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ABSTRACT

The High Flux Isotope Reactor (HFIR) is a high performance isotope production and research reactor which has been in operation at Oak Ridge National Laboratory (ORNL) since 1965. In late 1986 the reactor was shut down as a result of discovery of unexpected neutron embrittlement of the reactor vessel.

In January of 1988, a level 1 Probabilistic Risk Assessment (PRA) (excluding external events) was published as part of the response to the many reviews that followed the shutdown and for use by ORNL to prioritize action items intended to upgrade the safety of the reactor. A conservative estimate of the core damage frequency initiated by internal events for HFIR was 3.11×10^{-4}. In June 1989 a draft external events initiated PRA was published. The dominant contributions from external events came from seismic, wind, and fires. The overall external event contribution to core damage frequency is about 138% of the internal event initiated contribution and is dominated by wind initiators.

The PRA has provided a basis for the management of a wide range of safety and operation issues at the HFIR.

INTRODUCTION

The High Flux Isotope Reactor (HFIR) is a high performance isotope production and research reactor which has been in operation at the Oak Ridge National Laboratory (ORNL) since 1965. Its main missions are the production of transuranic and cobalt isotopes, materials irradiation research, and neutron scattering research.

In late 1986, a special internal post-Chernobyl review of HFIR discovered unexpected neutron embrittlement of the reactor vessel. As a result of the discovery, the reactor was shutdown in November 1986. The Department of Energy (DOE) and ORNL began an extensive review of the reactor design, safety, operation, maintenance, and management. Over twenty reviews of various depths have been conducted to date by DOE, ORNL, and independent oversite groups such as the National Academy of Science/National Research Council and the Advisory Committee on Nuclear Facility Safety.

Partly as a result of this review process, a Probabilistic Risk Assessment (PRA)[1] of HFIR was completed for internal initiated events in January 1988. This was the first PRA on a large research reactor in the United States. The PRA evaluation of external events was completed in draft form in June 1989. The approach used on the HFIR PRA, the results and the use of the PRA in the management of safety issues will be presented in this paper.

HIGH FLUX ISOTOPE REACTOR DESIGN

The HFIR is an 85-MW flux trap reactor. A schematic of the reactor is contained in Fig. 1. It is water cooled and beryllium moderated. It operates at 3.23-MPa (468-psi) pressure with an inlet temperature of 322 K (120°F) and outlet temperature of 343 K (158°F). The peak thermal flux in the flux trap is 5×10^{15} n/cm^2-s, which makes the HFIR the highest thermal flux reactor in the world. The core of the reactor is small [0.44-m (17 1/2-in.) diam, 0.61 m (24 in.) in height] with a 0.12-m (5-in.)-diam target hole through its center. The core contains about 9.6 kg of highly enriched (93 percent) U^{235}, arranged in two concentric cylindrical elements. The inner element contains 171 involuted plates and the outer 369 involuted plates. The core is made up of a U_3O_8/Al mixture clad in aluminum. The core is replaced every 24 days. The Be moderator surrounds the core and is about 0.304 m (1 ft) thick. Control is achieved by four safety plates arranged in a cylinder around a solid control cylinder. The outer cylinder is raised and the inner lowered to increase reactivity and keep a symmetric flux profile. These control cylinders are sandwiched between the core and the Be reflector and are composed of Eu_2O_3, and Ta.

