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HTGR PLANT AVAILABILITY AND RELIABILITY EVALUATIONS

VOLUME I: SUMMARY OF EVALUATIONS

by

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ABSTRACT

This report (1) describes a reliability assessment methodology for systematically locating and correcting areas which may contribute to unavailability of new and uniquely designed components and systems, (2) illustrates the methodology by applying it to such components in a high-temperature gas-cooled reactor [Public Service Company of Colorado's Fort St. Vrain 330-MW(e) HTGR], and (3) compares the results of the assessment with actual experience. The methodology can be applied to any component or system; however, it is particularly valuable for assessments of components or systems which provide essential functions, or the failure or mishandling of which could result in relatively large economic losses.

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1. INTRODUCTION

This study was initiated to evaluate the effectiveness of a reliability assessment program in systematically locating and correcting areas which contribute to the unavailability of new and uniquely designed (first-of-a-kind) components and systems. The helium circulator of the Public Service Company of Colorado's Fort St. Vrain (FSV) 330-MW(e) HTGR was the principal component involved in the evaluation. Recommendations for optional controls were based on economic criteria, and the results of the evaluation were compared with FSV experience.

The motives for developing a methodology that will help avoid component and system unavailability are principally economic. For large nuclear power plants, such unavailability often results in plant down time involving replacement power costs of several hundred thousand dollars a day. In addition, there may be indirect costs resulting from pollution to the environment and from imbalance of foreign trade if replacement power is provided by fossil fuels.

Even more severe losses can accrue due to equipment unavailability in other fields. For example, component or system unavailability due to failures in a critical research and development program could cause an entire technology to be delayed for years or even result in project cancellation. Such delays or cancellations could have severe consequences if related to critical defense projects. Hence, there are many instances besides nuclear power plant applications where component or system failure can have serious consequences. Therefore, it is desirable to have a methodology for locating and correcting areas which contribute to unavailability, particularly when the equipment involved is of a new and unique design.

The objectives of this report are (1) to describe the general methodology of conducting such a program, (2) to illustrate the methodology by applying it to the FSV helium circulator and other components associated with the circulation of helium, and (3) to compare the results of the evaluation with FSV experience.

Volume I presents a summary of the complete assessment. Volume II contains appendices that provide greater detail on the topics contained in Volume I.

2. METHODOLOGY

2.1. INTRODUCTION TO METHODOLOGY

The objective of the methodology described herein is to systematically and economically locate and correct areas which may contribute to unavailability of new and uniquely designed components or systems. Expressed in more general terms, the objective is to determine and correct controls that are expected to be economically inadequate. The controls are classed as (1) design controls, (2) quality assurance controls, or (3) operational controls.

This section provides a summary description of a general methodology for accomplishing the above-described objective. The method of solution is basically an application of reliability engineering (Refs. 1, 2, 3) and decision under uncertainty (Refs. 4, 5) principles which can be applied to any part, component, or system where risk of loss is involved. A more detailed description is given in Volume II, Appendix A.

2.2. EQUIPMENT DEFINITION

First, the equipment to be considered by the analyst must be defined. This can be done directly from a parts list, on a function basis, or on any other basis that finally includes all components and functions (including interfaces) the failure of which can cause a significant loss. The analyst should study the equipment until he thoroughly understands its design and functions. Every component and part should be identified as a potential source of significant loss until firmly established otherwise.

2.3. EQUIPMENT LIFE-CYCLE-EVENTS DETERMINATION

The life-cycle events (LCEs) for every potentially critical component and part should be determined (e.g., design, procurement, and fabrication). The analyst should study the LCEs of his equipment (including those for components and parts) until he thoroughly understands their functions and the controls. For potentially critical components and parts, every LCE should be assumed to be a source of significant loss until this is firmly established not to be the case. The analyst is then able to focus his attention on only those LCEs during which a significant loss could occur, and to evaluate the adequacy of the controls.

2.4. FAILURE EFFECTS DETERMINATION

The next step is to determine the potential ways in which trouble can occur, and the consequences (or "impacts"). This is usually performed initially on a qualitative basis. The qualitative evaluation in conjunction with experienced judgment may suffice to make a decision concerning the adequacy of many controls. Techniques that have proved useful for these qualitative evaluations include the use of checklists (Ref. 6), failure modes and effects analysis (FMEA) tables, and fault trees. When qualitative analyses in conjunction with judgment are inadequate (e.g., when there is insufficient experience, or mathematical complexity is involved) it becomes necessary to make quantitative evaluations. To minimize the time required to perform a quantitative evaluation, inequalities should be employed whenever they suffice and save time (e.g., by using the fact that an expected loss is <\$1500, rather than determine its actual value).

2.5. QUANTITATIVE EVALUATION

Quantitative evaluation requires estimates of the economic consequences (e.g., the cost of repair, and of schedule slippage or system unavailability), and of the probability or frequency of occurrence. The product of the probability and the associated loss is the expected loss.

The probability of occurrence can be calculated from evidence directly relating to the events of concern, or by analyzing the controls.

The expected losses are those of principal concern. These are due to imperfect controls (this includes imperfect knowledge concerning the controls). Therefore, inasmuch as expected losses must generally be accumulated over all components and LCEs (and eventually equitably distributed to the appropriate controls and compared with options to decide if a particular control is inadequate on an economic basis), it would seem natural and desirable to do this immediately after each expected loss is determined. However, controls are directly related to components, and failure rates of operational components are (unfortunately) usually published without reference to the fraction attributable to any particular control. Hence, for the operational LCEs, it is usually more efficient to accumulate the expected losses under components rather than under controls until analysis on this basis is unable to conclude whether the controls are economically adequate.

Before expected losses are computed, all losses should be converted to equivalent values at a particular instant in time (e.g., present value in January 1976 dollars). This requires considering inflation and interest rates. Simple inflation is most easily handled by making future loss estimates in terms of the reference-dollar values; interest rates are most easily handled by reflecting potential future losses back to present values. If other significant economic aspects are known to exist (e.g., an expected large increase in the cost of materials over and above simple inflation), then they should also be included in the analysis.

2.6. OPTION EVALUATIONS AND DECISIONS

Application of the above process provides the expected loss [perhaps in the form of an inequality, e.g., $E(L) \geq X$] associated with a particular component or control. The general problem is to determine an option which (including the cost of its implementation) will reduce the expected loss. The option may involve hardware, software, or both. It can achieve its purpose by reducing the probability of the loss, reducing the magnitude of the loss, or both. The determination of options depends primarily on the ingenuity of the analyst and those responsible for devising controls. Some of the common controls implemented to reduce risk of loss include (1) design controls: derating and redundancy, (2) quality assurance controls: inspections and process controls, and (3) operational controls: procedures and audits, alarms, and automatic checking.

Once an option is determined, it must be evaluated. If the decision maker is indifferent to chance situations having zero expected values, a decision on an option can be made on the basis of whether the option reduces the expected loss. Otherwise the decision maker's aversion to risk must be taken into consideration (Refs. 4, 5). All analyses in this report assume the decision maker is indifferent to chance situations having zero expected loss, and therefore all conclusions herein are based on expected values.

2.7. PRIORITIES

Priorities should be set by decision-under-uncertainty-analysis (Refs. 4, 5) methods. Initially, a plan should be drafted to evaluate every important component and LCE, setting priorities by schedule need dates. If resources available will not permit this, then schedule uncertainties should be determined and a revised plan developed utilizing that information. If this plan still requires more resources than those available, then options including analyses which may not be completed until after the equipment is in operation should be considered. Briefly, each possible avenue of evaluating a component should be explored and shown to be uneconomic before the component is dropped from consideration.

2.8. TERMINATION CRITERION

Evaluations should be terminated in each area of investigation when the remaining expected loss reduction is not positive and significant. A criterion should be established to flag management to consider such terminations to ensure that continued application of the methodology remains economic.

3. EXAMPLE ASSESSMENTS

3.1. GENERAL

The objectives of this section are to illustrate the application of the methodology to examples of new and uniquely designed components, to compare the results of the evaluation with experience, and thereby to assess the effectiveness of the methodology in locating and correcting areas which may contribute to the unavailability of the component, system, or plant.

The FSV helium circulator system and its auxiliaries were initially selected for the analysis. However, the number of components and phases involved were so extensive that it was concluded that the purpose of the evaluation would be better served by covering fewer components and phases. Hence, in a conference with ERDA it was agreed that the function "circulate helium" would be used as a base, the associated components were determined, and it was agreed that only the circulator operational phases (i.e., start-up, operation, and shutdown) were to be considered.

The drawings employed in the evaluations of the components were current issues if the component had experienced no significant problems in its development or operation. Otherwise, the drawing issue prior to the occurrence of the problem was employed. This permitted an estimate to be made as to whether the application of the methodology would be expected to have detected and avoided some actual problems, and, for components that had not experienced any problems, it provided an analysis of the current design which could be evaluated for its ability to detect and avoid problems if those components subsequently experience failures.

The following associated components were selected for inclusion in the evaluation:

1. Helium inlet
2. Support cone
3. Compressor rotor
4. Bearing assembly (including the shaft)
5. Brake
6. Shutdown seal
7. Diffuser
8. Helium shutoff (flapper) valve
9. Seals

Figure 3-1 illustrates the complete relative arrangement of the reactor components. A steel liner forms a vertical cylinder; the upper half contains the reactor core and its controls, and the lower half contains twelve steam generator modules and four helium circulator diffusers. The two halves are separated by the support floor. The core stands off the support floor on core support posts, and is contained in an open-topped cylinder called the core barrel.

Helium from the diffusers enters the plenum under the support floor, flows upward between the thermal barrier (attached to the liner) and the core barrel, flows downward through the core into the plenum beneath the core and above the support floor, and then flows through the twelve steam generator modules into the plenum beneath the lower floor, where it enters the helium circulator inlets. This lower plenum is divided into two separate volumes, each connected with one-half of the circulators and steam generators, thereby forming two independent loops.

Figure 3-2 illustrates the installation and overall function of a helium circulator including its inlet, shutoff valve, and diffuser. The circulator is attached to the liner (support flange) through the support cone. The diffuser has an outer cylindrical seal, which rests on the lower floor and attaches through a bellows to an inner cylindrical body. The

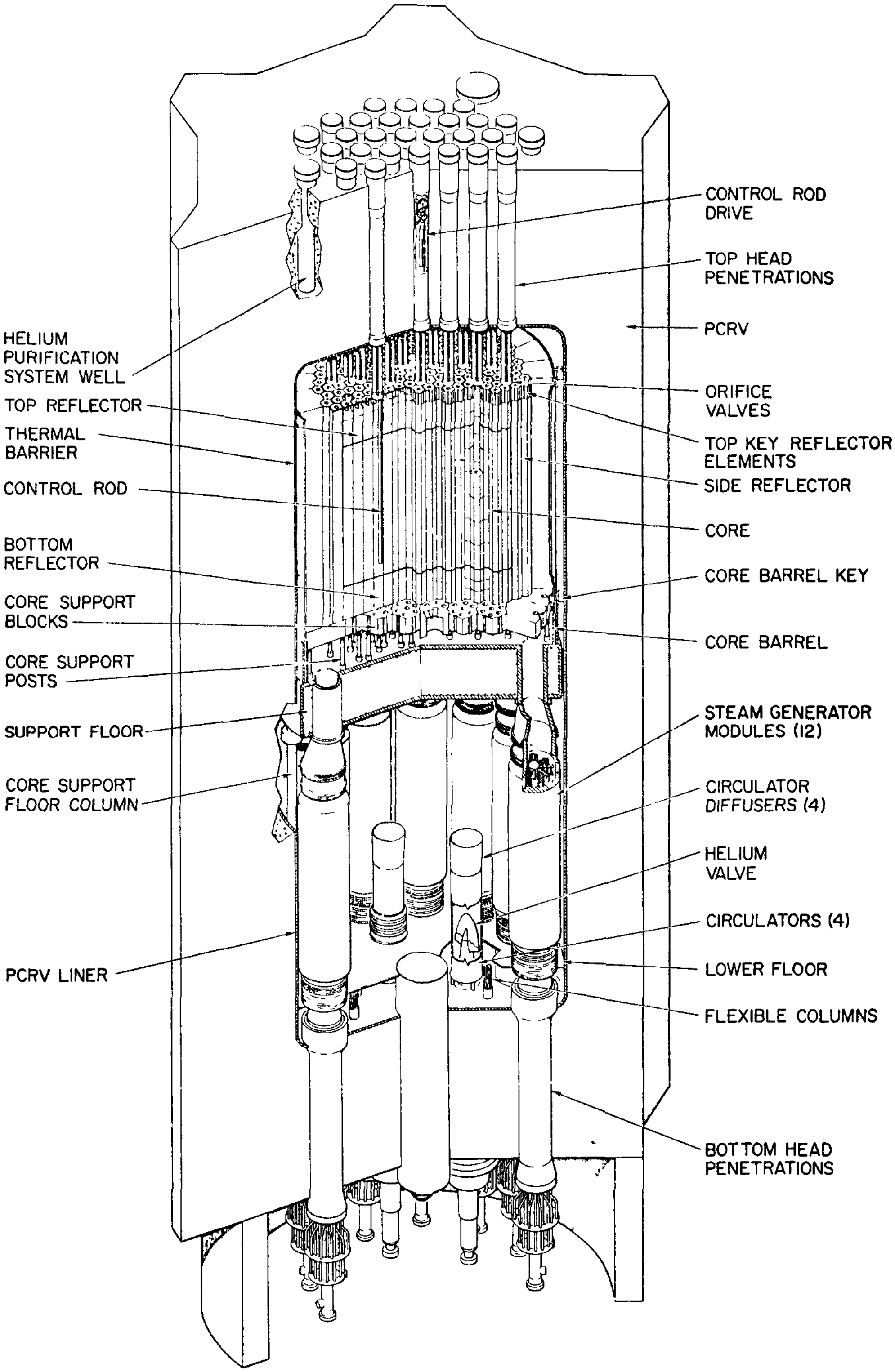

Fig. 3-1. Reactor arrangement

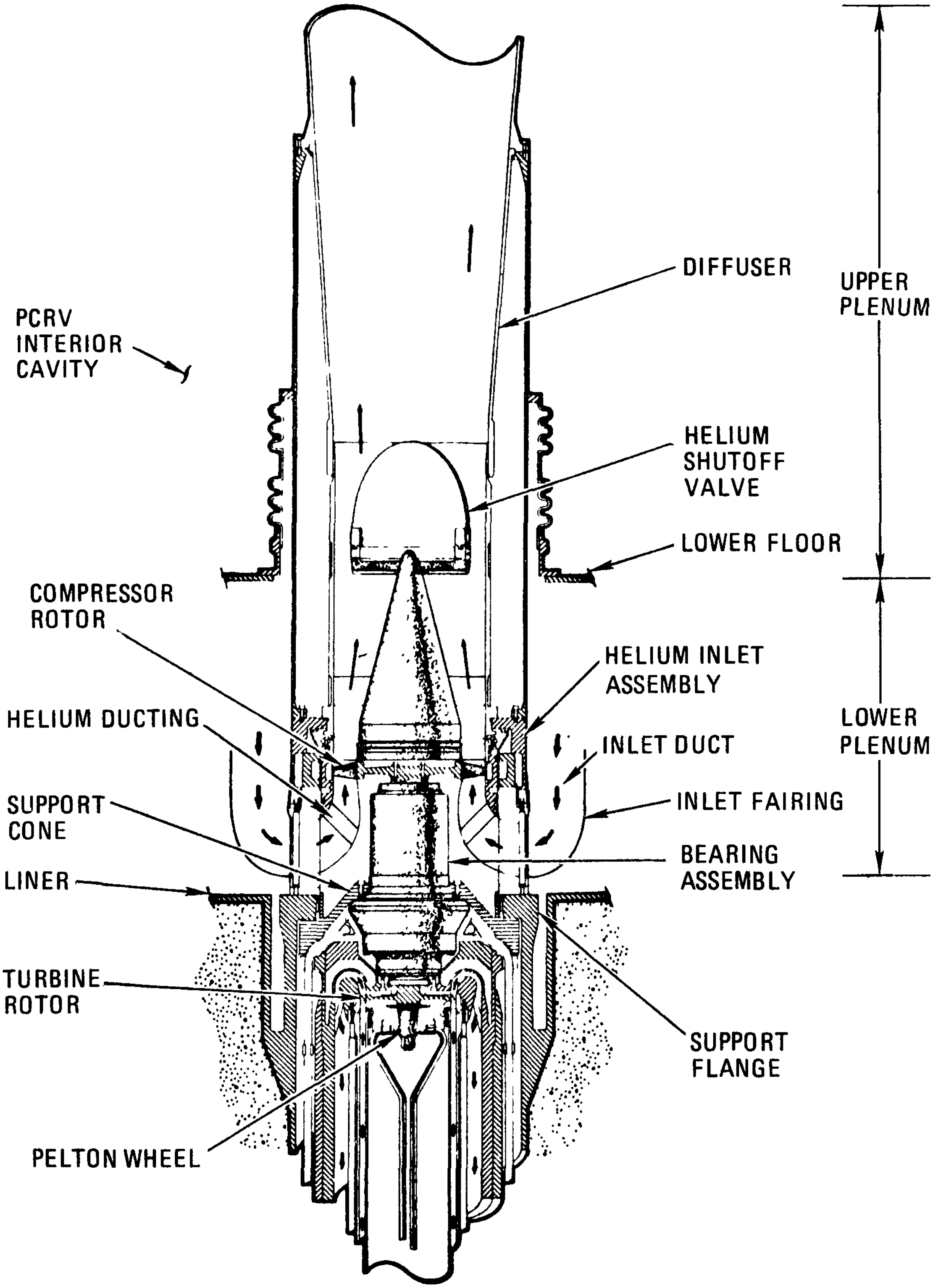

Fig. 3-2. Series steam turbine circulator PCRV installation

cylindrical body extends through the lower floor and rests on the helium inlet, which rests on the support flange. The diffuser also supports the helium shutoff (flapper) valve, which is hinged about even with the lower floor. The helium duct inlet is well above the liner bottom to reduce the chance and size of particulate matter entering the circulator. The arrows indicate the subsequent flow through the circulator and out of the diffuser.

Figure 3-3, a sectional view of the entire circulator machine, illustrates some of the machine's characteristics. For example, (1) redundant steam or water turbine drives exist, (2) water bearings are employed, (3) the labyrinth seals are purged by helium at the upper end, (4) the circulator has brakes, and (5) the circulator has a shutdown seal.

Figure 3-4 is another sectional view of the circulator machine showing details of the bearing and seal flow arrangements; it illustrates how the bearing water and purge helium and water are supplied and drained. It also illustrates the operation of helium-actuated brakes and shutdown seal.

The remaining sections of this volume will first present a qualitative analysis through the use of FMEA tables and fault tree analyses (FTAs), and will indicate how this alone can often suffice to make decisions. Then three example quantitative analyses will be presented. Each will evaluate an option which would reduce the expected loss through a change in controls. The first example employs a design control, the second employs a quality assurance control, and the third employs an operational control.

This example assessment will conclude by comparing the results of these analyses with FSV experience. The most significant problems with the entire FSV helium circulator system will be discussed. This discussion will include the means and likelihoods of each problem being detected, recognized as significant, and eliminated by application of the methodology described herein.

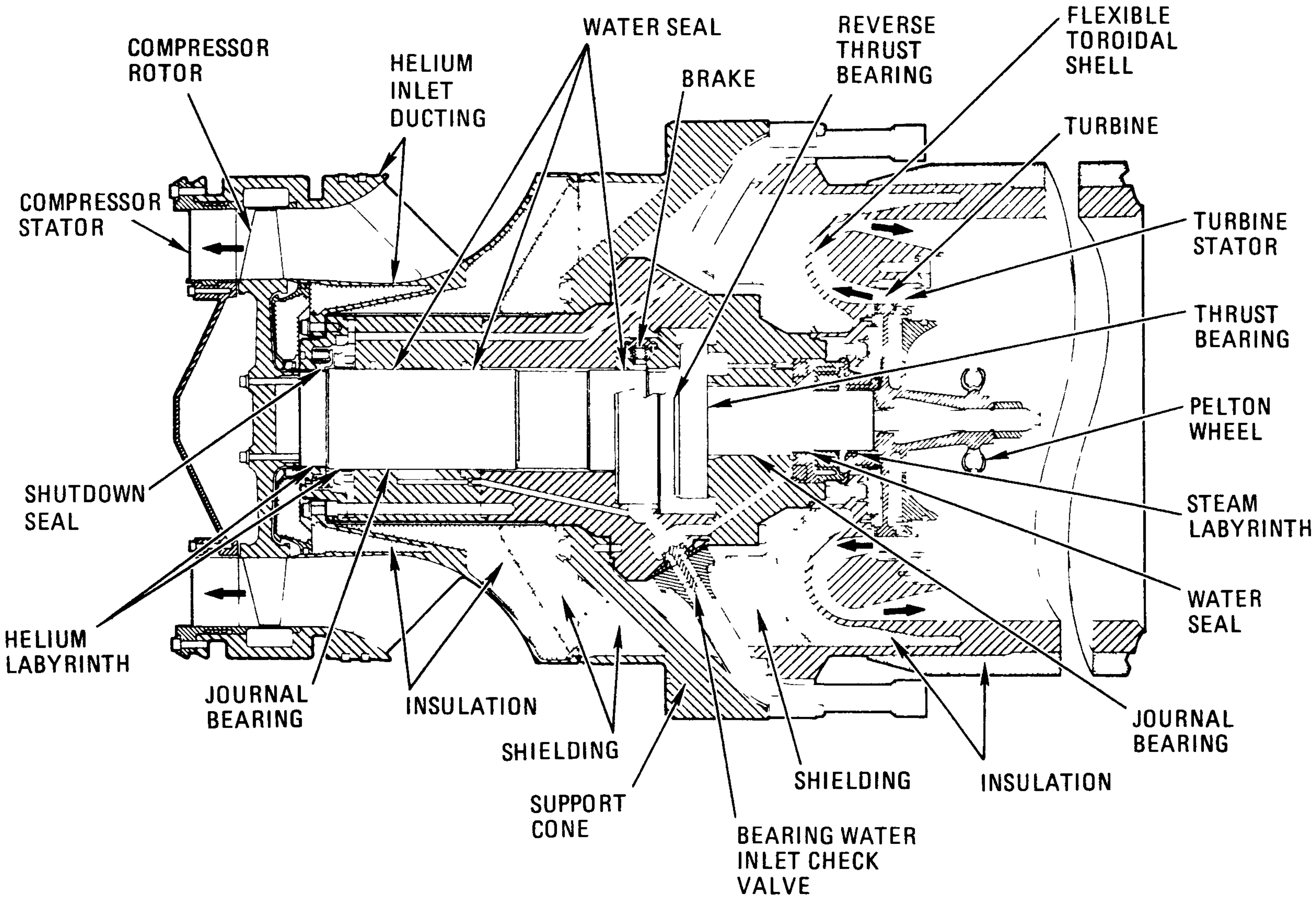

Fig. 3-3. Helium circulator assembly

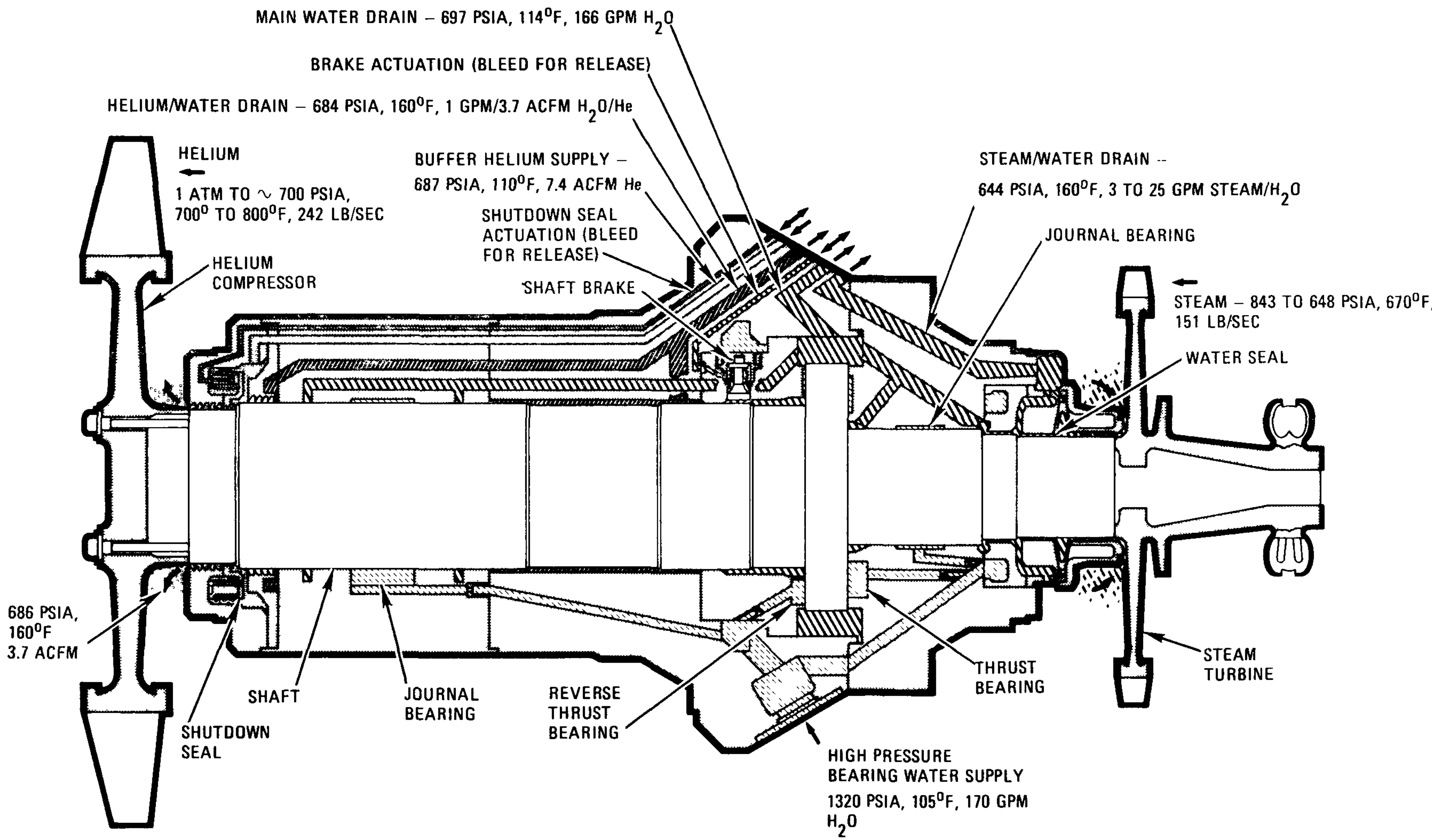

Fig. 3-4. Fort St. Vrain helium circulator bearing and seal flow arrangement

3.2. QUALITATIVE EVALUATIONS

3.2.1. Introduction

The purpose of the qualitative analysis phase is to identify failures, procedural errors, etc. (including combinations thereof) which are expected to contribute significantly to economic loss (for this example, to plant unavailability), thereby providing guidance for possible immediate corrective action on this basis alone, or for scheduling and setting priorities for quantitative analyses. To effect the qualitative analysis, both FMEAs and FTAs are employed. The differences between the FMEAs and FTAs are subsequently indicated, and the conclusions of the analyses are summarized and compared.

