07/96

U.S. Nuclear Regulatory Commission Information and Analyses

Edited by D. E. Hickman

Assessment of Spent Fuel Cooling

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Abstract: *This article presents the methodology, findings, and conclusions of a study conducted by the U.S. Nuclear Regulatory Commission's Office for Analysis and Evaluation of Operational Data (AEOD) on loss of spent fuel pool (SFP) cooling. The study involved an examination of SFP designs, operating experience, operating practices, and procedures. AEOD's work was augmented in the area of statistics and probabilistic risk assessment by experts from the Idaho National Engineering Laboratory. Operating experience was integrated into a probabilistic risk assessment to gain insight on the risks from SFPs.*

SUMMARY

As directed by the Executive Director for Operations, the Office for Analysis and Evaluation of Operational Data (AEOD) performed an indepe..dent assessment of the likelihood and consequences of an extended loss of spent fuel pool (SFP) cooling. The overall conclusions are that the typical plant may need improvements in SFP instrumentation, operator procedures and training, and configuration control.

Six site visits were conducted to gain an understanding of the licensees' SFP physical configuration, practices, and operating procedures. The assessment found great variation in the designs and capabilities of SFPs and systems at individual nuclear plants.

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In November 1992, two contractors working at the Susquehanna Steam Electric Station submitted a defects and noncompliance report on the Susquehanna SFP to the U.S. Nuclear Regulatory Commission (NRC). The contractors were interviewed by AEOD to gain a better understanding of their concerns. Their report, which has potential generic implications, provided the impetus for the NRC and the nuclear industry to take a closer look at the SFPs.

AEOD reviewed the applicable SFP regulations and the NRC Standard Review Plan (SRP) for the acceptance criteria and the applicable Regulatory Guides. Because of the evolution of the criteria and the different times that reactors were licensed, the criteria to evaluate the SFP designs vary among the operating facilities.

AEOD performed independent assessments of the electrical systems, instrumentation, heat loads, and radiation. These assessments were used to determine the typical SFP configurations and potential problems.

With the use of a previous Susquehanna risk analysis, Idaho National Engineering Laboratory (INEL) performed model refinements that resulted in better estimates of near-boiling frequencies. No quantitative estimates of core damage were performed, but the analysis provided qualitative insights for identification of improvements in the SFPs to lessen the risk of events.

AEOD's conclusions are:

- Review of more than 12 years of operating experience determined that loss of SFP coolant inventory greater than 1 ft has occurred at a rate of about 1/100

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reactor years (RY). Loss of SFP cooling with a temperature increase greater than 20 °F has occurred at a rate of about 3/1000 RY. The consequences of these actual events have not been severe; however, events have resulted in loss of several feet of SFP coolant level and have gone on in excess of 24 h. The primary cause of these events has been human error.

• Review of existing SFP risk assessments found that, after correction for several problems in the analyses, the relative risk as the result of loss of spent fuel cooling is low in comparison with the risk of events not involving SFP. The review determined that the likelihood and consequences of loss of SFP cooling events are highly dependent on human performance and individual plant design features.

• The need for specific corrective actions should be evaluated for those plants where failures of reactor cavity seal or gate seals or of ineffective antisiphon devices could potentially cause loss of SFP coolant inventory sufficient to uncover the fuel or endanger makeup capability.

• The need for improvements to configuration controls related to the SFP to prevent and/or mitigate SFP loss of inventory events and loss of cooling events should be evaluated on a plant-specific basis.

• The need for plant modifications at some multiunit sites to account for the potential effects of SFP boiling conditions on safe shutdown equipment for the operating unit, particularly during full core off-loads, should be evaluated on a plant-specific basis.

• Efforts by utilities to reduce outage duration have resulted in the occurrence of full core off-loads earlier in outages. This increased fuel pool heat load reduces the time available to recover from a loss of SFP cooling event early in the outage.

• The need for improved procedures and training for control room operators to respond to SFP loss of inventory and SFP loss of cooling events consistent with the time frames over which events can proceed, recognizing the heat load and the possibility of loss of inventory, should be evaluated on a plant-specific basis.

• The need for improvements to instrumentation and power supplies to the SFP equipment to aid correct operator response to SFP events should be evaluated on a plant-specific basis.