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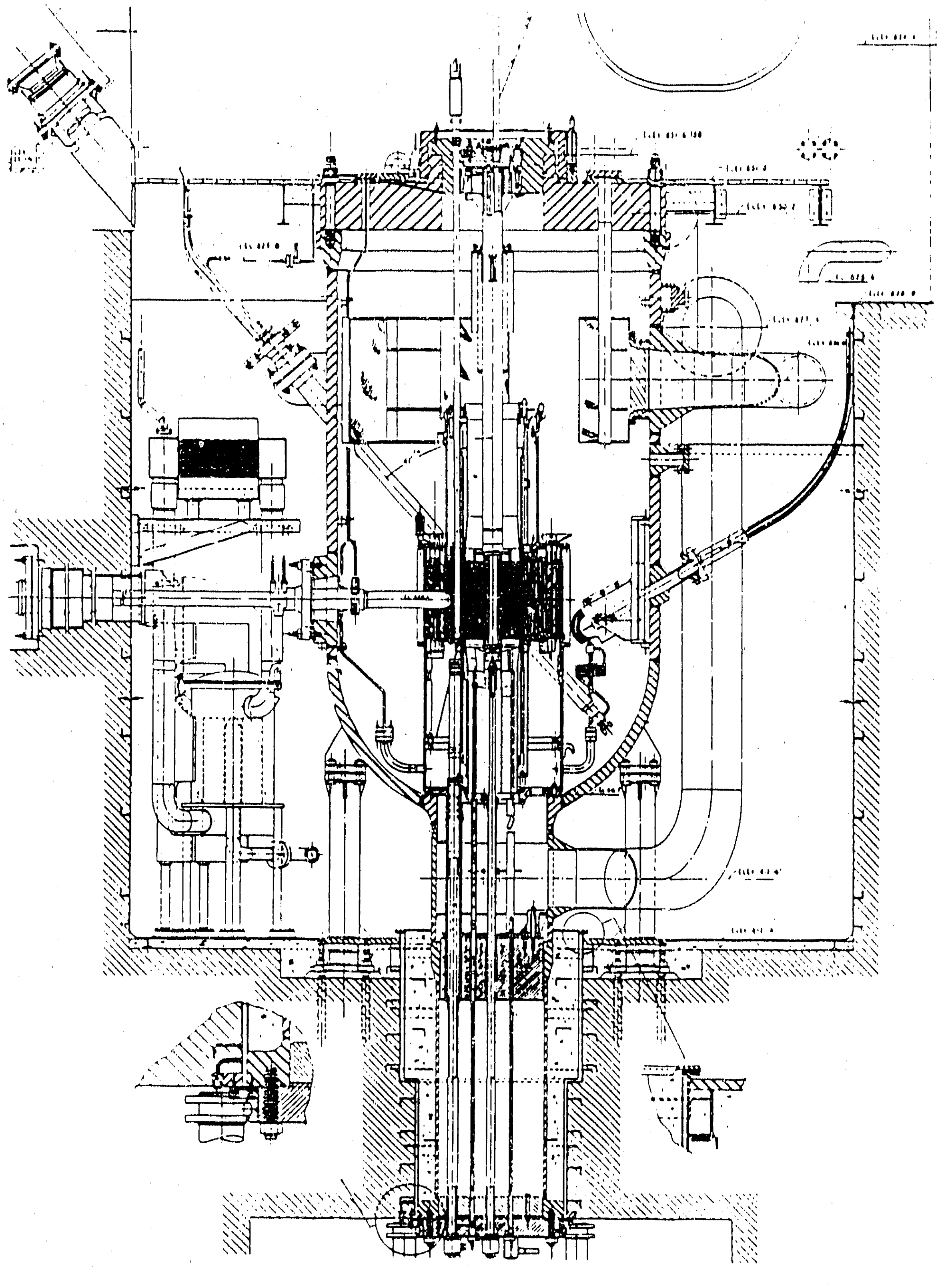

Fig. 1. Vertical Section of HFIR Reactor Vessel and Core

The reactor core is contained in an 2.43-m (8-ft)-diam pressure vessel that is about 5.79 m (19 ft) high. The pressure vessel is located near the bottom of a large pool [10.9 m (36 ft) deep and about 5.48 m (18 ft) across)] containing 386.4 m (85,000 gal) of water.

The 3.23-MPa (468-psi) pressure is maintained by compressing the primary system water using a pressurizer pump in combination with a system of letdown valves. The flow [7 x 10^{-4}m^3/s (16,000 gal/min)] is achieved by three out of four AC motor-driven primary pumps and it is downward through the core and target regions. Decay heat is removed using a small DC motor to drive the primary pumps. The power to the DC motor is supplied using a dedicated battery power supply or by using off-site power, on-site diesel generators, or portable diesel generators (AEPGs) connected to inverters.

A schematic of the HFIR process flow system is included in Fig. 2, and a schematic of the electrical power distribution system is included in Fig. 3.

The reactor is contained in a large reactor building 39.0 x 48.8 x 33.5 m (128 x 160 x 110 ft), which is maintained at a slight vacuum. Exhaust fans continuously pull air from the building through a series of filters and exhaust up a 76.2-m (250-ft) stack. The building, filters, fans and stack act as a dynamic confinement in the event of an accident.

The reactor was built in 1965 to Uniform Building Code Seismic Standards resulting in a seismic design acceleration of about 0.08 g. The primary coolant system was upgraded in 1987 to enable it to withstand 0.15 g, which is the safe shutdown earthquake for the HFIR.

