external equipment failure followed by a lack of action on the part of the operator. The Code of Federal Regulations (10CFR55, Appendix A) provides the retraining mechanisms by which such anomalous conditions can be brought to the attention of operating personnel, and the appropriate responses can be discussed prior to the occurrence of the problem. As an alternative to reliance on operator training, a more expensive seal design which employs the theory of redundancy might be considered.

If redundancy is considered in new designs for the helium supply as well as for the seals, the required operator response time could be extended from minutes to months. Additional information is discussed in the general bearing assembly conclusions and recommendations of Section B.5.6.

B.6. BRAKE FMEA

B.6.1. Physical Description

The helium circulator will self turbine at about 400 rpm on normal bearing water. Since the shutdown seal could be damaged if it were applied when the circulator is rotating, the shaft brake (item 5, Fig. B.5-1) is provided to prevent circulator rotation prior to shutdown seal application. During startup, it prevents rotation until the shutdown seal is released and the shaft is supported on bearing water. During circulator shutdown, the brake shoes are applied to the shaft when the speed is <500 rpm* to stop rotation before bearing water pressure is reduced.

The brakes make spot contact with the stainless steel shaft through four silver brake shoes spaced 90 degrees apart around the shaft. Application force is provided by a pressure-regulated bottled helium supply, and is transmitted to each brake shoe by a bellows arrangement.

B.6.2. Discussion of the FMEA

An FMEA on the shaft brake is shown in Volume I, Table 3-2, item 5. Depending on the severity of damage resulting from a failure of the brake, a circulator may need to be replaced before normal operation is resumed. In less severe cases, it may be possible to continue operation after flushing brake debris from the bearings or assuring that damage was not severe. Examples of failures likely to be severe enough to require circulator replacement include (1) application of the brake during circulator operation, resulting in brake shoe and/or shaft debris which could wedge in and damage the bearings; and (2) failure of the brake to stop circulator rotation before the shutdown seal is applied, scoring the seal so that it leaks excessively.

*The 500 rpm threshold was changed to 700 rpm subsequent to the drawing issue employed for these analyses.

B.6.3. Product Assurance Controls

Design Controls

Several design controls related to product assurance have been implemented, including features to prevent inadvertent application of the brake, minimize damage in the event of inadvertent application or failure, assure adequacy of braking force, and prevent improper sequencing of brake-seal release and application. These design controls are achieved by: (1) providing a vent on the actuation line which remains open until the brakes are to be applied, to prevent inadvertent pressurization; (2) using soft (silver) brake shoes which do not tend to seize with the shaft, or flake off, even when applied too soon; (3) flame spraying the bearing surfaces with chromium oxide to reduce the likelihood of damage from rubbing (e.g., during a shutdown with brake failure to stop the circulator); (4) signaling low helium bottle pressure so that the supply bottle can be changed to maintain sufficient pressure for adequate braking force; (5) providing an interlocking time delay after the brakes are applied to ensure that the circulator has stopped before the static seal is applied; (6) actuating both the brake and the seal from a common helium source so that a pressurization failure that would release (or fail to apply) the brakes would also release (or fail to apply) the seals; (7) using actuation bellows on the brake and seal with spring rates such that the seal applies and releases at a higher pressure than the brake does, assuring that the brake will apply before and release after the seal; and (8) providing an interlock to prevent brake release until the seal is depressurized sufficiently to have released.

Quality Assurance Controls

For quality assurance controls, see Section B.1.

Operational Controls

Operational controls applied consist primarily of interlocks which operate whether the brake is applied automatically or manually.

B.6.4. Conclusions and Recommendations

An effort has been made to keep the seal from being applied when the circulator is rotating by using a time delay interlock and a common helium source for the brake and the seal. Further assurance could be obtained by applying the seal only after either (1) a direct indication of no rotation, or (2) an appropriate time delay following an indication of speed well below the expected self-turbining speed.

A failure allowing bearing water to leak into the brake bellows actuation line faster than it could be vented would cause a spurious application of the circulator brake. Therefore, it may be advisable to position a water trap in the brake vent line to alarm water leakage and avoid possible circulator damage. However, the circulator would still have to be removed if no other means could be found to correct the leakage.

A potential supplementary solution to the above problem would be to attempt to greatly reduce the chance of water inleakage. The O-rings used to seal the interface could possibly be more thoroughly inspected and tested to further increase confidence in their quality. Due to the intense QA controls imposed for all circulator components, this avenue of reducing expected losses does not appear promising.

As the silver brake shoe insert wears away over the course of the 40-year plant life, the brake must extend further to reach the shaft. If the wear progresses far enough, the Nitralloy brake shoe itself could ultimately be pressed against the rotating shaft. Damage resulting from contact between these two parts could be avoided by providing a mechanical

stop to limit the distance a brake can be extended toward the shaft. For example, if the brake normally moves 0.10 in. to apply, and the shoe insert is 0.10 in. thick, a stop could be positioned to prevent extension beyond 0.19 in., allowing for a margin of protection.*

Since rupture of the actuation bellows or a weld crack on any one brake would make all four brakes in one circulator ineffective, a large margin should be assured between nominal operating pressure and design proof pressure. This should be done through design by specifying an operating pressure that can reliably apply the brakes and stop the shaft while retaining an adequate margin to the design pressure. In addition, redundant means could be provided externally to keep the applied pressure from approaching the design proof pressure.**

Since the effects of a failure can be mitigated or aggravated by an operator's response, operator training should include instructions on interpretation of instruments and alarms associated with failure of components in the brake system.

B.7. SHUTDOWN SEAL FMEA

B.7.1. Function of the Shutdown Seal

The shutdown seal provides separation of the reactor helium from the bearing water system when the circulator is inoperative. It is actuated by regulated high-pressure bottled helium piped into an annulus between two Inconel 718 bellows.

B.7.2. Physical Description

The silver-plated Inconel 718 seal ring is set against a shoulder in the circulator shaft near the middle of the helium labyrinth seals. Under

*This option is shown in Appendix C.2 to be uneconomic for FSV due to the plant down time as required for implementation.

**These recommendations have been implemented.

actuation pressure, the soft silver plating on the seal ring will conform to shaft irregularities to block leakage paths.

B.7.3. Environment

The shutdown seal external environment is normally helium at 150°F, with a maximum of 700°F. The shutdown seal is proof-tested at 1700 psid, while the differential pressure across the actuated seal is normally only 350 to 400 psi. The seal is designed to withstand 1000 cycles at full stroke (1/16 in.).

B.7.4. Discussion of the FMEA

The FMEA for the shutdown seal is shown in Volume I, Table 3-2, item 6. If buffer helium is not being supplied when the circulator is shut down, either the shutdown seal or the shutdown seal backup system, which maintains a water level near the midpoint of the bearing cartridge, is needed to separate the primary coolant from the bearing water. Depending on the pressure in the PCR, failure of this separation boundary can lead to leakage of radioactive primary coolant into the bearing water, or leakage of bearing water into the PCR. The former condition can be handled by diverting the contaminated water to the liquid waste sump for cleanup, while the latter requires that the plant be shut down if the water ingress is excessive, until the water content in the PCR is acceptable. Thus, leakage of water into the primary coolant is a consequence that can reduce plant availability. A total plant shutdown is required to remove and replace a circulator if the seal suffers damage that requires repair.

The components of the shutdown seal which are most likely to suffer damage are (1) the bellows, which may rupture, distort, or suffer a broken weld (e.g., from overpressurization or environmental effects), and (2) the seal ring, which may be scored (e.g., by being applied while the shaft is rotating).

B.7.5. Product Assurance Controls

Design Controls

The likelihood of seal damage is reduced by several design controls implemented to assure that the circulator is stopped when the seal is applied. Many of these controls are discussed in Section B.6.3, and pertain to preventing improper sequencing of brake-seal release and application. In addition, if the brakes should be released while the seal is still applied, the seal exerts enough pressure on the shaft to prevent it from self-turbining and damaging the seal when bearing water is applied.

Quality Assurance Controls

Quality assurance controls are discussed in Section B.1.

Operational Controls

Operational controls include using the same helium supply for both the brake and the seal, and employing interlocks which operate whether the brakes and seal are applied manually or automatically.

B.7.6. Conclusions and Recommendations

Much attention has been paid to stopping circulator rotation before application of the shutdown seal. One further suggestion would be to only apply the seal after either (1) a direct indication of no rotation, or (2) an appropriate time delay following an indication of speed well below the expected self-turbining speed. A sensor which alarms if the seal is applied while the shaft is still rotating could inform the operator and enable him to avoid the development of a serious problem forcing plant shutdown for circulator replacement. Only item (2) above appears potentially economic for FSV.

Protection against overpressurization of the actuation bellows could be improved by providing external redundancy to keep the applied pressure from approaching the design proof pressure under all conditions (e.g., use of redundant relief valves). As suggested in Section B.6.4, an operating pressure should be specified which retains an adequate margin to the design pressure while reliably blocking leakage paths.*

B.8. DIFFUSER AND STATOR FMEA, HELIUM CIRCULATOR

B.8.1. Function of the Diffuser and Stator

The diffuser converts a portion of the velocity of the primary coolant leaving the compressor rotor into static pressure. In this section, the contribution of the compressor stator and diffuser assembly to this function are examined. The stator changes the direction of the primary coolant flow leaving the compressor from helical to axial. The flow path within the diffuser is thus made more efficient. The diffuser converts the flow velocity into pressure by gradually and smoothly slowing the gas in a flow channel of increasing cross-sectional area. The flapper valve housing and cone participate in this diffuser action (see Section B.9).

B.8.2. Physical Description

The compressor stator is part of an assembly that includes the compressor shroud. The stator is an annulus containing cambered blades, each set on a radial axis with its exit surface essentially parallel to the circulator axis. The diffuser assembly is basically a long frustum of a cone through which the primary coolant flows. It also has a cylindrical section on the outside, which mounts on the compressor inlet assembly to provide physical support for the diffuser. The flapper valve housing and cone form part of the diffuser flow path. They provide the transition from an annular to a cylindrical flow channel while increasing the flow area.

*These recommendations have been implemented.

B.8.3. Environment

The environment of the diffuser assemblies is determined by the primary coolant discharging from the compressor. At 100% plant power, the primary coolant is estimated to be at 700 psia and 755°F. At 25% plant power, the pressure and temperature are estimated to be 591 psia and 571°F. Pressure and temperature are essentially the same inside and outside the diffuser. Therefore, no significant differential forces exist across the diffuser. Torsional loads are imparted to the stator by the primary coolant as its flow is straightened. Also, some flow disturbances are generated by the compressor rotor blades passing close by the stator blades.

B.8.4. Discussion of the FMEA

The FMEAs are presented in the sections that discuss the individual assemblies (Section B.8.6, etc.).

B.8.5. Product Assurance Controls

Refer to Section B.1 and to the following discussions of the individual assemblies (Section B.8.6, etc.).

B.8.6. Compressor Stator FMEA

B.8.6.1. Function of the Compressor Stator. The primary function of the compressor stator is to change the direction of flow of the primary coolant leaving the compressor rotor from helical to axial. This action minimizes flow losses. The compressor stator assembly also provides a shroud at the tips of the compressor rotor blades to minimize tip losses for the rotor blades. Finally, the assembly provides a closure over the compressor rotor disc.

B.8.6.2. Physical Description. The compressor stator assembly appears as an outer cylindrical shell and an inner flanged, conical disc joined by the

33 stator blades. The outer shell is formed by bases of the blades clamped and keyed between an alignment flange and sleeve. The inner disc clamps a projection on each blade between the flange of the end cone and the retaining ring. The outer cylinder of the stator assembly is bolted to the outer ring of the helium ducting.

B.8.6.3. Environment. Environment is described in Section B.8.3.

B.8.6.4. Discussion of the FMEA.

Impacts

If a blade were to break from the stator and not fall into the rotor, the effect would be to decrease the effectiveness of straightening the primary coolant flow. This would probably result in a decrease in efficiency too small to detect. However, if a blade were to break from the stator it would seem more likely that it would eventually fall back into the whirling rotor and cause its destruction. If the resultant damage is confined within the boundaries of the helium ducting, repair would be limited to removing the circulator machine assembly and replacing it with a serviceable unit. If damage extended outside the circulator machine assembly, more extensive and difficult repair would be required.

Failure Mode

The most likely failure mode appears to be fracture of a stator blade which results in breaking of the compressor rotor. The foot of each stator blade is keyed into the outer ring, and the tip of each blade has a projection that is simply clamped between flanges of the inner ring. A stator blade would have to escape from both joints to contact the compressor rotor.

B.8.6.5. Product Assurance Controls. Refer to Section B.1.

B.8.6.6. Conclusions and Recommendations. The design of the compressor stator is effective in its function and performance was satisfactory in qualification and acceptance testing. Current controls should be continued.

B.8.7. Diffuser Assembly FMEA

B.8.7.1. Function. The primary function of the diffuser assembly is to convert some of the velocity of the primary coolant exiting the compressor stator into static pressure. This is accomplished by providing a flow channel which has a gradually increasing flow area. The diffuser also supports, at its exit, the primary coolant sampling rake and lines that provide moisture and pressure information.

B.8.7.2. Physical Description. Refer to Section B.8.2 for a physical description of the diffuser.

B.8.7.3. Environment. Refer to Section B.8.3 for a description of the diffuser environment.

B.8.7.4. Discussion of the FMEA.

