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《Review》

A Post-TMI Lookat Boiling Water Reactor Plant Protection

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A General Electric evaluation of its current Boiling Water Reactor design, BWR/6, concludes that this nuclear system is highly resistant to plant damage or significant offsite radiological releases resulting from not only "TMI-type" events, but also from a broad spectrum of degraded events ranging from transient events with no pipe break to large pipe break accidents. BWR/6 post-TMI design improvements are described as well as BWR/6 features which respond to longer term design trends emerging in the aftermath of Three Mile Island.

Introduction

This paper presents the results of a General Electric evaluation of the Boiling Water Reactor performed following the March 1979 accident at the Three Mile Island (TMI) nuclear plant.

The objective of this evaluation was to assess the BWR capability to protect both the plant capital investment and the public health and safety by preventing or terminating potential accident sequences. Primary consideration is given to the performance and reliability of BWR core cooling and containment systems, and to the demands on the plant operator during emergency situations. The evaluation includes both the BWR response to the specific complications which occurred at TMI, and an assessment of BWR plant protection features in light of the broader lessons learned at TMI.

BWR design improvements since TMI are discussed as well as the potential impact of longer term post-TMI design trends on the BWR.

For consistency, this paper is restricted to the current GE BWR/6 standard plant design being offered for future construction. Many of the conclusions, however, are also valid for earlier GE BWRs.

Summary and Conclusions

The BWR/6 is highly resistant to plant damage or significant off-site radiological releases resulting from not only "TMI-type" events, but also from a broad spectrum of degraded events ranging from transient events with no pipe break to large pipe break accidents. The BWR/6 features which provide this protection are:

- Thirteen high-and low-pressure pumps which provide makeup water to the reactor vessel
- Rapid depressurization capability which can be used to make both high-and low-pressure pumps available to maintain reactor water level for any potential accident sequence
- Natural circulation internal to the reactor vessel which provides passive core cooling as long as vessel water inventory is maintained

Two top-entry spray systems which provide cooling, even if reactor vessel water inventory is depleted

Reactor water level measurement directly on the reactor vessel to provide a reliable basis for automatic and manual initiation of plant protection systems

Operation in the boiling mode familiar to plant operators under both normal and emergency operating conditions

A common operator response, based on symptoms rather than event diagnosis, to all reactor water inventory threatening events

Capability to vent noncondensible gases from the reactor vessel if necessary

A large suppression pool heat sink inside the containment which can accept decay heat for up to six hours with the reactor vessel isolated

Suppression pool "scrubbing" of fission products from safety/relif valve and loss-of-coolant accident discharges from the primary system

- Secondary containment with leakage filtration to provide an additional barrier against potential off-site radiological release

BWR/6 post-TMI product improvements are being implemented or considered in the areas of operator emergency guidelines, post-accident monitoring features, further auto-initiation of plant protection systems, and manmachine interface in the control room. These improvements do not represent a significant impact on BWR/6 design. In addition, the BWR/6 design already incorporates many features which respond to the longer term design trends which are emerging in the aftermath of TMI.