3.2.2. Failure Modes and Effects Analyses (Ref. 3)

The following sections summarize the results of failure modes and effects analyses (FMEAs) performed on each of the components defined for this ("circulate helium") function-based example evaluation. A more complete description of each component and discussion of each FMEA are given in the respective sections of Volume II, Appendix B. The complete FMEA tables are included in this volume.

The FMEA table entries employ some cryptic symbols concerning failure mechanisms, phase of plant life, impact levels, and estimated expected number of occurrences in the life of the plant. The definitions of these symbols are given in Table 3-1, which should be reviewed prior to attempting a thorough study of the FMEA tables.

The format of the FMEA table (Table 3-2) is a modification of the IEEE-352 standard form. The modified format was agreed on by considering the special needs of this analysis and the desire to retain the simpler and more familiar FMEA format which has been employed by reliability analysts for years. (The simpler and more familiar format is basically the section of Table 3-2 to the left of the double vertical lines.)

3.2.2.1. Helium Inlet FMEA. The function of the helium inlet is to direct the flow of primary coolant into the compressor rotor blades. The helium inlet is comprised of three principal sections. In the direction of normal flow the first is the inlet fairing, which resembles a large salad bowl. It directs the helium drawn from the lower plenum downward. Its upper portion is perforated and acts as a coarse screen in the event debris is carried by the primary coolant. The inlet fairing is mounted on the PCRV liner.

The second section of the inlet is the inlet assembly, which turns the primary coolant flow from downward to upward. It also supports the compressor diffuser assembly. The inlet assembly is mounted on the circulator penetration, which is in the bottom of the PCRV.

The third part of the inlet is the helium ducting (including the insulation), which continues to turn the flow upward and also causes the flow to accelerate. The helium ducting supports and locates the compressor stator and transmits the torque reactions of the stator to the circulator machine assembly of which the ducting is a part.

The inlet is static in operation. As indicated above, the inlet assembly and helium ducting sections support some external loads; the inlet fairing does not. All three sections are subject to vibration generated in and transmitted by the primary coolant.

Table 3-2, items 1.1 through 1.4, present failure modes and effects for these components. No failure modes were discovered which warrant corrective action. (See Volume II, Appendix B, Section B.2, for a more detailed discussion.)

3.2.2.2. Support Cone FMEA. The support cone is the structural member that mounts the circulator (bearing assembly) onto the PCRV penetration. It supports the weight and thrust loads of the circulator machine assembly, and positions it relative to the helium inlet and flapper valve assemblies.

The support cone is part of the primary coolant boundary and thus has primary coolant on its convex surface and buffer helium on its concave surface. Both inner and outer flanges of the support cone contain seals to prevent leakage of the primary coolant. The support cone is subject to some minor vibration from rotating parts but not from aerodynamic excitation because it does not border the flow stream. Table 3-2, item 2, presents the failure modes and effects for the support cone. No failure modes were discovered which warrant corrective action. (See Volume II, Appendix B, Section B.3, for a more detailed discussion.)

3.2.2.3. Compressor Rotor FMEA. When the compressor rotor is rotated, it accelerates the primary coolant causing it to circulate. The rotor consists of the disc, blades, and mounting bolts. It is a single-stage, axial-flow wheel with a blade tip diameter of 27.06 in. It nominally operates at 9550 rpm to pump 138,000 lb per hr of primary coolant, which enters the compressor at 686 psia and 742°F.

The disc is machined from a one-piece forging of Type 422 stainless steel. Each of the 31 blades has a twisted airfoil and is 5 in. high including its dovetail base that holds it in the disc rim. Eight bolts connect the disc to the shaft through a curvic coupling.

The rotor is a dynamic part and could therefore conceivably fail from forces developed within itself in addition to forces imposed by interference with adjacent parts or primary-coolant-borne impurities. Failure modes and effects are listed in Table 3-2, item 3. Testing conducted at speeds up to 146% of rated circulator speed indicate that the compressor rotor design is completely satisfactory. Therefore, no failure mode appears to warrant corrective action. (See Volume II, Appendix B, Section B.4, for a more detailed discussion.)

3.2.2.4. Bearing Assembly FMEA. The FMEA for the bearing assembly is shown in Table 3-2, items 4.1 through 4.7. The most likely failure modes of the bearing assembly, in order of likelihood, are instrument drift or loss of signal, leakage of fluids past seals, and binding of the shaft.

Instrument failures appear to have little impact on plant availability because loss of one signal does not require shutdown of a circulator since backup signals can be used by the operator to infer the lost readings. The next most likely failure mode appears to be leakage (internal or external) by loss of seal effectiveness. Separate FMEAs for each O-ring seal that contributes to this failure mode are discussed in Section 3.2.2.9. The effect for the general 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 that may contact the shaft. The most likely effect of this failure mode would be an extended plant shutdown for circulator repair if the shaft could not be jarred loose by the water turbine jets ("bumping").

The components analyzed in the bearing assembly FMEAs were initially designed using standard calculational models backed 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, feedback of this experience into the design of future units is important to devise improvements that can be economically implemented to avoid common operating problems.

As the operators also gain experience, they will be able to deal more rapidly with unusual conditions that arise during routine operation. Operator sensitivity to these anomalous conditions can minimize the consequences of problems. The operator must rapidly secure a circulator, if necessary, to avoid a potential extended shutdown.

On completion of the bearing assembly FMEAs it was recommended that the failure mode of water leakage into the reactor from the bearing assembly be selected for one of the example economic options. This recommendation was approved. The evaluation is presented in Volume II, Appendix C, Section C.4, and a summary is given in Section 3.3 of this volume. (See Volume II, Appendix B, Section B.5 for a more detailed discussion of this FMEA.)

3.2.2.5. Brake FMEA. An FMEA of the circulator brake is shown in Table 3-2, item 5. Brake failure modes severe enough to require circulator removal include (1) spurious application of the brake during circulator operation, and (2) failure of the brake to stop circulator rotation before the shutdown seal is applied, scoring the seal so that it leaks excessively.

Several design modifications have been suggested for consideration as a result of this FMEA. They include methods to (1) further assure that the seal is applied only after the circulator has stopped rotating; (2) prevent damage caused by inadvertent application of the brakes due to bearing water in-leakage; (3) prevent damage caused by wearout of the silver brake shoe insert; (4) prevent overpressurization of the brake bellows. (See Volume II, Appendix B, Section B.6, for a more detailed discussion.)

3.2.2.6. Shutdown Seal FMEA. An FMEA on the shutdown seal is shown in Table 3-2, item 6. Failure effects which can lead to plant unavailability include (1) allowing water to leak into the primary coolant in the absence of buffer helium, or (2) damage to the seal requiring circulator removal to repair.

Suggestions to protect the shutdown seal from damage are described in Volume II, Appendix B, Section B.7, along with a more detailed discussion on the FMEA. These suggestions include providing further assurance that the seal is applied only after the circulator has stopped, and methods to prevent overpressurization of the shutdown seal bellows.

3.2.2.7. Diffuser (Including Compressor Stator) FMEA. The compressor stator and the diffuser assemblies both contribute to the conversion of the velocity of primary coolant leaving the compressor into static pressure. The function of the stator is to straighten the helical flow from the compressor rotor into axial flow through the diffuser. The stator is part of the circulator machine assembly and is mounted on the helium ducting part of that assembly. The function of the diffuser assembly is to convert primary coolant velocity (kinetic) energy into pressure (potential) energy by gradually increasing the cross-sectional area of the flow path. The diffuser assembly is mounted on top of the inlet assembly, which is on the PCRV penetration.

The stator and diffuser assemblies are static parts and are exposed to the primary coolant flow stream. The primary coolant applies a significant torque load to the stator as its path is straightened. Both the stator and diffuser are subjected to vibratory excitation from flow disturbances in the primary coolant. These disturbances result from actions such as rotor blades passing through the wakes of the helium ducting struts and passing close by the stator blades. The above loads are included in the design analysis of the parts.

In the exit of the diffuser assembly, a cruciform-shaped sample rake takes samples of primary coolant for the moisture monitors. The sample tubes from the rake are routed down the outside of the diffuser assembly. There is also a sample tube from static pressure taps in the diffuser exit, which is routed down the outside of the diffuser assembly.

The failure modes and effects for the stator and diffuser are presented in FMEA Table 3-2, items 7.1 and 7.2, respectively. No failure modes were discovered which warrant corrective action. (See Volume II, Appendix B, Section B.8, for a more detailed discussion.)

3.3.2.8. Primary Coolant (Helium) Shutoff Valve FMEA. An FMEA on the helium shutoff valve is shown in Table 3-2, item 8. Failure modes leading to plant shutdowns for circulator replacement have been identified. They include failure of the valve in the closed position, and breakage of parts which subsequently fall into and damage the circulator or result in excessive backflow during circulator shutdown.

No specific recommendations for modification appear justified, but since flow disturbances have already been observed and remedied, it is recommended that any further design effort be directed toward reducing the likelihood of the valve failing to close, because this mode of failure would reduce the fraction of coolant that flows through the core. (See Volume II, Appendix B, Section B.9, for a more detailed discussion.)

3.3.2.9. Seals FMEA. An FMEA that concentrates on seals was performed and is shown in Table 3-2, item 9. Leakage past a seal is the primary mode of failure considered. Evaluation of the effect of leakage for all the various seals serves to identify the most important seals, and thus allows special arrangements to be provided to prevent or minimize leakage at those places.

Recommendations beyond providing special arrangements at key locations include careful preparation of the groove into which a seal is to be installed, and proper handling and cleaning of the seal itself before installation. (See Volume II, Appendix B, Section B.10, for a more detailed discussion.)

3.2.2.10. Fasteners. Fastener failures were considered during the FMEAs of the major components above (i.e., their failures were considered as failure mechanisms of the modes for the major components). Nevertheless, a separate specific review of fasteners themselves was performed to ensure that the type, locking device, and effect of failure are specifically considered for each. Table 3-3 summarizes the results of the review.

All fasteners and locking devices appear adequate. However, some improvement in fasteners should be considered for future circulators. For example, the bearing assembly set screw is located next to the shaft and secured by ring staking. This locking method is no longer recommended for fasteners in such locations (Ref. 7), and current GA standards do not allow its use in comparable situations. However, it does not appear justified to modify the FSV design because such action would bring about an economic loss (i.e., loss of plant availability) comparable to the one it was trying to avoid and which is now expected to be only a remote possibility. This locking device will not be employed on future designs.

TABLE 3-1
NOTATIONS EMPLOYED ON FMEAs

Column Caption	Description	Definitions
Failure mechanism	Number and letter superscripts on each mechanism	Number [signifies whether the cause is due to the component being analyzed, external source, or both]: 1 ≡ only the component being analyzed 2 ≡ only an external source(s) 3 ≡ both Letter [signifies estimate of fraction of all such causes that would be common to more than one circulator]: A ≡ <<10% but significant B ≡ on the order of 10% C ≡ >>10% X ≡ not significant
Phase	Phase of helium circulator operation covering startup through shutdown	SU ≡ helium circulator startup OP ≡ helium circulator operation SD ≡ helium circulator shutdown
Exp	Preliminary estimate of the expected number of times the particular line item is expected to occur in the life of the plant	A ≡ $1.0 \leq E(X)$ B ≡ $0.1 \leq E(X) < 1$ C ≡ $10^{-2} \leq E(X) < 10^{-1}$ D ≡ $10^{-3} \leq E(X) < 10^{-2}$ E ≡ $10^{-4} \leq E(X) < 10^{-3}$ F ≡ $E(X) < 10^{-4}$
Impact	Effect failure would have on entire plant availability to produce power whether immediate or delayed	I ≡ loss of 5% or more of the plant life capacity. II ≡ plant shutdown or power reduction resulting in loss of <5% of plant life capacity but ≥20% of plant capacity for the year. III ≡ plant shutdown or power reduction resulting in a loss of plant capacity for the year ≥0.01% and <20%. IV ≡ loss of plant output power <0.01% involving component and higher assembly failures. V ≡ loss of plant output power <0.01% involving component failure only.

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REFERENCE: See Component Identification (below)

TABLE 3-2

FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
1.	Helium Inlet									
1.1	Inlet Fairing (P/N 90-R1105-211)	Fails to properly direct primary coolant flow.	Fractured or distorted because of: a. Design error (1C) b. Non-design defect (1B) c. Unexpected loads (2B) d. Unexpected temps (2C)	SU OP SD	Loss of plant operating efficiency until plant shutdown for repair	II	Flow	Run circulator at higher speed	Failure might go undetected but if detected would probably permit repair delay until refueling time.	F D E E
			Screen section blocked by contamination (some flow bypasses the screen) (2C)	SU OP SD	Loss of plant operating efficiency until plant shutdown for repair	II	Flow	Run circulator at higher speed		D

PERFORMED BY/DATE: F.K. Jacobsen
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REFERENCE:

TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
1.2	Inlet Assembly (PN 90-C2101-270)	Fails to properly direct primary coolant flow	Part failure distorts flow path because: a. Design error (1C) b. Non-design defect (1B) c. Unexpected loads (2B) d. Unexpected temps (2C)	SU OP SD	Loss of plant operating efficiency until plant shutdown for repair	II	Flow	Run circulator at higher speed		 E E D D
			Airfoil fairing contaminated (2C)	SU OP SD	Loss of plant operating efficiency until plant shutdown for repair	II	Flow	Run circulator at higher speed		D
		Fails to properly support the diffuser assy.	Support column collapse because: a. Design error (1B) b. Non-design defect (1B) c. Unexpected loads (2C) d. Unexpected temp (2C)		Probable damage to circulator rotor requiring early plant shutdown for repair	II	Displacement & speed	Disc catcher		 E D D D
		Fails to provide pressure data for flow measurement	Pressure data not transmitted because; a. Sense ports blocked (2C) b. Sense tube leaks (1B)		Loss of data until plant shutdown for repair	II,IV	Pressure	Does not result in hardware breaking		 E C

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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
1.3	Helium Ducting (P/N 90-C2101-340)*	Fails to properly direct primary coolant flow	Support strut contaminated (2C)	SU OP SD	Loss of plant efficiency until plant shutdown for repair	III	Flow	Run circulator at higher speed		D
		Causes damage to the compressor rotor	One support strut breaks free and blows into the rotor blades.	SU OP SD	Early plant shutdown for repair	II,III	Displacement & speed	Disc catcher limits damage		
			a. Non-design defect (1B)							D
			b. Eroded (2C)							E
			All support struts on 1 compressor break and the compressor stator contacts the rotor and breaks the blades.	SU OP SD	Early plant shutdown for repair	II,III	Displacement & speed	Disc catcher limits damage		
			a. Design error (1C)							E
			b. Non-design defect (1B)							D
			c. Eroded (2C)							E
			d. Unexpected temps (2C)							E
			e. Unexpected loads (2B)							E

*Selected for economic analysis, Section 3.3.3

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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
1.4	Insulation, Compressor Side (P/N 90-C2101-310)	Interferes with compressor rotor	Housing breaks a. Design error (1C) b. Non-design defect (1B)	SU OP SD	Rub on rotor causes slowing or unbalance	II,III	Displacement & speed	Extra power is available to drive the circulator		F E
			Mounting bolts fracture a. Design error (2C) b. Non-design defect (1B)	SU OP SD	Rub on rotor causes slowing or unbalance	II,II		Extra power is available to drive the circulator	Bolt fragments can not escape	E D
			Mounting bolts loosen a. Design error (1C) b. Non-design defect (1B)		Rub on rotor causes slowing or unbalance			Extra power is available to drive the circulator	Mounting bolts can not escape	E D
2.	Support Cone (P/N 90-C2101-301)	Fails to properly support and align the circulator	Support cone distorted or fractured because a. Design error (1C) b. Non-design defect (1B) c. Unexpected loads (2A) d. Too high He temp (2B) e. Insulation failure (1B) f. Insulation wet (2B)	SU OP SD	Contact of circulator rotor with static parts causing blade fractures requiring plant shutdown to replace the circulator	II,III	Speed and/or displacement	Retention of blade fragments, & automatic overspeed trip		E D D D D D

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REFERENCE:

TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
			Inner or outer flange bolt failure: a. Design error (1C) b. Non-design defect (1B) c. Unexpected loads (2B) d. Overtorqued (2B) e. Unscrews (1B) f. Corroded (2C)	SU OP SD	Contact of circulator rotor with static parts causing blade fractures requiring plant shutdown to replace the circulator	II,III	Speed &/ or dis- placement.	Redundant bolts, retention of blade fragments, automatic overspeed trip		E D D C D D
		Fails to seal the primary coolant boundary	Leaks helium because: a. Design defect (1C) b. Mfg defect (1B) c. Installation damage (1B) d. Contamination (2B) e. Flange bolts loose (1B) f. Abnormal temperature (2B)	SU OP SD	Non-immediate plant shut- down to remove circulator and replace seals	II,III	Increased purge flow or radio- activity in the pene- tration	Helium purge & penetration cleanup if required		D C C C D E
3.	Compressor Rotor									
3.1	Blade (P/N 90-C2101-363)	Fails to acceler- ate primary cool- ant effectively	Blade shape distorted by erosion from: a. Particles in the primary coolant (2C) b. Water in the primary coolant (2A)	SU OP SD	Loss of plant efficiency until shutdown for replacement of all circulators	II	Speed	Circulator may be run above 100% speed	Condition will degrade gradually	C C

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REFERENCE:

TABLE 3-2

FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
			Blade shape distorted by contamination from: a. Material in the primary coolant (2C)	SU OP SD	Loss of plant efficiency until shutdown for replacement of all circulators	II	Speed	Circulator may be run above 100% speed	Condition will degrade gradually	D
		Blade breaks off of rotor	Blade fractures because: a. Design error (1C) b. Non-design defect (1B) c. Erosion (2C) d. Contact with stator or shroud (3B)	SU OP SD	Early plant shutdown for circulator repair	II,III	Displacement & speed	Disc catcher to retain fragments	All circulators will not fail simultaneously	E B C D
3.2	Disc (P/N 90-C2101-362)	Disc fails to support the blades	Disc fractures because: a. Design error (1C) b. Non-design defect (1B) c. Rubs on adjacent part (3B) d. Blade pin comes out allowing blade to rub (1B)	SU OP SD	Reduction in plant power until shutdown to repair the circulator(s)	II,III	Displacement & speed	Disc catcher contains fragments	All circulators probably won't fail simultaneously	E C D C
		Disc fails to rotate the blades properly	Curvic coupling fractures because; a. Design error (1C) b. Non-design defect (1B) c. Excessive load (2B) d. Disc rubs (3B)	SU OP SD	Reduction in plant power until shutdown to repair the circulator(s)	II,III	Displacement & speed	Disc catcher contains fragments	All circulators probably won't fail simultaneously	E D D D

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REFERENCE:

TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
			Disc rotates slow because it rubs on adjacent static parts (3B)	SU OP SD	Reduction in plant power until shutdown to repair the circulator(s)	II,III	Speed, feed water flow	Extra power is available to drive the circulator	Most likely response to high power requirement would be shutdown	D
3.3	Bolt, Mounting (90-C2101-307) (includes lockwasher 90-C2101-308)	Fractures	Tensile break from: a. Design error (1C) b. Non-design defect (1B) c. Overtorqued (2B) d. Corrosion (2B) e. Overload (2B)	SU OP SD	Reduction in power until plant shutdown for circulator replacement	II,III	Displacement & speed	Redundant bolts. Loose parts kept from flow stream	Will not fail all circulators simultaneously	F C C D E
			Threads shear from: a. Design error (1C) b. Non-design defect (1B) c. Other part defect (2B) d. Corrosion (2B) e. Overload (2B)	SU OP SD	Reduction in power until plant shutdown for circulator replacement	II,III	Displacement & speed	Redundant bolts. Loose parts kept from flow stream	Will not fail all circulators simultaneously	F D D E E
		Loosens	Creeps because: a. Design error (1C) b. Non-design defect (1B) c. Temperature high (2C) d. Corrosion (2B)	SU OP SD	Reduction in power until plant shutdown for circulator replacement	II,III	Displacement & speed	Redundant bolts. Loose parts kept from flow stream	Will not fail all circulators simultaneously	F D E E