Impacts

The diffuser assembly is a static unit. It is simply a large tubular structure mounted on one end, with the axis vertical. The pressure differential across the walls is small, and the flow through the unit is not particularly oscillatory. It does not appear likely to fail. However, if it does, it poses a difficult repair problem in that the circulator penetration is not large enough for the diffuser to be passed through. Therefore, any failure or damage that cannot be repaired in place requires the hardware to be remotely detached and removed through the larger center penetration.

Failure Modes

Structural failure of the diffuser assembly appears unlikely because it is a simple structure whose primary load is its own weight. One part of the assembly is a large bellows which seals the diffuser to the lower floor of the PCR.V. The purpose of this seal is to minimize leakage from the compressor discharge back to the inlet. The bellows provides a flexible fit and permits thermal expansion and contraction; it appears to have sufficient flexibility to prevent high stresses. However, as a flexing member it must be considered more susceptible to failure.

Another possible failure mode is the pressure and moisture sensing hardware, which is part of the diffuser assembly. It appears possible, depending on the level of contaminants in the primary coolant, for the sensing ports in the cruciform rake in the diffuser discharge to become plugged. This would mean the loss of moisture measurements. In addition, since a large quantity of tubing is used to bring out the measurement samples, it appears that the tubing offers a relatively significant opportunity for leakage failures.

B.8.7.5. Product Assurance Controls

Design Controls

A design evaluation was performed using numerous references and significant testing. Performance during the testing essentially substantiated that the design is adequate.

Quality Assurance Controls

As part of the circulator-associated hardware, close quality control was maintained over all nondesign aspects (e.g., fabrication and installation). Additional information is presented in Section B.1.

Operational Controls

The diffuser assembly is static in its operation and therefore not significantly affected by operational variations. Neither is it susceptible to failure due to maintenance or other direct operator actions.

B.8.7.6. Conclusions and Recommendations. The diffuser assembly is expected to be structurally and aerodynamically satisfactory. Some improvement in reliability and availability might be gained through revision of the pressure and moisture sensing lines to provide additional independence of the signals from one another. Present controls should be continued. An evaluation should be performed to determine if reliability can be improved through separation to provide independence of the sample lines for future plant designs.

B.9. PRIMARY COOLANT SHUTOFF VALVE FMEA

B.9.1. Description of the Primary Coolant Shutoff Valve (Ref. 1)

A primary coolant shutoff (flapper) valve is installed above each helium circulator to limit reverse flow of helium through a shut-down circulator (see Fig. 3-2 of Volume I). Each valve consists of two semielliptical ribbed plates, common support hinges, and a mechanical stop which prevents either plate from traveling past the full-open position. The plates are held at a small angle to the duct centerline (and each other) when full-open. A U-shaped seal strip is provided in the hinge area to reduce reverse flow leakage between the valve plates when the valve is closed. A 0.010-in. gap between the valve plates and the wall of the cylindrical housing limits leakage and prevents binding at the periphery of the plates.

Circulator operation causes the helium to flow vertically upward through the valve, opening the valve and holding it open. If the associated circulator is shut down, either gravity or reverse flow alone would

close the valve. The plates therefore function as a check valve; no actuator, spring-counterbalance, or weight-counterbalance system is required. When closed, the valve plates (flappers) are at an angle of 45 degrees to the vertical duct centerline (90 degrees to each other) and are supported by radial struts which permit the use of minimum plate thickness to withstand the pressure differential produced by the other operating circulators. This allows the plates to be of minimum weight, so they can be held open by circulator flow under all operating conditions.

B.9.2. Discussion of the FMEA

An FMEA performed on the primary coolant shutoff valve is shown in Volume I, Table 3-2, item 8. Soon after discovery of two of the failure modes shown (i.e., "fails closed," and "provides missiles" which damage a circulator), a plant shutdown would be necessary to remove the associated circulator and replace the defective valve part, since the plant output capacity would otherwise be limited to 65% of nominal. Such a reduction would be required because of a loss of helium flow and associated cooling capacity.

A few other failure modes have been identified which would shorten the life and reduce the efficiency of the equipment. Depending on when such failures are discovered and the severity of their effect on efficiency, they may or may not require a plant shutdown for correction.

B.9.3. Product Assurance Controls

Design Controls

Design controls include provisions to minimize binding of the hinges or valve plates. In particular, the hinges are relatively short to minimize binding due to misalignment. Stellite bushings are used to reduce the chance of wear, abrasion, galling, and seizure between the bushing and the Nitralloy hinge pin. This combination of materials has been shown by

testing to have an acceptably low coefficient of friction in a helium environment (Ref. 2). In addition, the coefficients of thermal expansion for these materials are such that they enhance hinge movement rather than hinder it with increasing temperature. A gap between the edge of a closed valve plate and the housing wall prevents binding in that area. The contact surfaces of the valve plates are flame-sprayed with a nickel-aluminide coating to prevent problems of wear, abrasion, galling, and seizure. As a result of performance tests, several modifications have been incorporated into the design of the flapper valve. Subsequent tests and operational experience support the design adequacy of the valve including all modifications.

Quality Assurance Controls

Quality assurance controls for nondesign factors are discussed in Section B.1.

Operational Controls

The simplicity of the valve design should enhance its operability since no actuation devices are utilized. In addition, the valve is to be tested once per year. Due to the inaccessibility, the valve is designed to require no preventive maintenance. Thus, the valve is not directly susceptible to operator or maintenance errors while in service.

B.9.4. Conclusions and Recommendations

It would appear that disturbance of the flow stream and failing open are the most likely modes of failure for the primary coolant shutoff valve. However, since flow disturbances have already been discovered and corrected as the result of performance tests, and 225 test cycles and hundreds of hours of operation have been observed with no indication of any problem, it appears that the probability of flow disturbance problems or failure to close is adequately controlled. Therefore, the primary coolant shutoff valve appears adequate for FSV.

For FSV, it is recommended that the valve performance be periodically monitored until substantial in-service experience is acquired, and that any failure that occurs be carefully analyzed to ensure that the failure rate is not excessive and the cause is not generic.

For future plants, any further design effort would appear best concentrated on reducing the likelihood of the valve failing to close. Data (Ref. 3) on check valves indicate that about 80% of the failures were failure to close. Mechanisms with a high common mode potential, such as corrosion and plateout which could possibly interfere with the hinge action, should be of primary concern. An economic evaluation should be performed to determine if this design effort is justified. The evaluation should utilize all available information including that which has accrued on the valves at FSV.

B.10. SEALS FMEA

B.10.1. Function of the Seals

Seals are employed in numerous locations in the circulator machine to prevent fluids from entering areas where they are not desired. Since seals are frequently a source of problems, an FMEA has been performed to specifically consider the effect of failure of the various seals utilized. The worst consequences can thus be identified, and steps taken to assure that particularly good quality seals are installed in those areas, for example, by the use of redundant seals or extra thick (silver) coating. Seals have also been considered under the "mechanism" column of FMEAs of the components in which they are to be installed.

B.10.2. Physical Description

Different types of seals have been used to fulfill the requirements of various sealing applications. Where the requirements call for prevention

of leakage of a high-pressure fluid from a vessel or passage, metal O-rings or V-seals have been utilized. In areas where a flow limitation is desired between parts which slide one inside another, metal seal rings are specified.

Metallic O-rings are made of metal tubing which is formed into circular or other required shapes. The typical application places a metallic O-ring in axial compression between parallel faces which are perpendicular to the fluid passage or vessel axis. The seal tubing buckles slightly under compression, resulting in two contact areas on each seal face and maximum contact stress between the seal and the mating faces (see sketch).

Metal V-seals are made of a high strength base material coated with a soft sealing material. When squeezed between flat surfaces, the seal forces the coating material into the mating surface roughness, blocking potential leakage paths.

Metal seal rings are used where installation requires the contact surfaces to slide. The ring material and surface treatment are chosen to be compatible with the contacting materials to deter scuffing and scoring. The sides are finished to close tolerances for proper clearance on installation.

B.10.3. Discussion of the FMEA

FMEAs for the seals are shown in Volume I, Table 3-2, item 9. The severity and location of leakage past a seal will determine the effect. Thus, there may be an insignificant effect in areas of low leakage, or there may be an effect on circulator efficiency to the extent that modified operation is required, or, where efficiency is downgraded appreciably or equipment is jeopardized, circulator replacement may be deemed necessary.

Of particular importance are the passages supplying and draining the various bearings of the circulator. To assure that the high-pressure fluid

in a supply passage will not leak directly into a drain, bypassing the bearing area, special seal-and-bellows arrangements or multiple seals and spacers have been provided.

B.10.4. Product Assurance Controls

The base material and coating of seal rings have been chosen to be compatible with the temperature, pressure, and fluid environments. For seals intended for use in the bearing assembly, Inconel, Inconel-X, Inconel X-750, and nickel alloy 718 were selected as base materials, coated with silver. Temperatures in the bearing assembly are expected to range up to 170°F. The materials chosen can stand environments up to at least 800°F. They are compatible with the water and helium with which they will be associated. The metal seals utilized are rated for pressures well above those expected; self-energizing or pressure-filled O-rings have been selected to increase their sealing effectiveness.

Installation of seals is controlled by specifications concerning circulator machine assembly. Fabrication, inspection, and packaging requirements are specified separately. Static seals such as those being discussed are located in areas which are intended to be inaccessible during the plant life. Therefore, no maintenance is expected, and seals are chosen to be able to withstand all anticipated operating conditions for the life of the plant.

B.10.5. Conclusions and Recommendations

In areas of high pressure or where leakage can cause significant consequences, specially selected seal configurations should be considered, including the possibility of redundancy.*

The groove into which a seal is positioned must be prepared carefully. It must have dimensions compatible with those of the seal in order for the

*Special seal configurations have been implemented in critical areas for FSV.

) seal to be compressed and function properly. The surface finish of grooves and mating faces should be flat and smooth to aid in getting good contact between the soft (silver) coating and the groove and flange faces.

Installation instructions require that proper preparation and installation of the seals be assured by quality control to avoid nicking the sealing surface, which could cause a flow path and possible leakage. Dirt, dust, scale, and other foreign material must be removed from the seal area prior to seal or O-ring installation.

All evidence indicates the controls employed for the FSV circulator meet these requirements and are adequate.

REFERENCES

1. "PSC Main Helium Circulator Design Report," GADR-85, Gulf General Atomic, April 1971.
2. Hedgecock, P. D., Gulf General Atomic, "Summary of Friction Wear Tests Which Have Been Performed Upon Metallic Materials and Flame-Sprayed Coatings at Gulf General Atomic," October 15, 1969 (unpublished data).
3. GIDEP Failure Rate Data Handbook, v. 6, Sources 370-484, Perm. Issue, June 1973.

APPENDIX C

QUANTITATIVE EVALUATIONS

C.1. INTRODUCTION

This appendix contains three detailed analyses illustrating options of design, quality assurance (QA), and operational control, respectively, to reduce expected losses. A real interest rate of 3%/year is employed, and plant down time is valued at \$4000/hr in the analyses. The basis for the plant down time cost is given in Appendix E.

C.2. EXAMPLE ECONOMIC EVALUATION EMPLOYING A DESIGN CONTROL OPTION

C.2.1. Definition of Problem

The current brake design consists of a 0.081-in.-thick silver brake pad inserted into a Nitralloy brake shoe. The silver insert is pressed against the circulator shaft by pressurizing a bellows.

Design problems postulated and evaluated here were the likelihoods that: (1) all of the silver could wear away due to normal application over the life of the circulator, allowing the Nitralloy brake shoe to press against the shaft; (2) the brakes would be spuriously applied, resulting in damage to the shaft due to silver loss as above; (3) the bellows would rupture due to the increased stroke resulting from the postulated wear, thereby causing brake failure and thus jeopardizing the shutdown seal.

C.2.2. Evaluation of Expected Losses

C.2.2.1. Problem Likelihoods. Figure C.2-1 shows an event tree for the postulated problems. Spurious application of the brakes has been evaluated

BRAKES APPLIED NORMALLY (NOT SPURIOUS)	SILVER IS LEFT ON BRAKE SHOE	BELLOWS RUPTURE	"BARE" BRAKE CREATES DEBRIS	BRANCH LABEL	SHUTDOWN SEAL ENDANGERED DUE TO LOSS OF BRAKES	CIRCULATOR DAMAGE	NO EFFECT
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Fig. C.2-1. Event tree for circulator unavailability due to brake failures

from the fault tree in Fig. C.2-2. It was estimated that if such an application occurred with the circulator running at normal operating speed, the probability is essentially 1.0 that all the silver would wear away, and debris would damage the circulator.

The likelihood that all of the silver wears away due to normal actuation was evaluated as described below. There was no direct evidence available to determine if debris generated by the Nitralloy brake shoe rubbing the shaft would cause damage, and discussions with specialists led to the conclusion that indirect evidence was also insufficient to determine if damage is more likely than not; therefore, a probability of 0.5 was assigned for this event.

The likelihood of bellows rupture due to increased stroke is also evaluated below.

Probability of Silver Wear

To determine the probability that all the silver will wear off under normal actuation conditions (P_{normal}) it is necessary to determine the probability density functions $f(\)$ for the thickness of the silver shoe (t), the wear rate of silver per cycle (w_r), and the number of cycles expected in a plant life (n). These are combined to yield the probability that the wear w exceeds the thickness t . Thus,

$$P_{\text{normal}}(w > t) = \int_{t=0}^{\infty} f(t) \int_{w_r=0}^{\infty} f(w_r) \int_{n=t/w_r}^{\infty} f(n) dn dw_r dt$$

where $w \equiv w_r n$.