BWR/6 Description

The direct cycle BWR/6, coupled with a

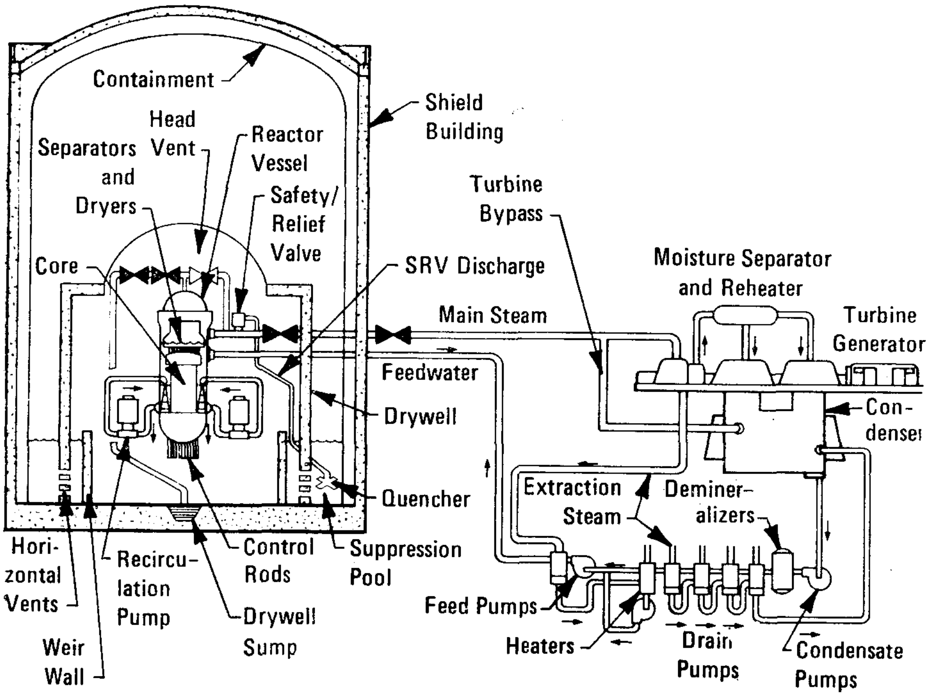

Figure 1. Direct Cycle BWR Nuclear System

reference Mark III pressure suppression containment, is shown in Figure 1. Steam is generated in the reactor and carried directly to the turbine while the feedwater system returns water directly to the reactor. Pressure relief is through safety/relief valves piped directly to the suppression pool. This self-contained pool acts as a massive quench tank for the steam releases during transients and provides both a heat sink and source of water for reactor core cooling during a loss-of-coolant accident. The containment system includes primary and secondary fission product barriers and provides filtration of any primary containment bypass leakage.

Response to "TMI-Type" Events

The TMI accident was a small break loss-of-coolant accident which was not recognized by the plant operators. It was the result of a series of complications—equipment failures and operator errors—which combined to produce severe damage to the plant. The major complications encoun tered at TMI and BWR/6 features which would prevent or accommodate each complication are:

- **Loss of Heat Sink**—The TMI accident began with a loss of feedwater and unavailability of auxiliary feedwater which combined to isolate the reactor from its heat sink. The Mark III containment has a large suppression pool heat sink inside the containment which can store decay heat for approximately six hours with the reactor isolated from its normal heat sink.
- **Stuck-Open Relief Valve**—The TMI event became a small break loss-of-coolant accident when a poweroperated primary relief valve stuck open, leading to overpressurization of its quench tank, discharge of primary system water to the containment, and activation of emergency core cooling systems. BWR/6 relief valves are piped to the suppression pool which is sized to handle a full blowdown of the primary system within normal operating limits. The containment is not pressurized by this blowdown and normal makeup systems maintain reactor water level without initiation of emergency core cooling systems. The BWR/6 response to a stuck-open relief valve is a minor transient.
- **Reactor Water Level**—The TMI operators were misled about reactor water level by indirect and ambiguous measurement on the pressurizer. Water level in BWR/6 is measured directly on the reactor vessel.
- **Boiling in the Core**—The TMI operators did not recognize and therefore did not respond promptly to the existence of boiling in the reactor. Boiling is the normal mode of BWR operation.
- **Noncondensible Gases**—The noncondensible gases trapped in the TMI reactor vessel could not be vented. The BWR/6 vessel can be vented either through the safety/relief valves or a vessel dome ventline (Figure 1).
- **Natural Circulation**—Natural circulation at TMI was interrupted by voids resulting from boiling and/or non-condensible gases trapped in the primary system. Strong natural circulation internal to the reactor vessel is an inherent feature of the BWR/6. The natural circulation path is independent of any piping integrity or valve alignment conditions.
- **Depressurization**—The TMI reactor was

maintained partially pressurized following the accident because of concern over boiling in the reactor and possible core uncovery due to expansion of the noncondensible gas bubble. Since BWR/6 is designed for boiling and has provisions for venting of noncondensible gases, it can be safely depressurized during an emergency. Rapid depressurization capability, through the relief valves to the suppression pool with both automatic and manual initiation capability, is provided.

- **Cooling of Uncovered Core**—Partial uncovering of the core at TMI led to inadequate core cooling and resulting core damage. Steam cooling in the lower power density BWR/6 core would provide effective cooling of a partially uncovered core. In addition, BWR/6 is designed with two top entry core spray systems which can provide core colling even if the core becomes completely uncovered.
- **Radiation Release**—TMI released radiation to the environment because of incomplete containment isolation and containment bypass leakage. The Mark 111 primary containment isolates when emergency core cooling systems initiate. In addition, the Mark 111 containment provides suppression pool "scrubbing" of potential fission product releases, and secondary containment with engineered safeguard leakage filtration systems.

These comparisons demonstrate the capability of BWR/6 to prevent or accommodate each of the maior complications encountered at TMI and lead to the conclusion that BWR/6 is highly resistant to this type of event.