BACKGROUND

In recent years there have been several instances in which the adequacy of SFP cooling systems has been brought into question; for example, two contractors at Susquehanna Steam Electric Station plant submitted a Title 10, *Code of Federal Regulations* (10 CFR),[1] Part 21 report[2] on the adequacy of SFP cooling at Susquehanna.

The Susquehanna 10 CFR 21 report[2] postulated that loss of SFP cooling resulted in boiling of the SFP and failure of the emergency core cooling system (ECCS) and other equipment as the result of steam releases and condensation of SFP vapors, reactor core heatup and damage, spent fuel heatup and damage, and large off-site radioactivity releases.

The AEOD study included the following activities:

• Development of generic configurations delineating SFP equipment for a boiling-water reactor (BWR) and a pressurized-water reactor (PWR) and the use of these generic configurations to assess the loss of SFP cooling and inventory.

• Review and assessment of 12 years of operational experience for both domestic reactors and foreign reactors with designs similar to those of the United States.

• Performance of six site visits to gather information on SFP physical configuration, practices, and procedures; conducting interviews with the authors of the 10 CFR 21 report[2] to better understand their concerns.

• Review of applicable SFP regulations and the NRC SRP for the acceptance criteria and applicable Regulatory Guides.

• Performance of independent assessments of electrical systems, instrumentation, heat loads, and radiation to better understand the role of these issues related to loss of SFP cooling.

• Contract with INEL to review existing risk analyses and use risk assessment techniques to evaluate the risk of losing SFP cooling and coolant inventory.

SPENT FUEL COOLING

A survey of SFPs indicates that a wide variety of configurations exists. Because most plants were built before issuance of specific NRC regulatory guidance, diverse designs would be expected. For purposes of this article, loss of spent fuel cooling is considered to include subcategories of loss of SFP coolant inventory and loss of SFP cooling; this convention will be used throughout. Potential problems with SFP coolant inventory and SFP cooling, which can lead to loss of spent fuel cooling, are discussed. The potential consequences of loss of spent fuel cooling are considered. Once the problems have been identified, possible approaches to prevention and response to loss of spent fuel cooling situations are described. Figure 1 shows a "generic" PWR SFP, and Fig. 2 shows a "generic" BWR SFP.

The following discussion considers potential scenarios that can lead to loss of spent fuel cooling as the result of (1) loss of SFP coolant inventory sufficient to interrupt heat transfer to the cooling system or result in uncovery of the fuel and (2) failure of the SFP cooling system pumps and heat exchangers to transfer heat from the pool to the ultimate heat sink. Figure 3 is a schematic classification of the types of events that could lead to loss of spent fuel cooling.

Loss of SFP Coolant Inventory

The primary pathways for loss of SFP coolant inventory can be broadly categorized as (1) loss through connected systems, (2) leakage through movable gates or seals, and (3) leakage through or failure of the fuel pool or the fuel pool liner.

Connected Systems. Piping connected to the SFP may include the SFP cooling and purification system; the spent fuel shipping cask pool and fuel transfer canal drains; and, when in communication with the reactor during refueling operations, reactor piping systems such as the residual heat removal (RHR) system and the chemical and volume control system.

Losses through connected systems could include both pipe breaks or leaks and configuration control problems. Piping systems that extend down into the SFP have the potential to siphon. For most designs, the loss of SFP coolant inventory via the SFP cooling system piping, whether initiated because of a pipe break or configuration control problem, would be limited because of antisiphon devices; however, siphoning can occur if the antisiphon devices are incorrectly designed, plugged, or otherwise fail. A recent survey of all power reactors conducted by the Office of Nuclear Reactor Regulation (NRR)[3] determined that some sites do not have antisiphon devices in potential siphon paths.