The thickness of the silver shoe in the existing design was taken to be normally distributed, with 90% of the shoes falling within the tolerances specified, and 1% of the out-of-tolerance shoes remaining in the

3 7E-4/YR = 1 5E-2/PLANT LIFE

Fig. C.2-2. Fault tree: spurious application of brakes; present design

population after inspection. Thus, the distribution is as shown in Fig. C.2-3.

Fig. C.2-3. Probability density function of silver shoe thickness

A distribution on the upper limit wear rate has been established based on the information that: (1) plating applied to a small piece, such as a brake shoe, will vary in thickness from the minimum specified to slightly more than the minimum; (2) silver-plated brake shoes were actuated to stop circulator rotation 50 times during testing without the silver plating wearing off. Thus, if a nominal 0.002 in. of plating did not wear off in 50 cycles, a distribution on the wear rate, based on the upper limit, is found to range between 4×10^{-5} and 6×10^{-5} in. of wear per application.

A distribution of the number of cycles the brake shoe is expected to see during the life of the plant has been developed by using the number of cycles recorded so far at the Fort St. Vrain plant, estimates made by cognizant personnel concerning cycles expected during plant operation, and engineering judgment.

If one integrates over these distributions, the probability that a brake shoe will wear out during the life of the plant from normal actuation is

$$P_{\text{normal}} (w > t) = 1.7 \times 10^{-4} .$$

Probability of Bellows Rupture

To determine the probability that the bellows will rupture under normal actuation conditions, it is necessary to determine the probability that the bellows will rupture for a given stroke or elongation. This is combined with the probability density functions for the wear rate of the silver brake shoe per cycle (w_r), and the number of cycles (n) expected in a plant life, to give the probability that the bellows will rupture over the life of the plant.

The probability that a bellows will rupture for a given elongation has been determined from discussion with a bellows manufacturer, who estimates that 1% of bellows fail before they have seen their rated number of cycles, and that 50% of the bellows fail by the time they have seen 25% more than their rated number of cycles. The distribution of failures is taken to be log normal above the rated number of cycles, and rectangular below the rated value.

A linear relation was postulated for the rated number of cycles for a given elongation, given that the rated number of cycles is 4280 for a nominal 0.105-in. stroke, and assuming that at 0.186-in. stroke the rated number of cycles is 0 (see Fig. C.2-4). The probabilities of given elongations are found using the distributions for silver wear (w_r) and cycles (n), which were described above.

These three distributions (on bellows rupture, silver wear, and cycles) were then combined to yield the probability that the brake bellows will rupture over the life of the plant.

C.2.2.2. Consequence Values. The economic consequences of failure of the brakes as described may vary from a slight loss due to time spent confirming the failure and determining the extent of damage which is minor, to

Fig. C.2-4. Bellows rated cycles versus elongation

a significant loss resulting from removing, replacing, and repairing a circulator which has suffered operational impairment.

Using the Fort St. Vrain plant down-time cost of \$96,000/day derived in Appendix E, and engineering estimates (and confirming experience) that circulator replacement time ranges from 21 days to 56 days, the plant down-time loss associated with replacing a circulator is between \$2,000,000 and \$5,400,000.

C.2.2.3. Expected Losses. The expected losses due to brake failures can thus be calculated, and are shown in Table C.2-1. The upper-bound present values of these expected losses were calculated by dividing the expected loss into 40 equal payments over the life of the plant, and using a 3% real interest rate. This method was also used for the lower-bound present value of loss due to spurious brake application, since this event is equally likely to occur anytime during the life of a plant. However, because the likelihoods of silver wear and brake rupture increase with plant life, the lower-bound present values of loss due to these events were computed under the assumption that the accumulated expected losses occur at the end of the plant life. Thus, one payment is assumed, at the end of 40 years, and a 3% real interest rate is again used. The resulting present values are shown in Table C.2-1. It can be seen that the largest loss is due to spurious application of the brakes. A very small loss is expected from wear of all of the silver.

C.2.3. Options

Any design option affecting the amount of silver on the brake shoe or the resistance of the brake bellows to rupture would cost at least \$2,000,000 to install in each of the circulators at Fort St. Vrain (i.e., the cost of replacing a circulator). Thus, since the present value of expected damage due to failure of these items is under \$3500, it is not economically justified to make any such design changes at FSV.

TABLE C.2-1
EXPECTED LOSSES DUE TO BRAKE FAILURES

	A Bellows Rupture	C Silver Wear	G Spurious Application
Branch probability per plant life (from Fig. C.2-1)	1.1×10^{-3}	8×10^{-5}	1.5×10^{-2}
Consequence, \$	$>2 \times 10^6$ $<5.4 \times 10^6$	$>2 \times 10^6$ $<5.4 \times 10^6$	$>2 \times 10^6$ $<5.4 \times 10^6$
Expected loss, \$	$>2,200$ $<5,940$	>160 <432	$>30,000$ $<81,000$
Present value of expected loss, \$	>675 $<3,430$	>49 <250	$>17,340$ $<46,800$

Further testing of the wear characteristics of the silver brake shoes should be considered to determine the wear rate more precisely for future designs, since the probability of wear calculated here is based on an estimated upper value for the wear rate. Reduction of this uncertainty could readily yield an even lower present value of the expected loss and make it economically unjustified in future designs to pursue design options for the sole purpose of reducing the expected loss due to shoe wear or bellows rupture.

Design options that would reduce the likelihood of a spurious application of the brakes fall into two classes. Those requiring modification of the circulator machine, at a cost of $\geq \$2,000,000$, are not justified for Fort St. Vrain. Those that would modify the pressurization valves or controls outside of the circulator may be justified if the implementation cost does not exceed the present value of expected loss reduction obtained by implementing the option.

A design option that was considered involved modifying the arrangement of the pressurizer and vent valves so that both redundant sets of valves must be actuated before the brakes are spuriously applied. The present design allows spurious brake application when one set of redundant valves is actuated (see Fig. C.2-5). This design option is feasible provided that, if the brakes are failed when bearing water is removed, the chromium oxide on the bearing surfaces allows the circulator to come to a stop without circulator damage. An additional time-delay interlock is included in this option to prevent seal application until circulator rotation is halted. This is accomplished by use of a time delay following receipt of a speed signal indicating brake effectiveness, i.e., that rotation has been reduced to well below self-turbining speed. The reduction in loss can be computed by evaluating a fault tree based on the new design, as shown in Fig. C.2-6.

Since this option utilizes the same valves, implementation costs are based on the additional interlock circuitry and the manhours required to

Fig. C.2-5. Schematic of brake actuation valve arrangements

Fig. C.2-6. Fault tree: spurious application of brakes; design option A

physically change the valve arrangements, execute functional and proof pressure tests, and prepare and review documentation of the change.

The implementation cost estimate of this option for FSV is \$3125 per circulator. Comparing this to the reduction in present-value expected loss of $\geq \$13,090$ per circulator, it appears to be economically justified (see Table C.2-2).

C.2.4. Conclusions

An event tree evaluation of brake failures was used to determine the present values of expected losses over the life of a plant. These values show that the only economically justified area where the design might be modified to reduce losses at Fort St. Vrain is outside the circulator, in the brake actuation valve arrangement. Further testing is recommended to verify the silver wear rate before deciding on the justifiability of other options inside the circulator for future plants.

C.3. EXAMPLE ECONOMIC EVALUATION EMPLOYING A QUALITY ASSURANCE CONTROL OPTION

C.3.1. Introduction

This section presents an example of detecting and reducing expected losses through QA controls. The helium ducting part of the circulator machine assembly was selected as the sample part for this analysis.

The QA function influences the operability of the helium ducting by verifying that the material is correct, that the fabrication is properly done, that the assembly is correct, that the handling and transportation do not cause damage, and that installation is proper. This analysis concentrates on the life cycle events for a helium ducting part for which QA controls are applied, and evaluates their effectiveness in terms of the expected loss associated with control imperfections for each life cycle event, which might have been prevented by improved QA controls.

TABLE C.2-2
COMPARISON OF EXPECTED LOSSES (\$) PER CIRCULATOR DUE TO OPTIONS IN
BRAKE ACTUATION SYSTEM DESIGN

	Design			
	FSV		3000-MW Plant	
	Present	Option A	Present	Option A
$P_v[E(L)]$	>17,340 <46,800	>4,250 <11,500	>52,020 <140,400	>12,750 <34,500
$P_v[E(L)]$ savings (loss)	--	>13,090 <35,300	--	>39,270 <105,900
Implementation costs	--	3,125	--	300
Net savings (loss)	--	>9,965 <12,185	--	>38,970 <105,600

The first step in the evaluation is to determine the life cycle events (LCEs) and the operations to be examined in each. Next, it is necessary to evaluate the probability of error or failure for each operation under the existing QA controls. Then the consequence of each error or failure, considering both hardware repair or replacement and resulting plant outage, must be evaluated. The product of probability and associated loss for each potential mishap is the expected loss for that event. Each potential mishap and its expected loss must be examined to determine if there is a QA control option that will reduce the net expected loss.

C.3.2. Discussion

Evaluation of the efficacy of the QA controls requires examining, individually, all of the operations in which the helium ducting is involved. This is accomplished as follows:

1. Divide the life of a helium ducting into distinct phases to be called life cycle events (LCEs).
2. Within each LCE for which QA controls would be applicable, examine each operation to determine events that could result in a loss of plant availability, and whether optional controls could reduce the net expected loss.
3. Evaluate the expected probability of each such event for the lifetime of the plant occurring under the existing controls.
4. Evaluate the associated loss of recovering from each such event. (Include the cost of repair or replacement of hardware, and cost of replacement power during plant startup delay or plant outage.)
5. Calculate the expected loss for each LCE.
6. Examine each LCE and its expected loss to define possible QA control options that should decrease costs or probabilities of damage.

7. Evaluate net expected losses associated with each option.
8. Make recommendations for incorporating or not incorporating options.

C.3.2.1. Life Cycle Events (LCEs). The life of a helium ducting was divided into seven LCEs. The LCEs provided a framework for defining the specific operations on the helium ducting to be evaluated in the analysis. Several representative operations were selected for each LCE. A listing of selected LCEs and operations is presented in Table C.3-1. The operations were selected on the basis of their being significantly influenced by QA controls and also offering the possibility of significant damage to a helium ducting with attendant losses.

C.3.2.2. Probabilities. A review of LCE operations (Table C.3-1) reveals that human error is the most likely cause of damage to the helium ducting. For example, in machining and welding, operator errors in setting up the work, reading the instruments, or adjusting the machine could cause damage; in handling, operator errors in hitching on cables or operating a crane could cause damage. It is true that cables can break and machines can fail, but the probabilities for these failures are relatively small and are therefore omitted from this analysis.

To provide probabilities for human errors for this analysis, each activity was examined and a similar activity sought in Ref. 1. Several activities listed in Ref. 1 and judged to be most similar to the activities in the LCEs for the helium ducting are presented in Table C.3-2. In the detailed evaluation, presented as in Section C.3.4, the operation required for the activity is stated, followed by a number in parentheses. The number in parentheses in Section C.3.4 is a reference to the number of the activity listed in Table C.3-2 that is judged most similar to the activity of the operation.

TABLE C.3-1
ACCIDENT COST EXPECTED VALUE EVALUATION FOR FIRST PRODUCTION UNITS

LCE and Cause of Damage	Existing Control		
	Probability	Cost/Event (\$)	Expected Cost per Plant Lifetime (\$)
1. Fabrication			
1.1. Machining error	0.0083	294,300	-2,443
1.2. Welding error	0.0083	293,400	-2,435
1.3. Drop of helium ducting	0.094	297,000	-27,918
2. Assembly			
2.1. Thread stripping	0.00020	292,800	-59
2.2. Drop of helium ducting	0.00015	297,000	-45
3. Shipping for test (Valmont)			
3.1. Hit by shipping canister	0.0000070	681,000	-5
3.2. Drop of circulator during recline	0.000051	49,320	-3
3.3. Transportation accident	0.0073	49,320	-360
4. Test			
4.1. Drop of circulator during erection	0.000051	49,320	-3
4.2. Hit by shipping canister when removed	0.0000070	96,000	-1
4.3. Interference when raised	0.0000087	1,353,000	-12
5. Shipping to site			
5.1. Hit by shipping canister	0.0000070	1,353,000	-9
5.2. Drop during recline	0.000051	49,320	-3
5.3. Transportation accident	0.0013	49,320	-64

TABLE C.3-1 (Continued)

LCE and Cause of Damage	Existing Control		
	Probability	Cost/Event (\$)	Expected Cost per Plant Lifetime (\$)
6. Installation at site			
6.1. Drop during erection	0.000051	49,320	-3
6.3. Hit by shipping canister	0.000023	96,000	-2
6.4. Hit by lower shield cask	0.0000070	1,353,000	-9
6.6. Interference when raised	0.0000087	1,353,000	-12
7. Replacement of failed circulator			
7.1. Damage to a replacement	(see text)		-37

TABLE C.3-2
HUMAN RELIABILITIES ^(a)

Ref. No.	Operation	Reliability
1	Position ZERO IN knob	0.9976
2	Read time (watch)	0.9983
3	Read pressure gage	0.9969
4	Read technical instructions	0.9918
5	Position 2-position switch	0.9985
6	Install lockwire	0.9961
7	Record reading	0.9966
8	Inspect for rust and corrosion	0.9963
9	Inspect for bellows distortion (visual)	0.9961
10	Inspect for dents, cracks, and scratches	0.9967

^(a) From Ref. 1.