PERFORMED BY/DATE: F.K. Jacobsen & G.W. Hannaman
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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
			Unscrews because: a. Lockwasher failure (1B)	SU OP SD	Reduction in power until plant shutdown for circulator replacement	II,II	Displacement & speed	Redundant bolts. Loose parts kept from flow stream	Will not fail all circulators simultaneously	C
			Mating part threads shear (2B)	SU OP SD	Reduction in power until plant shutdown for circulator replacement	II,II	Displacement & speed	Redundant bolts. Loose parts kept from flow stream	Will not fail all circulators simultaneously	C
4.	Bearing Assembly									
4.1	Circulator Shaft (90-C2101-521 Mtl:SST 422 with some chrome oxide coating)	Binds	Cracking of oxide coating (3C) Rubbing (3B) Corrosion (3B)	SU OP SD	Eventual plant shutdown required if circulator repair or replacement is necessary	IV then III or II	Speed, flow	Natural flushing action of bearing water (app. 160 gpm)	Impact depends on common mode factor	C B B
			Loss of brg water (BW) (3B)	SU OP SD	Eventual plant shutdown required if circulator repair or replacement is necessary	Same	Speed, flow	Redundant B.W. supply		E
			Tolerance overlap (3B) Radiation or temp. induced dimensional changes (3C)	SU OP SD	Eventual plant shutdown required if circulator repair or replacement is necessary.	Same	Speed, displacement, & temp.	Disc catcher (in worst case)	Overlap more likely on a replacement	D F

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REFERENCE:

TABLE 3-2

FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
			Flaking of brake surface into bearings (3C) Pitting (electro-magnetic effects) (3C) Vibration (2B) External causes (2B)	SU OP SD	Eventual plant shutdown required if circulator repair or replacement is necessary	IV then III or II	Operator observation of speed transient		Shaft material much harder than brakes	E C B NA
		Yields	Cracking, wear or loosening of internal threads (3B)	OP	Eventual plant shutdown required if circulator repair or replacement is necessary.	IV then III or II	Displacement & speed	Disc catcher (in worst case)		C
			External cause (2B)	OP	Eventual plant shutdown required if circulator repair or replacement is necessary			Operator observation		NA
		Breaks (loss of torque)	Cracking, fatigue, or overstress (3B) External cause (2A)	OP	Power reduction and eventual plant shutdown for circulator removal and repair	IV then III or II	Speed, displacement, & flow		Failure mode unlikely due to low design stress	E NA
		Separates (outside assembly)	Cracking, fatigue, or overstress (3B) Poor assembly procedure (3B) External cause (2B)	OP	Immediate plant shutdown for circulator removal and repair	III or II	Displacement, & speed		Cracks have been observed in other curvic couplings	D C NA
		Vibrates	Inherent critical freq. (3C) External cause (2B)	OP	Change in plant steady state operating conditions (He flow)	V	Displacement	Operational procedures	Change in operating water pressure	A NA

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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

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NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Leaks (along shaft)*	Erosion (3B) Wear (3B)	SD OP	Delay in plant startup while removing moisture	V	Helium leakage	Helium dryers. Adjustment of buffer helium supply pressure	If leakage persists; circulator replacement may become necessary	A B
			External cause (2B)	SD OP	Reduction in power due to moisture monitor level. Eventual plant shutdown, for circulator removal and replacement	IV then III or II	Moisture monitors			NA
4.2	Main Brg Housing (90-C2101-508 SST 420 "Demagnetized")	Leaks, cracks, or yields	Seal failure (3B) Excessive stress (3B) Vibration (3B) Erosion (3B) Tolerance (3B) Assembly prob. (3B) External cause (2B)	SU OP SD	Eventual plant shutdown for bearing housing repair, if operating conditions become unsatisfactory.	III	Temp., speed, displacement, pressure, & flow	Moisture removal system, external system adjustment using backup supply at lower pressure	Bypass of normal brg wtr flow path, water into pressure taps, potential for water into core	A C B C B A NA
		Blocks water, helium passages	Loose parts in passages (3B) Poor fabrication (3B) Corrosion (3B) External cause (2B)	SU OP SD	Plant shutdown for circulator removal if blockage can't be cleared externally	V or III	Pressure, displacement	Redundant inlets, & in some cases remove blockage by external means	Circ. trip on loss of buffer helium supply	B C C NA
		Instrumentation drifts	Environmental variation (3B) Vibration (3C) Corrosion (3B) External cause (2B)	SU OP SD	Plant operators ignore and continue power output or take action to shutdown reactor until prob. resolved	V or IV	Loss of or abnormal signal			A A B NA
		Binds with shaft	Speed probes loosen due to bolt failure, or (3B) Locking failure (3B)	SU OP SD	Plant shutdown for repair circulator removal, etc.	III	Speed, displacement	Redundant bolts, locking devices on each bolt	Noise content of speed signal increases	B B

*Selected for economic analysis, Section 3.3.4 (with Item 4.7)

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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
4.3	Circulator Machine Lower Bearing (90-C2101-505 SST 420) & High Pressure Feed Housing (90-C2101-502 SST 420) Demag., Chrome Oxide)	Binds	Surface flakes (3C) Rubbing (3B) Corrosion (3B)	SU OP SD	Eventual plant shutdown required to repair circulator if flush out and bumping is not successful	III or V	Speed, flow	Ability to flush out bearings		C B B
			Tolerance overlap (3B) Induced dimensional changes (3C) Loss of brg water (3B)				Speed, displacement, temp.		In the event of extremely rapid seizure extended damage may occur	C C C
			Vibration (2B) External cause (2B)				Speed & operator observation			B NA
		Cracks, yields, or distorts	Environmental cause (3C) Uneven torque (3B) Erosion, wear (3B) Fretting (3B) Processing (3B) External cause (2B) (transient conditions)	SU OP SD	Eventual plant shutdown required for circulator repair	III	Changes in normal operating conditions & operator observation		If operator takes no actions, may result in binding	C C B B B NA
		Leaks	Seal failure (3B) Excessive stress (3B) Machine tolerance (3B) Environmental (3C) External cause (2B)	SU OP SD	Eventual plant shutdown required for circulator removal if external actions are ineffective in controlling leakage	III or IV	Temp, speed, displacement		Bypass for normal bearing water flow increase in steam/water drain flow	A C B C NA

PERFORMED BY/DATE: G.W. Hannaman
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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Plugs a flow path	Loose debris in path (3B) Poor fabrication (3B) Environment (3C) External cause (2B)	SU OP SD	Degraded performance until shutdown can be performed with minimum impact	III	Speed, temp, displacement	Redundant paths & pads	If steam/ water drain plugged, immediate shutdown may be required	B D C NA
		Loss of instrumentation or drifts	Temp (3B) Pressure (3A) External cause (2B)		Small impact if nearby probes and sensors can be used to estimate important variables.	V or III	Operator observation of signals	Redundant sensors & diverse probes	Would be repaired if circ. removed for other reasons	A A NA
4.4	Lower Labyrinth (90-C2101-517, SST 420) Steam Fairing (90-C2101-527, SST 420) Water Seal (90-C2101-527, SST 420)	Binds	Tolerance overlap (3B) Loose mtl in gap (3B) Parts break and jam (3B) Corrosion and pitting (3B) External cause (2B)	SU OP SD	Shutdown for circulator removal and repair	III	Displacement, speed, steam/water drain flow	Rubbing should occur on bearings first	Increase in shaft vibration, possible to shear hp. housing, additional damage to machine	B B C B NA
		Leaks, along shaft, or yields	Shaft vibration (3B) Erosion (3B) Thermal expansion (3B) Excessive wear (3B) External cause (2B)	OP	Some external modification may allow continued operation with degraded performance until removal for another reason occurs	V or III	Steam/water drain flow, steam into BW, or loss in reactor pressure	Designed with controlled leak expected	Increase in leakage rate	A B C A NA
		Leaks (external)	Seals Fail (3B) Erosion (3B) Mtl defect (3B) Distortion, crack (3B) External cause (2B)	OP	Little impact on plant operation	V	Steam/water drain flow, steam into BW, or loss in reactor pressure		Additional path to steam water drain	A B C C NA

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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Separates	Vibration (3B) Mtl defect (3B) Corrosion (3B) External cause (2B)	SU OP SD	Shutdown for circulator removal and repair.	III	Speed, flow, displacement		Locking lip falls into steam turbine causing damage	B C B NA
		Loosens	Vibration (3B) Locking key failure (3B) Bolts back out (3B) External cause (2B)	OP	Shutdown for circulator removal and repair.	III	Pressure, temp, speed, displacement	Redundant bolts	High pressure feed housing leaks, thus lower bearing support lost	B C C NA
4.5	Upper Thrust* Assembly (90-C2101-530, SST 410, Cr O, & Demagnetized) & Deflector 90-C2101-548 *Brakes in Section 5.0	Binds	Surface flaking (3C) Pin lock unscrews (1B) Ring stake breaks (1B) Deflector loosens (1B) Tolerance overlap (3B) Corrosion (3B) Dimensional change (3C) Rubbing (3B) Loss of brg. water (3B) External cause (2B)	SU OP SD	Delay in plant startup or plant shutdown, if circulator removal required. Power reduction, or extended shutdown if circ removal required. Same as startup	IV or III	Speed, displacement, temperature Operator observation of speed transient	Natural flushing action of bearing water system	The ring stake must withstand the flow of water for life of plant	C B A C C B D B B NA
		Distorts, cracks, or yields	Environmentally induced (3C) Uneven torque (3B) Erosion (3B) Fretting (3B) Processing (3B) External cause (2B)	SU OP SD	Extended plant shutdown for circulator removal and repair.	III	Changes in normal operating characteristics observed by operator displacement			C B B B B NA

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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Plugged (water passage)	Loose material (3B) Poor fabrication (3B) External cause (2B)	SU OP SD	Degraded performance which may progress to need for circulator removal and repair.	V or III	Speed, displacement	6 pads with separate inlets, and thrust pressure increases as gap decreases	Increase in shaft/ bearing wear since shaft moved closer to weak bearing	B B NA
		Plugged (helium passage)	Loose Mtl. (3B) Fabrication (3B) External cause (2B)	SU SD	Startup delay as system "bumped", and potential for no brake effectiveness could lead to damage & circ. removal if needed.	V or III	Pressure, speed	Redundant brakes, external control of brake exhaust pressure	Failure to release brakes, failure to apply brake	B B NA
		Leaks - water	Seal failure to hold pressure (3B) External cause (2B)	OP	Eventual circulator replacement required	III	Speed, displacement, pressure		Water bypasses bearing, degraded performance	A NA
4.6	Upper Journal Bearing (90-C2101-514, SST 410 with a Cr_2O_3 coating, demagnitized)	Binds	Surface flaking (3B) Tolerance overlap (3B) Corrosion (3B) Induced dimensional change (3B) Rubbing (3B) Loss of brg water (3B) External cause (2B)	SU OP SD	Delays startup while bumping is used to free circulator rotation. If unsuccessful, requires extended shutdown for circulator removal & repair. If external adjustments to brg. water flow fail to free rotor, extended plant shutdown required for repair. Same as startup	III or IV	Speed, temperature, displacement	Natural flushing action of brg. water	If binding occurs rapidly (seizure), damage external to the journal may occur.	D D B C B D NA

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TABLE 3-2

FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Cracks, leaks (external) or distortion	Uneven torque (3B) Erosion (3B) Mtl. defect (3B) Seal leakage (3B) External cause (2B)	SU OP SD	Plant shutdown required to remove and repair circulator	III	Housing temperature, pressure; moisture in core; displacement; failure to actuate seals		High press. brg water could seep into other ports such as water into buffer helium supply etc.	D C C B NA
		Leaks (along shaft)	Erosion (3B) Rubbing (3B) Wear (3B) Tolerance (3B) External cause (2B)	SU OP SD	Delay in plant startup due to water ingress Imbalance in seal conditions leads to high moisture in core, may require circulator removal same as startup	IV or III	Moisture, displacement, pressure	Helium system dryers Shaft rotation increase improves seal effectiveness Blocked by shutdown seal	External system adjustments by operators may be able to control problem without circulator removal	B B B C NA
		Blocks	Loose parts in passage (3B) Corrosion (3B) External cause (2B)	OP	Reduction in power or shutdown while passages cleared externally, or circulator removal required	IV or III	Pressure		If unable to clear may require extended shutdown	B B NA
		Yields	Fretting (3B) Wear (3B) Loosen (seals shrink) (3C) External cause (2B)	SU OP	Increase in circulator vibration results in eventual plant shutdown for circ. repair	III	Displacement		If uncorrected may lead to more extensive damage of the circulator components	D C B NA

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Instrumentation drifts	Grounded signal (3B) Environmental effects (3B) Corrosion (3B) External cause (2B)	SU OP SD	Delay plant startup until problem resolved Plant effect minor unless (1) another fault results in req. for circ. removal which could have been prevented by operator action, or (2) operator responds to the bad signal by circ. shutdown leading to some loss of plant capacity	V or IV	Change in signal response	Redundant or near by signals available		A B C NA
4.7	Dynamic Upper Seal System: Slinger (SST 420), Upper Journal Lab. Upper Labryinth, Shaft Fits	Binds	Tolerance overlap (3B) Corrosion (3B) Rubbing (3B) Loose material in gap (3B) External cause (2B)	SU OP	Minor delay in startup, if the "break loose" procedure is successful. During operation seal binding would be self-correcting until, (1) seal characteristics change until the seal is ineffective or (2) the condition results in shaft seizure.	V V or III	Speed, temperature, displacement	Seal wear into place as shaft vibrates	Bearing clearance is 0.003" compared to 0.005" for seals. Therefore, binding would occur only in one spot	E D E C NA
		Leaks (along shaft)*	Loss of buffer helium supply (3B) Excessive wear (shaft or seals) (3B) Switching pressure transients (3C) Shaft rotation too slow for seal effect. (3B) External cause* (2B)	SU OP SD	Effect on plant is related to the ability of operators to identify & correct problem before a shutdown is req. Plant shutdown would occur, if operators ignore the signals, due to trip on moisture level, & subsequent removal.	V or III	Buffer/mid buffer ΔP reading ; moisture,or activity	Proper operator action to keep the impact from getting worse Shutdown seal	Helium dryers primary coolant purifiers are used to mitigate the effects. During shutdown dynamic seal effect is reduced & static seal is needed	C C A C NA

*Selected for economic analysis, Section 3.3.4 (with Item 4.1)

PERFORMED BY/DATE: G.W. Hannaman

CHECKED BY/DATE: R.J. Stokely

REFERENCE:

TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Yields	Internal threads wear, loosen, crack (3B) Fretting (3B) External cause (2B)	OP	The loose parts result in circulator shutdown leading to a plant shutdown.	III	Displacement, speed	Redundant fasteners, external to shaft	Bolt backs out only small distance before finding interference, low stress	C C NA
		Blocks fluid path a. Sensor path b. Helium supply c. Water/helium drain d. Shutdown seal supply	Loose mtl in passage (3B) Corrosion (3B) External cause (2B)	OP SU SD	(a,b,c) Trip on buffer/mid buffer trip signal if passage can't be opened, plant shutdown req. for circulator repair. (d) Potential for moisture ingress & plant shutdown	IV III V or III	Pressure	Circulator trip & secured helps to limit effects		C C NA
		Leaks to (external)	O-ring leaking (3B) Erosion (3B) Component crack (3B) External cause (2B)	OP	Degraded performance by loss of helium, or moisture into reactor coolant. May lead to plant shutdown if moisture ingress is greater than removal rate.	V, IV, or III	Operator observation of helium loss rate Moisture		Helium bypass into core, or steam/water drain	A B C NA
			O-ring leaking (3B) External cause (2B)	SD	Delay in startup due to moisture ingress.	III	Moisture		Failure to hold shutdown seal in place because of leaking supply cavity O-ring	A NA

PERFORMED BY/DATE: G.J. Cadwallader
CHECKED BY/DATE: R.J. Stokely
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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

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5.	Brake (90-C2101-530J)*	Fail to press against shaft	No actuating helium supply (2A)	SU SD	No effect unless possible shutdown seal damage occurs, requiring plant shutdown for circulator replacement	IV or III	Speed, pressure	Common supply to brakes & seal; redundant bearing water systems; chrome oxide on bearing	Circulator not held stopped; speed not alarmed.	NA
			Binding or corrosion of shoe or piston in housing (1B) Clogged helium passage (1B) Bellows buckle from increased extension due to shoe wear (1C)	SD	No effect unless all brakes affected, then possible shutdown seal damage requiring plant shutdown for circulator replacement.	V or III or II	Displacement speed	Redundant brakes; redundant bearing water	Impact II if common mode (e.g., corrosion); slight unbalanced brake force due to loss of one brake.	B C C
			O-ring leak or broken bellows or weld (3A)	SU SD	No effect unless possible shutdown seal damage occurs requiring plant shutdown for circulator replacement	IV or III	Displacement speed, pressure	Common supply to brakes & seal; redundant bearing water systems; chrome oxide on bearing	Cannot pressurize brakes	A
			Failed bolts allowing housing to back brake out of cavity, away from shaft (1B)	SU SD	No effect unless bearing water bypasses thrust bearing, then must shutdown plant to replace circulator	IV or III	Displacement	Redundant brakes; brake cover contains bolt debris & housing; retaining force (~600 psi) from bearing water ΔP	Water trap & alarm on brake vent line would aid detection; slight unbalanced brake force due to loss of one brake	D

*Selected for economic analysis, Section 3.3.2

PERFORMED BY/DATE: G. L. Cadwallader

CHECKED BY/DATE: R. L. Stokely

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FAILURE MODE & EFFECTS ANALYSIS

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		Fail to stop rotation	Premature application (2B)	SD	Debris from brake may wedge in bearing, may require plant shutdown to replace circulator	III	Displacement; speed	Soft (silver) brake shoes	Interlocked to apply <500 RPM	NA
			Insufficient application force (3C)	SU SD	No effect unless shutdown seal scored, then plant shutdown possibly required to replace circulator	IV or III or II	Displacement; speed	Redundant bearing water; chrome oxide on bearings	Seal actuation should await positive shaft stoppage measure. Wrong mat'l should be caught & fixed early	C
			Contamination (water or lubricant) between shaft & brake surface (2C)							NA
			Insufficient friction force due to wrong materials (3C)							F
		Fail to release	Unvented actuation helium (2A)	SU	If efforts to release fail, may require plant shutdown to replace circulator	IV	Speed			NA
			Clogged helium passage (3B)			IV				C
			Binding of brake shoe or piston in housing (1B)			III			May draw brake back by venting to atmosphere	B
			Loose brake shoe jamming shaft (1A)			III				C
			Welding of brake shoe to shaft (3B)			III		Soft silver would shear.		C
			Debris from brake or shaft wedged in bearing (3A)			III				A
			Inability of brake bellows to retract (1B)			IV		Differential pressure aids retraction of bellows		B

PERFORMED BY/DATE: G.J. Cadwallader
CHECKED BY/DATE: R.J. Strokely
REFERENCE:

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FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Applies when not desired	Application of helium (2A)	SU SD OP	Debris from brake may wedge in bearing, may require plant shutdown to replace circulator	III	Displacement; speed	Soft silver brake shoes; brake vent valve open		NA
			Housing or O-ring failure allowing bearing water to pressurize brakes (3A)			III				A
			Shoe falling off & jamming shaft (1A)			III				C
6.	Shutdown Seal (90-C2101-518K)	Fails to apply	Bellows rupture (3B)	SD	If water enters the PCRV, must shutdown plant until primary coolant impurities are reduced to acceptable level. May require plant shutdown to replace affected circulator	III	Pressure	Fails retracted so circulator can operate	Water may enter PCRV if buffer helium not operating	B
			Broken weld (3A)			III				B
			Clogged helium passage (3B)			IV				C
			No actuating helium supply (2A)			IV				NA
			Leaking helium passage (3B)			III				C
			Bellows breakdown due to environment/fatigue (3C)			II				D
		Releases too soon/fails to remain applied	Bellows rupture (3B)	SU SD	If water enters the PCRV, must shutdown plant until primary coolant impurities are reduced to acceptable level. May require plant shutdown to replace affected circulator	III	Pressure	Fails retracted	Water may enter PCRV if buffer helium not operating	B
			Broken weld (3A)			III				B
			Removal of actuating helium (2A)			IV				NA
			Leaking helium passage (3B)			III				C
			Environment or fatigue induced bellows break down (3C)			II				D

PERFORMED BY/DATE: G.J. Cadwallader

CHECKED BY/DATE: R.J. Stokely

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FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Fails to release	Continued application of actuating helium (2A)	SU	Delays startup of circulator & increase of plant power. May require plant shutdown to repair damaged circulator	IV	Pressure; speed	Pressurized seal can prevent circulator self-turbining. Silver plating minimizes damage	May score seal surface if rotation occurs while seal touches shaft	NA
			Bellows distortion preventing complete retraction (3B)			III				A
			Corrosion or self-welding of seal to shaft (3B)			III				E
		Applies too soon	Supply of actuating helium (2A)	OP SD	May require eventual plant shutdown to replace circulator because of leaking seal	III	Pressure		Seal scored by contact with rotating shaft	NA
			Pressurization of helium supply line (3B)			III				B
			Separation of seal ring from bellows (3B)			III				C
			Unfastened ring mounting (3B)			III				D
		Allows leakage past seal area	Insufficient actuation force (3B)	SU SD	If water enters PCRV, must shutdown plant until primary coolant impurities reduced to acceptable level. May require plant shutdown to replace affected circulator	III	Pressure	Silver plating conforms to shaft surface. Buffer helium can minimize water leak		C
			Proper seating obstructed by corrosion or debris (2C)			IV or III				NA
			Scored seal surface (3B)			III				A

PERFORMED BY/DATE: F.K. Jacobsen
CHECKED BY/DATE: R.J. Stokely
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FAILURE MODE & EFFECTS ANALYSIS

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7.	Diffuser and Stator									
7.1	Compressor Stator (P/N 90-C2101-380)	Fails to straighten primary coolant flow efficiently	Blade(s) distorted by erosion (2A)	SU OP SD	Loss of plant efficiency until shutdown for repair	II	Pressure	Can run compressor faster		D
			Blades distorted by contamination build-up (2A)	SU OP SD	Loss of plant efficiency until shutdown for repair	II	Pressure	Can run compressor faster		D
		Causes rotor failure by contact	Blade breaks because: a. Design error (1C) b. Non-design defect (1B) c. Erosion (1B) d. Corrosion (1B)	SU OP SD	Plant shutdown for repair	II,III	Unbalance & speed	Helium ducting may contain fragments. Disc catcher probably will contain them.		E C D D
7.2	Diffuser Assembly (P/N 90-C2101-210)	Fails to recover pressure	Diffuser distorted because: a. Design error (1C) b. Non-design defect (1B) c. Unexpected load (2B) c. Unexpected temp (2C)	SU OP SD	Loss of plant efficiency until shutdown for repair	II	Pressure	Can run compressor faster		F D D D D
		Loss of pressure or moisture data	Sample ports clogged by contamination (2C)	SU OP SD	Plant shutdown for repair	II,III	Flow	Reverse flow can be forced through the ports to try to clear them.		D

PERFORMED BY/DATE: F.K. Jacobsen and G. J. Cadwallader
CHECKED BY/DATE: R.J. Stokely
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FAILURE MODE & EFFECTS ANALYSIS

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			Large leak in sample line because:	SU OP SD	Plant shutdown for repair	II,III	Slow response to test	Flow is into leak from the circulator discharge plenum. Gets about same reading only slower		
			a. Design error (1C)							E
			b. Non-design defect (1B)							D
			c. Unexpected load (2B)							D
		Leak in seal to lower floor	Bellows cracked because:		Loss of plant efficiency until plant shutdown for repair	II		Can run compressor faster		
			a. Design error (1C)							D
			b. Non-design defect (1B)							C
			c. Unexpected load (2B)							D
8.	Helium Shutoff Valve (90-C2101-600K)	Fails open	Hinge misalignment (1B)	SD	Inefficient operation of other circulators due to backflow. Eventual plant shutdown required to remove circulator & repair valve. If backflow causes circulator to rotate during loss of bearing water, damage may result requiring plant shutdown to replace circulator & repair valve	III	Pressure	Gravity & reverse flow tend to close valve	May be able to work flappers loose by cycling circulator from high to low speed	B
			Plateout onto hinge pin (3C)			II				B
			Loose or fractured fasteners jamming mechanism (3B)			III				C
			Hinge galling (1C)			II				C
			Flapper mislocation (1B)			III				C
			Flapper self-welding open (3B)			III				B
			Flapper distortion (3B)			III				D
			Housing distortion (3B)			III				D
			Corrosion (3C)			II				C
			Flapper allowed too far open (3B)			III				D

PERFORMED BY/DATE: G.J. Cadwallader

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FAILURE MODE & EFFECTS ANALYSIS

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		Leaks	Fractured seal strip (3B)	SD	Inefficient operation of other circulators due to backflow. Eventual plant shutdown required to remove circulator & replace valve	III	Pressure			C
			Proper seating of flapper prevented by debris (2A)			IV			May be able to jar debris away	NA
			Flapper distortion (3B)			III				C
			Housing distortion (3B)			III				C
			Seal strip wrong dimension (3C)			III				C
		Fails closed	Hinge misalignment (1B)		Circulator cannot pump helium, must limit reactor power & eventually shutdown plant to remove circulator & replace valve	III	Pressure	Helium flow tends to open valve	May be able to work flappers loose by cycling circulator from high to low speed	B
			Plateout onto hinge pin (3C)			II				B
			Hinge galling (1C)			II				C
			Binding at flapper edge (3B)			III				C
			Debris wedged at flapper edge (2A)			III				NA
			Corrosion (3C)			II				C
		Provides missiles to flow stream	Flapper embrittlement (3C)	SU & OP & SD	Must shutdown plant to repair damage caused by impact of loose parts	II	Displacement	Disc catcher if missiles fall into circulator. High helium flow tends to carry locse parts parts away from circulator.	Circulator removal required	B
			Broken support struts (3B)			III				D
			Broken fasteners (3B)			III				C
			Broken hinge pin (3B)			III				C
			Broken support beam (3B)			III				C
			Broken housing (3B)			III				D
			Lockwashers break, move between housing & stator to enter flow stream (3B)			III				C

PERFORMED BY/DATE: G.J. Cadwallader
CHECKED BY/DATE: R.J. Stokely
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TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
		Disturbs flow	Flapper distortion (3B)	OP	Adjust reactor operating level if necessary. May need to shutdown plant & remove circulator to replace valve if plant efficiency significantly disturbed or life of affected parts shortened by pressure fluctuations.	III	Pressure			C
			Flapper flutter (1C)			II			Should correct during tests.	C
			Spoiler flutter (1C)			II				C
			Incorrectly shaped or installed support struts (1B)			III				C
			Incorrectly positioned support cone (1B)			III				C

PERFORMED BY/DATE: Cadwallader/Hannaman/Jacobsen
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REFERENCE:

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ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
9.	Seals									
9.01	O-ring (Item 8 on drwg C2101-530J) Located around base of brake housing.	Leak	See Note 1	SD	Could allow bottled helium to leak out along shaft, & release brake.	IV or III	Pressure		Alarm on low helium bottle pressure.	B
				OP	Could allow BW along shaft to leak up into brake actuation port, possibly pressurizing brake & applying it spuriously.			Brake vent valve open		
9.02	O-rings (Item 11 on drwg C2101-530J). Located around brake housing & helium supply cavity.	Leak	Internal leak; see Note 1	SD	Could allow helium to leak out along shaft, & release brake.	IV or III	Pressure	Seal would release before brake.	Alarm on low helium bottle pressure.	B
				OP	Could allow bearing water to pressurize brake actuation port, applying brake spuriously.			Brake vent valve open.		
9.03	O-ring (Item 4 on drwg C2101-505). Located around thermocouple penetration into Lower Bearing.	Leak	See Note 1		Could allow steam or water into temperature sensing penetration.	V	Temperature		Loss of temp signal not critical.	C

Note 1. Mechanisms of leak include dirt; corrosion; erosion; scratching; scoring; thin wall; defective weld; crimping; improper installation.