BWR/6 has been reevaluated since TMI not only for "TMI-type" events, but also for a broad spectrum of degraded events ranging from non-break transients to large break accidents. The results have shown certain BWR/6 plant protection features to be highly effective for many events in protecting both the plant capital investment and the public health and safety. The following three sections identify the BWR/6 core cooling, containment, and emergency operation features which provide this high degree of protection.

BWR/6 Core Protection

Systems to Supply Water to Core

The key to adequate core cooling in a BWR is maintenance of water inventory in the reactor vessel. If adequate water inventory is maintained, passive natural circulation and boiling heat removal mechanisms will remove decay heat to main condenser or suppression pool heat sinks.

Figure 2 summarizes the BWR/6 capability to supply water to the core. The BWR/6 operates at a relatively low reactor vessel pressure of 7170kPa (1040psi). Four high-pressure and two low-pressure systems, comprising 13 pumps and 29×10^6 W (39,000 horsepower) of pumping capacity, are available to supply water to the core. Eleven of these pumps have sufficient capacity to individually provide sufficient makeup water for decay heat removal and inventory maintenance in a nonbreak event.

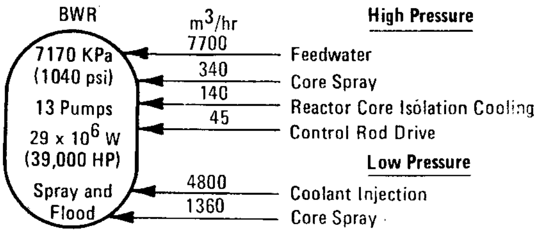

Figure 2. Systems to Supply Water to BWR/6 Core

The BWR/6 systems include the capability to spray the core from above and refill it from below at both high and low pressure. The diverse and redundant water supply capability to the BWR/6 reactor vessel is partly due to the direct cycle BWR design in which normal pumping systems(feedwate, r, control rod drive cooling, and reactor core isolation cooling) provide makeup water to the reactor vessel.

Natural Circulation

Strong natural circulation (Figure 3) ensures decay heat removal in BWR/6 provided that reactor water inventory is maintained. The natural circulation is internal to the reactor vessel and independent of any piping integrity or valve alignment considerations. It is strengthened by boiling in the reactor core. Because of strong natural circulation, a covered core is a cooled core in BWR/6.

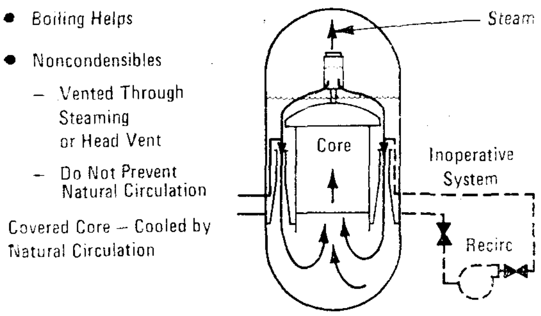

Figure 3. BWR/6 Natural Circulation

Water Level Measurement

Consistent with its central importance to core cooling in BWR/6, reactor water level is measured directly on the reactor vessel (Figure 4). Redundant differential pressure cells perform continuous measurement of reactor water level above the core and provide redundant indications of water level within the plant operator's view in the control room. Direct measurement of reactor water level provides a reliable basis for automatic and manual initiation of plant protection systems.

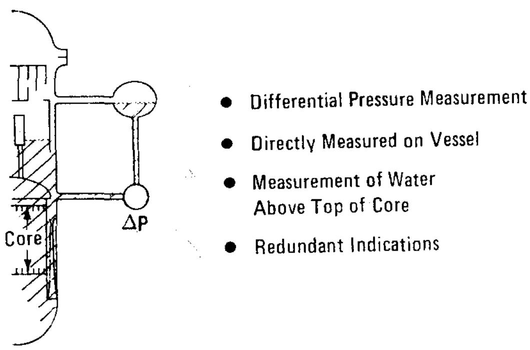

Figure 4. Water Level Measurement

Depressurization

The BWR/6 reactor can be rapidly depressurized through turbine bypass valves to the main condenser or through the safety/relief valves to the suppression pool (Figure 1). If necessary, full depressurization of the primary system can be achieved within approximately five minutes. Once the vessel is depressurized, additional water sources are available to supply water to the core. The large number of reactor water makeup pumps, coupled with the ability to rapidly depressurize and make all pumps available for all events, provides highly effective core protection for the BWR/6.

Mark III Pressure Suppression Containment

Passive Heat Sink

The large suppression pool heat sink in the Mark III containment performs a key role in mitigation of both transient and accident events. Figure 5 summarizes the role of the suppression pool(Figure 1) in quenching safety relief valve discharges and in providing a heat sink for primary system energy during a loss-of-coolant accident.