The operator's performance of an operation is, in many cases, divided into several separate actions which are evaluated separately and then combined. Where an inspector is present to check an operation, the probability of his also making an error is evaluated separately.

It is assumed that five "production" helium circulators are manufactured. The fifth one is planned to be a spare. It is further assumed that there is only one circulator assembly facility, and that plant startup will be delayed 14 days for each of the first four circulators that are damaged. Therefore, the probability of damage used in the evaluation is the probability that one or more of the first four suffers damage.

C.3.2.3. Consequence Cost. The cost of recovery from damage to the helium ducting is considered to derive from four basic sources. These are:

1. The cost of associated analyses and deciding on corrective action.
2. The cost of materials required for constructing a new helium ducting.
3. The cost of the labor required to restore and inspect the damaged helium ducting.
4. The cost of replacement power during a delay in plant startup or a plant outage resulting from the damage to the helium ducting.

To simplify the determination of how much plant startup delay or outage was associated with each operation, it was assumed that the prototype and each production unit were on the critical path for plant startup in the production phase. As a result, each day of helium ducting unavailability is taken to represent a day of plant startup delay. The cost of replacement power during plant startup delay or plant outage is estimated to be \$4000/hr or \$96,000/day for the 330-MW(e) FSV plant. This is roughly equal

to a cost of \$0.012/kWh. The cost of a complete helium circulator is estimated to be \$300,000. The helium ducting is estimated to account for 3% of that cost. Therefore, the manufacturing cost of a replacement helium ducting part is taken to be \$9000.

If a helium ducting part is dropped or otherwise receives a hard blow, it is assumed that the outer shell is displaced relative to the inner shell by bending of one or both of the shells and/or bending of the support struts. The compressor stator, which mounts on the outer shell of the helium ducting, must be precisely aligned with the compressor rotor. Thus, the outer shell must be precisely aligned with the inner shell and, once bent, it is assumed impossible to realign. Damage to the helium ducting is therefore expected to result from dropping or striking during installation of the shipping container for shipping or during installation of the lower shielding cask at FSV. The resulting bending would be expected to require fabrication of a new helium ducting, which is estimated to take 15 calendar days. If the helium ducting part of one of the first four production circulators is damaged, it is assumed that the helium ducting part from the next scheduled production circulator could be substituted with only a 3-day delay in circulator and plant startup schedules.

Only minor damage is considered possible to occur to the helium ducting part of a circulator during removal of the shipping container because the relative motion is less. Consequently, only a 1-day delay for refinishing is allocated. While the helium ducting (as part of the helium circulator) is installed in the PCRV, there appears to be no way that QA controls can affect it. However, even though the circulators are designed for a 40-year life, it is possible that one or more will have to be removed during the plant lifetime. If, during installation of a replacement circulator, the helium ducting were damaged, then the plant would be out of service until either the initially failed or the replacement circulator could be repaired. For this analysis, it is assumed that the initially failed circulator would be so severely damaged that it would be necessary to repair the lesser damaged replacement and the resulting plant outage is set accordingly. It is assumed that circulator replacement is required four

times in a 40-year plant life. The present value is calculated for the expected values of the future occurrences. An interest rate of 3% is used.

C.3.2.4. Expected Values. Table C.3-1 lists the values of probability of occurrence, cost per occurrence, and expected loss for each operation of each LCE for the production circulators. The expected value is the present value of the expected loss in a plant lifetime due to that event. Of course, the helium ducting is exposed to damage primarily during the LCEs of initial manufacturing, testing, and installation. Therefore, the expected losses derive primarily from these events in the preliminary part of a plant lifetime. Only one possibility for damage is presented for the operating LCE (i.e., Table C.3-2, item 7.1).

A review of the expected losses for each production circulator reveals that most of the values are quite small. One, however, is outstandingly large. This is the expected loss of \$27,918 for operation 1.3, which pertains to the possibility of dropping the helium ducting while lifting it onto a machine for a fabricating operation. Thus, it is seen that the technique has indicated one operation that has a significantly greater expected loss than any of the others.

C.3.2.5. Corrective Action. In Table C.3-1, the primary reason for the high expected loss for item 1.3 is a high probability of occurrence. The probability of this event (see Section C.3.4) is based on a probability of error by the operator ($P_{\text{error}} = 0.0039$), the number of lifting operations per circulator ($N_o = 3 \times 2 = 6$), and the number of circulators ($N_c = 4$). The number of circulators is fixed by the plant configuration. The number of lifts is presumed fixed by the required fabricating operations. One way to reduce the probability of occurrence then is to reduce the probability of an operator error, and one way to do this is to require that the hitch, made by the operator, be inspected before the lift is made. Then the probability of error becomes the probability that the operator makes the error ($P_o = 0.0039$) and that the inspector fails to detect the error [$P_I = 0.0033$ (10)]:*

*Refers to similar activity listed in Table C.3-2.

$$P_{\text{error}} = P_o \times P_I = 0.0039 \times 0.0033 = 0.0000129 \quad .$$

The probability of damage to one of the first four production circulators for this operation then becomes

$$P_{\text{damage}} = 4 \times (3 \times 2 \times 0.0000129) \times 1 = 0.00031 \quad .$$

The expected loss for the event then becomes

$$E(L)_{\text{production}} = 0.00031 \times \$297,000 = \$92.07 \quad .$$

This is estimated to result from a requirement for one inspector to spend about 1 hr per inspection for six inspections per circulator for five circulators at a cost of $\leq \$40/\text{hr}$. Thus, the cost of the added inspections is

$$\text{cost} \leq 1 \times 6 \times 5 \times 40 \leq \$1200 \quad .$$

In summary, a means has been shown for reducing the expected loss by \$27,826 (\$27,918 - \$92) in expected loss from damage by expending not more than \$1200 for additional inspection operations.

C.3.3. Conclusions

The economic evaluation technique illustrated by the analysis presented herein is a useful means for determining areas of operation where expected losses can be reduced by improving QA controls. By evaluating the expected losses associated with existing QA controls, and comparing these with expected losses under optional controls, the controls can be established on an economic basis. When this is done across all the controls for a system or component, the actual losses experienced should be reduced proportionately to the reduction made in expected losses.

C.3.4. Detailed Calculations for Life Cycle Event Evaluation (see Table C.3-1)

C.3.4.1. Fabrication.

1. Machining

Basis. The part is large (32 in. o.d. x 24 in. high). Some precision machining is required after welding. Major cuts have a safety inspection operation. Cutting undersize would require cutting off and replacing a piece or building up with weld and then remachining. Rework is estimated to take 10 days.

Probability. The operator sets the machine; quality control verifies the setup. Twenty precision cuts are required per unit. The operations required and the failure probability for each cut are:

Read base position (2)*	0.0017
Record base position (7)	0.0034
Calculate required setting (7)	0.0034
Make setting (2)	0.0017
P (operator total probability of error for 1 precision cut)	= 0.0102
P (QC error) = 0.0102 (same as for operator)	
P (4 production units) = $4 \times (20 \times 0.0102 \times 0.0102)$	= 0.0083

Consequence. Calendar time for repair is determined from the following activities and times required:

*Numbers in parentheses refer to Table C.3-2 reliabilities for similar events.

<u>Activity</u>	<u>Calendar Time</u>
Plan the repair	1 day
Weld (or flame spray)	2 days
Inspect	1 day
Heat treat	2 days
Set up on machine	1 day
Total	<u>7 days</u>

Manpower costs for repair are determined on the basis of 1.5 men, 2 shifts per day for 7 days, at \$300 per man-shift. Cost is therefore $1.5 \times 2 \times 7 \times 300 = \6300 . Material cost for repair is negligible.

The total cost for production unit damage (spare substitution allows outage time equal to 3 days: 2 days to complete next unit plus 1 day setup)

$$\text{Cost (production unit)} = 3 \times 96,000 + 6300 = \$294,300 \quad .$$

Expected Losses

$$E(L) \text{ production} = 0.0083 \times 294,300 = \$2443 \quad .$$

2. Welding Error

Basis. There are 5 circumferential welds on the inner shell totaling about 250 in. The 48 curved welds, which hold the 12 struts to the inner and outer shells, total about 120 in. in length. The welds are qualified by sample welds and x-ray. Finding a defective weld requires cutting out the defect and then rewelding and reheat treating.

Probability. The probability of welding errors is judged to be about the same as for machining errors as described in (1) above, or

$$P (4 \text{ production units}) = 0.0083 \quad .$$

Consequence. Calendar time for repair is estimated to be 1 day less than for machining errors because welding will take 1 day instead of 2. Repair time thus is 6 days.

Manpower costs for repair are figured on the basis of 1.5 men, 2 shifts per day, for 6 days at \$300 per man-shift, or $1.5 \times 2 \times 6 \times 300 = \5400 . Material cost for repair is negligible.

Total cost for production unit damage (spare substitution allows outage time equal to 3 days):

$$\text{Cost (production unit)} = 3 \times 96,000 + 5400 = \$293,400 \quad .$$

Expected Losses

$$E(L) \text{ production} = 0.0083 \times 293,400 = \$2435 \quad .$$

3. Drop of Helium Ducting

Basis. The welded assembly is lifted from the skid to the machine and down again three times by operators using a small electric crane. There is no quality control check of the hitching.

Probability.

$$P [\text{operator connects the hitch wrong (6)}] = 0.0039 \quad ,$$

$$P (\text{production units}) = 4 (3 \times 2 \times 0.0039) \times 1 = 0.0936 \quad .$$

Consequence. A drop is considered to cause distortion that requires making a new helium ducting unit. Making a new unit,

including procuring material, is estimated to require 15 calendar days average.

Total cost for production unit replacement (spare availability allows outage time equal to 3 days):

$$\text{Cost (production)} = 3 \times 96,000 + 9000 = \$297,000 \quad .$$

Expected Losses

$$E(L) \text{ production} = 0.094 \times 297,000 = \$27,918 \quad .$$

C.3.4.2. Assembly.

1. Thread Stripping

Basis. Stripping of tapped holes in outer shell flange onto which the stator clamps appears possible by overtorquing. Such an event would require removing the helium ducting from the bearing assembly, plugging and retapping the hole, and remounting the helium ducting.

Probability. The torquing is accomplished by an operator and checked by an inspector. The following probabilities for human error are selected:

$$P [\text{operator sets the torque wrong (1)}] = 0.0024 \quad ,$$

$$P [\text{QC checks torque wrong (2)}] = 0.0017 \quad .$$

Total probability of error for a production unit (there are 12 holes per circulator):

$$\begin{aligned} P (\text{production unit}) &= 4 (12 \times 0.0024 \times 0.0017) \times 1 \\ &= 0.00020 \quad . \end{aligned}$$

Consequence. Repair of damaged unit is expected to require plugging the damaged hole with weld and retapping. Repair is estimated to require 1 day to replace the helium ducting plus 6 days for repair.

Cost of manpower to repair the damaged unit requires 2 men for 8 days at \$300/day:

$$\text{Cost (manhours)} = 2 \times 8 \times 300 = \$4800 \quad .$$

Cost of materials for repair is negligible.

Total cost for damage to production unit (outage time equals 3 days to bring up spare):

$$\text{Cost (production unit)} = 3 \times 96,000 + 4800 = \$292,800 \quad .$$

Expected Losses

$$E(L) \text{ production unit} = 0.00020 \times 292,800 = \$58.96 \quad .$$

2. Drop of Helium Ducting

Basis. Helium ducting is moved from a skid to the top of the circulator machine assembly and down again three times for measurement, fitting, and assembly. Consequences are identical to those in Section C.3.4.1(3).

Probabilities. It is assumed that a written procedure is used and that an inspector is present to check on the operation. Activity probabilities are:

$$P [\text{operator attaches the hitch wrong (6)}] = 0.0039 \quad ,$$

$$P [\text{inspector does not catch the error (10)}] = 0.0033 \quad ,$$

$$P \text{ (production units)} = 4 (3 \times 0.0039 \times 0.0033) \times 1 \\ = 0.00015 \quad .$$

Consequence.

$$\text{Cost (production unit)} = \$297,000 \text{ [same as in C.3.4.1(3)]} \quad .$$

Expected Losses

$$E(L) \text{ production unit} = 0.00015 \times 297,000 = \$44.55 \quad .$$

C.3.4.3. Shipping for Test.

1. Hit by Shipping Canister

Basis. The shipping canister is fitted over the compressor end of the circulator. The canister, estimated to weigh 500 lb, is considered to swing and strike the helium ducting, thereby damaging the ducting but not damaging other circulator parts.

Probabilities. The following activities and probabilities are considered part of this accident:

$$P \text{ [crane operator causes canister to swing (5)]} = 0.0015 \\ P \text{ [hitcher allows canister/compressor overlap (9)]} = 0.0039 \\ \text{Probability of major damage if hit} = 0.3 \\ \text{Probability of minor damage if hit} = 0.5 \quad .$$

Total probability of minor damage:

$$P \text{ (production/minor)} = 4 \times (0.5 \times 0.0015 \times 0.0039) \times 1 \\ = 0.000012 \quad .$$

Total probability of major damage:

$$\begin{aligned} P(\text{production/major}) &= 4 \times (0.3 \times 0.0015 \times 0.0039) \times 1 \\ &= 0.000007 \end{aligned}$$

Consequences. Minor damage is assumed to be scratches and/or dents that can be polished out in place in 1 day. Major damage is considered to require that a new helium ducting be manufactured. For major damage to a production unit, the spare helium ducting is presumed to be substituted in 7 days (i.e., 2 days to return to assembly area, 3 days to fit the new helium ducting, and 2 days to prepare to ship).