HFIR PROBABILISTIC RISK ASSESSMENT (INTERNAL EVENTS)

The Probabilistic Risk Assessment (PRA) was subcontracted to Pickard, Lowe and Garrick Inc. (PL&G), Newport Beach, California, and work began in July 1987 with the final report (excluding external events) issued in January 1988. Several basic assumptions were set forth to guide the work. These are shown below:

1. Core damage will be defined as occurring at the onset of incipient boiling.
2. The reactor configuration assessed would be that at restart (includes power reduction and all pre-restart design modifications) with the addition of the portable diesel generators (AEPGs).
3. The probability of vessel failure would come from the "Evaluation of HFIR Pressure-vessel Integrity Considering Radiation Embrittlement," ORNL/TM-10444, edited by R. D. Cheverton.[2]
4. The plant specific HFIR data is to be used wherever possible and to the extent possible.
5. Consideration should be given to accidents which have occurred at other research reactors when exploring initiating events.
6. Results should be expressed in such a way as to facilitate ease in calculation of off-site consequences.
7. Models should be fluid (easily modified as the design changes) in order to make the assessment a "living PRA".

The internal initiating events were selected by applying the following six steps: (1) examine the 20 years of operating history and the quarterly technical reports, (2) review the HFIR Accident Analysis Report,[3] (3) review the HFIR design, drawings, and operational procedures, (4) old discussions with the original HFIR design team, (5) extensively review the incidents at other research reactors and applicable commercial nuclear power reactor experience, and (6) create a master logic diagram (MLD) which generally examines how the HFIR core could be damaged.

In order to facilitate source term determination and subsequent off-site consequence analysis, the results of the HFIR PRA were expressed in terms of plant damage states. The plant damage state matrix is shown in Fig. 4. The matrix categorizes the end state of an event tree as to (1) the extent of the damage, (2) whether the primary system is intact following the accident, (3) in case of a loss of coolant accident (LOCA), whether the break is inside or outside the reactor pool (which provides fission product scrubbing), and (4) whether power is available to one, two or all three exhaust fans.

The results of the PRA are also expressed in terms of frequency of core damage. Table 1 indicates the overall frequency of core damage as a result of internal initiated events.

The dominant internal event initiated accident scenarios for HFIR are flow blockages which contribute 29 percent of the total core damage frequency followed by loss of all AC power at 18 percent, large loss of coolant accidents at 10 percent, fuel defects at 7 percent and manual scrams at 7 percent, and degraded primary flow at 7 percent.

EXTERNAL EVENTS PRA APPROACH

Following the internal events assessment the same subcontractor began to examine the risks associated with external event initiators. The initiators considered consisted of the nine major categories below:

Seismic
Wind/Tornado
Fire/Smoke
Floods (External and Internal)
Spray (Steam and Water)
Explosions
Missiles
Caustic Attack
Falling Objects