The primary system energy stored in the fluid and metal in the BWR/6 is approximately 470×10^9 Joules (450 million Btu). For safety/relief valve discharges, the Mark III suppression pool is sized to contain 520×10^9 Joules(490 million Btu) before exceeding the 66°C(150°F) normal temperature limit. This large in-containment heat sink can be used to store decay heat for approximately six hours with the reactor isolated, or can be used to rapidly depressurize the primary system if necessary to make lowpressure water sources availabl to the reactor vessel. The BWR/6 reactor depressurization capability and the capability of the Mark III suppression pool to accept the depressurization energy represent an important complementary relationship between the BWR/6 reactor and Mark III pressure suppression containment.

For a loss-of-coolant accident, the Mark III suppression pool is sized to contain 810 $\times10^9$ Joules (770 million Btu) before exceeding the 85°C(185°F) qualification limit for emergency conditions. Since the primary system energy is only 470×10^9 Joules(450 million Btu), it is clear that the Mark III containment has more than sufficient passive heat sink capacity to accommodate its contained energy sources. The 340×10^9 Joules(320 million Btu) margin provides the operator with ample time to establish active containment cooling following a loss-of-coolant accident.

Fission Product Control

The Mark III containment contains a number of features for control of potential fission product releases. Major ones are:

- Suppression Pool
- Containment Sprays
- Bypass Leakage Control
- Secondary Containment
- Leakage Filtration

The effectiveness of these features in control of noble gas, halogen and particulate fission products is summarized below.

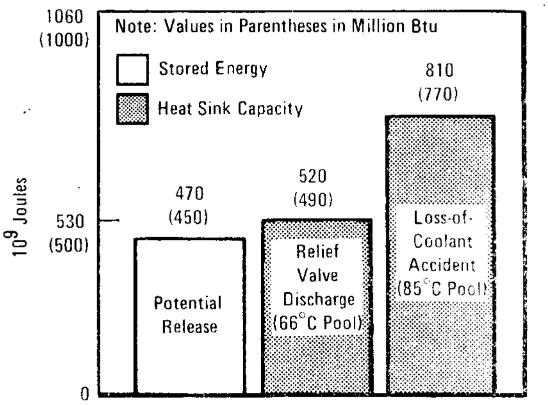

Figure 5. Comparison of Stored Energy to Suppression Pool Heat Sink Capacity in Mark III Containment

Noble Gases

Table 1 summarizes the performance of the BWR pressure suppression containment in the control of noble gases based on a hypothetical core melt source. For a given fuel failure mode, the release of noble gases to the environment depends primarily on the containment leakage rate. An attainable Mark III containment leak rate is 0.1 % per day, (For BWR operator convenience, the allowable is typically 10 times that level).

The suppression pool delays release of the noble gases into primary containment air providing a reduction factor of 1×10^{-1} to 1 in the noble gas site boundary dose. Secondary containment holdup and dilution

Table 1. Retention of Fission Products by the Mark III Containment

	Noble Gases		Halogens and Particulates	
	Regulatory Basis	Realistic Basis	Regulatory Basis	Realistic Basis
Source Term		Core Melt (NRC Regulatory Guide 1.3)		
Atmospheric Dispersion (sec/m^3) (a)	2×10^{-3}	2×10^{-3}	2×10^{-3}	2×10^{-3}
Primary Containment Leak Rate (%/day)	1×10^{-1}	1×10^{-1}	1×10^{-1}	1×10^{-1}
Reduction or Removal Factors				
Suppression Pool	1	1×10^{-1} to 1	1	1×10^{-2} (b)
Containment Spray	—	—	5×10^{-1}	1 (c)
Secondary Containment	1×10^{-1}	1×10^{-1}	2.5×10^{-1}	2.5×10^{-1}
Leakage Fitration	—	—	1×10^{-2}	1×10^{-3}
Total Reduction or Removal Factors	1×10^{-1}	1×10^{-2} to 1×10^{-1}	1.25×10^{-3}	2.5×10^{-6}
Two-Hour Whole Body Dose (rem)	2	2×10^{-1} to 2	—	—
NRC Whole Body Dose Limit (rem)	20	20	—	—
Two-Hour Whole Body Dose (% of NRC Limit)	10	1 to 10	—	—
Two-Hour Inhalation Dose (rem)	—	—	4	8×10^{-3}
NRC Two-Hour Inhalation Dose Limit (rem)	—	—	150	150
Inhalation Dose (% of NRC Limit)	—	—	3	5×10^{-3}

[a] All BWR sites licensed to date have more favorable meteorology than 2×10^{-3}.