Cost of repairing minor damage:

$$\text{Cost (production/minor)} = 1 \times 96,000 = \$96,000$$

Cost of repairing major damage [circulator returned to the assembly area (4 days) to fit spare helium ducting (3 days)]:

$$\text{Cost (production/major)} = 7 \times 96,000 + 9000 = \$681,000$$

Expected Losses

$$E(L) \text{ production/minor} = 0.000012 \times 96,000 = \$1.15$$

$$E(L) \text{ production/major} = 0.0000070 \times 681,000 = \$4.77$$

Note that the expected loss from major damage is significantly greater than for minor damage because both probability and cost are greater. Therefore, only the major damage entry will be calculated and tabulated for this and succeeding LCEs.

2. Drop of Circulator During Recline

Basis. The circulator is assembled with its axis vertical and shipped with its axis horizontal. The circulator is lowered to the horizontal by picking it up with a crane, setting pivots on the lower assembly into yokes on the shipping skid, and then reclining the upper part into a cradle on the other end of the shipping skid.

Possibilities. The probabilities are similar to those of Section C.3.4.2 except there is a single lift.

$$P [\text{operator attaches the hitch wrong (6)}] = 0.0039 \quad ,$$

$$P [\text{inspector does not catch hitching error (10)}] \\ = 0.0033 \quad ,$$

$$P (\text{production units}) = 4 \times (1 \times 0.0039 \times 0.0033) \times 1 \\ = 0.000051 \quad .$$

Consequence

Hardware Repair. This accident is assumed to result in a cost of hardware repair and replacement equal to the cost of a new circulator (\$300,000). The helium ducting is assumed to represent 3% of this amount, or \$9000.

Plant Outage for Production Unit Damage. In the event an assembled production circulator suffers major damage, it is assumed the next circulator in the production schedule is following by 14 days and is substituted. Because the whole circulator is presumed damaged, the helium ducting share of the outage loss is taken to be 3% of the total.

$$\begin{aligned}\text{Cost (production)} &= 9000 + 3\% \times 14 \times 96,000 \\ &= 9000 + 40,320 = \$49,320 \quad .\end{aligned}$$

Expected Losses

$$E(L) \text{ production} = 0.000051 \times 49,320 = \$2.52 \quad .$$

3. Transportation Accident

Basis. The circulator is shipped with shockmaster units having 5, 10, and 50-g trip settings. Evaluation by design indicates that tripping of even a 50-g unit does not indicate damage to a machine. Consequently, transportation is evaluated on the basis that only a truck accident will damage the helium ducting.

Probabilities. Values are based on the article, "Transportation Accidents - How Probable," in Nuclear News for May 1973. Value used is the sum for all speeds, and all severities for trucks.

$$P \text{ (truck accident)} = 1.6 \times 10^{-6} \text{ per mile} \quad .$$

$$\text{Distance (San Diego to Denver)} = 1134 \text{ miles} \quad .$$

$$\begin{aligned}P \text{ (accident, production)} &= 4 \times (1134 \times 1.6 \times 10^{-6}) \times 1 \\ &= 0.0073 \quad .\end{aligned}$$

Consequence. Consequences are the same as for Section C.3.4.3(2).

$$\text{Cost (production)} = 9000 + 3\% \times 14 \times 96,000 = \$49,320 \quad .$$

Expected Losses

$$E(L) \text{ production unit} = 0.0073 \times 49,320 = \$360.04 \quad .$$

C.3.4.4. Test.

1. Drop of Circulator During Erection

Basis. The circulator is received at the test site in a horizontal attitude and must be erected for installation in the test facility.

Probabilities. Probabilities are the same as for Section C.3.4.3(2).

$$P [\text{operator attaches the hitch wrong (6)}] = 0.0039 \quad .$$

$$P [\text{inspector does not catch the hitching error (10)}] \\ = 0.0033 \quad .$$

$$P (\text{production}) = 4 \times (1 \times 0.0039 \times 0.0033) \times 1 = 0.000051 \quad .$$

Consequence. Consequences are the same as for Section C.3.4.3(2).

$$\text{Cost (production unit)} = 9000 + 3\% \times 14 \times 96,000 \\ = 9000 + 40,320 = \$49,320 \quad .$$

Expected Losses

$$E(L) \text{ production unit} = 0.000051 \times 49,320 = \$2.52 \quad .$$

2. Hit by Shipping Container

Basis. The shipping container must be removed from the circulator assembly. It is judged that this operation permits only a light blow to be struck to the helium ducting, doing light damage that can be repaired in place in 1 day.

Probabilities. Probabilities are the same as in Section C.3.4.3(1).

$$P [\text{crane operator causes canister to swing (5)}] = 0.0015 \quad .$$

$$P [\text{hitcher allows canister/compressor overlap (9)}] \\ = 0.0039 \quad .$$

$$P (\text{production unit}) = 4 \times (0.3 \times 0.0015 \times 0.0039) \times 1 \\ = 0.000007 \quad .$$

Consequence. Consequence is cost of 1 day delay in plant startup. Cost of repair (i.e., polishing out minor dents or scratches) is negligible.

$$\text{Cost (production unit)} = 1 \times 96,000 = \$96,000 \quad .$$

Expected Losses

$$E(L) \text{ production unit} = 0.000023 \times 96,000 = \$2.21 \quad .$$

3. Interference When Raised

Basis. The circulator is raised into its installed position in the test facility by a hydraulic ram. It is guided into place by temporarily installed guide rods. The requirement for the helium ducting to slip up inside the inlet assembly provides an opportunity for interference and damage. It is assumed that overload is protected against by hydraulic pressure switches and gages similar to those provided for installation at the plant site.

Probabilities

$$\begin{aligned} P (\text{pressure switch fails to actuate}) &= \lambda_g \times \text{FMFR} \times K_{\text{vib}}^* \\ &= 0.000022 \times 0.635 \times 50 \\ &= 0.0007 \quad . \end{aligned}$$

$$P [\text{operator reads pressure gage wrong (3)}] = 0.0031 \quad .$$

$$\begin{aligned} P (\text{production unit}) &= 4 \times (0.0007 \times 0.0031) \times 1 \\ &= 0.0000087 \quad . \end{aligned}$$

Consequences. Consequence estimate assumes damage is discovered during the installation. Unit is lowered and returned to San Diego for replacement of the helium ducting only. For the production unit assume next unit in line is substituted 14 days after damage (total outage cost is assigned to helium ducting).

$$\text{Cost (production unit)} = 9000 + 14 \times 96,000 = \$1,353,000 \quad .$$

Expected Losses

$$E(L) \text{ production unit} = 0.0000087 \times 1,353,000 = \$11.77 \quad .$$

C.3.4.5. Shipping From Test Site to Plant Site.

Basis. It is assumed that each production circulator is shipped directly from the test site to the plant site.

1. Hit by Shipping Canister

Basis. The canister must be installed before shipping.

*Values from FARADA source 444 - where λ_g = generic failure rate, FMFR = failure mode frequency ratio, and K_{vib} = vibration correction factor.

Probabilities. Operations and probabilities are judged to be the same as for Section C.3.4.3(1) (only major damage evaluated).

$$\begin{aligned} P (\text{production unit}) &= 4 \times (0.3 \times 0.0015 \times 0.0039) \times 1 \\ &= 0.000007 \quad . \end{aligned}$$

Consequences. This analysis assumes there is no further need for the prototype after the testing is completed. For a production unit it assumes the next unit in line is substituted after 14 days. Cost of a new helium ducting is required.

$$\begin{aligned} \text{Cost (production unit)} &= \text{hardware cost} + \text{outage cost} \\ &= 9000 + 14 \times 96,000 \\ &= \$1,353,000 \quad . \end{aligned}$$

Expected Loss

$$E(L) \text{ production unit} = 0.000007 \times 1,353,000 = \$9.47 \quad .$$

2. Drop During Recline

Basis. Each production circulator must be reclined to the horizontal position for shipping.

Probability of Dropping. This is assumed to be the same as in Section C.3.4.3(2).

$$P (\text{production unit}) = 0.000051 \quad .$$

Consequence. The whole circulator is assumed damaged; therefore, the helium ducting share of the cost is taken as 3% of the hardware cost and outage cost.

$$\begin{aligned} \text{Cost (production unit)} &= 3\% (300,000 + 14 \times 96,000) \\ &= 3\% (1,644,000) = \$49,320 \quad . \end{aligned}$$

Expected Loss

$$E(L) \text{ production unit} = 0.000051 \times 49,320 = \$2.52 \quad .$$

3. Transportation Accident

Basis. Damage results only from accident. Probability of accident per mile same as in Section C.3.4.3(3).

Probability. Assume 200 miles from test site to plant site.

$$\begin{aligned} P(\text{production unit}) &= 4 \times (200 \times 1.6 \times 10^{-6}) \times 1 \\ &= 0.0013 \quad . \end{aligned}$$

Consequence. Entire circulator is assumed damaged. Helium ducting portion of cost is 3% of cost of new circulator plus plant outage of 14 days.

$$\begin{aligned} \text{Cost (production unit)} &= 3\% (300,000 + 14 \times 96,000) \\ &= \$49,320 \quad . \end{aligned}$$

Expected Loss

$$E(L) \text{ production unit} = 0.0013 \times 49,320 = \$64.12 \quad .$$

C.3.4.6. Installation at the Plant.

1. Drop During Erection

Basis. Each circulator must be erected from the horizontal shipping attitude to the vertical installation attitude.

Probability of Dropping. This is assumed to be the same as in Section C.3.4.5(2).

$$P \text{ (production unit)} = 0.000051 \quad .$$

Consequence. This value is assumed to be the same as for Section C.3.4.5(2).

$$\text{Cost (production unit)} = \$49,320 \quad .$$

Expected Loss

$$E(L) \text{ production unit} = 0.000051 \times 49,320 = \$2.52 \quad .$$

2. Hit by Shipping Canister

Basis. Shipping canister must be removed. Limited possible movement assumed to limit damage to minor scratches and dents repairable by local polishing.

Probability. Assumed to be the same as for Section C.3.4.4(2).

$$P \text{ (production unit)} = 0.000023 \quad .$$

Consequence. Assumed to be the same as for Section C.3.4.4(2).

$$\text{Cost (production unit)} = \$96,000 \quad .$$

Expected Loss

$$E(L) \text{ (production unit)} = 0.000023 \times 96,000 = \$2.21 \quad .$$

3. Hit by Lower Shield Cask

Basis. The lower shield cask is a heavy cylindrical container which must be fitted to the installation fixtures over the circulator. Its hitting the helium ducting is anticipated to cause

major damage to the ducting but not to the rest of the circulator.

Probability. Judged to be the same as for Section C.3.4.3(1).

$$P \text{ (production unit)} = 0.000007 \quad .$$

Consequence. Judged to be the same as for Section C.3.4.5(1).

$$\text{Cost (production unit)} = \$1,353,000 \quad .$$

Expected Loss

$$E(L) \text{ (production unit)} = 0.000007 \times 1,353,000 = \$9.47 \quad .$$

4. Interference When Raised

Basis. The circulator is guided into position by pins and keys and tapered sections. Possible binding on any of these is protected against by pressure switches and gages in the hydraulic system, which are set to restrict hydraulic pressure and thus prevent overloads.

Probability. Same as for Section C.3.4.4(3).

$$P \text{ (production unit)} = 0.0000087 \quad .$$

Consequence. Same as for Section C.3.4.4(3).

$$\text{Cost (production unit)} = \$1,353,000 \quad .$$

Expected Loss

$$E(L) = 0.0000087 \times 1,353,000 = \$11.77 \quad .$$

C.3.4.7. Replacing a Failed Circulator.

Basis. Although the circulators are designed for a life of 40 years without maintenance, it is considered logical to expect a need for circulator removal and replacement for unanticipated reasons. For this analysis it is postulated that four such removals will be required for reasons other than helium ducting deficiencies. The only way in which an expected loss can accrue to the helium ducting is if the helium ducting of the replacement (spare) unit is damaged during installation.