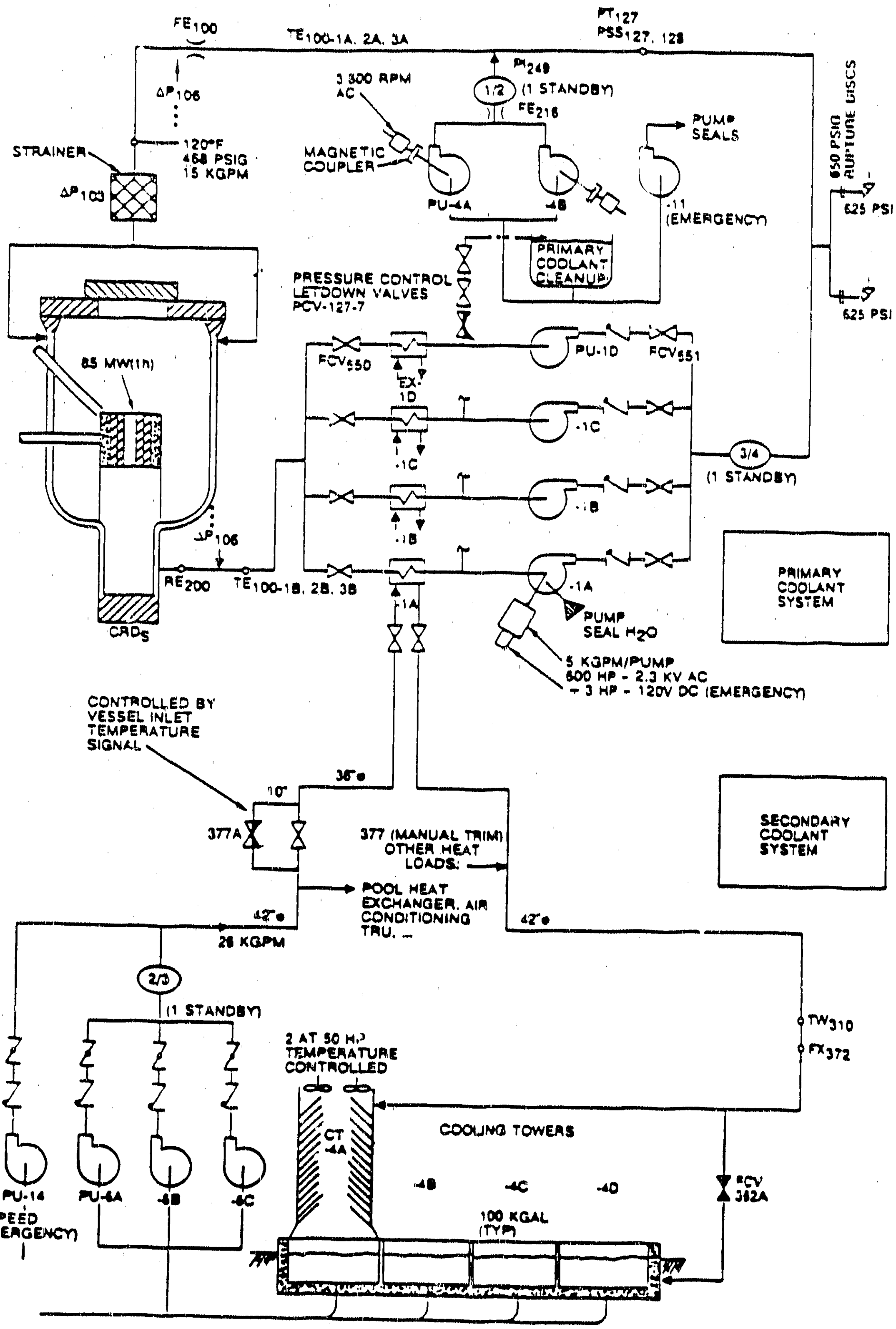

Fig. 2. HFIR Process Flow Schematic (primary and secondary systems)