[b] The apparent removal factor observed at TMI is 1×10^{-4}.

[c] Credit for both containment spray and suppression pool not assumed.

provides an additional reduction factor of 1×10^{-1}.

Thus, the effective total reduction factor for noble gases in the BWR pressure suppression containment is between 1×10^{-2} to 1×10^{-1}. This results in a realistic off-site whole body dose of 1 to 10% of the 20-rem NRC regulatory limit even assuming core melt source terms (Regulatory Guide 1.3) and very conservative meteorological conditions. Using conservative NRC regulatory basis assumptions, the calculated off-site dose is still only 10% of the regulatory limit.

Halogens and Particulates

Table 1 also summarizes the performance of the BWR pressure suppression containment in control of halogens and particulates based on a hypothetical core melt source.

The drywell encloses the reactor coolant pressure boundary and channels any released steam-air mixture into the suppression pool. The suppression pool "scrubs" the primary coolant system releases, thereby reducing halogen and particulate releases by a factor of 1×10^{-2}.

Any particulates or halogens that pass through the suppression pool or leak from the drywell are contained in the primary containment volume where the containment spray could remove an additional 50% of the halogens and particulates.

Leakage from the primary containment is trapped within the secondary containment (maintained at negative pressure) where holdup and dilution provides an additional removal factor of 2.5×10^{-1}. The secondary containment volume is then filtered before discharge to the environment, providing yet another removal factor of 1×10^{-3}.

Thus, the total removal factor for halogens and particulate fission products in the BWR pressure suppression containment is

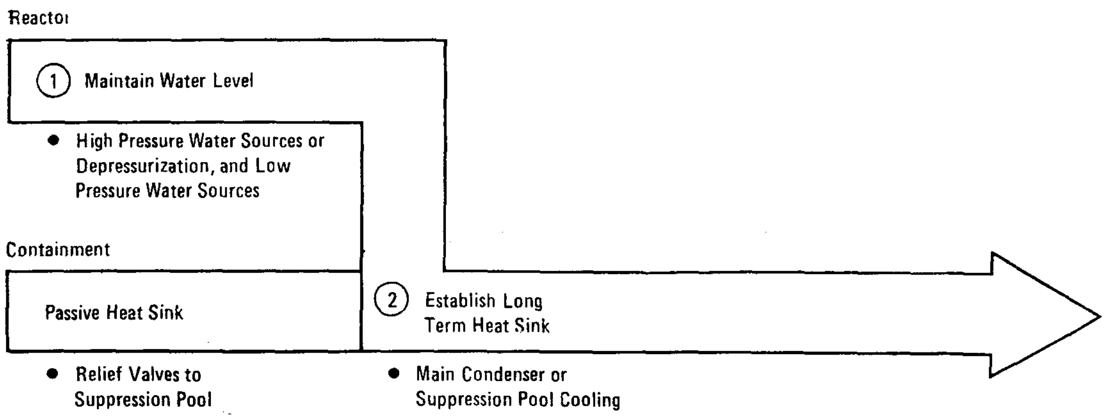

Figure 6. BWR/6 Operator Response to All Inventory Threatening Events

approximately 2.5×10^{-6}, yielding a realistic off-site inhalation dose of less than 0.005% of the 150-rem NRC regulatory limit even assuming core melt source terms (Regulatory Guide 1.3) and very conservative meteorological conditions. Using conservative NRC regulatory basis assumptions, the calculated off-site dose is still only 3% of the regulatory limit.

In summary, the Mark III containment fission product control features are engineered to hold potential off-site releases to values well below regulatory limits.

BWR/6 Emergency Operation

The direct cycle BWR/6 exhibits a number of features which facilitate emergency operation. The system is inherently simple—one loop with one vessel and direct water level measurement. This enables the operator to concentrate his attention during an emergency on the primary objective of maintaining reactor water level. In addition, operation of a BWR/6 during an emergency has important similarities to normal operation. These include use of normal pumping systems (feedwater, control rod drive cooling, reactor core isolation cooling) as the first line of defense, and emergency operation in the boiling mode familiar to plant operators.

The operator response is the same for all inventory-threatening events in BWR/6. This two-part response (Figure 6) consists of:

- First—Maintaining reactor water level. This may be done using high-pressure water sources, or through depressurization and use of low-pressure sources. During the period the operator's attention is concentrated on maintaining water level, decay heat is passively rejected to the suppression pool through the relief valves.
- Second—Establishing a long-term heat sink after the reactor water level is stabilized. This is done by reestablishing the main condenser heat sink, or initiating suppression pool cooling.