Probability. Damage can occur to the replacement if it is dropped during erection, hit by the shipping canister, hit by the lower shield cask, or overloaded when raised into the penetration. The probabilities of each event, given that replacement is required, are taken from Sections C.3.4.6(1) through C.3.4.6(4) and divided by four to convert to one replacement circulator instead of four production units. They are as follows:

$$P (\text{dropped during erection}) = 1/4 \times 0.000051 = 0.0000127 \quad .$$

$$P (\text{hit by shipping canister}) = 1/4 \times 0.000007 = 0.00000175 \quad .$$

$$P (\text{hit by lower shield cask}) = 1/4 \times 0.000007 = 0.00000175 \quad .$$

$$P (\text{overloaded when raised}) = 1/4 \times 0.0000087 = 0.00000217 \quad .$$

Consequences. The cost of outage for removing and replacing the initially failed circulator is assigned to that failure, not to the damage to the replacement. The consequence for the replacement event "dropped during erection" assumes that the entire cost of recovery is equivalent to three weeks of plant outage for inspection and repair. Because the damage is to the total circulator and the helium ducting represents 3% of the total, the cost estimate is:

$$\begin{aligned}\text{Cost (dropped during erection)} &= 3\% \times 3 \times 7 \times \$96,000 \\ &= \$60,480 \quad .\end{aligned}$$

The consequence for the replacement event "hit by shipping container" is assumed to be 2 days of plant outage to inspect and polish out minor scratches and dents. The cost is totally assigned to the helium ducting as:

$$\text{Cost (hit by shipping container)} = 2 \times 96,000 = \$192,000 \quad .$$

The consequence for the event "hit by lower shield cask" is assumed to be major damage to the helium ducting only. The repair is assumed to require three weeks of plant outage plus the fabrication of a new helium ducting part. The cost is calculated as follows:

$$\begin{aligned}\text{Cost (hit by lower shield cask)} &= 3 \times 7 \times 96,000 + 9000 \\ &= \$2,025,000 \quad .\end{aligned}$$

The consequence for the event "overloaded while raising" is assumed to result in major damage to the helium ducting only. Thus, the cost is estimated to result from three weeks of required additional plant outage and the cost of a new helium ducting part:

$$\begin{aligned}\text{Cost (overloaded while raising)} &= 3 \times 7 \times 96,000 + 9000 \\ &= \$2,025,000 \quad .\end{aligned}$$

Expected Losses. The expected loss for each event is the product of the probability of the event occurring and the loss incurred if the event occurs. Thus, the expected loss for each event described is:

$$E(L) \text{ dropped during erection} = 0.0000127 \times 60,480 = \$0.77 \quad .$$

$$E(L) \text{ hit by shipping canister} = 0.00000175 \times 192,000 = \$0.34 \quad .$$

$$\begin{aligned} E(L) \text{ hit by lower shield cask} &= 0.00000175 \times 2,025,000 \\ &= \$3.54 \quad . \end{aligned}$$

$$\begin{aligned} E(L) \text{ overloaded while raising} &= 0.00000217 \times 2,025,000 \\ &= \$4.39 \quad . \end{aligned}$$

The total expected loss associated with the replacement unit for a failed circulator is the sum of the above:

$$E(L) \text{ total} = 0.77 + 0.34 + 3.54 + 4.39 = \$9.04 \quad .$$

Present Value. The present value of the expected loss can be calculated using the following equation, which was previously developed:

$$V_p = S_v \times 23.115$$

where V_p = present value,

S_v = (the probability of occurrence per year) x (the cost of an occurrence) $\equiv$ expected loss per year.

The probability of occurrence per year is equal to the probability of damage, given that circulator replacement is required, times the probability per year that circulator replacement is required. The probability per year that replacement is required (P_{RR}) is based on the estimate that four replacements are required in 40 years or

$$P_{RR} = 4/40 = 0.1 \quad .$$

Therefore, the present value of expected loss resulting from estimated requirements to replace circulators is

$$V_p = (0.1 \times 9.04) \times 23.115 = \$20.90 \quad .$$

C.4. EXAMPLE ECONOMIC EVALUATION EMPLOYING OPERATIONAL (AND DESIGN) CONTROL OPTIONS

C.4.1. Introduction

During the construction and startup phase of the FSV plant, the circulators were operated under various conditions such as low primary coolant pressure and temperatures compared with design operating points. On several occasions water leaked through the upper seal of a circulator into the primary coolant loop. In each case a delay in plant startup resulted while the core and thermal insulation were dried out by the helium purification system. This section addresses various economic options which reduce the likelihood of water ingress occurrence, the amount of ingress, or both, hence increasing plant availability.

C.4.2. Method of Option Selection

For this example economic analysis, three major areas where product assurance controls can easily be modified or improved are examined for potential solutions to the problem of occasional water leakage into the primary coolant through the upper circulator seal system. Figure C.4-1 shows the possible combinations of changes that might be employed to reduce this cause of plant unavailability.

The options that include changes in the quality assurance controls were not considered in this analysis for two reasons. First, the parts and components of the circulator received 100% inspection and careful attention during installation at the site. These procedures are not expected to change for future plants or modifications at FSV. Second, the causes of water ingress during the plant construction and startup phase have been the result of maintenance, construction, and operator errors. Therefore, options involving QA changes (i.e., Fig. C.4-1, Options 2, 3, 6, and 7) are deemed uneconomic for this analysis. Thus, Options 1, 4, and 5 are candidates for economic options to the present condition, Option 0.

PROBLEM	DESIGN CONTROL (D)	QUALITY ASSURANCE AND CONSTRUCTION CONTROL (Q)	OPERATIONS CONTROL (ϕ)	PLAN	OPTION
WATER INGRESS THROUGH UPPER SEAL	D	Q	ϕ	DQ ϕ	0
			$\Delta\phi$	DQ $\Delta\phi$	1
		ΔQ	ϕ	D $\Delta Q\phi$	2*
			$\Delta\phi$	D $\Delta Q\Delta\phi$	3*
	ΔD	Q	ϕ	$\Delta DQ\phi$	4
			$\Delta\phi$	$\Delta DQ\Delta\phi$	5
		ΔQ	ϕ	$\Delta D\Delta Q\phi$	6*
			$\Delta\phi$	$\Delta D\Delta Q\Delta\phi$	7*
Δ $\equiv$ CHANGE IN "-- --" D $\equiv$ DESIGN CONTROL Q $\equiv$ QUALITY ASSURANCE CONTROL ϕ $\equiv$ OPERATIONAL PROCEDURES CONTROL * OPTIONS NOT EVALUATED IN THIS ANALYSIS.					

Fig. C.4-1. Assurance plan options against water ingress

C.4.3. Construction Phase History of Problem

A history of the water ingress problem at FSV during the construction phase is given in Table C.4-1. Considerable failure analysis of the causes of the events has revealed that human-related maintenance and construction errors on the buffer helium system, bearing water systems, and water turbine drain control have been the causes of these events. In the cases listed, the ingress continued for an excessive amount of time because control-room indications were ignored or misinterpreted by the plant operators. Because the reactor was still in the construction phase, no safety-related or other effect was possible through graphite water reactions. Only the economic losses associated with startup delays ensued. It should also be noted that if any of these ingresses had taken place at power, the actual loss would be expected to be much less than it was under the shutdown conditions, because the protection system shuts the reactor down on high moisture immediately after the onset of the ingress. Thus, attention would be called to the fact that a water ingress was occurring.

C.4.4. Description of Methods Employed for This Economic Analysis

Review of the historical data for the construction phase is used to estimate an occurrence rate, a most likely ingress rate, and a removal rate. Also, these data are combined with operator error rate data to develop a present condition baseline operator probability of success versus response time curve. From these parameters and information in the operation and maintenance manual (Ref. 2), an event tree is developed for water ingress incidents which displays the various outcomes of such an occurrence. Use of the event tree then provides a method for calculation of the baseline losses associated with the event under existing conditions and determination of the effects of various options on the expected losses. The details of this analysis are described in the following sections.

C.4.4.1. Occurrence Rate. The median value for water ingress events during the construction phase can be estimated simply by the formula

TABLE C.4-1
WATER INGRESS DATA AT FSV DURING CONSTRUCTION AND TESTING PERIOD
6-72 THROUGH 5-76

Date of Occurrence	Ref.	Amount of Inleakage (gal)	Most Probable Ingress Rate	Cleanup Time	Estimated Response Release Time (3 gpm)
6-72	(a)	600	Sporadically for 2-3 weeks	Unknown	200 min
8-74	(b)	1850 $\pm$ 50	Est. <1 gal/min	3.5 weeks	600 min
1-75	(c)	4250	3.0 gal/min	7 weeks	1417 min
2-76	(d)	350	3 to 6 gal/min	3 weeks	120 min

(a) Jackson, J. P., "Incident Report No. FSV-26, Leakage of Helium Circulator Bearing Water into Reactor System," May 2, 1973.

(b) Private communication with FSV site personnel (P. Newman, R. Phelps) on review of PSC operating logs.

(c) Docket-50267-260, Fort St. Vrain Nuclear Generating Station, Abnormal Occurrence Report No. AO-75-7-A: One Hopper of Reserve Shutdown Material Inadvertently Released into the Core (Public Service Co. of Colorado), April 4, 1975.

(d) Docket-50267-487, Fort St. Vrain Nuclear Generating Station, Reportable Occurrence Report No. RO-76-03: Water Migrated up the Shaft of Helium Circulator 1C and Into the Primary Coolant System (Public Service Co. of Colorado), March 25, 1976.

$$\lambda_{\alpha} = \frac{\chi^2_{2(r+1),\alpha}}{2nT} \quad .$$

Using standard table values for $\alpha = 0.5$, $r = 4$, and 33,840 hr (T) of operation in one plant (n), one obtains $1.38\text{E-}4/\text{hr}$ for the median value of the occurrence rate of major ingress events during the construction phase. The 90% confidence interval on the occurrence rate ranges from a point three times the median to a point one-third lower than the median for the present operating conditions. This judgment is based on a review of the information in Table C.4-1. For the purpose of this analysis, two situations are considered. First, when the plant is shut down for repairs or refueling the same failure rate is assumed with a 0.1 unavailability factor.* Thus, the shutdown occurrence rate is:

$$(0.1 \times 8760 \text{ hr/yr}) \times (1.38 \times 10^{-4}/\text{hr}) = 0.12/\text{yr} \quad .$$

Second, during operation it is assumed that the occurrence rate is a factor of 10 less than during the construction phase.** Thus, the occurrence rate during operation is

$$(0.9 \times 8760 \text{ hr/yr}) \times (1/10 \times 1.38 \times 10^{-4}/\text{hr}) = 0.1/\text{yr} \quad .$$

The initial occurrence rate calculation is based on the occurrence of large ingresses and may not include minor incidents that were rapidly corrected by the operator. This factor is assumed to be partially offset by the expected improvement in the occurrence rate during the operational phase.

C.4.4.2. Ingress Rate. Failure analyses indicate that the ingress rate depends on the type of equipment failures that initiate the event. The

*This assumes an average plant availability factor of 90% for the life of the plant.

**Failure occurrence rate improvement factors of 100 are not uncommon between the construction and the operation phases. Therefore, this expected reduction in the occurrence rate may be viewed as pessimistic.

maximum potential ingress rate through the upper labyrinth seal is less than 20 gpm, which would require a pressure differential greater than 600 psig. The minimum ingress is, of course, minute. Based on the failure analyses and the normal upper seal flow rate of 1 to 2 gpm, a most likely ingress rate of 3 gpm with loss of the helium flow is used for this analysis.

C.4.4.3. Removal Rate. During normal operation, a fraction of the circulating helium is run through the purification system. The function of this system is to continuously remove impurities including any moisture from the primary coolant. Thus, very small leaks result in routine removal with no effect on plant availability. However, if the leak rate were greater than the removal rate a moisture buildup would cause a reactor trip and loop dump when the moisture level reached a concentration of 500 ppm. A graph representing gallons removed versus removal times for the large ingress events is shown in Fig. C.4-2. For this analysis, a constant removal rate of 3 gal/hr is used. The variability in the data points is a result of moisture penetrating the thermal insulation, thereby increasing the removal time significantly. In addition, the removal rate is a function of temperature and pressure. Hence, after plant operation starts, the ability to reduce pressure for dryout periods would be limited by heat removal requirements. Thus, less than 1 gal/hr may be the most likely removal rate after operation starts. Such a reduction in the removal rate would increase the expected losses.

C.4.4.4. Operator Error Rate. For this analysis the initial operator error rate is based on the FSV operator error rates presented by Kaman Sciences Corporation (Ref. 3) for similar levels of operator decision and activity. For longer times, the total volume of ingress divided by the estimated ingress rate is used to determine the operator error probabilities for the successive time intervals. Figure C.4-3 shows the best judgment estimate of the operator error curve employed in this analysis for the existing conditions, and improved curves which result from corrective actions and operation at power.

Fig. C.4-2. Estimate of average removal rate

Fig. C.4-3. Cumulative probabilities of operator response time (based on data from Table C.4-1 and Ref. 10)

The probability values were estimated in the following manner. The initial error rate from Ref. 3 was assumed since operator actions that immediately stopped the ingress were not necessarily recorded. Thus, the initial likelihood of correct response is about 0.5. Following the initial response, four incidents of slow response times are known, and have been divided into equal probability intervals for the cumulative probability of success in each succeeding time period. Refinements to this curve could be made by a more exhaustive review of operator logs. Such a review could be used to reduce the uncertainty associated with the curve shown in Fig. C.4-3, and may result in a shift up or down for the initial success probability, but it is not justified for the purpose of this example analysis.