PERFORMED BY/DATE: Cadwallader/Hannaman/Jacobsen

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ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
9.04	O-ring (Item 30 on drwg C2101-500U). Located around outside of Lower Bearing supply cavity between H.P. Feed Housing & Lower Bearing	Leak	See Note 1		Could allow bearing water to bypass lower bearings, exit through steam/water drain.	III	Increase in steam/water drain flow, bearing temp			B
9.05	O-ring (Item 31 on drwg C2101-500) Located around middle of Upper Thrust Brg, between it & Main Housing	Leak	See Note 1		Allows BW to bypass thrust bearing. May degrade circulator performance	III	Increase in temp.			B
9.06	O-ring (Item 41 on drwg C2101-500) Located around top of Upper Thrust Brg, between it & Main Housing	Leak	See Note 1		Allows leakage from BW supply cavity, bypassing thrust bearings. Depending on severity of bypass may have to shutdown to repair if bearing performance degraded.	III	Increase in operating temp - may lead to shaft wobble & binding.			B
9.07	O-ring (Item 69 on drwg C2101-500) Located around Shutdown Seal between Upper Labyrinth & Shutdown Seal.	Leak	See Note 1	SD	No significant effect. Required only when shutdown seal applied	V	Leakage of primary coolant when seals applied	Closure of drain & entrance valves with water seal maintained		B

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9.08	O-ring (Item 70 on drwg C2101-500) Located around Shut-down Seal supply hole, between Upper Labyrinth & Shutdown Seal	Leak	See Note 1	SD	May allow actuation helium to escape & release shut-down seal, allowing primary coolant into bearing assembly or BW into PCRV. Required only during shut-down seal actuation.	V or III	Leakage of primary coolant when seals appl-ied.	Closure of drain & entrance valves with water seal maintained.		B
9.09	O-ring (Item 72 on drwg C2101-500) Located around inside of lower bearing supply cavity between H.P. Feed Housing & Lower Bearing	Leak	See Note 1		Allows bearing water to leak out along shaft & into steam water drain.	III	Increase in steam/water drain flow.			B
9.10	O-ring (Item 77 on drwg C2101-500) Located around the steam/water drain between the Main Housing & the Lower Bearing	Leak	See Note 1		Could allow drain fluid to exit from circulator machine back into steam water cavity,	V				B
9.11	O-ring & Seal Ring (Item 79 & 81 on drwg C2101-500) Located between Main Housing & Lower Bearing	Leak	See Note 1		Could allow main bearing drain water to leak out of circ machine into steam/water drain cavity.	V				B

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9.12	O-ring & Seal Ring (Items 80 & 82 on drwg C2101-500) Located around circ between Upper Journal Bearing & Upper Labyrinth.	Leak	See Note 1		Allows leakage of buffer helium or helium/water out of circ machine, or allow water to seep into instrument passages.	V or III		Backed up by Item 102		C
9.13	O-ring & Seal Ring (Items 80 & 82 on drwg C2101-500) Located around circ between Main Housing & Upper Journal Bearing	Leak	See Note 1		Could allow leakage of helium/water out of circ machine; Could allow bearing water at drain pressure to seep into upper insulation or primary coolant.	V III	Flow of helium/ water; Increase in PPS moisture level.	Backup by Item 103		C
9.14	O-ring (Item 83 on drwg C2101-500) Located around bolts between Upper Labyrinth & Upper Journal Bearing	Leak	See Note 1		Allows primary coolant into bolt holes, may be able to enter other fluid passages from bolt holes.	V on III	Increase in bearing assembly temp		May contaminate fluids, requiring cleanup.	C
9.15	Seal (Item 84 on drwg C2101-500) Located around Bearing Water Supply between Main Housing & Lower Bearing	Leak	See Note 1		Bearing water could bypass lower journal bearing, leak into bearing water drain or out of circ machine.	III	Increase in bearing assembly temp.			B

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9.16	O-ring (Item 92 on drwg C2101-500) Located around buffer helium penetration in Main Housing	Leak	See Note 1		No significant effect - some buffer helium leaks into steam water drain	V				B
9.17	Seal (Item 93 on drwg C2101-500) Located around bearing water supply between Main Housing & Lower Bearing	Leak	See Note 1		Bearing water could bypass lower journal bearing, leak into bearing water drain or out of circ machine into steam water drain.	III	Increase in bearing assembly temp			B
9.18	O-ring (Item 103 on drwg C2101-500) Located between Upper Journal Bearing & Upper Journal Labyrinth	Leak	See Note 1		Allow helium/water drain fluid to escape from line & machine.	IV	Flow of buffer helium.	Backup by Item 82		C
9.19	O-ring (Item 104 on drwg C2101-500) Located around instrument taps in Main Housing	Leak	See Note 1		No significant effect - allows seepage of drain pressure water into steam/water cavity.	V				C

PERFORMED BY/DATE: Cadwallader/Hannaman/Jacobsen
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FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
9.20	Seal (Item 105 on drwg C2101-500) Located between Upper Journal Labyrinth & Upper Labyrinth	Leak	See Note 1		Allow buffer helium to leak out of supply chamber Would require more makeup helium, could allow primary coolant into helium water drain.	V or III	Flow of buffer helium.		Cleanup of fluids may be required.	B
9.21	Seal (Item 106 on drwg C2101-500) Located around Shutdown Seal supply line between Upper Labyrinth & Upper Journal Labyrinth	Leak	See Note 1	SD	Allows actuation helium to escape, could allow shutdown seal to release, or keep it from being applied	V or III	Shutdown seal leakage, loss of bellows pressure.			B
9.22	Seal (Item 107 on drwg C2101-500 Located around buffer helium supply in Upper Journal Labyrinth	Leak	See Note 1		Buffer helium could go out helium/water drain, bypassing labyrinth seals. Could allow primary coolant into buffer helium system	V or III	Flow of buffer helium out of machine.			B
9.23	O-ring (Item 108 on drwg C2101-500) Located around instrument taps & Shutdown Seal supply between Upper Journal Labyrinth & Upper Journal	Leak	See Note 1	OP SD	Could allow helium to leak into or out of pressure tap, giving erroneous reading. Also, helium supply to shutdown seal could leak, releasing seal if applied	V or III	Increase in buffer helium loss, erratic pressure readings.		Impact III if leak becomes major	B

PERFORMED BY/DATE: Cadwallader/Hannaman/Jacobsen

CHECKED BY/DATE: R.J. Stokely

REFERENCE:

TABLE 3-2

FAILURE MODE & EFFECTS ANALYSIS

NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
9.24	Seal (Item 113 on drwg C2101-500) Located around Brake Supply into Upper Thrust Bearing	Leak	See Note 1		Allows helium supply to escape to shaft area. May allow bearing water into brake supply helium	IV	Excessive bottled helium usage			B
9.25	Seal (Item 113 on drwg C2101-500) Located around bearing water drain between Upper Journal & Main Housing	Leak	See Note 1		Allows bearing water along shaft to leak into drain, bypassing upper journal bearing. Potential seepage into primary coolant blocked.	V		Blocked by Drawing Items 80, 82		B
9.26	Seal (Item 117 on drwg C2101-500) Located around journal bearing water supply between Main Housing & Upper Journal	Leak	See Note 1		Bearing water could enter other supply ports, pressurize them spuriously (e.g. shutdown seal).	V or III	Shaft binding, increase in bearing temp.	Backed up Drawing O-ring Items 103 & 113		B
9.27	O-ring (Item 102 on drwg C2101-500) Located between Upper Journal & Upper Journal Labyrinth	Leak	See Note 1		Allows helium/water drain fluid to leave circulator machine & possibly seep into primary coolant	V		Backup by Items 80, 82		B

PERFORMED BY/DATE: Cadwallader/Hannaman/Jacobsen
CHECKED BY/DATE: R.J. Stokely
REFERENCE:

TABLE 3-2
FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
9.28	O-ring (Item 34 on drwg C2101-300) Located around 7 of the Main Housing penetrations	Leak	Scored due to handling or installation		Fluid intended for bearing assy internals may leak out.	V	Pressure			A
9.29	O-ring (Item 35 on drwg C2101-300) Located around Bearing Assembly under support cone.	Leak	Scored during installation or handling; wall too thin; defective weld contaminated		Allows helium down around circ bearing assembly, may heat machine unduly.	V or III	Temperature			C
9.30	O-ring (Item 60 on drwg C2101-300) Located around 2 of the Main Housing penetrations	Leak	Scored during installation or handling		Fluid intended for bearing assy internals may leak out, but must leak past 2 seals.	V	Pressure			A
9.31	O-ring (Item 78 on drwg C2101-300) Located around Buffer Helium supply penetration into Main Housing	Leak	Handling or installation		Buffer Helium may leak out of bearing assembly	V or III	Pressure			A
9.32	Seal ring (Item 5 on drwg R1105-314) Located below diffuser bellows, as a backup to bellows, to restrict flow	Leak	Handling or installation Groove too large; coating flakes off.	OP	No effect unless bellows is also failed, then reduced efficiency of circulator	V or III	Pressure, temperature			B

PERFORMED BY/DATE: Cadwallader/Hannaman/Jacobsen

CHECKED BY/DATE: R.J. Stokely

REFERENCE:

TABLE 3-2

FAILURE MODE & EFFECTS ANALYSIS

ITEM NO.	COMPONENT IDENTIFICATION	FAILURE MODE	FAILURE MECHANISM	PHASE	SYSTEM (REACTOR PLANT) EFFECTS	IMPACT	METHOD OF DETECTION	INHERENT COMPENSATING PROVISION	REMARKS AND OTHER EFFECTS	EXP
9.33	Seal ring (Item 10 on R1105-314) seals the clamp between base of diffuser & lower floor	Leak	Scored, installed improperly. Too small; material defect; contaminated		Allows backflow of compressed helium into circ inlet, reduces circ efficiency	V or III	Temperature			B
9.34	Seal Ring (C2101-343) around helium ducting	Leak excessively	Installed, handled carelessly; slotted; too large to seat in groove; too small to seal; contaminated	OP	Increase recirculation, decrease efficiency of circulator.	V	Pressure			B
9.35	Seal Ring (C2101-312) around compressor insulation to protect it	Leak excessively	Improper installation; too large for groove; too small to seal; contaminated		Could allow leaking bearing water (if any) to wet insulation	IV				B

TABLE 3-3

FASTENER LOCKING METHOD AND FAILURE EFFECTS SUMMARY

FORT ST. VRAIN - HELIUM CIRCULATOR - FASTENER EVALUATION

PREPARED BY: Cadwallader/ Hannaman DATE:

ASSEMBLY		FASTENER				EFFECT OF LOOSE PARTS	COMMENTS
NUMBER AND NAME	ITEM NO.	PART NUMBER	TYPE	QUAN	LOCKING METHOD		
90-C2101-518 Shutdown Seal	6	3/16 dia x 1/2 lg	Pin dowel	2	Blocked	Can go nowhere.	Locating pin.
90-C2101-534 Brake Shoe Assy	5	1/16 dia x 5/16 lg	Dowel	1/ bra-ke	Interference fit	May jam brake in housing.	
90-C2101-530 Upper Thrust Bearing Assy	10	1/8 dia x 3/4 lg	Dowel	4/ circ		May jam brake in housing.	No locking device specified.
	12	10-24 UNC 2 x 3/4 lg	Soc hd screw	31/ circ	Lockwire	None-trapped by brake cover.	
	13	3/16 dia x 1/2 lg	Dowel pin	4	Blocked	Can go nowhere.	Locating pin.
90-C2101-500 Bearing Assy (quantities per circulator)	17	C2101-515	Lockwasher	4	Bent tab	Needed during assembly; unused in operation; if loose could rattle around in the steam water drain & provide flow restriction.	Overhanging lip prevents lockwasher from turning.
	39	C2101-500	Hex head screw	4	Bent tab & torque	(same as above)	
90-C2101-300 Machine Assy	45	EWB-0420-12H28	Bolt	1	Lockwire	Lockwire in space between steam housing & insulation.	No direct effect.
	52	90-C2101-315	Bolt	14	Lockwire	Bolts loosen; allows leak past high press. housing seal	Bolts pass through steam water barrier HP housing distorts leaks FMEA 4.3
90-C2101-500 Bearing Assy	18	90-C2101-523	Keeper nut	12	Thermocouple lead & lockwire	Held in dead air space between bearing assembly & external support housings.	May loosen thermocouples but their loss should not affect operation.
	35	EWB-420-10-10	Screw 5/8-18 UNF 2,210 ft lbs	4	Set screw drilled through	Holds upper bearing assembly to main housing; blockage of an upper journal drain.	

TABLE 3-3

FASTENER LOCKING METHOD AND FAILURE EFFECTS SUMMARY

FORT ST. VRAIN - HELIUM CIRCULATOR - FASTENER EVALUATION PREPARED BY: G.J.Cadwallader DATE: ______

ASSEMBLY		FASTENER				EFFECT OF LOOSE PARTS	COMMENTS
NUMBER AND NAME	ITEM NO.	PART NUMBER	TYPE	QUAN	LOCKING METHOD		
90-C2101-600 Flapper Valve Assy	7	90-C2101-605	Hinge pin	2	Key	Whole - can go nowhere; pieces - can get into helium flow stream	Key blocked by other parts.
90-C2101-620 Flapper Support	8	1/4 dia x 1 3/8 lg	Dowel pin	4	Blocked	Can go nowhere.	
	9	1/4-20 UNC 2 x 2 1/4 lg	Hex hd screw	4	Lockwasher	Fall into support cone.	
	10	5/16-18 UNC 2 x 3/4 lg	Soc hd cap screw	2	Blocked	Can go nowhere.	
90-C2101-600 Flapper Valve Assy	13	3/8-16 UNC 2 x 1 lg	Hex hd screw	8	Lockwasher	Screw trapped outside housing; washer can enter flow stream between stator & flapper housing.	
	14	1/2-20 UNC 2 x 1 1/4 lg	Hex hd screw	9	Lockwasher	(same as above)	
	15	3/8-16 UNC 2 x 1 1/4 lg	Hex hd screw	6	Lockwasher	(same as above)	
	16	3/8 dia x 1 lg	Dowel pin	5	Blocked by lock-washer; inter-ference fit	(same as above)	
	17	1/2 dia x 7/8 lg	Dowel pin	4	Interference fit blocked by lock-washer	(same as above)	
	18	3/8-16 UNC 2 x 7/8 lg	Hex hd screw	24	Lockwasher	(same as above)	
	19	1/2 dia x 1 1/2 lg	Dowel pin	2	Interference fit; blocked by lockwasher	(same as above)	

Table 3-3

FASTENER LOCKING METHOD AND FAILURE EFFECTS SUMMARY

FORT ST. VRAIN - HELIUM CIRCULATOR - FASTENER EVALUATION

PREPARED BY: Hannaman/ Cadwallader DATE: ______

ASSEMBLY		FASTENER				EFFECT OF LOOSE PARTS	COMMENTS
NUMBER AND NAME	ITEM NO.	PART NUMBER	TYPE	QUAN	LOCKING METHOD		
90-C2101-500 Bearing Assy	48	D-35	Dowel pin 1/2" x 1" lg	2	Interference fit	None	Main housing (0.4995") upper thrust bearing (0.504").
		A-35	Dowel pin 1/2" x 1" lg			None	Main housing to external (0.4995") support cone.
	49	90-C2101-520	Pin	32	Blocked by insertion	(Water flow restriction is the normal function).	See FMEA 4.3, 4.5: flow blockage by loose parts.
		D-23	0.0956"x 0.406"				
		B-16					
	50	B-14	Dowel pin 1/8" x 5/8" lg	2	Interference fit	None	Held between lower lab. (0.1247") & water seal (0.136")
	74	LH540AH8	Hex head cap	6	Blocked by upper lab.	Blockage of water.	FMEA 4.5: flow blockage.
		C-6	Screw #10-24			He drain.	
	90	C-24	Hex head cap	4	Lockwasher [89]	Flow restriction	FMEA 4.2.
	89	90-C2101-545	Lockwasher	2	Bar between bolts	Same as above	(same as above)
		C-24					
	100	D-26	Hex head nut 1/4 - 28, 2B	1	Stake	Restrict helium flow path.	See FMEA 4.7, blocks helium supply at connection supply for He.
	101	D-24	Socket head cap screw 1/4-20 5/8" lg	4	Compression retainer	Into dead air space (allows He leakage).	
	99	90-C2101-573			Nut [100]	Restrict helium flow path.	Function is part of orifice control.
90-C2101-530 Upper Thrust Assy (except brake assy components)	13		Dowel pin 3/16" dia 3/4" lg	4	In between components (shrink fit) in upper assy.	Falls into drain & exhausted	Upper assembly (0.186") deflector ring (edge of shield & bottom).

TABLE 3-3

FASTENER LOCKING METHOD AND FAILURE EFFECTS SUMMARY

FORT ST. VRAIN - HELIUM CIRCULATOR - FASTENER EVALUATION PREPARED BY: F.K. Jacobsen DATE:

ASSEMBLY		FASTENER				EFFECT OF LOOSE PARTS	COMMENTS
NUMBER AND NAME	ITEM NO.	PART NUMBER	TYPE	QUAN	LOCKING METHOD		
90-C2101-300 Circulator Machine Assy	5	90-C2101-307	Bolt	8	Lockwasher	Rotor unbalance &/or disc damage &/or end cone damage &/or blade damage.	Bolt or lockwasher fragment may lodge behind rim of rotor or jamb between disc & end cone. Lock washer fragment can pass between rotor & stator & damage rotor blades.
	40	LWB-922-14H-38	Bolt	24	Lockwire	None.	Loose parts contained in interspace between the support cone & the helium ducting.
	43	1/2-13UNC-2A x 1" lg	Soc hd cap screw	16	None.	None.	16 screws hold 8 shims (90-C2101-409) & 8 spacers (90-C2101-427) onto the bottom of the support cone outside flange. Fragments can not escape. Loose screws not detrimental.
	39	5/8-11UNC-2A x 4	Soc hd cap screw	8	Lockwire	None.	Loose pieces do not get into a fluid stream or an active part area.
	41	1/4-20UNC-2A x 1	Soc hd cap screw	8	Lockwire	None.	Loose parts retained by helium ducting and inlet assy.
90-R1100-100 Reactor General Assy	140	90/91-M-19-15-94	Stud	24	Lockwire	No parts released.	Very long stud held captive by other parts.
	144	90/91-M-19-15-97	Nut	24	Lockwire	Nut, bearing, & cup are released but confined.	Parts are captive between the steam outlet piping & the outer steam piping.
	83	90-C2101-101	Bolt.	40	Self-locking screw	None	Loose parts contained by the penetration & support cone flanges.
R-1103-403 Helium Circulator Penetration Liner	7	R-1103-403-7	Dowel pin	2	Interference fit	Loose parts not possible.	Retained between penetration flange & inlet aerodynamic fairing.
90-C2101-340 Helium Ducting	7	1/4 dia x 7/8 lg	Roll pin	3	Interference fit	Fragments cannot migrate.	Fragments retained between helium ducting & shield cone.