During refueling operations, when a flow path exists to the reactor vessel, inventory loss through the RHR, chemical and volume control system, or reactor cavity drains would not be limited by the antisiphon devices; the same applies when the SFP is open to the spent fuel shipping cask pool drains. For these

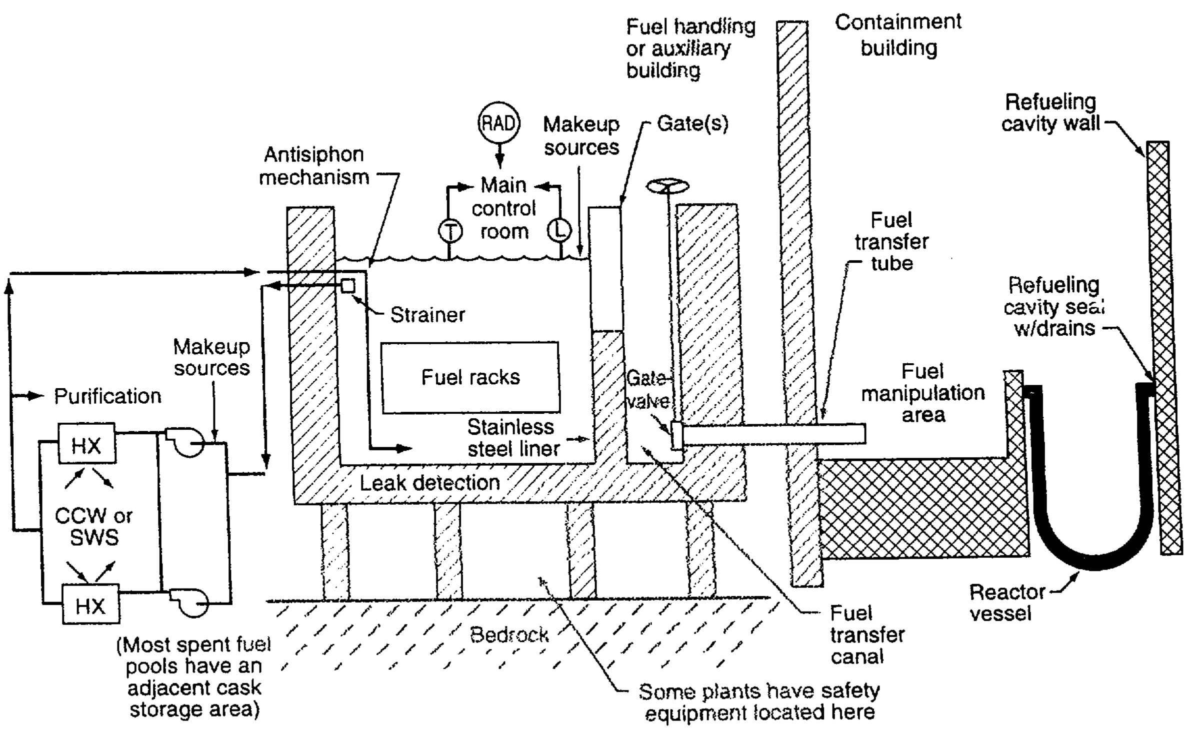

Fig. 1 Pressurized-water-reactor spent fuel cooling systems. HX is heat exchanger, CCW is component cooling water, SWS is service water system, RAD is radiation monitor, T is temperature measurement, and L is level measurement.