C.4.5. Event Trees for Economic Evaluation

For an initiating event of water leakage through the upper seals of a circulator into the primary coolant, the possible outcomes are examined in Figs. C.4-4 and C.4-5. The first response is expected to be an automatic circulator trip on negative ΔP across the upper labyrinth seal. The first circulator trip then locks out the other circulators from tripping. Thus, failure to automatically isolate a leaking circulator can result from either failure of the trip mechanism on a single leaking circulator, or two leaking circulators and only one tripped. For this analysis the automatic system failure to stop the leak is assessed at 0.1 for the shutdown condition, because of the common cause failure potential and the lockout characteristic of the first trip. This is reduced to 0.02 for the operating condition, owing to the moisture monitor backup which trips the reactor and dumps the steam generators of the affected loop. In the event that the automatic system fails to stop the ingress, the operator action is needed to stop the leak. The amount of inleakage, and thus cleanup time required, is then related directly to the length of time required by the operator to stop the leak. Four time periods are considered for ingress and subsequent moisture removal. These are less than 5 min (median 1/2 min), 5 min to 100 min (median 50 min), 100 to 600 min (median 350 min), and greater than 600 min (median 1000 min). These time increments were picked on the basis of

INITIATING EVENT: WATER INGRESS DURING SHUTDOWN/ REFUELING CONDITION	AUTOMATIC RESPONSE: NEGATIVE ΔP ONLY	OPERATOR RESPONSE: BEST JUDG- MENT CURVE	CUMULATIVE PROBABILITY PER YEAR	EXPECTED AMOUNT OF INGRESS	CLEANUP TIME FOR MOISTURE REMOVAL (3 GAL/HR)	BRANCH COST PER OCCURRENCE AT \$4000/HR PLANT DOWN TIME COST FOR RESTART DELAY	S_V (EXPECTED YEARLY LOSS)	P_V (EXPECTED PRESENT VALUE LOSS AT 3% INTEREST)
PROBABILITY PER YEAR (1)	PROBABILITY PER EVENT (2)	PROBABILITY PER EVENT (RESPONSE TIME)		GAL.	HOUR	BASELINE OCCURRENCE = \$ 0		
0.12/YR	0.9	1					0	0
	0.1	0.5	0.005	1.5	0.5	\$2,000	\$12	\$280
		(0 TO 1 MIN) 1/2 MIN						
		0.16	0.002	150	50	\$200,000	\$380	\$8,900
		(1 TO 100 MIN) 50 MIN						
		0.28	0.003	1050	350	\$1,400,000	\$4,700	\$109,000
		(100 TO 600 MIN) 350 MIN						
		0.06	0.0007	3000	1000	\$4,000,000	\$2,900	\$66,000
		(GREATER THAN 600 MIN) 1000 MIN						
						TOTAL EVENT COST	\$8,000	\$184,000

(1) BASED ON CONSTRUCTION, TESTING OCCURRENCE RATE FOR SHUTDOWN CONDITIONS.

(2) SECOND UNIT IS INHIBITED FROM TRIPPING.

Fig. C.4-4. Event tree for water ingress through upper labyrinth circulator seals

WATER INGRESS PLANT AT POWER	MOISTURE MONITORS AND NEGATIVE ΔP BOTH EFFECTIVE	FACTOR OF 2 BETTER THAN BEST JUDGMENT CURVE	CUMULATIVE PROBABILITY PER YEAR	EXPECTED AMOUNT OF INGRESS (GAL)	CLEANUP TIME FOR MOISTURE REMOVAL (HR)	EVENT TREE BRANCH COST PER OCCURRENCE AT \$4000/HR DOWN-TIME COST	S_v EXPECTED YEARLY LOSS	P_v EXPECTED PRESENT VALUE LOSS AT 3% INTEREST
PROBABILITY PER YEAR	PROBABILITY PER EVENT	PROBABILITY PER EVENT ⁽¹⁾						
0.1/YR	0.98					BASELINE OCCURRENCE COST = \$0		
	0.02	0.76	1.5E-3	1.5	0.5	\$2,000	\$2	\$46
		(0 TO 1 MIN) 1/2 MIN						
		0.08	2E-4	150	50	\$200,000	\$32	\$739
		(1 TO 100 MIN) 50 MIN						
		0.13	3E-4	1050	350	\$1,400,000	\$364	\$8,413
		(100 - 600 MIN) 350 MIN						
		0.03	6E-5	3000	1000	\$4,000,000	\$240	\$5,548
		(GREATER THAN 600 MIN) 1000 MIN						
						TOTAL EVENT COST	\$638	\$14,736

(1) THE OPERATOR RESPONSE TO AN ABNORMAL CONDITION IS EXPECTED TO BE BETTER DURING PLANT OPERATION THAN DURING SHUTDOWN PERIODS.

Fig. C.4-5. Event tree for water ingress problems which occur during normal plant operating conditions

the operating history, and categorized for simple application of the economic options. Figures C.4-4 and C.4-5 display these conditions in event trees, which are subsequently used to explore the economic effects of various options that affect the occurrence rate and the operator response curve.

C.4.6. Event Description

When a water ingress event occurs, and the automatic system response is not sufficient to stop the inleakage, the operator is first required to take mitigating actions to stop the leak. Then he can start cleanup and moisture removal procedures as needed. These operator actions are detailed in the event tree by probability intervals so that the economic effects of the options can be explored. In this example only the expected value estimates of the important parameters are employed to quickly determine the economic effects of different options.

The length of shutdown time required for water removal is directly proportional to the ingress time allowed by the operator. The dryout procedure, however, takes a much longer time. Once the moisture level is above the trip point, it is estimated that the removal time is about 60 times longer than the ingress time on the basis of the data in Table C.4-1. The removal time then approximately equals the delay in startup, or the shutdown time required. Hence, for this example, the event cost equals this delay times the unavailability cost (power differential as described in Volume I, Section 3.3.1). The present value cost is then calculated using a 3% real interest rate for yearly payments. These payments equal the expected annual loss (i.e., the probability of annual occurrence times the cost per occurrence). Thus, the occurrence rate and probability of operator actions can be related to expected losses. Moreover, the effects of money spent to reduce expected losses can be explored for their potential benefit.

C.4.7. Economic Options

C.4.7.1. Present Condition Option 0. From the figures, plots, and data presented in the previous sections, the estimated present value (cost) of water ingress through the circulator seals is approximately \$200,000.* More than 90% of the cost is expected during shutdown periods when maintenance operations on buffer helium, bearing water, or other systems are most likely performed. Based on this estimate of expected loss, various economic options to reduce this value can be explored.

C.4.7.2. Option 1 Change in Procedures. The first option selected for consideration is to include plant maintenance personnel in portions of the operator requalification program (10CFR55, Appendix A). The discussions dealing with component failures, maintenance procedures, and expected actions in the control room could be held before each planned shutdown. The purpose of these discussions would be to clearly define operator/maintenance interactions in the event of abnormal conditions arising from the maintenance activities on the bearing water, buffer helium system, and similar systems critical of operator action. The primary objective of the retraining program is to improve operator response to abnormal conditions. Thus, Option 1a is to increase operator retraining discussions on water leakage events. Option 1b is to review maintenance procedures with the personnel responsible for maintaining and testing the circulators with the intent of reducing the occurrence likelihood. Finally, Option 1 is a combination of Options 1a and 1b so that both objectives are carried out together. Option 1 is the most desirable since both reactor operators and maintenance personnel would be aware of the others' needs. This could lead to more rapid responses to the ingress problem.

C.4.8. Economic Evaluation of Options

C.4.8.1. Options 1a, 1b, and 1. Figures C.4-5, C.4-6, and C.4-7 show a comparison of the reduction in water ingress occurrence rate [i.e., maintenance improvement factor (MIF)] and improvement in operator response time

*Sum of the present value losses for operating and shutdown phases.

WATER INGRESS DURING SHUTDOWN AND REFUELING	NEGATIVE ΔP ONLY, INHIBITS SECOND TRIP	FACTOR OF 2, 3, 4 BETTER THAN BEST JUDGMENT CURVE	CUMULATIVE PROBABILITY PER YEAR	EXPECTED AMOUNT OF INGRESS (GAL)	CLEANUP TIME FOR MOISTURE REMOVAL (HR)	EVENT TREE BRANCH COST PER OCCURRENCE AT \$4000/HR DOWN TIME COST	S_v EXPECTED YEARLY LOSS	P_v EXPECTED PRESENT VALUE LOSS AT 3% INTEREST	OIF
PROBABILITY PER YEAR (1)	PROBABILITY PER EVENT	PROBABILITY PER EVENT (2)							
0.12/YR	0.9								
		0.88 (OIF = 4)	0.1				\$21	\$490	(4)
		0.85 (OIF = 3)	0.01				\$20	\$470	(3)
	0.1	0.76 (OIF = 2)	9E-3	1.5	0.5	\$2,000	\$18	\$420	(2)
		(0 TO 1 MIN)							
		1/2 MIN							
		0.04	5E-4				\$96	\$2219	(4)
		0.04	5E-4				\$96	\$2219	(3)
		0.08	1E-3	150	50	\$200,000	\$192	\$4438	(2)
		(1 TO 100 MIN)							
		50 MIN							
		0.065	8E-4				\$1092	\$25,241	(4)
		0.09	1E-3				\$1512	\$34,950	(3)
		0.13	1.6E-3	1050	350	\$1,400,000	\$2184	\$50,483	(2)
		(100 - 600 MIN)							
		350 MIN							
		0.015	1.8E-4				\$720	\$16,642	(4)
		0.02	2.4E-4				\$960	\$22,190	(3)
		0.03	13.6E-4	3000	1000	\$4,000,000	\$1440	\$33,285	(2)
		(GREATER THAN 600 MIN)							
		1000 MIN							
						TOTAL EVENT COST	\$2349	\$54,297	(4)
							\$2588	\$59,821	(3)
							\$8834	\$88,623	(2)

(1) MAINTENANCE FACTOR CHANGES DIRECTLY AFFECT THE INITIATING EVENT PROBABILITY.

(2) OIF IS THE OPERATOR IMPROVEMENT FACTOR DEFINED BY THE CURVES IN FIG. C.4-3 AND THE FORMULA IN FIG. C.4-7.

Fig. C.4-6. Economic evaluations for Options 1 and 4 with improved operator response during shutdown and refueling operations

Fig. C.4-7. Potential savings for a reduction in the operator error rate

[i.e., operator improvement factor (OIF)] with present value savings. To gain this improvement economically, about \$2000/yr could be spent to achieve a factor of 2 reduction in the occurrence rate and a factor of 2 in the improvement rate in the operator response. Thus, Option 1 appears best conducted by covering potential ingress modes and consequences prior to every shutdown and maintenance operation that might affect operation of the upper seals. If the entire crew is involved, the training effort required to reduce the operator failure rate by a factor of 0.2 should not exceed several hours just prior to each shutdown. A comparison of this option with others is presented in Table C.4-2.

C.4.8.2. Option 4 Design and Operator Change. Figure C.4-8 shows that a direct design change that ensures a reduction in the operator error rate by a factor of 2 throughout the life of the plant is worth up to \$110,000. An example of this option would be to spend money now to add an additional alarm in the control room which leaves no doubt in the mind of the operator as to subsequent actions that should be taken. This would be expected to reduce the operator failure rate for this condition by at least a factor of 3 or 4. Based on the existing instrumentation, such an addition might be possible for a capital investment of about \$40,000. This option is compared with others in Table C.4-2 and Section C.4-9.

C.4.8.3. Option 5 Design Change. An improved upper seal design employing redundant dynamic seals under all operating conditions should reduce the occurrence rate by at least an order of magnitude. This estimate assumes a 10% common cause failure factor between the redundant seals. Hence, this option could save about \$180,000. However, the plant down-time cost alone associated with removing and replacing just one circulator is over \$2 million. Therefore, although such a design change option is uneconomic in the present system, such modifications may be economic in future designs and should be given a full evaluation for these designs. This result is also summarized in Section C.4-9 and Table C.4-2.

TABLE C.4-2
SUMMARY TABLE FOR OPTIONS (a) (\$)

	Present Condition Option 0	Option 1a	Option 1b	Option 1	Option 4	Option 5
Present value of expected loss	200,000	89,000	100,000	45,000	55,000	20,000
Expected yearly loss payment	8,652	3,834	4,308	1,951	2,380 + 1,730 CI	865 + >120,000 CI + down time
CI ^(b) of option	~0	~0	~0	~0	40,000	4×10^6 down time + 5×10^5 CI
Continuous yearly payment for option implementation	0	800	1,200	2,000	300	300
Yearly savings (loss)	--	~4,000	~3,100	4,700	4,200	(>120,000)
Present value savings (loss)	--	~93,000	~73,000	109,000	98,000	(> 4×10^6)

(a) Options: 1a - Training, retraining program for reactor operator reduces error rate by a factor of 2. 1b - Retraining program for maintenance personnel before shutdown reduces occurrence rate by 2. 1 - 1a and 1b combined. 4 - Improved signals for operator reduce operator error rate between 3 and 4. 5 - Redesign and replacement of upper seal with a redundant seal system reduces occurrence rate by a factor of 10.

(b) CI = capital investment.

Fig. C.4-8. Potential savings for a reduction in the maintenance error rate

C.4.9. Conclusion of Operations Economic Analysis

As can be seen in the summary table (Table C.4-2), Options 1a, 1b, 1, and 4 are cost-effective while Option 5 is not cost-effective because of the delay caused by removal of all circulators. If the training programs for both operators and maintenance personnel can be included simply as part of the required programs, the \$2000 yearly cost of the option may have been overestimated, and Option 1 would then even more clearly be the most cost-effective option. On the other hand, if additional programs are required, the cost of which considerably exceeds the \$2000/year, Option 4 would appear to be the most promising.

In any case, the design option change is clearly not justifiable on an economic basis for FSV. However, the design option could be the most economic for future plants, if major design modifications were being made to the circulator or a sufficient number of units were to be built that the design costs could be amortized to an acceptable per-unit value. The methods described in this report could be applied to evaluate any particular situation.

REFERENCES

1. Garrick, B. J., et al., "Effect of Human Error and Static Component Failure on Engineered Safety System Reliability," Holmes and Narver Report HN-194, November 1967.
2. "Operation and Maintenance Manual for the Fort St. Vrain 330-MW(e) HTGR Helium Circulators," General Atomic Report GA-A10349 (Rev. B), August 26, 1976.
3. Becar, N. J., et al., "Analysis of Effect of Human Interactions on HTGR Safety and Reliability," USERDA Report KSC-1037-2, Kaman Sciences Corporation, April 5, 1976.