This common operator response to all inventory threatening events has made it possible to develop a set of BWR Operator Emergency Procedure Guidelines which are based on "symptoms" rather than "events."

The development of these guidelines has been a joint effort of BWR owners and GE since TMI. To date, the guidelines cover GE plants up to the BWR/5 product line. They will be extended to BWR/6 in the near future. Figure 7 summarizes the structure of these guidelines. Three guidelines covering reactor water level control, achieving cold shut-down, and containment cooling are sufficient for all inventory threatening events. Each guideline has defined symptoms for entry and provides preferred and prioritized backup means for performing each function. Contingency guidelines are provided and referenced for highly degraded situations.

The inherent simplicity, similarities between emergency and normal operation, and "symptomatic" emergency guidelines combine to minimize the chance of operator error in BWR/6.

BWR/6 Improvements Since TMI

The TMI accident focused the nuclear industry's attention on a number of areas where improvements were needed to enhance the safety of LWRs and provide greater protection of the utilities' investment. The NRC has now required implementation of these improvements. General Electric has initiated programs in response to the NRC requirements, and the resulting improvements will even further enhance the BWR/6 plant protection capability. Several significant improvements which are being required of all nuclear power plants are:

- Improved Emergency Procedure Guidelines—To provide plant operators with concise procedures to follow during an emergency.
- Improved Safety/Relief Valve Position Indication—To provide a faster, more direct indication of an open valve to the plant operator for appropriate action.
- Improved Post-Accident Sampling Capability—Provisions for obtaining a post-accident "grab sample" of reactor water and containment air at an accessible location to facilitate assessments of core damage.
- Improved Containment Instrumentation—To monitor containment pressure and radiation level and suppression pool water level following an accident.
- Improved Effluent Monitors—To provide capability to monitor plant effluents over

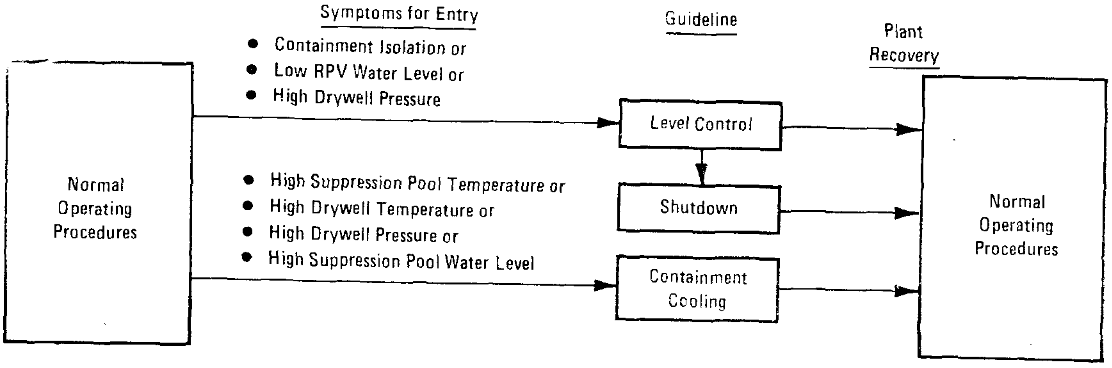

Figure 7. Structure of "Symptomatic" BWR Emergency Procedure Guidelines for Inventory Threatening Events

full range from normal to accident conditions.

- Control Room Improvements—To provide an improved man-machine interface in the control room and facilities for responding to an emergency. Examples of improvements under consideration include: (1) a Plant Safety Parameter Display to provide key plant safety parameters in a clear, concise format; (2) an on-site Emergency Response Center for coordination of emergency response; and (3) a Nuclear Data Link to provide key plant safety information to the U.S. Nuclear Regulatory Commission.

Two other areas are specific to BWR design and response to a TMI-type event:

- Auto-Restart of High-Pressure Core Spray —To provide automatic restart at low reactor level in the event the operator takes manual control of the system and subsequently fails to maintain water level.
- Auto-Depressurization for Non-break Events—To provide automatic depressurization logic for non-break events (e.g., loss of feedwater) accompanied by failure of all high-pressure cooling systems.

Reliability Analyses

Reliability analyses of BWR/6 have been performed since TMI to confirm the capability of BWR/6-Mark III design to protect both the plant capital investment and the public health and safety by preventing or terminating potential accident sequences. Probabilities of occurrence of potential accident sequences that could lead to significant core damage and radiological release are very small—in fact, significantly lower than those presented in WASH-1400.[1]

Event trees were used to define and describe accident event sequences and to produce a model for calculating event sequence probabilities. Fault trees were used to analyze core cooling and containment systems and to calculate the system reliabilities used in the event tree models. The event and fault tree models consider common mode and common cause failures as well as human error.