TABLE 3-3

FASTENER LOCKING METHOD AND FAILURE EFFECTS SUMMARY

FORT ST. VRAIN - HELIUM CIRCULATOR - FASTENER EVALUATION PREPARED BY: F.K. Jacobsen DATE:

ASSEMBLY		FASTENER				EFFECT OF LOOSE PARTS	COMMENTS
NUMBER AND NAME	ITEM NO.	PART NUMBER	TYPE	QUAN.	LOCKING METHOD		
90-C2101-380 Compressor Stator	10	69241B-8205-13	Bolt	12	Lockwire	Lockwire can enter the flow stream & damage the circulator blades.	Larger fragments cannot enter the flow stream or contact active parts. Lockwire fragments can pass between the stator & flapper valve into the flow stream.
	12	1/4-20UNC-2A x 1 lg	Bolt	12	Lockwasher	Lockwasher fragments could pass into the flow stream & damage the compressor rotor blades.	Larger fragments would be confined between the compressor end cone & the flapper valve support cone. Fragment of the lockwasher could pass through.
	13	1/4-20UNC-2A x 7/8	Soc. hd cap screw	10	None	None	Fragments would be confined by the helium ducting & flapper valve flanges. Clamping is provided by other bolts in the final assembly.
	7	90-C2101-387	Dowel	1	Interference fit	None	Fragments of conceiveable sizes would be contained by helium ducting, inlet, & flapper valve.
90-C2101-310 Insulation Assy	4	LH14U040J10	Soc hd cap screw	12	Self-locking screw	None	Fragments would be confined to this assembly by a retaining ring that is welded in place.
90-C2101-210 Diffuser Assy	6	5/8 dia x 1-1/4 lg	Dowel pin	1	Interference fit	None	Dowel pin is captive between two flanges of the diffuser.
	16	1/4-20UNC 2 x 9/16 lg	Soc hd cap screw	4	Lockwire	None	Loose parts most likely fall to floor (may fall onto Marmon-type Diffuser clamp). Do not encounter active parts or assemblies or the helium flow stream.
	17	3/8-16UNC-2 x 3/4 lg	Soc hd cap	8	Lockwire	None	(same as above)
	20	5/8-11UNC 2 x 3-1/4 lg	Hex hd screw	16	Lockwasher	None	(same as above)

TABLE 3-3

FASTENER LOCKING METHOD AND FAILURE EFFECTS SUMMARY

FORT ST. VRAIN - HELIUM CIRCULATOR - FASTENER EVALUATION PREPARED BY: F.K. Jacobsen DATE:

ASSEMBLY		FASTENER				EFFECT OF LOOSE PARTS	COMMENTS
NUMBER AND NAME	ITEM NO.	PART NUMBER	TYPE	QUAN	LOCKING METHOD		
90-C2101-210 Diffuser & Inlet Assy	5	3/4 dia x 1-1/2 lg	Dowel pin	1	Interference fit	None.	Dowel pin is captive between flanges of the diffuser & inlet assemblies.
	6	3/4-10UNC-2 x 3 lg	Soc hd screw	16	Lockwire	Possible damage to the compressor rotor blades from small fragments.	Larger loose parts shielded from the flow stream & active parts by the inlet, diffuser, flapper valve, & helium ducting assemblies. 1/8 inch gap between helium ducting & flapper valve may allow thin fragments to enter flow stream & damage circulator rotor.
90-C2101-270 Helium Inlet Assy	6	90-C2101-272	Stud	12	Cotter key at top	None.	Loose parts confined by the bolt cover.
					Pin at the bottom	None.	Loose parts confined by various inlet assembly parts & the circulator penetration flange.
	13	1/2-20UNF 2 x 10-1/4 lg	Hex head screw	12	Tab lock washer	None.	Loose parts confined between the inlet mounting flange & duct segment lower.
	14	3/8 dia x 1-1/4 lg	Dowel pin	24	Interference fit	None.	Loose parts confined by the airfoil fairing & the upper & lower duct segments.
	15	1/4-28UNF 2 x 3/4	Hex head screw	16	Tab lock washer	Possiblity of damage to the circulator rotor blades from small fragments.	Larger parts confined between the disc catcher protection sleeve, flapper valve, & helium ducting. Small fragments could pass through 1/8" gap between helium ducting & flapper valve.
	24	1/2 dia x 2" lg	Dowel pin	4	Cover over opening	If cover fragments, same as above.	(same as above)
	25	EWB-930-10H-14	Bolt	4	Lockwire	Same as above.	(same as above)
	26	3/4 dia x 1-3/4 lg	Dowel pin	1	Interference fit	None.	Loose part confined between inlet & diffuser flanges.

3.2.3. Fault Tree Analyses (FTAs)

3.2.3.1. Introduction. The following sections present the fault tree for this example assessment. The top event of concern is a loss of 0.01% or more of the plant energy generation capacity (EGC) during one calendar year (cumulative from any one cause). A loss of 0.01% EGC amounts to ∿1 hr of unscheduled plant unavailability and is defined as E_s. Figure 3-5 defines the symbols employed in the fault tree (Ref. 8).

Figure 3-6 is a fault tree for the loss of the main function (i.e., ability to generate electrical energy) resulting in a loss $\geq E_s$. It shows each of the principal functions that must be satisfied, from generation of thermal power in the core to the transformation of thermal power in the secondary coolant (steam) into electrical power at the alternator.

The function "circulate helium" is a subfunction of the function "transport power from core to steam generators," as illustrated in Fig. 3-6(a). The figure also shows the two other comparable (i.e., same level) functions that must be provided, and defines the contributors to the failure to properly circulate primary coolant (helium). These contributors are the Impact I, Impact II, and Impact III classes of events defined in Table 3-1.

The following subsections present and describe fault trees for each event related to the top event through the function "circulate helium" on which this example assessment is based. They show the similarities between the FTAs and the FMEAs, and the tie-in of both to the quantitative evaluation which follows (Section 3.3).

3.2.3.2. Loss of Main Function Fault Tree. Fault tree analyses formally begin with the principal (top) event of concern, and employ the symbols shown in Fig. 3-5. For this example assessment the top event is a loss $\geq$0.01% of the plant's energy generation capacity (EGC) for one calendar year. Figure 3-6(a) illustrates seven broad classifications of causes for such loss. These classifications are exhaustive and appear logical, but

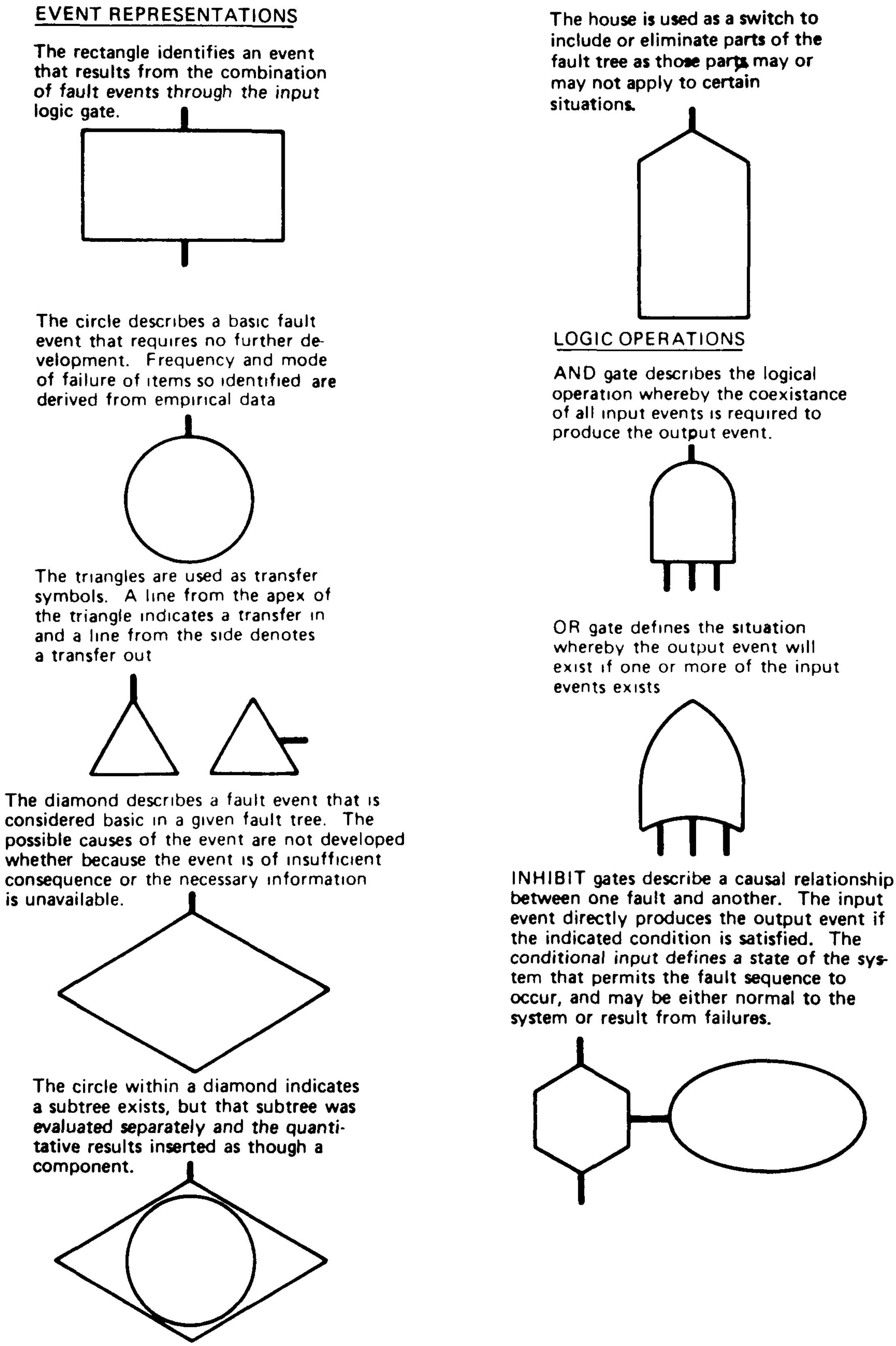

Fig. 3-5. Standard fault tree logic and event symbolism (from Ref. 8)

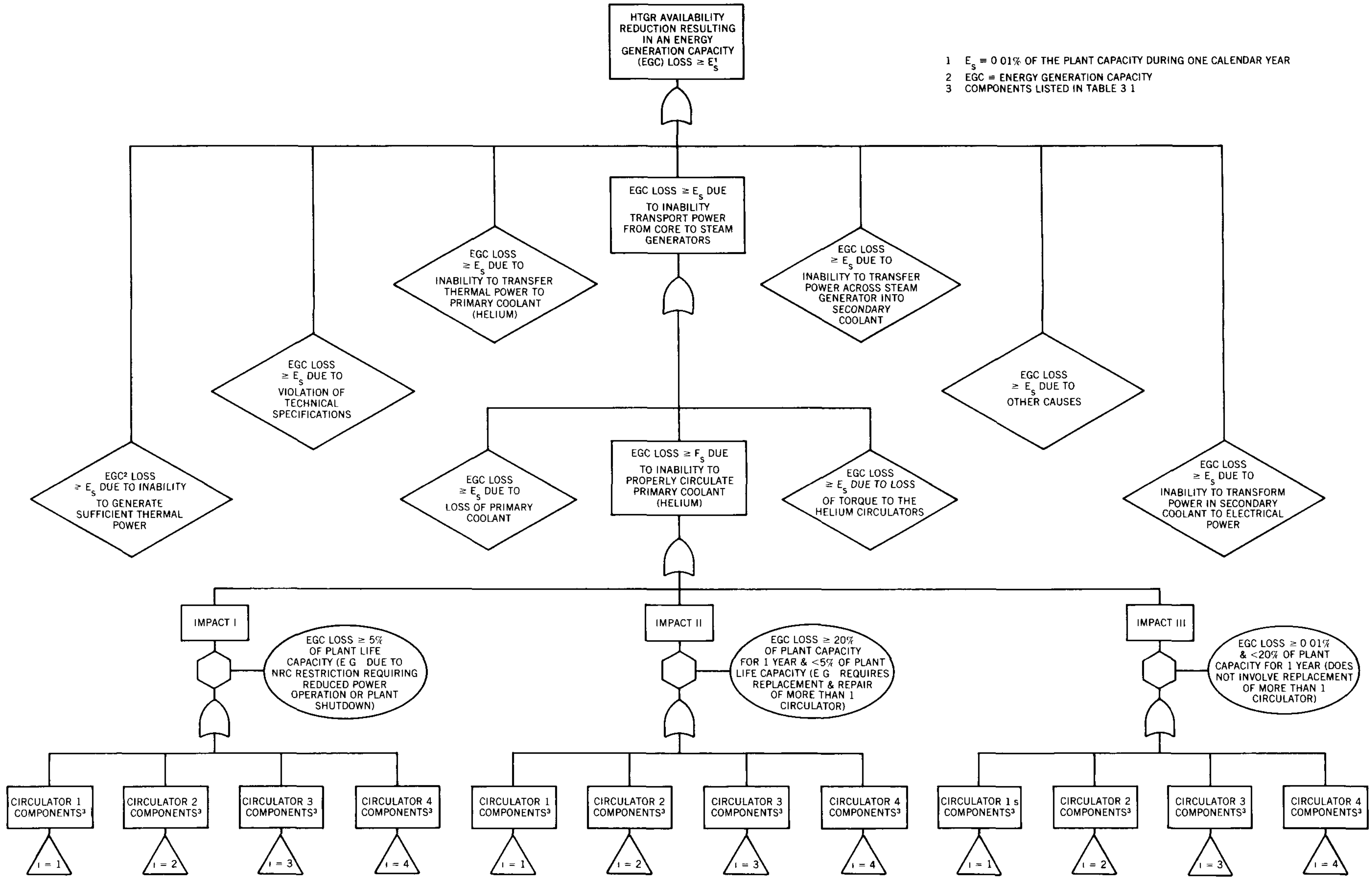

Fig. 3-6(a). Fault tree for loss of plant energy generation capacity greater than 0.01% for one year

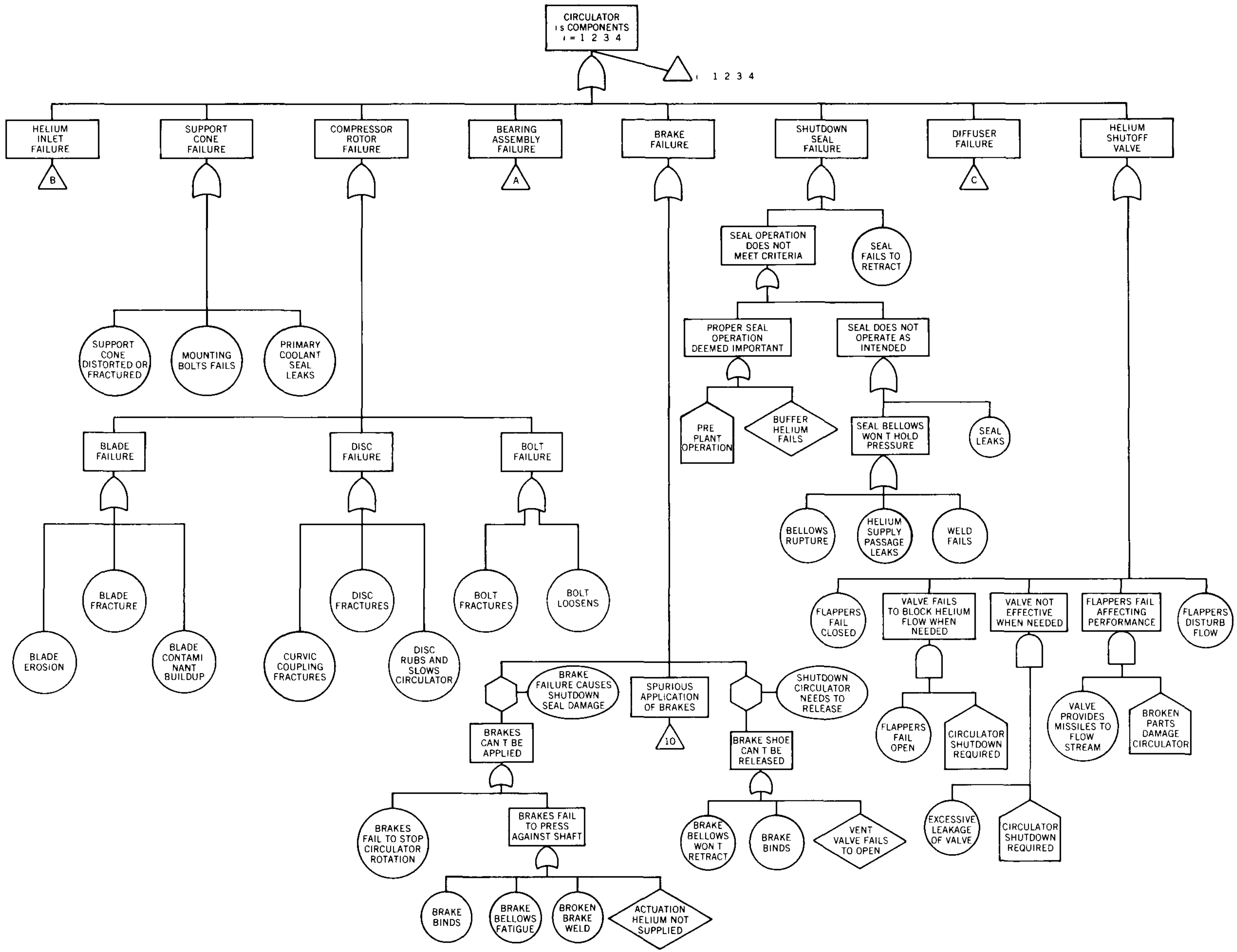

Fig. 3-6(b). Fault tree for loss of plant energy generation capacity greater than 0.01% for one year

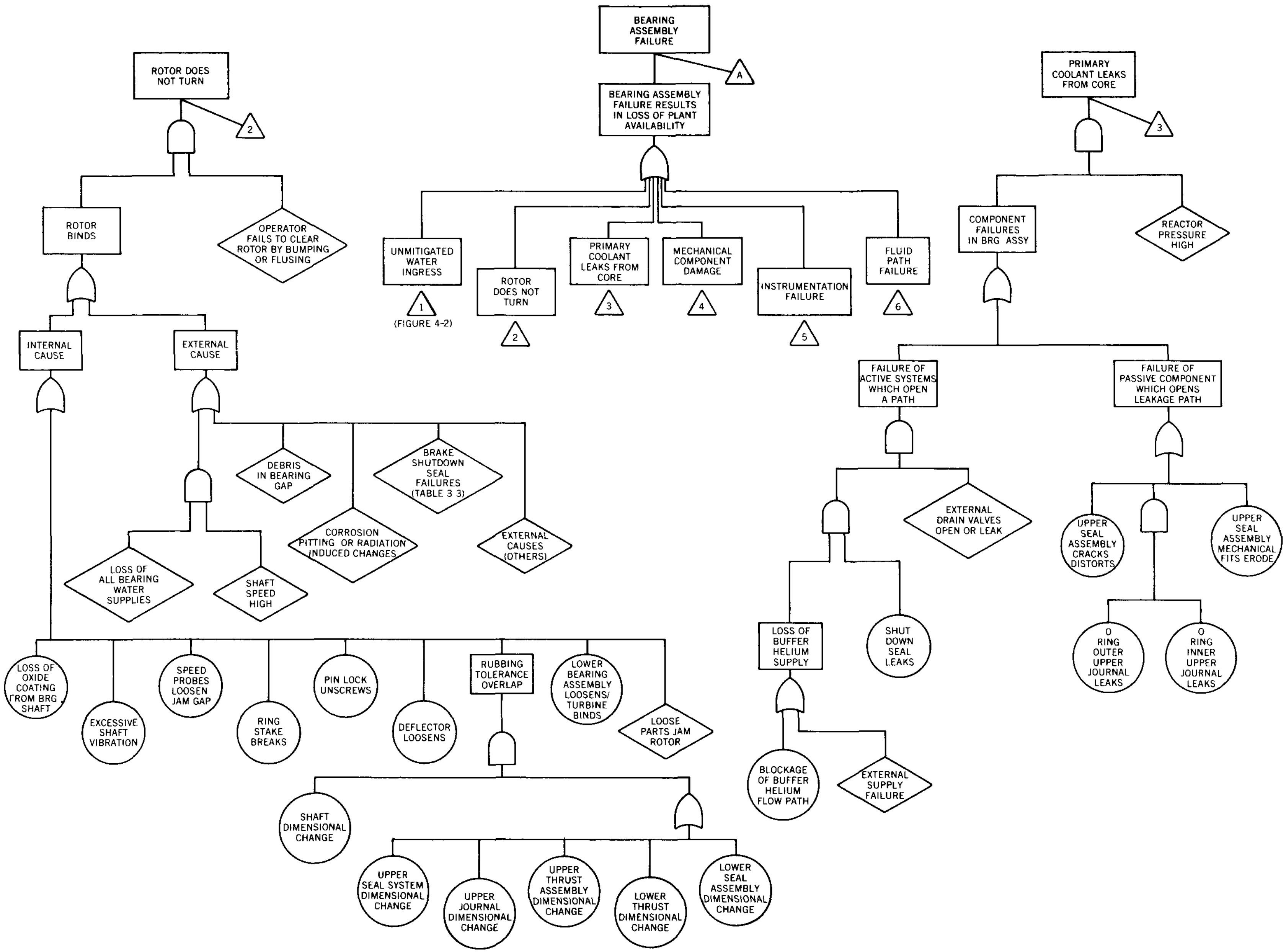

Fig. 3-6(c). Fault tree for loss of plant energy generation capacity greater than 0.01% for one year

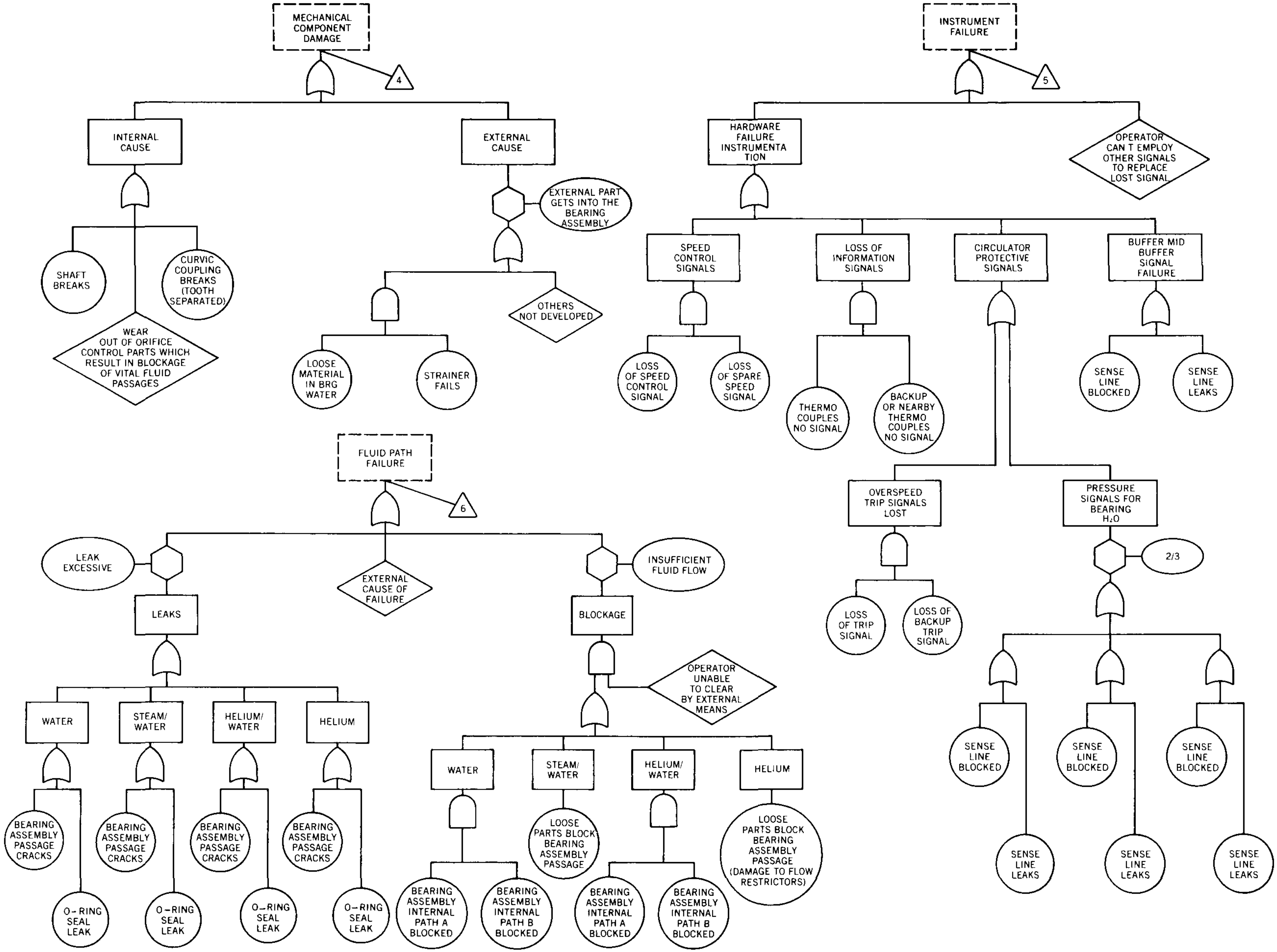

Fig. 3-6(d). Fault tree for loss of plant energy generation capacity greater than 0.01% for one year