APPENDIX D

COMPARISON WITH EXPERIENCE

D.1. INTRODUCTION

This appendix contains discussions of three water ingress events which require more space to discuss fully than could be justified in the main body of the report. The other seven problems described in Volume I, Section 4, were adequately covered in Volume I and are therefore not further discussed here.

D.2. CIRCULATOR BEARING WATER INGRESS (SUMMER 1972)

If a large amount of water enters the PCRV, extended plant down time may be required to remove the water. The circulators are one of the possible sources of water entering the PCRV due to their water-lubricated bearings and water-driven auxiliary turbines. A fault tree which describes the possible conditions for water entry from a circulator into the PCRV is presented as Fig. D.2-1. The right-hand side of this figure summarizes the causes for water reaching and penetrating the upper labyrinth seal. Several of the possible contributors to water ingress (represented by diamonds in the figure) would be pursued to the final level of part failure in a complete analysis, but will not be pursued further for evaluating the water ingress problems which actually occurred.

The incident report (FSV-26) covering circulator bearing water ingress during the summer of 1972 indicates that modes of operation inherent in performing POT 21-03 created the conditions for water to flow up and into the PCRV. The right-hand side of the fault tree in Fig. D.2-1 reveals that this is possible if an operator opens a bearing water supply valve when the drains are closed or if he closes the bearing water drain valve when bearing water is flowing.

Fig. D.2-1a. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1b. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1c. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1d. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1e. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1f. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1g. Fault tree for water ingress into the PCRV through the helium circulator

Fig. D.2-1h. Fault tree for water ingress into the PCRV through the helium circulator

The incident report also indicates that the water ingress prevention system shuts down the circulators correctly when a negative pressure differential is sensed. It was determined that water was entering the pressure sensing tubes and causing erratic operation, and the repeated shutdowns and alarms led to the water ingress prevention system being disconnected. Such a possibility is addressed in Fig. D.2-1b.

The fault tree thus illustrates that the conditions for water ingress can be initiated by the operators and that the water ingress prevention system can also be deactivated by the operators. Consequently, water ingress can occur without a hardware failure.

It is expected that a more thorough evaluation of the pre-startup event POT 21-03 would have detected the conditions for ingress and would have controlled the amount of ingress to an acceptable level.

D.3. CIRCULATOR BEARING WATER INGRESS (FEBRUARY 1976)

A second incident involving circulator bearing water ingress occurred in February 1976 while circulators A and B were shut down and circulators C and D were rotating freely. The problem was initiated by the failure in the open position of the pressure control valve (PCV 2367-1) in the makeup buffer helium supply. As a result, the makeup helium pressure rose to 80 psi above reactor pressure, the bearing water surge tank rose 8 to 10 psi above reactor pressure, the buffer return flow dropped to zero, and the circulator C high-pressure separator flooded. Coincidentally, the circulator C bearing water drain valve controller had failed, closing the valve to its limit and increasing the back-pressure on the helium water drain by 40 psi. The helium/water drain pressure thus was an estimated 57 psi above reactor pressure, and water was carried into the PCRV at about 14 gpm.

The low buffer helium return flow caused an alarm. The high water level in the circulator C high-pressure separator also caused an alarm. Plant operating procedures direct that the circulator be shut down for either of the above events. However, trip was delayed for approximately 35

minutes. The buffer/mid-buffer pressure measurement did not trip the troubled circulators because of an automatic inhibit due to the other loop being shut down.

The fault tree of Fig. D.2-1 would indicate the failure of the makeup buffer helium valve as a potential water ingress initiator if carried to completion. The failure closed of the bearing water drain valve is identified directly on the fault tree as a potential contributing cause of bearing water ingress. As with the fault tree of the buffer/mid-buffer measurement, the possibility of the operator ignoring the warning alarms would be diagrammed, but it would probably have been considered as very unlikely. Water ingress by this combination of circumstances could therefore have been detected as a possibility by the methodology, but protection against its occurrence would only have been recommended provided the much higher human error rates experienced with the relatively informal operations during the pre-startup phases had been recognized.

D.4. CIRCULATOR PELTON TURBINE WATER INGRESS

Through a series of reactor operating tests on January 21 to 23, 1975, it was determined that there was excessive moisture in the PCRV. Water removal operations recovered about 4250 gal. An investigation of the possible sources of ingress eliminated all sources except the circulators. Further investigation showed:

1. Leakage through the water turbine supply block valves had been experienced and the corrective action had not been demonstrated effective.
2. There were several diverse indications of circulator flooding which the operators did not interpret to indicate water ingress into the PCRV.

3. Tests performed on the spare circulator demonstrated that, with a circulator shut down, water under pressure could lift the static seal and leak into the PCR.V.
4. Tests performed on the spare circulator also demonstrated that, under certain conditions, circulator bearing water could ingress into the PCR.V but not enough to account for the quantity found.

It was concluded that leaking water turbine supply block valves accounted for the water that entered the PCR.V. The failure to properly interpret the indications of water ingress permitted a large quantity to enter the PCR.V.

The right-hand side of the fault tree in Fig. D.2-1a has a block which describes the fault, "Pelton turbine water supply valve leak supplies water." As shown by the fault tree, this can occur only if the valve leaks and the turbine cavity drain valve is closed. If the drain valve is closed, as it was for this event, the leaking water cannot escape. Therefore, it eventually fills the turbine drain cavity and then floods the circulator bearing assembly with more than enough pressure behind it to lift the static seal and allow water into the PCR.V.

During the time of the ingress, alarms were experienced due to the buffer/mid-buffer pressure differential going negative. The alarms were erratic because of water in the pressure sensing tubes. Expected value of the measurement is maximum at 100% power at 1.25 psid, which is equivalent to about 35 in. of water. The pressure sensing tubes extend downward from the sensing ports over 15 ft. Having more water in the mid-buffer tube gives a false low-pressure reading. The negative pressure alarms were not responded to properly; this possibility is accounted for on the fault tree in Fig. D.2-1b. As a result of the event's actual occurrence, instructions to open the turbine cavity drain valve were reinforced, interlocks were installed, and high water level sensors and alarms were installed for the

cavity. It is expected that application of the methodology described in this report would have detected the problem area and resulted in improved operational controls and interlocks. However, an economic evaluation would probably not have justified the installation of the high level alarms.

APPENDIX E ESTIMATED COST OF PLANT UNAVAILABILITY

This appendix estimates the cost of the Fort St. Vrain 330-MW(e) HTGR being unavailable. If the plant is unavailable (due to either startup delay or forced outage) the electrical power it could have produced must be provided by other sources. Considering crude-oil-fired plants, for example, the cost per hour for the oil alone would be approximately:

$$\begin{aligned}
 C &\approx \frac{330,000 \text{ kWh(out)}}{1 \text{ hr}} \times \frac{10^4 \text{ Btu(out)}}{2.93 \text{ kWh(out)}} \times \frac{1 \text{ Btu(in)}}{\mu \text{ Btu(out)}} \times \frac{1 \text{ lb oil}}{18,000 \text{ Btu(in)}} \\
 &\times \frac{1 \text{ gal oil}}{7 \text{ lb oil}} \times \frac{1 \text{ bbl oil}}{37 \text{ gal oil}} \times \frac{\$10}{1 \text{ bbl oil}} \\
 &= \frac{2,416}{\mu} \frac{\$}{\text{hr}}
 \end{aligned}$$

where μ = plant net efficiency.

If $\mu = 0.333$, then $C \approx \$7240/\text{hr} = 21.9 \text{ mills/kWh}$ for crude oil.

If replacement power is provided by coal-fired units, the fuel cost would be considerably smaller. H. A. Bethe (Ref. 1) shows (see Fig. E-1) the average fuel cost/kWh of prospective oil- and coal-fired plants is about 12 mills/kWh (i.e., \$0.012/kWh) greater than that for nuclear plants. An article published by the American Nuclear Society (Ref. 2) presents similar fuel cost figures, which are repeated here in Fig. E-2. In addition, a conversation with FSV plant management concluded that replacement power fuel costs would be between 12 and 15 mills/kWh (i.e., between \$3960 and \$4950 per hour of FSV down time).

When FSV is not available it also does not consume its nuclear fuel, and this is a benefit that one might consider. However, the nuclear fuel

Fig. E-1. Fuel costs (from Ref. 1)

Fig. E-2. Fuel costs (from Ref. 2)

that is "saved" will not effectively be available for use until the end of the nominal plant life, at which time the plant can be considered to make up the lost power operation time. At an inflation-compensated interest rate of 3% (used throughout this report) the present value of earnings 40 years from now is only 0.307 ($=1/3.262$) times the earnings. Hence, 1 hr of down time lost from the beginning of plant life would only have a compensatory value of about \$1320 to \$1650/hr, assuming a fossil alternative, due to the fact that the power could not be made up until 40 years later. If the alternative is not fossil, the "savings" 40 years hence should be less. The above costs, however, do not include the cost of nuclear and fossil plant component life reduction resulting from the startup and shutdown of both plants and from the fossil plant furnishing the replacement power. Assuming on the average these costs essentially compensate for the present value of nuclear fuel "saved," the net cost per hour of plant down time is $\geq$ \$3960/hr. A conservative value of \$4000/hr was therefore employed throughout this report for the economic loss associated with plant unavailability as an approximation to minimize the distraction from the principal purpose of the report, which is to illustrate the methodology.

REFERENCES

1. Bethe, H. A., "The Necessity of Fission Power," Scientific American 234 (1976).
2. "Nuclear Power and the Environment," American Nuclear Society, San Diego Section (revised edition), April 1976.

APPENDIX F

PROBABILISTIC USE OF INTEREST FORMULAS FOR RARE EVENTS

This appendix deals with the determination of the expected present value for events leading to plant unavailability which rarely occur in the life of the plant. The expected loss for a rare event in this study has been treated as a "virtual" payment made each year which equals the product of the event probability per year and the magnitude of its cost in present day dollars. The total expected loss is then the interest-rate-adjusted sum of these yearly payments over the 40-yr life of the plant.

The cost of a nuclear power plant shutdown is calculated from the amount of down time times the outage cost rate plus repair costs. Since nuclear plants have a significantly lower fuel cost than their makeup power sources, the down-time cost usually dominates the equipment repair costs. Thus, a large expenditure can be expected when low probability equipment failures lead to a plant shutdown. The following formulations are presented to demonstrate how the present value (cost) of these rare events can be calculated to provide a basis for comparing the cost of implementing changes to the present conditions.

Interest factors for the cost of a chance event can be treated in the same manner as an actual payment schedule. Note that the present value of a payment in the future is related by the compound interest formula

$$P_v = S_v \frac{1}{(1 + i)^n} \quad , \quad (F-1)$$

where P_v is the present cost, S_v is the future cost, i is the yearly interest rate, and n is the number of years between the present and the future cost.

For probabilistic events, P_v is assumed to be a "virtual" payment which is made each year in the life of the plant, rather than at one time. The basis of this assumption can be justified by assuming that a large number of identical plants exist (e.g., 10^6). Then an event with a true probability of 10^{-6} /yr would (on the average) occur once each year. If the cost of this occurrence was distributed over all the plants, it would equal the virtual payment S_v . The present value of these yearly virtual payments over the plant life is calculated as shown in Eq. F-2 by summing the yearly expected payments adjusted by their interest factor over the plant life:

$$P_v = S_v \sum_{k=1}^n \frac{1}{(1+i)^k} \quad (F-2)$$

where $k = 1, 2, \dots, 40$.

Since Eq. F-2 is difficult to apply, the following simplification is made.

Consider the geometric series

$$T = \sum_{\ell=1}^n t^{\ell} \quad , \text{ and } tT = \sum_{\ell=1}^n t^{\ell+1}$$

$$\text{where } t = \frac{1}{1+i} \quad .$$

$$\text{Therefore, } tT - T = \sum_{\ell=1}^n (t^{\ell+1} - t^{\ell})$$

$$= (t^2 + t^3 + \dots + t^n + t^{n+1}) - (t + t^2 + \dots + t^n) \quad .$$

$$\text{Hence, } T = \frac{t(t^n - 1)}{t - 1} = \sum_{\ell=1}^n \left(\frac{1}{1+i} \right)^{\ell} \quad .$$

The term T is equivalent to the summation part of Eq. F-2 when $t = 1/(1+i)$. The short form of T is easier to use; therefore, its substitution is made into Eq. F-2. With the following manipulations, Eq. F-3 can be

recognized as the present value of annuity:

$$\begin{aligned}
 P_v &= S_v \left(\frac{1}{1+i} \right) \left[\frac{\left(\frac{1}{1+i} \right)^n - 1}{\left(\frac{1}{1+i} \right) - 1} \right] ; \\
 &= S_v \left(\frac{1}{1+i} \right) \left[\frac{\left(\frac{1}{1+i} \right)^n - \left(\frac{1+i}{1+i} \right)^n}{\left(\frac{1}{1+i} \right) - \left(\frac{1+i}{1+i} \right)} \right] ; \quad (F-3) \\
 &= S_v \left[\frac{1 - (1+i)^n}{-i(1+i)^n} \right] ; \\
 P_v &= S_v \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] .
 \end{aligned}$$

Thus, the present value of the yearly virtual payments for a probabilistic event is treated the same as annuity payments, and can also be expressed as

$$P_v = S_v \left[\frac{1 - (1+i)^{-n}}{i} \right] . \quad (F-4)$$

For a 3% interest rate over 40 payments,

$$P_v = S_v \times 23.115$$

where S_v = the probability of occurrence/year times the cost of an occurrence.