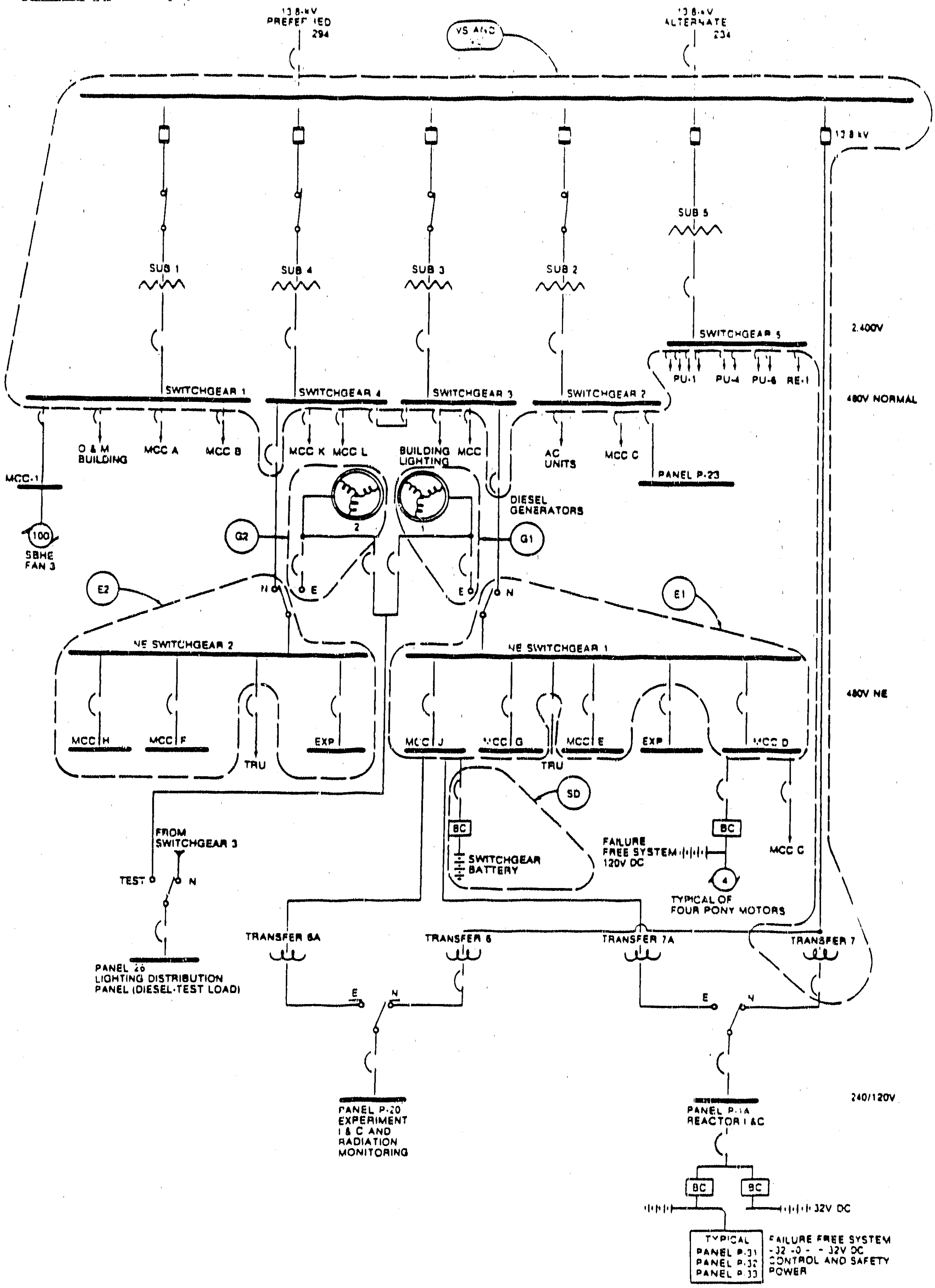

Fig. 3. HFIR Electrical System Schematic

EXTENT OF CORE DAMAGE													
PARTIAL CORE DAMAGE							TOTAL CORE DAMAGE						
PRIMARY SYSTEM INTACT?							PRIMARY SYSTEM INTACT?						
Y		N					Y		N				
—		BREAK IN POOL?					—		BREAK IN POOL?				
—		Y		N			—		Y		N		
—		—		IN CONFINEMENT?			—		—		IN CONFINEMENT?		
—		—		Y		N	—		—		Y		N
SBHE/CHOG/OHOG SUPPORT SYSTEMS AVAILABLE?*													
Y	N	Y	N	Y	N	—	Y	N	Y	N	Y	N	—
1A/1G/1H	2	3A/3G/3H	4	5A/5G/5H	6	7	8A/8G/8H	9	10A/10G/10H	11	12A/12G/12H	13	14

*WHERE:
nA INDICATES BOTH MCC G AND MCC H ARE ENERGIZED FOR STATE n.
nG INDICATES MCC G IS ENERGIZED AND MCC H IS DEENERGIZED FOR STATE n.
nH INDICATES MCC H IS ENERGIZED AND MCC G IS DEENERGIZED FOR STATE n.

NOTE. A "B" SUFFIX IS ATTACHED FOR THOSE SEQUENCES IN WHICH CORE DAMAGE OCCURS EARLY IN CORE LIFE.

Fig. 4. HFIR Plant Damage State Matrix

Table 1. Contribution of Fire, Flood, and Other Environmental Hazards to Core Damage Frequency

Description	Contribution Core Damage Frequency	Percent of Internal Initiating Event Core Damage Frequency
Fire Scenarios	1.83×10^{-5} per year	5.88
Flood and Other Environmental Hazard Scenarios	1.81×10^{-6} per year	0.58
Fire, Flood, and Other Environmental Hazard Scenarios	2.01×10^{-5} per year	6.46
Internal Initiating Event	3.11×10^{-4} per year	

Except for the first two initiators, the other contributors were all assessed using the same general approach. The latter seven initiators will be referred to as Internal Hazard Initiators (IHI).

The assessment of the The assessment of the internal hazard initiators began with an identification of initiators and an assessment of potential interactions between the hazard and the plant equipment, referred to as spatial interactions. This was accomplished by an extensive examination of plant drawings, plant layout, and a detailed plant walk-down. In the case of the HFIR, 207 possible accident scenarios involving IHIs were identified for further analysis. Fires dominated the internal hazard scenarios. Results of Internal Hazard Initiators are shown in Table 1.