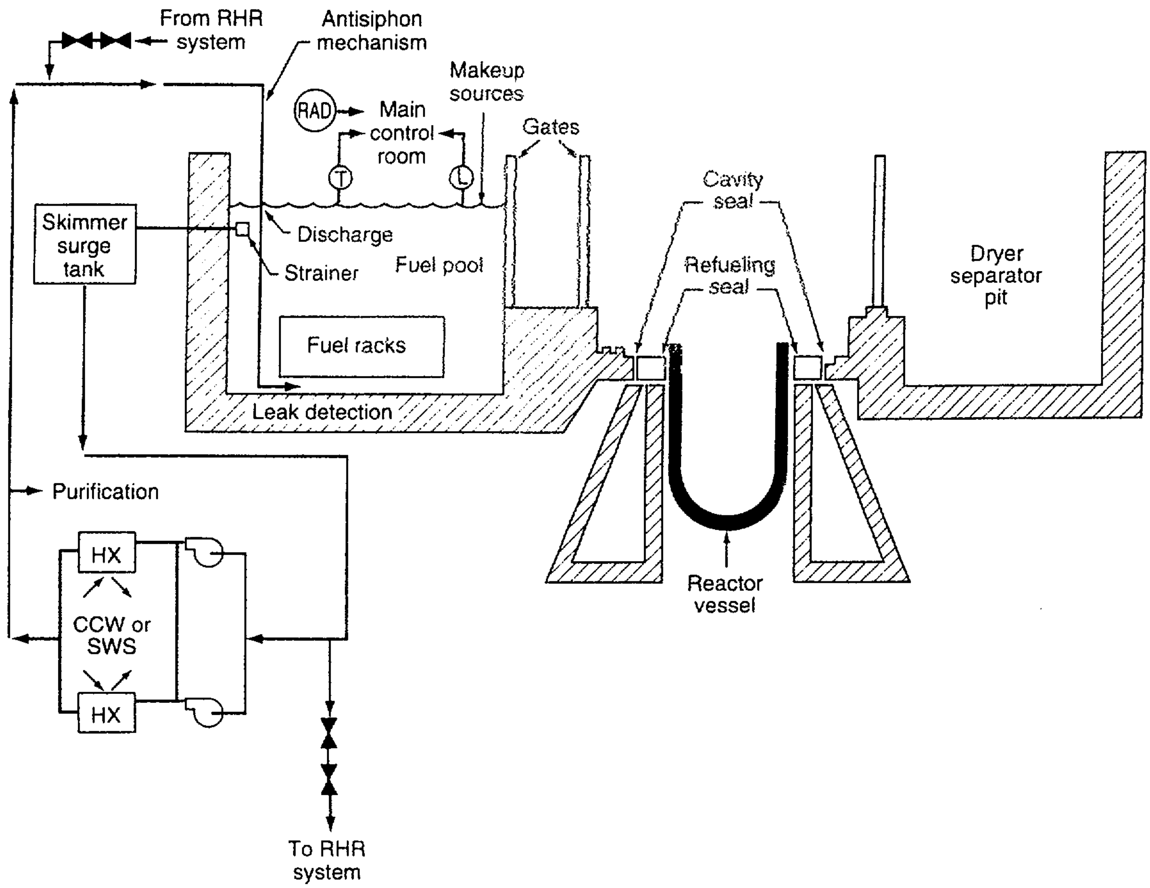

Fig. 2 Boiling-water-reactor spent fuel cooling systems. RHR is residual heat removal, HX is heat exchanger, CCW is component cooling water, SWS is service water system, RAD is radiation monitor, T is temperature measurement, and L is level measurement.

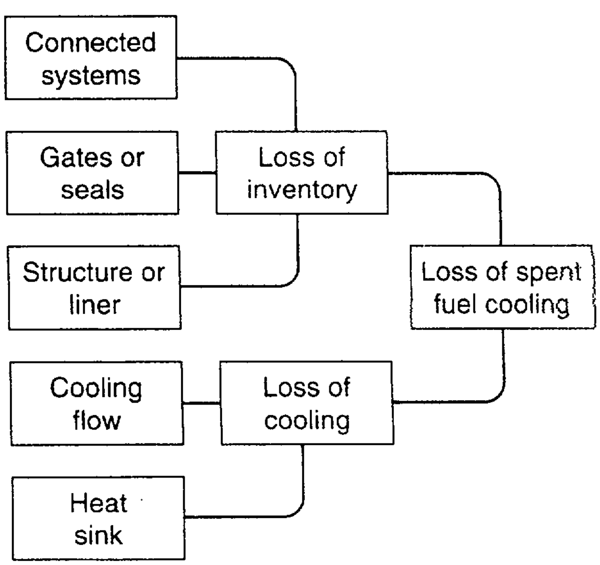

Fig. 3 Schematic classification of the types of events that could lead to loss of spent fuel cooling.

situations, for many designs the extent of the inventory loss is limited by internal weirs or drain path elevations that maintain the level above the top of the stored fuel in the SFP.

Gates and Seals. A second classification of inventory loss is through movable gates or seals and, during refueling operations, the reactor cavity seal. As shown in Figs. 1 and 2, both PWRs and BWRs have seals that keep water above the vessel in the refueling cavity during refueling. For BWRs, two seals are usually required to keep refueling water above the reactor vessel; in Fig. 2 these seals are referred to as the refueling seal and the cavity seal. Some plants use inflatable bladders to form a seal between the reactor vessel flange and the containment building (PWRs) or between the drywell and the reactor building (BWRs). In some BWRs, these cavity seals are permanent spring steel bellows that are expected to have little susceptibility to large leaks. Several other types of seals are used that do not rely on inflatable bladders. These include bolted cavity seal rings that use gaskets to seal between mating surfaces and permanent seals that are welded in place. These types of seals are not prone to rapidly developing large leaks.