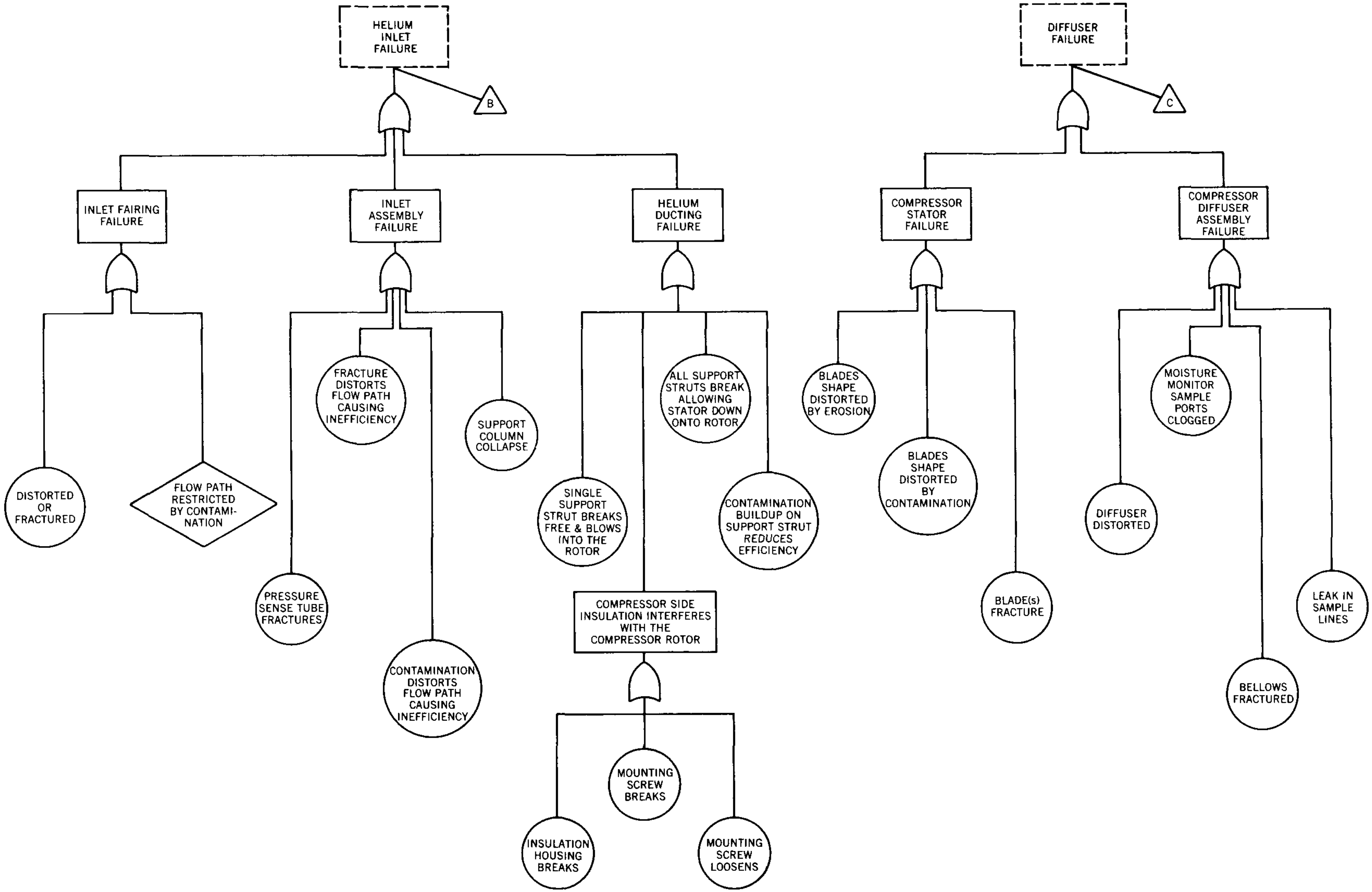

Fig. 3-6(e). Fault tree for loss of plant energy generation capacity greater than 0.01% for one year

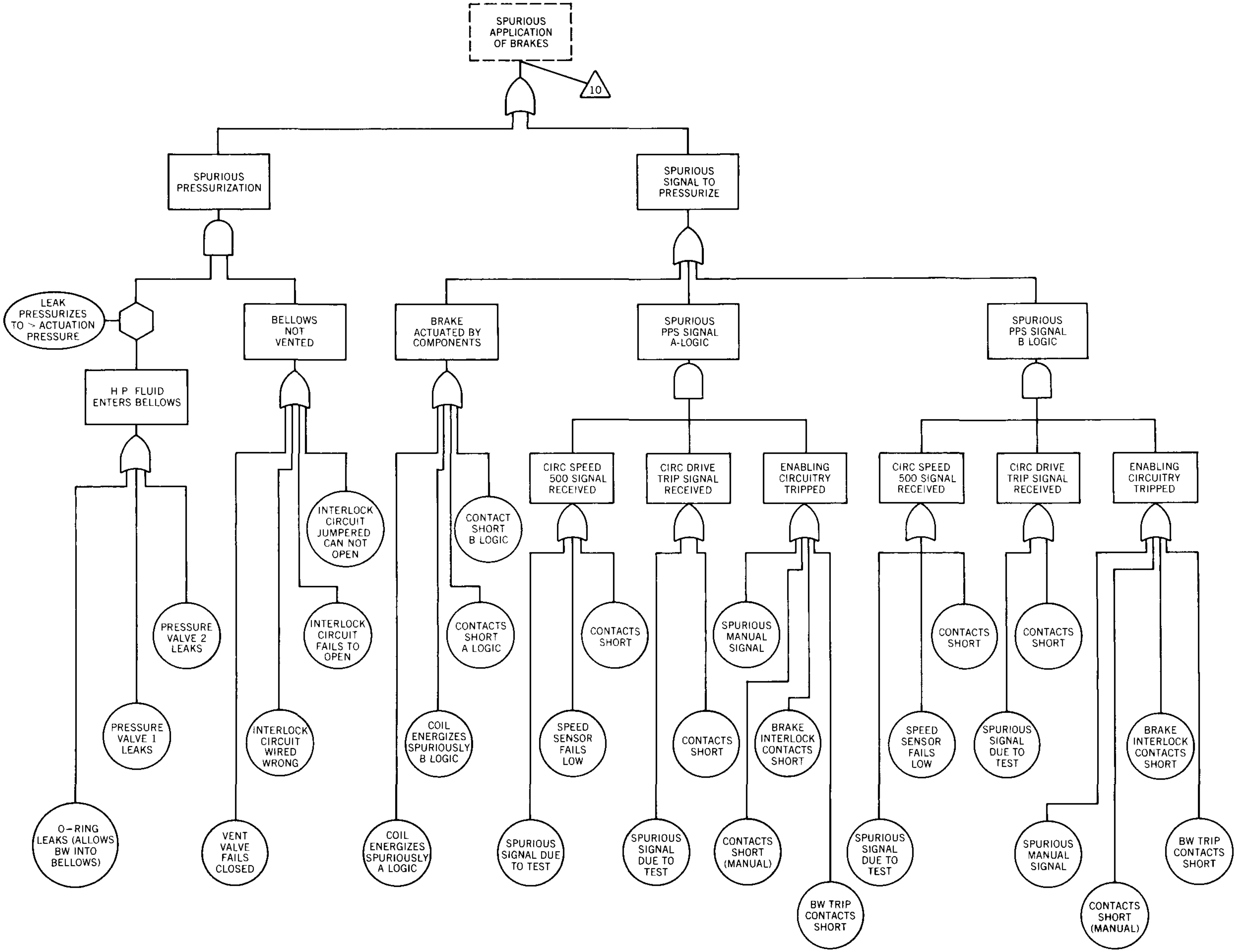

Fig. 3-6(f). Fault tree for loss of plant energy generation capacity greater than 0.01% for one year they are not necessarily independent, mutually exclusive, or unique. The breakdown has been by function because the selection of components was on that basis. However, an independent analyst would probably have defined a different set of events contributing to the top fault, and any such set is satisfactory that is exhaustive and not awkward to use or check. During the development of a fault tree, however, the sooner independent events can be defined and entered into the tree the simpler the subsequent branches of the tree become.

Referring to Fig. 3-6(a), the fault of concern for this analysis which is just below the top fault is: "inability to transport power from the core to the steam generators." Figure 3-6(a) shows that this fault has three contributors, one of which (i.e., "inability to properly circulate helium") is the very fault of concern for this analysis. The other two faults are concerned with loss of helium and loss of torque, respectively. This same figure shows that the contributors to the fault "inability to properly circulate helium" are the faults Impact I, Impact II, and Impact III defined earlier (Table 3-1) for the FMEAs.

Figure 3-6(a) shows that a failure of the components associated with any particular circulator could lead to any particular impact level, depending primarily on the number of circulators affected (which would be determined from the failure analysis) and on whether the plant safety committee or the Nuclear Regulatory Commission (NRC) required an extended reduction of power or plant shutdown until a satisfactory failure analysis and/or corrective action(s) were achieved.

3.2.3.3. Impact Level III Fault Tree. Figure 3-6(a) includes the Impact III fault (i.e., a loss of EGC $\geq$0.01% and <20% of the plant capacity for one calendar year). Any one of the four circulators can fail and cause such a loss. Figures 3-6(b), (c), etc., display the components and failure modes contributing to such losses. The fact that a number of components feed directly below the Impact III fault through OR gates, and that many of these would require circulator replacement, serves as a warning that these components must be very reliable. Fortunately, this is believed to be the case because there is no rubbing contact during machine operation. It should be remarked that, should one of these failures in Fig. 3-6(b), (c), etc., occur, it is very likely to require the replacement of a circulator, causing 3 to 8 weeks of plant down time (i.e., result in an Impact III event).

3.2.3.4. Impact Level II Fault Tree. Figure 3-6(a) also shows the Impact II fault (i.e., a loss of EGC ≥20% of the plant capacity for one year, but <5% of the plant-life capacity). To encounter this level of loss would entail more than just a simple replacement of one circulator. Impact II losses would be primarily due to common-cause type failures which implicate more than one machine, requiring two or more to be removed, repaired, or otherwise modified, and replaced. (Note, however, that only one circulator might have actually failed at the time, but if the failure analysis implicated other machines, an Impact II loss would probably result.) Most losses caused by significantly inadequate design would be of this class. However, most LCEs have the potential to cause such a problem. For example, inadequate packaging for shipping could result in bearing damage to two or more units and lead directly to an Impact II level of loss. Obviously, then, controls that affect all units must be given more consideration than those that can affect only one unit.

3.2.3.5. Impact Level I (Fault) Tree. Figure 3-6(a) also shows the Impact I fault (i.e., a loss of EGC ≥5% of the plant-life capacity). This sort of loss could only be due to a circulator failure(s) that would require considerably more than replacement of all four circulators. Because of the favorable results of extensive testing and operation of the circulators, this appears highly unlikely. However, it is almost always conceivable that any event can occur. The most likely avenue for the circulators to lead to an Impact I type of loss appears to be through a failure that would have possible safety implications, resulting in the plant safety committee or the NRC shutting down the plant until the safety-related uncertainties were satisfactorily resolved, and resolution requiring ≥1.8 years.

3.2.3.6. Comparison of Fault Trees with FMEA Tables. An examination of the fault trees reveals that they start (at the top) with the (undesired) effect or event and work down to the component and failure modes at the bottom. Referring back to the FMEA tables, it can be seen that they commence with the component and failure mode (on the left), and work across to the effect (on the right). Hence, the two methods are opposite approaches to deriving information of concern.

There are a number of differences, however, that should be noted. First, the FMEA table generally includes many failure modes with no serious effect whereas the fault tree contains only events that can lead to the top (significant) event. Also, the FMEA usually considers single failures, whereas the fault tree should include all possible combinations that make a significant contribution. Finally, for the reasons just mentioned, the fault tree is directly useful for incorporation of likelihoods of the various events and subsequent calculation of the probability of the top event. The FMEA is not generally useful for this purpose. Hence, their appearances are totally different, while much of their content is identical. They provide diverse methods of deriving basic failure information, but only the fault tree formulation is generally directly useful for computing probabilities because it alone includes all possibilities and directly combines them properly.

3.2.3.7. Conclusions Concerning Fault Trees. Fault trees have been developed from the principal event of concern (i.e., the loss of more than 0.01% of the plant's EGC for one year) through an exhaustive set of main plant functions, to the function of "circulate helium" upon which the selection of the components employed in this example analysis was based. The classes of contributors to this (failure to "circulate helium") fault have already been defined in Table 3-1 for the FMEA tables as Impacts I, II, and III. A fault tree including contributions to each of these impact classes by the components included in the analysis was presented. It was shown that high reliability components were required (and expected) to avoid even Impact III losses, for most failures would result in losses closer to the higher end of the bracket than to the lower end. Impact II type losses would be expected to be due primarily to common-cause type failures affecting two or more circulators, and Impact I type losses would be expected to be due primarily to extended plant shutdowns to resolve uncertainties related to plant safety.

3.2.4. Conclusions of the Qualitative Evaluations

Five mutually exclusive and exhaustive classes of failure consequences (Impacts I, II, III, IV, and V) have been defined. FMEAs and FTAs have been performed for each component for the circulator phases of startup, operation, and shutdown. The following conclusions can be drawn from these qualitative analyses:

1. Many component failure modes result in at least an Impact III consequence. Hence, component reliability is extremely important, and considerable effort appears justified to achieve high confidence that the reliability is adequate.

2. Impact II consequences appear most likely to result from failures that have common causes and thereby implicate other units. It is therefore necessary to more carefully examine the controls over all LCEs affecting more than one circulator to ensure that the likelihood of common cause problems is adequately controlled.

3. Impact I consequences appear most likely to result from a failure that would raise doubt in the opinion of the plant safety committee or the NRC about an adequacy which is safety-related, and would therefore result in a prolonged power reduction or plant shutdown until the doubt was removed.

4. Application of brakes or shutdown seal while the circulator was operating would probably wear off the silver friction pad and damage the circulator if the steel base material contacted the shaft. Similarly, the absence of bearing water while the circulator was rotating could damage the shaft or bearings. Also, the

absence of buffer helium in the presence of bearing water could result in water ingress if the circulator were shut down. All these events could result in Impact III consequences, and each could possibly occur due to some external cause (e.g., operator error) which often requires special consideration to enable control over long exposure periods. Therefore, the qualitative analysis alone is sufficient to strongly indicate that controls be considered that will provide long-term protection against such losses. For example, physical stops could be considered for the brakes and shutdown seal to make the type of damage just described virtually impossible.

Hence, the qualitative analysis alone can reveal many potential problem areas and, therefore, with sufficient experience, simple prudent judgment may suffice to make many decisions. This is usually most easily done during the design phase before change reviews and approvals are required. The more documents and hardware affected, the more approvals or considerations are required. The more of the latter involved, the more a change costs and the more justification is required. Justification is most (and often only) effective if it can be quantized to show that authorization of the recommended change is economically justified. The next section gives several examples of economic evaluations to determine whether to recommend that increased controls be implemented to reduce expected losses.

3.3. QUANTITATIVE EVALUATIONS

3.3.1. Introduction

The following sections summarize three example quantitative (i.e., economic) evaluations. The detailed evaluations are given in Appendix C. These were selected to illustrate evaluation of expected losses associated with uncertainties concerning controls, and to illustrate options employing controls from the three principal broad, distinct classes [i.e., design, quality assurance (QA), and operational] to reduce the expected losses on an economic basis.

The first example deals with the probability of losses due to inadvertent application of brakes to an operating circulator, and it evaluates design controls to reduce the expected loss. The second example deals with the helium inlet, evaluates its QA controls for adequacy to prevent loss, and devises and evaluates a QA control to reduce the expected loss. The third example evaluates the expected losses associated with the upper (helium/water) seal and evaluates operational controls and design controls (changes) to reduce the expected loss.

For each of these evaluations the value of plant down time, whether due to startup delays or forced outage time, was set at $4,000/hr (i.e., $96,000/day). Appendix E gives the basis for the cost estimate for plant down time. A real (i.e., inflation corrected) interest rate of 3% per year was also employed, and the decision maker was assumed to be indifferent to chance situations having expected values of zero.

3.3.2. Example Economic Evaluation with Design Control Option

3.3.2.1. Case Definition. An analysis was performed to determine the economic justifiability of exploring and/or implementing options to the design of the circulator brakes. The analysis is documented in Volume II, Appendix C, Section C.2, and a summary is presented here.

3.3.2.2. Evaluation. Three potential problems associated with the present brake design were evaluated using an event tree to determine the expected losses resulting from each one over the life of the plant. These losses were converted to present values, and are as follows:

Potential Problem Description	Present Value Expected Loss
1. Silver brake shoe insert wears away due to normal application of brakes, allowing nitralloy brake shoe to press against shaft, generating debris which damages circulator.	>$92 <$250

2. Brake bellows ruptures due to increased stroke resulting from wear due to normal application of brakes. >$1,270 <$3,430

3. Spurious application of brakes during circulator operation damages shaft, or causes debris to be generated which damages circulator. >$17,340 <$46,800

3.3.2.3. Conclusions. Because an internal circulator modification would cost over $2 million in plant down time, these values show that the only economically justified area where the brake design might be modified to reduce losses at Fort St. Vrain is outside the PCRV in the brake actuation valve arrangement (i.e., item 3 above). The expected savings, after deducting implementation costs of the proposed option, were found to be >$11,200 and <$33,410.

This option will be considered for future plants. Before deciding on the justifiability of brake options inside the PCRV or circulator for future plants, further testing to verify the silver wear rate is recommended.

3.3.3. Example Economic Evaluation with QA Control Option

3.3.3.1. Case Definition. This section summarizes an example application of the methodology employing QA controls to reduce expected plant losses. The helium ducting part of the circulator machine assembly was selected as the example part. Quality assurance provides the procedures and the inspections whereby it is assured that hardware is built to meet drawing and specification requirements and is not damaged by subsequent events in its life (e.g., handling, storage, shipping, etc.).

3.3.3.2. Evaluation. To evaluate the effect of QA controls on expected plant losses, it is necessary to identify all the events and operations in the life of the helium ducting wherein QA controls can have a significant effect (see Table 3-4). In this evaluation, the role of QA becomes primarily one of reducing damage resulting from human error. Therefore, in

TABLE 3-4
ACCIDENT COST EXPECTED VALUE EVALUATION FOR FIRST PRODUCTION UNITS

Life Cycle Event (LCE)/Cause of Damage	Existing Control			Optional Control			Option Savings	Option Cost
	Probability	Cost/Event	EV $	Probability	Cost/Event	EV $		
1. Fabrication								
1.1. Machining error	0.0088	294,300	2443	0.00031	297,000	92	27,826	960
1.2. Welding error	0.0083	293,400	2435					
1.3. Drop of He ducting	0.094	297,000	27918					
2. Assembly								
2.1. Thread stripping	0.00020	292,800	59					
2.2. Drop of He 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 release	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 container	0.0000070	1,353,000	9					
5.2. Drop during recline	0.000051	49,320	3					
5.3. Transport accident	0.0013	49,320	64					
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 replacement	(see text)		21					

the next step, probabilities of damage were based on the probability of human errors (e.g., the probability of an operator making an error and the inspector not detecting and correcting it). For this example, probabilities were selected from tabulated human reliability values for similar activities (Ref. 9).

Next, it was necessary to estimate the cost of recovery from the damage. As applicable, this cost included the cost of hardware repair or replacement and the cost of power to replace that lost while the plant undergoes a startup delay or outage as a result of the required repair.

The product of the probability of damage and the cost of recovery is the expected loss for the operation. The results of the analysis to this point are presented in Table 3-4. It is seen from this table that the expected loss of operation 1.3 is significantly higher than the others. Analysis shows that the higher expected value results from a higher probability of damage from dropping, which in turn results from this operation being performed a large number of times and the absence of a QA inspection of the hitching operation.

3.3.3.3. Option and Conclusion. A reevaluation reveals that adding a QA inspection is estimated to cost about $1200 per plant but would reduce the expected loss by about $28,000 per plant. It is concluded that this method of evaluating QA provisions offers the possibility of effecting a significant reduction in the associated expected loss. (Details of this analysis are in Volume II, Appendix C, Section C.3.)

3.3.4. Economic Evaluation Involving Operational and Design Control Options

3.3.4.1. Case Definition. The subject of this economic analysis, water ingress through the upper labyrinth circulator seal, was selected on the basis of item 4.7 of the FMEAs (Table 3-2) and the FMEA recommendations of Section 3.2.2.4.

3.3.4.2. Methodology. Several options to the present conditions were evaluated by logically considering the possible combination of design, QA, and operational controls which could be changed to reduce expected losses. Figure 3-7 shows a logic tree for this selection process. The options which include changes in the quality assurance plan were not considered in this analysis for two reasons. First, the circulator components as designed had already received 100% inspections during manufacturing and the utmost attention during installation at the site, which is also expected for future modifications. Second, the most prominent cause of the ingress problem appears to arise from human-related postinstallation maintenance or operation errors, and not from QA errors. Thus, from Fig. 3-7, the following options were selected as the most promising candidates for economic solutions to the water ingress problem:

Option 1 ($\Delta\phi$)	Change in operational procedures
Option 4 (ΔD)	Change in the design
Option 5 ($\Delta D \Delta\phi$)	Change in both the design and operation

A review of the historical data for circulator operation during the plant construction phase revealed that this economic analysis could be performed by determining several key parameters from the water ingress information available. The parameters estimated from these data were the occurrence rate, a most likely water ingress rate, and a removal rate; in addition, operator error rate data (Ref. 10) were combined with the observed response times to develop a best-judgment curve for operator probability of correct action versus response time for the existing training level. This curve is shown in Fig. 3-8.

From these parameters and information in the operating and maintenance manual (Ref. 11), an event tree was developed to display the various outcomes of a water ingress occurrence. Use of the event tree (Ref. 12) then provides a method for calculation of the base-line losses associated with this event under present conditions and allows for determination of the economic effect of various control options on the expected losses.

PROBLEM	DESIGN CONTROL (D)	QUALITY ASSURANCE AND CONSTRUCTION CONTROL (Q)	OPERATIONS CONTROL (ϕ)	PLAN	OPTION
WATER INGRESS THROUGH UPPER SEAL	D	Q	ϕ	DQϕ	0
			$\Delta\phi$	DQ$\Delta\phi$	1
		ΔQ	ϕ	DΔQϕ	2*
			$\Delta\phi$	DΔQ$\Delta\phi$	3*
	ΔD	Q	ϕ	ΔDQ ϕ	4
			$\Delta\phi$	ΔDQ$\Delta\phi$	5
		ΔQ	ϕ	ΔDΔQϕ	6*
			$\Delta\phi$	ΔDΔQ$\Delta\phi$	7*

Δ ≡ CHANGE IN "– – –"

D ≡ DESIGN CONTROL

Q ≡ QUALITY ASSURANCE CONTROL

ϕ ≡ OPERATIONAL PROCEDURES CONTROL

*OPTIONS NOT EVALUATED IN THIS ANALYSIS.