The seismic risk analysis consisted of five steps: (1) determine the seismic hazard for the HFIR site (frequency of ground motion acceleration of various sizes), (2) perform a fragility analysis (response of structures and/or components to various magnitudes of ground acceleration), (3) analyze the plant response to the seismic failures resulting from steps 1 and 2, (4) obtain a mean (point estimate) of the core damage frequency and assign core damage states resulting from a combination of steps 1-3, (5) finally, perform an uncertainty analysis for those scenarios found to be dominant contributors to the seismic risk.

The analysis of the effects of high winds and tornados on the HFIR followed the same approach as for seismic analysis. The steps were: (1) create tornado/wind hazard curves (frequency of wind events at various velocities), (2) perform a fragility analysis, (3) perform a tornado missile analysis, (4) combine steps 1-3 with the plant logic and obtain an estimate of core damage frequency and plant damage states, and (5) perform an uncertainty analysis.

The results of the External Events PRA are shown in Table 2 and comparisons made to the internal events PRA.

Table 2. Summary of External Events Results

Initiator	Mean Core Damage Frequency
Fire	1.88×10^{-5}/year
Wind	2.86×10^{-4}/year
Seismic	1.23×10^{-4}/year
Other	1.81×10^{-6}/year
Subtotal - External	4.30×10^{-4}/year
Subtotal - Internal	3.11×10^{-4}/year
Total HFIR Mean Core Damage	7.41×10^{-4}/year

USE OF THE PRA TO MANAGE SAFETY ISSUES

The HFIR PRA was developed from the start with several uses in mind. Foremost, it was required by the DOE design review team; within ORNL it was intended that it be used for safety improvement and to help prioritize the many design and administrative changes required by the numerous review committees. In addition, it is also found useful for operator and engineer training, emergency planning, technical specification modification, maintenance improvements, as a basis for environmental qualification to help define and document the safety design basis of the plant, and as input to the upgrade of the Safety Analysis Report. Examples of each of these are found below.

One of the main uses was as a justification for restart of the HFIR. In particular, the completion of the PRA itself was a restart issue, but more so the approach and results of the PRA were used to justify restart for several review committees by providing quantitative and qualitative responses to technical inquiries.

The PRA along with specialized analysis is being used to provide a technical justification for interpretation of requirements found in DOE orders.

The PRA was the basis for reconstructing the safety design basis of the HFIR. It was also used as a basis for constructing the safety-related equipment list and for determining the equipment and environments needed for environmental qualification.

The Research Reactors Division was faced with an ever increasing list of requirements and design changes. A risk-based management program was implemented to prioritize these requirements. The PRA is used for the basis for the frequency and consequence of the event that the requirement is expected to affect. The final prioritization, however, also takes into account input from other areas such as cost, exposure limits, operational restrictions, etc.

Scenarios from the PRA are used in the operator training program and also as a basis for emergency planning. Technical specification modifications and safety assessments associated with technical specifications and surveillance frequencies are based on PRA results where appropriate.

The transients used in Chapter 15 of the Safety Analysis Report (SAR) are shaped by the PRA sequences. Also, since the SAR is being generated for an old plant, the PRA is being used as a basis for determining the extent and necessity that systems comply with Nuclear Regulatory Commission requirements.

The PRA was used to make specific design changes during the restart of the HFIR. Examples of these are discussed below:

1. The most comprehensive change was the use of a PRA methodology to identify and eliminate the contributors to flow blockage.
2. The PRA was used to justify the need to refurbish the primary pumps in which bearings, seals, and shafts were replaced prior to restart.
3. A high bearing temperature trip was added to the primary pump to prevent bearing damage due to a possible loss of bearing cooling following a reactor scram.
4. A technical specification surveillance of the pool to vessel check valve was initiated after its importance during a loss of coolant accident was identified in the PRA.
5. Comparative risk arguments based on PRA results led to a decision to reverse the failure mode of the recently added emergency depressurization valves in the event of a loss of power or instrument air.
6. The need for the auxiliary emergency power generators (AEPGs) was identified as part of the re-analysis of long-term decay heat removal, the placement, number and, process for implementing their use were dictated by external event PRA issues.
7. Two design seismic upgrades were driven by the PRA. These involved the venting of the pony motor battery room to accommodate a tornado depressurization event and the addition of a check valve in the pool cleanup system to prevent loss of pool water in the event of a seismic event.

CONCLUSION

It is anticipated that in the future the PRA will provide input into technical specifications and limiting conditions for operation. The PRA has been and continues to be a valuable tool in the operation, design upgrade, and safety assessment of the HFIR. The PRA used in risk-based management has also been invaluable in managing the many issues associated with upgrading the facility.

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