The equipment failure rates and initating event frequencies used in the event and fault tree models are mean values based on current BWR/2, 3, and 4 operating experience. Where BWR/6 equipment is significantly different than BWR/2, 3, and 4 equipment, suitable modifications were made to the failure rate data based on an evaluation of changes in failure modes and their probabilities due to identified design differences. Important BWR/6-Mark III design features and performance characteristics based on design changes and operating experience that were not in the WASH-1400 analysis, but which are included in the present analysis, are as follows:

- Recent analyses show that the BWR/6 feedwater and control rod drive cooling systems are capable of maintaining reactor water level during many more transient and accident events than credited in WASH-1400.
- BWR/6 has a high-pressure core spray system with a dedicated diesel power supply to improve water delivery reliability to the reactor core independent of reactor pressure.
- BWR/6 automatic depressurization system logic is being extended to encompass "non-break" events.
- Product improvement changes are in progress to provide the BWR/6-Mark III standard plant with more assured capability to maintain core cooling during loss

of suppression pool cooling events, to prevent such events from leading to core damage. This can be accomplished by allowing the suppression pool to boil and venting the containment to prevent overpressure.

BWR/6 emergency core cooling systems are already capable of such operation.

- An anticipated transient without scram mitigation system will be added to BWR /6 in response to NRC requirements. The present analysis credits this system with the following major fetures:

—Alternate rod injection utilizing diverse sensors and logic

—Automated recirculation pump trip

—Automated feedwater runback

—Automated 86 gpm liquid boron injection

A comprehensive evaluation of BWR plant operating experience and design and licensing basis transient events was conducted to identify all possible event sequences that could lead to significant core or containment damage. From this evaluation, the transients were organized into "consolidated events" that could be represented by a single event tree. The consolidated events and their frequencies, based on experience where possible and analysis otherwise, are shown in Figure 8.

The final results of the event/fault tree analysis, shown in Figure 9, are compared with comparable results derived from WASH-1400. Based on these results, it is concluded that the public risk associated with the BWR/6-Mark III design is significantly less than that shown in WASH-1400. In examining the results of Figure 9, it is important to observe that no single accident sequence probability dominates the total probability of core damage. This result indicates that the design is balanced and optimized from a reliabiltiy viewpoint.

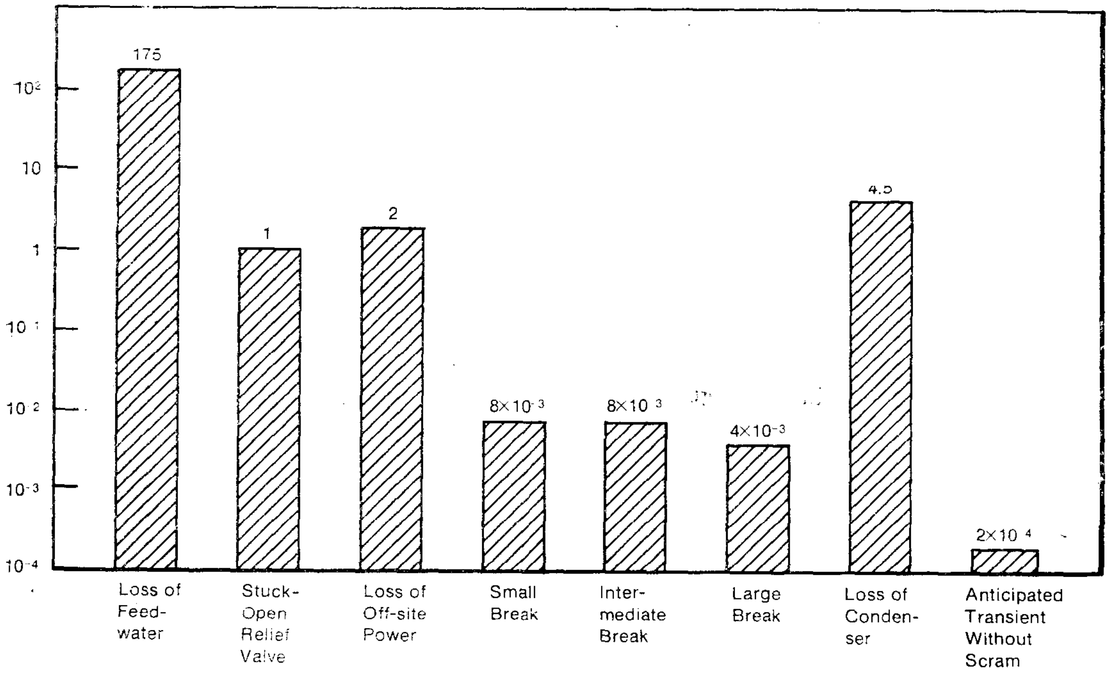

Figure 8. BWR/6 Event Frequencies (40 Years)