Fig. 3-7. Assurance plan options against water ingress

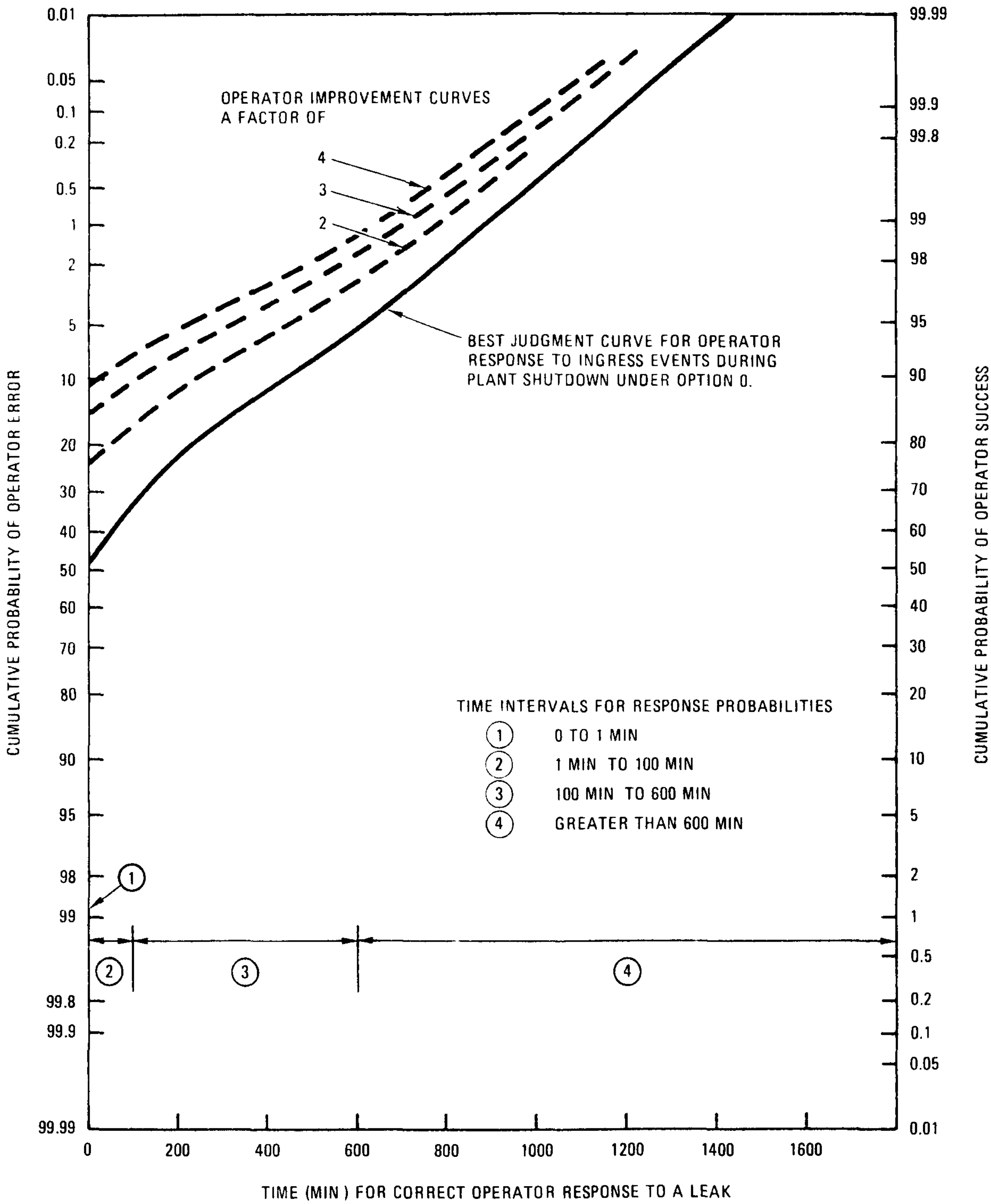

Fig. 3-8. Cumulative probabilities of operator response time (based on data from Table C.4-1 and Ref. 10)

3.3.4.3. Assumptions. To reduce the complexity of the calculations, several simplifying assumptions were made. First, the water ingress occurrence rate is 0.12 per year during shutdown and refueling periods (which is highly dependent on maintenance error), and 0.1 per year during plant power operation (which is more dependent on equipment failures than maintenance errors). Second, the ingress rate for each occurrence is 3 gal per min until terminated by automatic response or operator action. Third, the water removal rate averages 3 gal per hr by presently available methods including helium evacuation. Fourth, the typical control room operator response curve under existing conditions is the "best judgment" line shown in Fig. 3-8. Finally, the automatic protective systems operate much better during power operation since the moisture monitors are also effective in terminating an ingress event.

The initial operator response judgment line in Fig. 3-8 is based on the estimated operator response times for four ingress events at FSV. Since the number of successful responses was not available, the initial response probability was derived from data in Ref. 10 that require a similar level of operator perception based on the control conditions during shutdown and testing periods. To justify a higher estimated operator response curve, more than four successful immediate ingress terminations would have to have occurred.

3.3.4.4. Analysis. The event tree of Fig. 3-9 shows how these conditions and assumptions were combined to determine the major portions of the expected losses associated with a water ingress event and the possible outcomes. When an ingress is initiated, the first chance for termination is afforded by the automatic system response. If this fails, operator actions are needed to stop the ingress. After the ingress is terminated, cleanup operations can begin to reduce the primary coolant moisture to an acceptable operating level (about 1000 ppm). The operator response curve is divided into probability intervals and associated with expected water ingress volumes for each interval response time. Then the moisture removal time is calculated from the total water ingress and average removal rate (3 gal per hr). The cost for each occurrence is determined from the down time

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			
0 12/YR	0.9		1			BASELINE OCCURRENCE = $ 0	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. 3-9. Event tree for water ingress through upper labyrinth circulator seals cost of \$4000 per hr (Volume II, Appendix E) multiplied by the removal time. The yearly expected loss (S_V) is calculated by multiplying the branch probability per year by the branch event sequence cost. Finally, the present value expected loss (P_V) is calculated using the interest formulas as described in Volume II, Appendix F.

The expected losses for the options are determined in a similar manner except that the improved operator response curve is used to adjust the probability of operator action in the various branches. The occurrence rate for the shutdown period is reduced by a factor of 2 to account for the improved awareness of the maintenance personnel under Option 1.

Option 4 is based on a design change which also affects operator performance. This design change could be new instrument channels in a prominent position which clearly signal water ingress and the need for immediate action. A capital investment of \$40,000 is assumed to cover the cost of such a change which could improve the operator error rate by a factor of 3 or 4. The economic effects of this option were explored by adjusting the operator response curve for the same occurrence rate.

Option 5 is a design change in the labyrinth seal itself, which employs the principles of redundancy at the seal such that a redundant or diverse seal is effective even when buffer helium supply is lost on a shutdown circulator, or abnormal pressures exist. This type of design modification could easily reduce the occurrence rate by a factor of 10. These changes were incorporated into the probabilities of the event tree for the options considered. Table 3-5 summarizes the economic results of each option.

3.3.4.5. Conclusions. The following conclusions can be drawn as a result of this analysis. The most economic option, Option 1, is the one which extends the operator retraining program to include maintenance personnel. This is most effective prior to any plant shutdown involving shutdown and startup of the circulator, or maintenance of systems affecting the circulator. Such a program would be geared toward reducing the occurrence rate

TABLE 3-5
SUMMARY OF ECONOMIC LOSSES FOR VARIOUS OPTIONS ($)

	Existing Condition	Option 1	Option 4	Option 5
Present value of expected loss	200,000	45,000	55,000	20,000
Expected yearly loss payment	8,652	1,951	2,380+ 1,730 CI	865+ >120,000 CI
Capital investment(CI) $\sim$	$\sim$0	$\sim$0	40,000	>4x10^6 down time loss + $\sim$5x10^5 CI
Continuous yearly payment for option implementation	-0	2,000	300	300
Yearly savings (loss)	--	4,700	4,200	(>120,000)
Present value savings (loss)	--	109,000	98,000	(>4x10^6)

Options:

1. A program where operators and maintenance personnel discuss water ingress problems as part of the operator retraining program (10CFR55). Reduces operator error rate by a factor of 2, and maintenance errors by a factor of 2.
4. Improved signals for the operator by external instrumentation changes; reduces operator error rate between 3 and 4.
5. Redesign and replacement of the upper seal with a redundant seal system; reduces occurrence rate by a factor of 10.

of water ingress as well as improving the operator response time to this condition. If the Option 1 program can be implemented for less than $2000 per yr while reducing the occurrence rate by a factor of 2, and improving the operator response time by a factor of 2, then this option is clearly the most economic (see Table 3-5).

Option 4 evaluations are based on additional instrumentation channels from each circulator capable of directly notifying the operator clearly when an ingress begins under any circulator state. Such a manual interface continues to give the operator the flexibility to interpret the instrument readings before taking action, thus avoiding the spurious circulator shutdowns associated with additional automatic trip signals. This option may require an initial capital investment (∿$40,000) for the improved instrumentation channels, and could then result in an expected operator response improvement of between 3 and 4 over the present condition. Option 4 is also economic but less so than Option 1.

Seal design changes for FSV, Option 5, are uneconomic because of the high initial capital cost and long plant down time required for installation. However, this option may be the most economic for future designs if a new bearing water primary coolant seal is being considered. A more detailed analysis is presented in Volume II, Appendix C, Section C.4.

3.4. CONCLUSIONS OF EXAMPLE ASSESSMENTS

An example based on the function "circulate helium" was selected to illustrate application of the methodology. This involved eight principal components. Each was first evaluated qualitatively using FMEAs and FTAs to detect possible sources and causes of plant unavailability. This qualitative evaluation alone was able to point out (1) the need for high reliability of components due to a large number of failure modes of single components being able to require plant shutdown for circulator removal and repair, (2) the need for emphasis on operator training to control the likelihood of loss from human error, and (3) potential design modifications to minimize consequences of failures.

To illustrate the application of the methodology to design, QA, and operational controls, three examples were chosen. Each of these illustrated the use of a different type of control, and found an option which would have been economic to implement had it been recommended prior to fabrication and shipment of the units. Two of the options would still be expected to be economic for Public Service Company of Colorado to implement at FSV, and the others appear worth implementation or further evaluation for future circulators.

The conclusion is that the example assessments each appear to have shown that the methodology is effective in detecting potential problem areas and in selecting options on an economic basis. The methodology employs data for estimates of probabilities, when available, but it also permits the quantization and use of judgment with or without supporting data. Hence, it permits an orderly rational evaluation to be made from any state of knowledge.

4. COMPARISON OF ASSESSMENTS WITH FSV EXPERIENCE

4.1. GENERAL

Having applied the methodology to the FSV helium circulator components associated with the function "circulate helium" (including example analyses illustrating the use of design, quality assurance, and operational control options to reduce expected losses), a comparison of the assessments with FSV experience was performed to determine whether the evidence tends to support or refute the methodology as an effective tool for reducing expected losses.

Two avenues of comparison were generally available: (1) to examine whether the methodology predicted a significant number of (success or loss) events which might have occurred by this time but have not, (2) to evaluate whether a significant number of (success or loss) events have occurred which the methodology would not have predicted. Due to the limited scope of the quantitative analyses, only the latter comparison could be made.

Each incident involving the FSV helium circulator system was evaluated. The following sections give a brief discussion of each problem, its failure analysis and corrective action taken, and an evaluation of whether the methodology could have been expected to have detected and avoided the incident. The authors have attempted to be objective in these evaluations. However, the problems had, of course, already occurred, and the possibility of hindsight bias is therefore unavoidable. Hence, confidence in the methodology must be based on (1) the logic of procedure, and (2) empirical evidence, no significant portion of which should contradict the position that the methodology would be effective. The latter includes the incidents that have already occurred and any future incidents that may occur.

The logic alone would appear to suffice to conclude that the methodology would be effective in detecting and avoiding problems provided sufficient resources are made available. Hence, the crucial question should concern cost effectiveness, that is, whether the application of the methodology reduces expected losses. This will be the case as long as the following economic condition is satisfied: the expected loss associated with the remaining average potential problem area to be evaluated is greater than (1) the methodology's cost to detect, evaluate, and apply additional controls to the area, plus (2) the subsequent expected loss associated with the area. Fulfillment of this condition could therefore be a criterion for continuing to apply the methodology in a particular area.

For some systems or components the expected losses are so low that application of the methodology would prove uneconomic from the start. However, for any situation, application of the methodology would finally become uneconomic. To ensure that the above-mentioned economic condition is met, expected loss reduction estimates for the most recent five or ten evaluations in a particular area could be used to flag consideration of terminating application of the methodology to the area (analogous to moving average control chart techniques).

In addition to the example economic evaluations of Section 3.3 that generated expected loss reductions totaling more than $148,000 after only three evaluations, two further indications are available of expected loss reductions that might have been achieved by initially applying the methodology to the FSV helium circulator: first, the entire effort that went into this evaluation was comparable to the cost of just one day of FSV down time; second, this evaluation was directed to illustrate methodology, not to select the most economically fruitful problem areas.

4.2. INCIDENT ASSESSMENTS

4.2.1. Brake Problem

During circulator acceptance testing at Valmont, in January and February 1970, a piece of lockwire used to secure the screws holding the shaft brake assembly broke loose, entered the bearing water supply cavity, and progressed through the system to the main thrust bearing. The main thrust bearing runner was scored (Ref. 13). Therefore, the design was changed to include a protective cap over the exposed lockwired bolts to prevent reoccurrence. The protective cap is locked in by an adjacent part.

An FMEA performed on fasteners and locking devices would be expected to have identified broken lockwires as a failure mode and flagged that the fragments could travel into the bearing water supply and damage the circulator. Considering the (turbulent water) environment, if this possibility had been identified before installation, a high failure probability should have been estimated and something similar to the cap should have been recommended for incorporation into the design to greatly reduce the probability of failure, and to trap the lockwire if it were to fail.

4.2.2. Shutdown Seal Bellows Failures

4.2.2.1. Bellows Failure No. 1. Beginning June 15, 1974, a significant increase was noted in brake and seal helium usage for circulator A (C2101), from less than 1 bottle per week to 1 to 3 bottles per day (Ref. 14). The cause of the leakage was subsequently determined to be a ruptured bellows in the shutdown seal. The circulator was replaced, which resulted in a schedule slippage. Metallurgical analysis of the ruptured metal verified the conclusion that overpressurization was the cause.

Although the source of the overpressurization could not be identified with certainty, two possible causes were determined. One possible source of the overpressurization was found to be a pressure test on another system, which could have overpressurized the shutdown seal bellows if (1) a vent valve was inadvertently left closed by test personnel, contrary to the test procedure, and (2) an isolation valve leaked. Another possible source of the overpressurization was found to be the helium supply bottle if the pressure control valve setpoint was set too high. In this case, it was found that the associated relief valves could allow a pressure level on the bellows somewhat above the nominal relief setpoint, sufficient to cause bellows rupture.

It is expected that these sources of failure would have been identified by developing a fault tree for the shutdown seal as shown in Fig. 4-1. On the right side of the figure, the influence of other systems has been taken into account during various phases of the plant life (i.e., LCEs), including testing. In the center of Fig. 4-1, the influence of the helium bottle pressure control valve and relief valve is considered, including setpoint miscalibration. Hence, these sources should have been detected as potential problems provided a thorough analysis covering all LCEs had been performed, including interfaces.

To avoid the first potential source of failure, steps could be taken to prevent the high pressure of a test from reaching the bellows. For example, when the test procedure calls for venting, it would appear worthwhile to introduce an independent check to verify that the vent was opened. To avoid the alternate potential source of failure, the margin between the relief setpoint and the maximum tolerable pressure would have had to be questioned and justified in light of all LCEs including when the reactor is depressurized. Application of this methodology would have been expected to have resulted in a general administrative control that would have avoided this and similar improper adjustments.

Knowledge of the actual cause would be required to further determine if the methodology could be expected to have avoided the problem.

4.2.2.2. Bellows Failure No. 2. On March 10, 1976, the static seal actuation line could not be pressurized due to a rupture of the static seal bellows. The associated circulator was removed and replaced, causing a 3 to 4 week delay in startup tests (Ref. 15). Failure analyses for the cause of the rupture have not been completed at this writing (May 1976).

The FMEA shown in Table 3-2, item 6, identifies a general bellows rupture as a failure mechanism and ranks it as one of the more likely failure mechanisms. Potential causes of such a rupture may include a design error, e.g., predicting stresses or cycle life, a fabrication error, e.g., skipping a heat treatment, or exposure to an environment where vibration or a pressurized fluid creates an excessive unpredicted recurring stress.

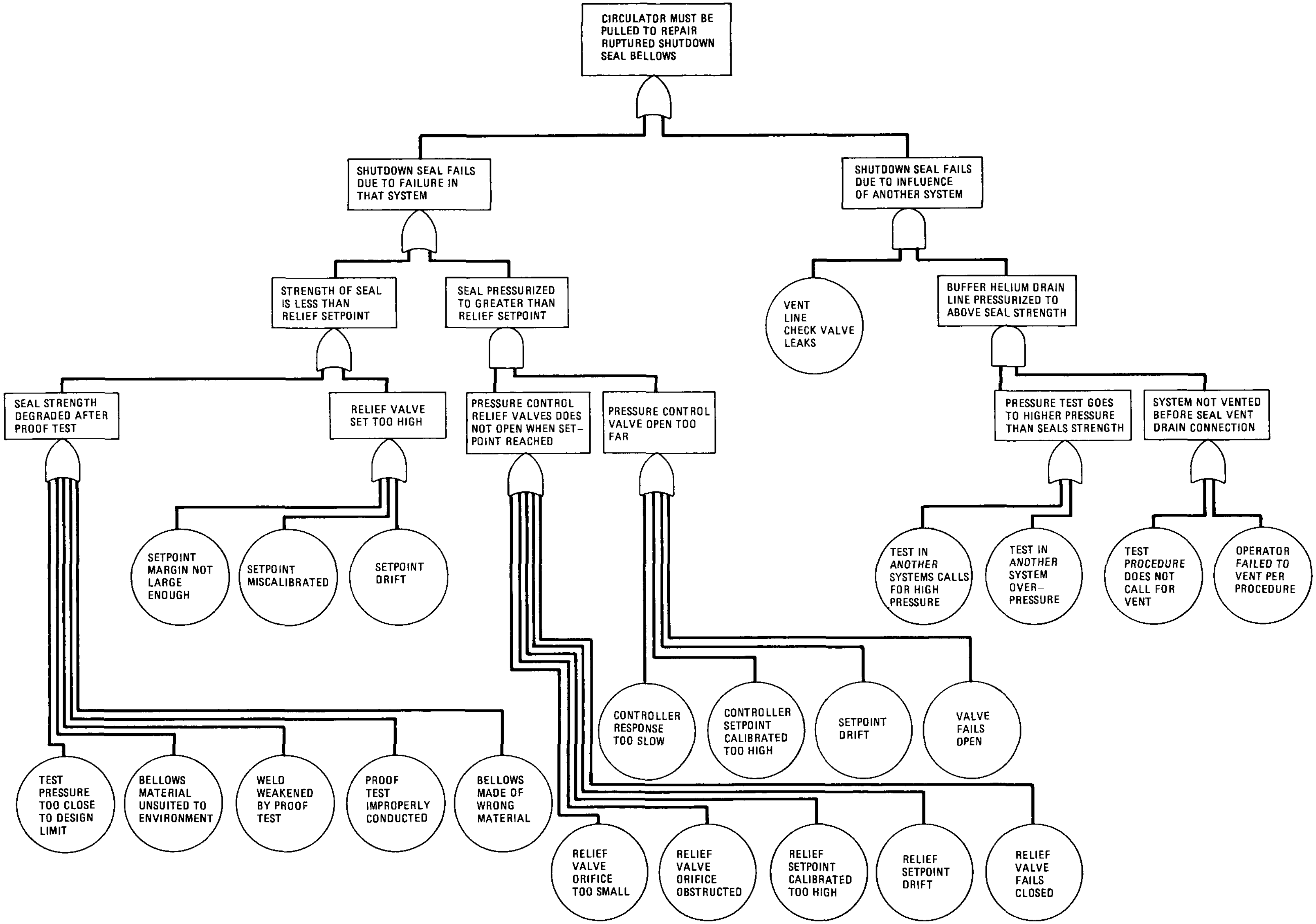

Fig. 4-1. Fault tree for shutdown seal bellows failure

The expected loss due to each potential source could have been evaluated by the methodology explained herein. Evidence indicates that additional assurance could not have been justified except possibly concerning the normal and abnormal vibration or cycling environments to which the seal could have been exposed during transportation or operation LCEs. Additional assurance in these areas would have required determining these normal and abnormal environments for the seal, evaluating the seal's response and expected loss to each, and devising and evaluating economic controls to reduce the total expected loss.

If the cause of the bellows rupture is determined to be other than an unanticipated environment, then the methodology would not have avoided this failure because the controls employed over the actual cause of the failure would have been considered adequate.

4.2.3. Shutdown Seal Failure

On March 29, 1975, while circulator B was removed from service and isolated from the bearing and buffer helium auxiliaries for construction purposes, it was noted that the shutdown seal was leaking. The leak rate was determined to be $\simeq$54.0 lb/day of helium at 10 psid, which was considered to be a degradation of the primary coolant boundary, but not in violation of the technical specification limit of 400 lb/day at 10 psid (Ref. 16).

Subsequently, a decision was made to replace the circulator. The seal was determined to be leaking due to foreign material on the sealing surface, which could have been introduced due to insufficient filtration or lack of cleanliness of the system.

This problem was identified in this evaluation on an FMEA (see Table 3-2, item 6) for the general case of seal leakage caused by corrosion or debris. The specific sources of debris or corrosion would be identified on a fault tree or in economic evaluations which consider the interactive effects of other systems. Considering the extensive problems that debris has caused in sensitive systems, it is expected that additional controls would have been recommended after the FMEA had identified the possibility.

4.2.4. Pelton Wheel Failures

4.2.4.1. Prenuclear Pelton Wheel Failure. Special pelton wheels were designed and installed on the FSV circulators for the hot flow testing. The primary coolant was heated by delivering 2500 hp per circulator to increase the primary coolant temperature. During the test on July 31, 1972, increased wobble was noted on circulator D, and this circulator was later shut down because the vibration became excessive. The hot flow test was discontinued when increased wobble was also observed in circulator A on August 12, 1972.

Metallurgical examination of the prenuclear pelton wheel revealed that the failure cause was severe cavitation damage. This damage resulted from forces developed when vapor bubbles collapsed against the solid bucket surface. Examination also revealed cracks at the bucket roots which were caused by fatigue loading (i.e., alternating stress cycles which equal the number of revolutions times the number of nozzles).

A research testing program was employed to determine an optimum solution. The following changes were made. Bubbles in the water jet and their effects were minimized by (1) increasing the cavity pressure (30 psi above deaerator pressure), (2) decreasing the drive water temperature, (3) optimizing the nozzle shape to suppress bubble formation, (4) changing heat treatment cycle of 17-4PH to improve pelton wheel fatigue strength, and (5) smoothing bucket contours to reduce crack propagation.

4.2.4.2. Nuclear Pelton Wheel Failure. Routine inspections of the nuclear pelton wheels with a dye penetrant revealed hairline cracks not visible to the unaided eye. Cracks were found in the curvic coupling teeth and the bucket roots (Refs. 17, 18). The cracks were due to high-cycle fatigue, which was promoted by abnormal operating conditions at the Valmont test site and high-speed water operation at FSV. The hairline cracks were also shown to be self arresting.

To correct the problem, the pelton wheel material was changed from cast to wrought Inconel 718, to improve alternating stress fatigue resistance, and the pelton wheel operation was limited to 8000 rpm with an overspeed trip setting of 8800 rpm.

4.2.4.3. Evaluation of Methodology Effectiveness in Avoiding the Problems. A more detailed reliability design review of the pelton wheel would have been expected to result in detailed questions about the mean time between failure (MTBF) of the wheel (see Appendix A, Table A-3, Question A.6.a), and thus would have identified the desirability of accelerated life tests that could be performed by changing environmental conditions, such as drive water temperature, pressures, etc.

A second method of reliability analysis, FMEAs and fault trees, should also have uncovered the potential for such failures. The identification of the most likely modes (cracking or imbalance) would probably lead to the consideration of such primary causes as cavitation or high cycle fatigue.

It is expected that reliability analysts performing these more detailed analyses during the initial design phase would have provided valuable input to the pelton wheel testing program, and added a different review viewpoint to the design. Definition of the required life and test life should have then been addressed and reflected in the initial system design. Thus, it is expected that delays caused by subsequent failures would have been avoided by application of the methodology to the test and design phases. The actual and expected economic losses associated with these pelton wheel failures were large, and could probably have been considerably reduced by application of the methodology.