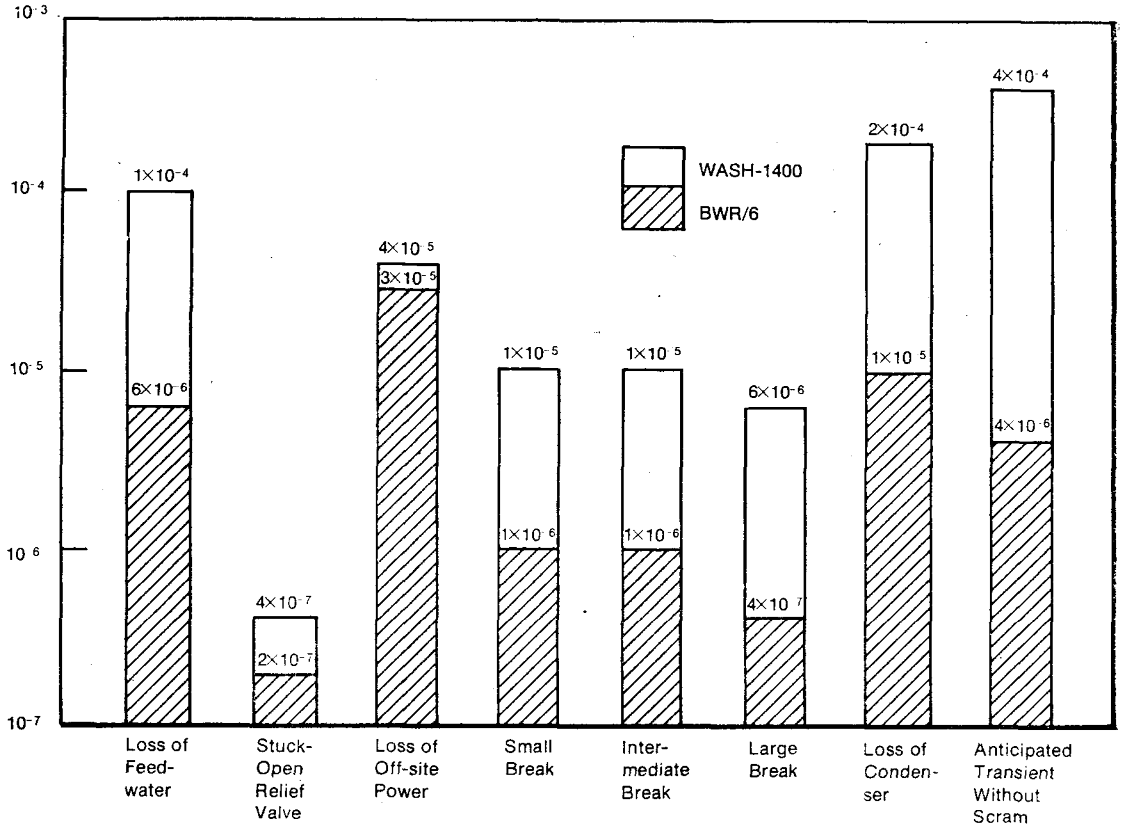

Figure 9. BWR/6 Probability of Core Damage (40 Years)

Trend	**Responsive BWR Features**
Design emphasis on more probable events • Non- and Small Break Accidents • Multiple Failures • Operator Error	Numerous primary pumps Core spray and flood capability Depressurization capability Large containment heat sink Simple emergency operation
Design for boiling during emergencies	Current practice
Improved operator interface	Simple emergency operation Nuclenet™ control console employing cathode ray tube displays
Consideration of degraded core accidents	In-depth core protection Low power density Suppression pool Secondary containment

Post-TMI Design Trends

Numerous studies of the TMI accident have been performed in an effort to determine the lessons learned and prevent reoccurrence. These have included the Kemeny[2] and Rogovin[3] reports, as well as the U.S. Nuclear Regulatory Commission's short- and long-term TMI Lessons Learned Reports.[4,5] Out of these and other studies of the TMI accident, certain "post-TMI design trends" are beginning to take shape. These trends and the BWR/6 features responsive to each are:

It is clear that the BWR/6 already incorporates many features which respond to the long-term post-TMI design trends.

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