4.2.5. Water Ingress No. 1

Water ingress into the PCRV is one of the unplanned events that first comes to mind when considering causes of unplanned plant down time. Because the water required for the circulator bearings and water turbine drive is separated from the PCRV only by dynamic seals, equipment failures

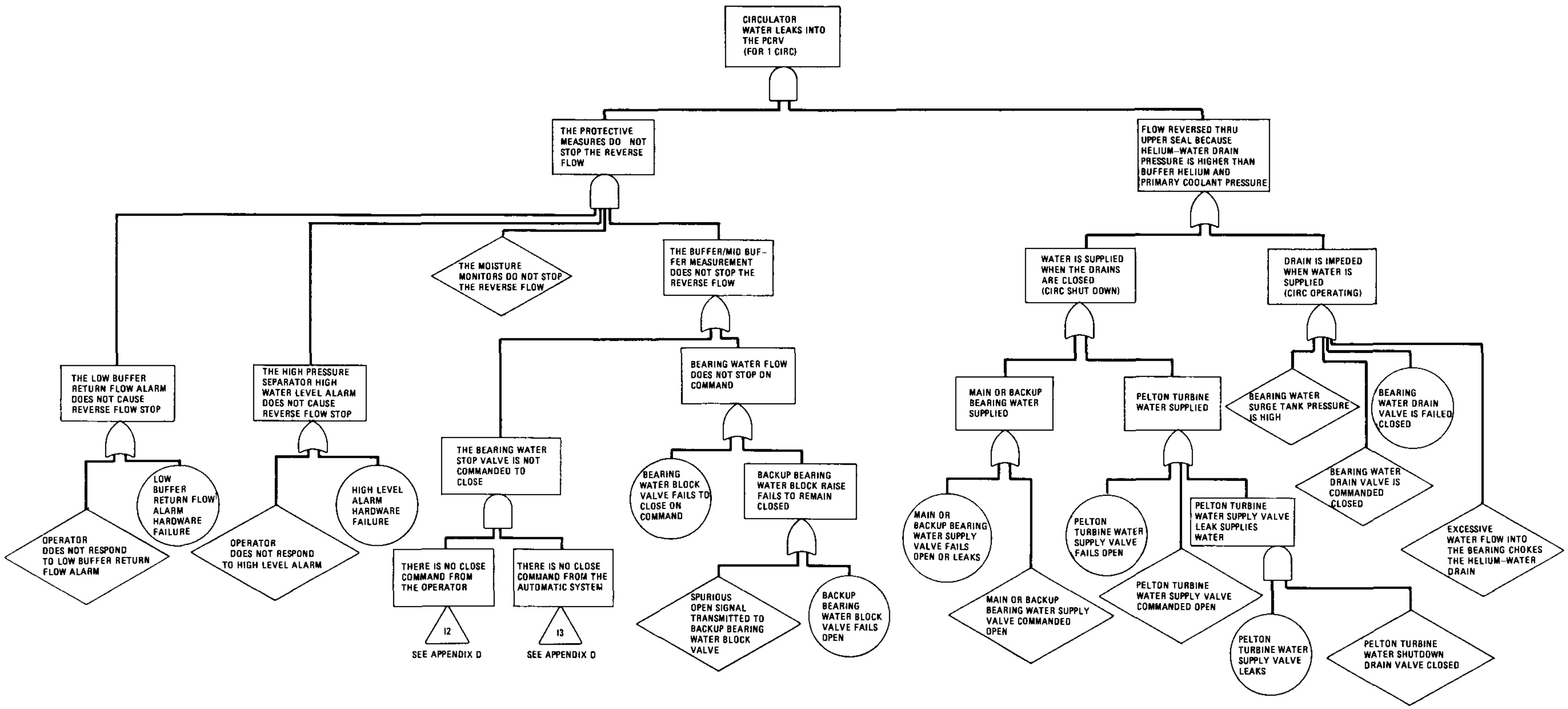

Fig. 4-2. Fault tree for water ingress through the circulator

that disrupt pressure conditions at the dynamic seal are potential causes of water ingress. For these reasons it is virtually certain that water ingress from the circulators would be included in an analysis of unplanned plant outage. A fault tree, such as that presented in Fig. 4-2, is an effective way of investigating the conditions for circulator water ingress. The right-hand side of that figure summarizes the causes for water getting up to and through the upper labyrinth seal. The figure shows that water ingress can also occur because of operator error alone.

The first significant incident of water ingress, as reported in Ref. 19, occurred during the initial operation and tuning of the circulator auxiliary systems. There is no definite information on the many variations of conditions of operation that were tried. Investigation of these incidents indicated that the ingresses resulted from loss of normal pressure conditions at the dynamic seal during these initial system tests. The detailed evidence indicates that the conditions for water ingress were present more than once.

The left-hand side of Fig. 4-2 summarizes the provisions for detecting and preventing water ingress. The incident report indicates that the automatic circulator trip had functioned on occasion and interrupted testing. The report also indicates that spurious indications of water ingress were being caused by water in the pressure sensing lines. As a result, the automatic circulator trip was disabled and the water ingress indications were disregarded. It is expected that a fault tree, such as Fig. 4-2, prepared early in the plant design phases, would have alerted the analyst and thereby the test procedure writers so that the procedures would have provided tighter controls over the conditions for ingress. It is considered unlikely that the protective system being disabled would have been considered significantly probable. Additional discussion is presented in Volume II, Appendix D, Section 2.

4.2.6. Water Ingress No. 2

This incident of circulator bearing water ingress was initiated by a hardware failure. The pressure control valve in the buffer helium supply failed open. Subsequently, the C circulator bearing water drain valve controller failed and closed the valve. The result was that the helium/water drain pressure rose to an estimated 57 psi above reactor pressure. This failed-closed condition of the drain valve is depicted in Fig. 4-2 as a cause of water ingress.

An automatic circulator trip did not occur because the circulators in the other loop were shut down, thereby disabling the automatic trip circuitry. Indications of water ingress included loss of helium return flow and high water level in the high-pressure separator. Due to an attempt to quickly correct the problem, shutdown of the circulator was delayed (considerably longer than specified in plant operating procedures) until after a significant quantity of water had entered the PCRV.

It is expected that the methodology would not have predicted a significant expected loss for this event due to the numerous alarms, and therefore that this incident would not have been avoided by the methodology except possibly indirectly through an evaluation of the operator training program. For further discussion see Volume II, Appendix D, Section 3.

4.2.7. <u>Water Ingress No. 3</u>

This ingress of water was from the pelton turbine drive system. It occurred on a circulator that was shut down. It resulted from a combination of the internal leakage failure of the turbine water block valve and closure of the water turbine cavity drain valve. During this incident the indications of water ingress by negative buffer/mid-buffer pressure were not responded to properly, and a large quantity of water was allowed to enter the PCRV. Corrective action resulted in an administrative procedure (operational) control on the drain valve and several interlocks (design controls) on this valve.

It is expected that this avenue of water ingress would have been detected by a fault tree analysis such as that shown in Fig. 4-2. An evaluation of the associated expected loss probably would have recommended additional administrative controls, and perhaps interlocks as well, thereby reducing the expected loss and probably avoiding the ingress provided the extended construction phase and the associated higher human error rates were considered. However, it is not expected that application of the methodology would have justified the turbine cavity water level sensor and alarm system being installed as they were after this incident. For further discussion see Volume II, Appendix D, Section 4.

4.2.8. Backup Bearing Water System Valve Failure

4.2.8.1. Problem Description. Valve PV-21105-1 is in parallel with PV-21105, the main valve which controls the pressure between the emergency feedwater header and the backup bearing water (BUBW) system. The smaller PV-21105-1 valve was added to reduce the circulator bearing cartridge pressure transient when the normal bearing water supply (Ref. 11) is switched to the BUBW system, and to provide a vernier flow control.

After PV-21105-1 was dismantled and reassembled, during repair operations on PV-21105, leaks were observed in PV-21105-1 and corrected by tightening the cover bolts on several occasions. On April 10, 1975, the emergency feedwater header pressure was being tested. When the test pressure reached approximately 4000 psi, the actuator of PV-21105-1 was ejected from the valve and the upper stem packing was blown from the bonnet (Ref. 20).

4.2.8.2. Failure Analysis. A detailed review of the damaged parts, logs, and valve design led to the following conclusions:

1. The valve was reassembled with the ring seal inverted. Review of drawings and similar valves shows that assembly with the ring seal inverted increases the stack height by 0.1 in., but does not preclude further assembly.

2. Further assembly was possible only by deformation of various parts of the valve. This occurred as a result of excessive bolt torque during reassembly (Ref. 20).

4.2.8.3. Corrective Action. New yoke clamps of wrought rather than cast material were installed in this valve and all similar valves. It has been concluded that more care must be taken during valve reassembly to maintain reasonable gland flange torque values, thus minimizing material stresses and eliminating the need for excessive packing to prevent stem leakage. In addition, a second relief valve is used as a backup to limit maximum pressure during operation.

It has been recommended that PSC develop a plan for inspection and proper reassembly of safety-related mechanical restraints for the life of the plant, and that PSC establish a review committee to consider the effect of maintenance and repair actions in context with system performance (Ref. 21).

4.2.8.4. Evaluation of Methodology Effectiveness in Avoiding the Problem. It is expected that a more detailed reliability design review of the valve using a special design review checklist would have addressed the potential for improper assembly. If recognized as a potential problem, it could have been further controlled by a number of methods (e.g., by using a special color code for valves requiring extreme care and checking during maintenance or repair operations, by modifying the valve design so it is impossible to assemble components improperly, or by requiring the use of a detailed checklist during maintenance for repair of each such valve, component, etc.). However, this valve was off-the-shelf hardware. Hence, such a design review would only have been conducted if the methodology had included such hardware. This indicates the need to consider all components as recommended by the general methodology.

In the case under discussion, a large number of similar valves have been manufactured by the particular company, and experience indicates that the likelihood of such a failure as this is low, although valve leakage is expected. For these reasons, application of the methodology to this valve would probably have concluded that the general controls on all such valves for this failure mode were already sufficient, since the expected loss from this particular valve failure mode is low. Therefore, unless, through the design review mentioned above, a general control was imposed against improper assembly of high-pressure and other critical off-the-shelf hardware, it appears unlikely that the methodology applied to this valve alone would have recommended such a control for it and avoided the problem. Although valve leakage and other valve problems are recognized to be a major problem in large power plants, there are a large number of valves in such a plant. Hence, an economic evaluation would be required to decide whether a general control would have been justified that would be expected to have avoided the problem.

4.2.9. Circulator Bearing Water Strainer Failure

On April 1, 1972, difficulty was experienced in initiating self-turbining on all circulators. Even pelton wheel "bumping" did not prove effective in initiating self-turbining for circulator A. This circulator was manually torqued to about 100 ft-lb by the nut on the pelton wheel turbine to initiate self-turbining (Ref. 22).

Prior to this startup problem, the main bearing water filters had ruptured, allowing the filter material to clog the Y strainers in the bearing water inlet piping. The increased pressure differential across the strainer then caused the screen to rupture. Contamination resembling iron oxide, normally filtered from the bearing water, was released downstream to the circulators. Upon reaching the bearing assembly, this contamination was the primary cause of failure to self-turbine without assistance.

Several actions were taken to prevent such occurrences in the future (Ref. 23). Initially, (1) the helium circulator lines were flushed, (2) the strainers were replaced with heavier capacity Y strainer backup rings, and (3) the bearing water filters were replaced with finer mesh cartridges to ensure that the filters would load up before the strainers; later, (4) permanent differential pressure indicators with remote alarms were installed to signal contamination load-up on strainers in addition to the ones already on the filters, (5) permanent bearing water bypass lines were added to allow preflushing of the normal and backup bearing water system prior to permitting water to enter the helium circulator, and (6) a secondary makeup water line was also installed in the condensate system with aprticulate filters on the bearing water makeup pump. These corrective actions were taken to ensure that proper system cleanliness can be maintained.

It is expected that use of the FMEAs and fault trees on the bearing system would have identified the potential for this problem. The highest potential for the contamination problem appears to be during the construction phase, when cleanliness is most difficult to control. After operations begin, corrosion and erosion due to water chemistry problems are expected to be the most likely potential causes of this failure mode based on application of the methodology.

If the problem area had been identified by prior analysis it is expected that: a flushing method similar to the two actually taken above would have been suggested; the low-cost modification (item 3 above) would have been recommended as a result of considering potential mitigating solutions; items 5 and 6 above would have been considered, but their inclusion as definite design improvement recommendations would have had to be based on the likelihood of contamination in the revised design. Hence, it is expected that prior application of the methodology would have detected the potential problem and avoided it.

4.3. PLANT TROUBLE REPORTS

Routine problems observed by plant personnel at the Fort St. Vrain site are normally documented as plant trouble reports (PTRs). Disposition of such a report is accomplished by rectifying the problem. These PTRs bring to the attention of cognizant groups such problems as leaking valves, indicators out of calibration, mislabeled or missing equipment, or malfunctioning controls.

Since a sufficiently large number of small problems can cause delays as significant as those caused by a few large problems, a random sample of 50 PTRs has been evaluated to identify trends in the types of problems observed at FSV during typical preoperational tests involving the helium circulator auxiliary systems. Also, an estimate was made of the percentage of such problems which could have been detected by the application of techniques described in this report.

The general natures of the sample of 50 PTRs have been grouped into six major categories, as shown in Fig. 4-3. These categories are: (1) design errors or omissions, (2) errors or omissions at installation, (3) impaired operations, (4) random component failures, (5) errors or omissions in procedures or tests, and (6) not confirmable.

The failures in the operations-impaired category (Fig. 4-3) break down into classifications involving leaks, cleanliness, calibration, misadjusted setpoints, and impaired instrument references (see Fig. 4-4). Examination of the PTRs indicates that these problems would be principally due to either installation errors or random failures. However, the PTRs are not explicit enough in their failure analyses to determine into which category they should be placed. Therefore, the operations-impaired category was created.

It can be seen from Fig. 4-3 that the percentages of problems in the design, installation, and failure categories are comparable. If the operations-impaired category could be divided among its contributors, it would be expected that the installation and failure categories would become the two largest contributors of small problems, followed by the design category.

Interpretation and extrapolation of the (often meager) information contained in the PTRs resulted in an estimate (on a binomial trials basis) that more detailed design reviews would have been expected to detect 86% of the design and procedure types of problems observed during the preoperational tests on the helium circulator auxiliary systems. Similarly, it appears that a more intensive quality assurance effort at the site could have been expected to detect 82% of the installation problems. The expected values and the 60% and 90% lower confidence limits for the fractions that could have been detected are shown in Table 4-1.

The initially high rate of problems appears to have the potential to cause a significant amount of startup delay. More detailed information

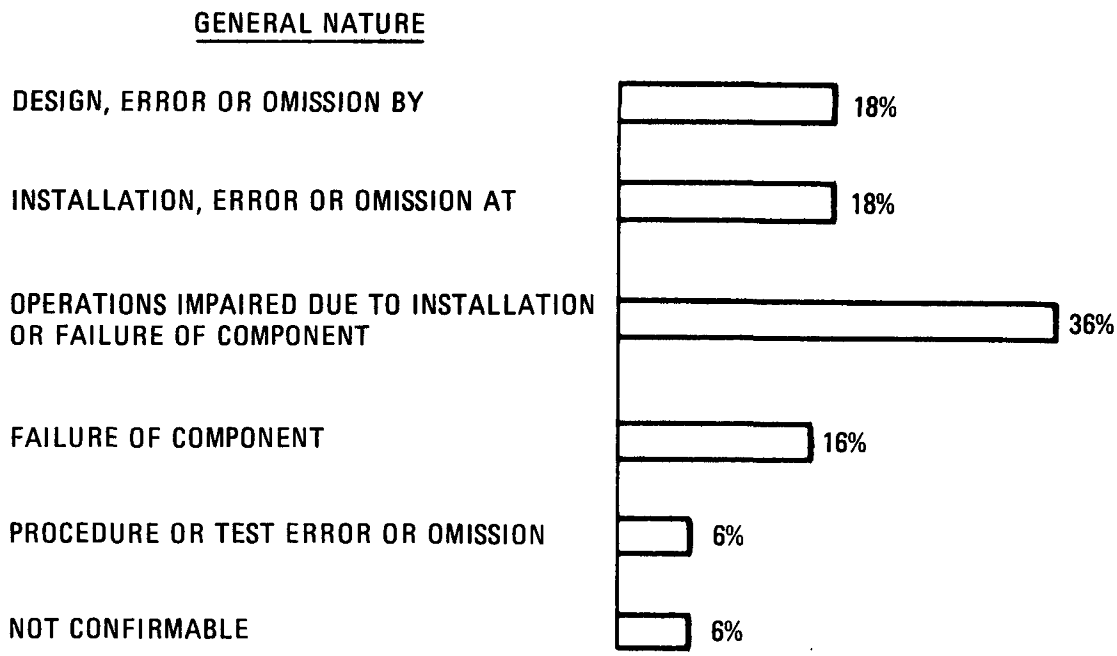

Fig. 4-3. Distribution of general natures of 50 (randomly selected) plant trouble reports

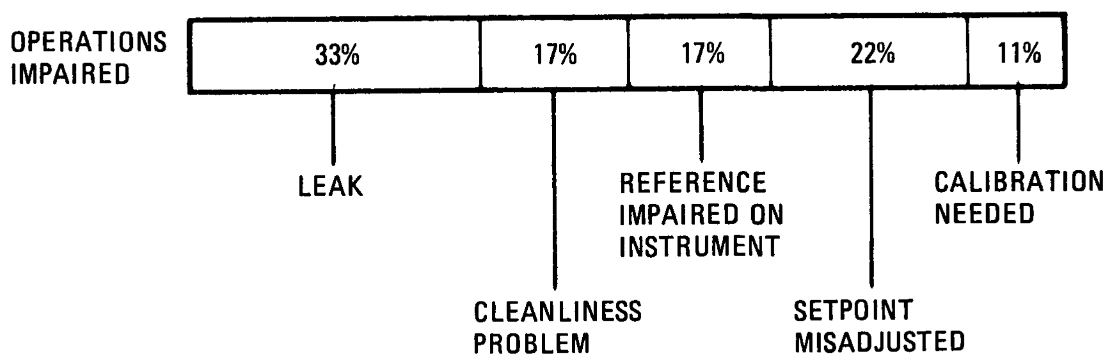

Fig. 4-4. Contributors to "operations impaired" category

TABLE 4-1
PERCENTAGE OF OBSERVED SAMPLE PROBLEMS DETECTABLE BY PROPOSED METHOD

	Design and Procedural Problems (Detected: 11 out of 12) (%)	Installation Problems (Detected: 8 out of 9) (%)
Expected value	86	82
Lower 60% confidence limit	83	77
Lower 90% confidence limit	68	57

concerning the problems and their consequences would be required to determine whether application of the methodology would have significantly reduced such problems. The principal areas for reducing expected losses for this system are expected to be installation, design, and possibly random failures.

It is recommended that efforts to reduce delays during the construction phase include a better reporting method than PTRs. More complete analyses of problems could be documented, at least on a sample basis, so that trends in the nature of problems can be evaluated, and the effectiveness of the reliability methods utilized can be determined.

From the preceding data and analysis it can be concluded that (1) numerous small problems occur which require correction during the construction/pre-startup phase of a plant, (2) such problems appear capable of causing significant delays in startup, (3) the methodology described in this report is expected to be able to detect a preponderance of such problems, and to determine by economic analyses those for which additional controls are justified, and (4) a more thorough method is needed for reporting at least a sample of the smaller type problems, to adequately evaluate their collective significance and direct the corrective measures.

4.4. CONCLUSIONS OF COMPARISON WITH EXPERIENCE

The most significant aspect of the above analyses and discussions of actual FSV problems is that only an unusually thorough program could be expected to have identified and avoided most of the sample problems. Even then, about one-fourth of the problems probably would have been evaluated to present such a low expected loss in the specific evaluation that no additional controls would have appeared justified, and therefore these could only be expected to have been avoided by general controls which amortize the cost of implementation over a large number of components or operations.

The examples emphasize the importance of considering every life cycle event for every critical component. Nearly 50% of the problems involve life cycle events that would probably be overlooked in a cursory analysis. More than half the problems involve probabilities of human error which are generally much higher during pre-startup phases than during operation. If ignored in a cursory analysis, such incorrect assumptions could result in failure to avoid many problems even though they were detected as possibilities in the analyses.

Economically, the value of the methodology for FSV (at ~\$100,000/day of plant down-time) is indicated by the fact that one engineer applying the methodology for one year would be more than justified if the effort could be expected to reduce plant down-time by even one day, and five engineers applying the methodology for eight years would be more than justified if the effort could be expected to reduce plant down-time by the time required for even one helium circulator removal and replacement. The actual FSV circulator problems caused considerably more plant down-time than that associated with the removal and replacement of one helium circulator. Hence, even avoiding a few of these problems could have been worth a great deal more than the cost of five engineers applying the methodology for eight years. However, even two engineers applying the methodology to the circulator system over a period of only five years could prob ably have detected and avoided nearly all of the major FSV circulator problems.

Therefore, the conclusions are that the evidence surrounding FSV experience not only does not refute the position that the methodology could have economically detected and avoided the preponderance of the actual problems, but it strongly supports the necessity of most of the principal tenets of the methodology, namely: The approach must consider all components, functions, and life cycle events for critical components. Realistic failure probabilities and cost estimates must be used, and analyses should be closely coordinated with each group responsible for implementing controls (i.e., design, QA, operational procedures, etc.). Also, analyses and option recommendations should be coordinated with actual schedules. The methodology should be applied as early as possible to maximize its effectiveness, but it must also keep abreast of all changes in design, LCEs, and controls. If properly supported and applied, the methodology should cease to be cost effective in most areas long before the equipment becomes operational. In any case, an economic criterion analogous to that given in Section 4.1 should be established, and results monitored to assure prompt consideration of terminating analyses in areas when the criterion is no longer met.

A program which is not sufficiently thorough in its basis and implementation will probably not be clearly cost effective. Such a program could identify relatively obvious problems, but very few subtle problems (e.g., those involving complex interactions between systems) would be detected. When appropriately developed and applied to a project having large expected losses due to component or system unavailability, however, the methodology illustrated herein should prove cost effective and increase component and system availability significantly.

5. SUMMARY AND CONCLUSIONS

A method has been described for systematically locating and eliminating areas which may contribute to unavailability of any component or system. Application of the method has been illustrated using the components directly involved with causing or allowing helium to circulate in the Public Service Company of Colorado's Fort St. Vrain 330-MW(e) high-temperature gas-cooled reactor.

Failure modes and effects analyses (FMEAs) and fault tree analyses (FTAs) were employed to locate potential problem areas. Decision-under-uncertainty analysis methods were employed to evaluate example options illustrating the use of the three principal classes of controls (i.e., design, QA, and operational), and using the economic criterion with plant down time valued at $4000 per hr and a real interest rate of 3% per year.

A comparison with experience was made by examining actual problems encountered by the FSV helium circulator system components, and judging whether prior application of the methodology would have been expected to have (1) identified the problem, and (2) concluded it was economic to implement a control that would have avoided the problem.

The conclusions of the evaluation are that the methodology:

1. Can be applied to any component or system.

2. Can only prove economic (i.e., at least pay for the evaluation itself) provided significant expected losses exist. This situation is most likely to exist for new and uniquely designed components and systems (due to uncertainties), for projects with severe potential losses (due to failure to control probabilities,

or due to aversion to risk), for projects with histories of recent losses which are individually or cumulatively very high (i.e., direct evidence of insufficient controls) and for projects analogous to other projects that suffered large actual losses.

3. Requires careful technical staffing and proper management to be effective.

4. Requires that every component and life cycle event be adequately considered. Each should be considered suspect until evidence is accrued to justify dropping it from further consideration.

5. Requires use of realistic models and parameters (e.g., the conditional probabilities of human error rates given that the reactor is under construction or shut down).

6. Should include and monitor an economic criterion to assure prompt consideration of termination of the effort in each principal area of the evaluation when the effort becomes uneconomic.

7. Can be expected to be economic and effective in significantly reducing the number of problems encountered and the associated expected losses when applied under the above-recommended conditions.

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