The refueling cavity seal and movable gate seals at some plants are inflatable seals of many different designs. Depending on the physical relationship of adjacent structures, catastrophic failure of an inflatable seal could result in rapid loss of inventory; however, the geometry of the relationship between the SFP, adjacent cavities, reactor vessel, and connecting structures must be considered when evaluating the vulnerability to loss of SFP coolant inventory as the result of inflatable seals. Many seal failures will result in only limited level loss because of the various physical configurations.

In BWRs, the bottom of the movable gate separating the reactor cavity from the SFP is generally above the top of the stored fuel; so, for a loss of the cavity seal, the level in the SFP will remain above the top of the fuel. Although the fuel would not immediately be uncovered, SFP cooling would be lost because of tripping of SFP pumps on loss of suction; the remaining SFP coolant inventory would heat up to near boiling within a few hours. Also, because of reduced water level above the fuel, high radiation fields would inhibit access to the refueling floor. Plants that have gate bottoms or internal weirs that limit the draindown from cavity seal or gate seal failures to a level that would continue providing sufficient radiation shielding to not hinder operator actions would be more likely to mitigate these events. When not in refueling, most BWRs have two gates in series at major openings.

Where PWRs do not have interposing structures between the fuel transfer tube and the SFP or where the gates between the SFP fuel transfer canal are left open, a vulnerability to loss of SFP coolant inventory through the fuel transfer tube is increased. The NRR survey assessment found that only five SFPs have fuel transfer tubes that are lower than the top of the stored fuel without interposing structures.

Pool Structure or Liner. Finally, inventory loss could occur directly as the result of SFP liner leakage or gross failure of the SFP structure. The impact of dropping a heavy load or a seismic event are potential causes of gross failure. SFPs are designed to survive seismic events. Radiological and structural response and makeup capability for drops of light loads (those weighing no more than a fuel assembly) are bounded by analyses of a fuel-handling accident. Conversely, drops of heavy loads have the potential to exceed the design basis of the fuel pool structure and the makeup system. Thus heavy load control programs have been instituted to evaluate potential heavy load drops or implement special controls on the design and operation of he... load handling equipment.

Consequences of Loss of SFP Coolant Inventory. For a large loss of SFP coolant inventory, the primary consequence is potential uncovery of the stored fuel. Given the unlikely occurrence of a large leak at the bottom of the SFP structure, beyond the available makeup capacity, the fuel could uncover and heat up to the point of clad damage and release of fission products. The uncovery of the fuel would also result in extremely high radiation fields around the SFP area.

A more likely sequence would be a loss of inventory through a gate or seal that would terminate when the level reached the elevation of the leak. Then, because of the decreased inventory of water in the SFP and the loss of suction to the SFP cooling system, the remaining water in the pool would boil away until the fuel was uncovered. Unless corrective actions are taken, the final consequences would be similar to the loss of SFP coolant inventory described previously.

Loss of SFP coolant inventory events for which corrective actions are taken before the severe consequences described previously have the potential for other problems. Even a minor loss of SFP coolant inventory can lead to loss of SFP cooling because the lower SFP level causes loss of suction to the SFP cooling system. Losses of SFP coolant inventory may produce flooding or environmental problems in other areas of the plant. Ventilation and drain systems can transport water and steam to other parts of the plant and impact emergency equipment. A significant amount of water vapor may be generated either by direct boiling or evaporation from the SFP. Various SFP equipment and ventilation configurations may allow the water vapor to accumulate on SFP cooling equipment and cause it to fail, which would further exacerbate the loss of inventory.

Where the SFP area atmospheric water vapor can be transported to areas that house other equipment important to safety, that equipment may be affected. This potential problem is important in some multiunit sites during and immediately following full core off-loads, where the fuel pool atmospheric water vapor from the unit refueling can be transported to areas housing safety equipment for the unit operating at or near full power. In this situation this transport could cause equipment required for a safe shutdown of the operating unit to be damaged or to fail. This issue is discussed in a later section on risk assessment. Most plants have sufficient flood protection, ventilation, and equipment separation so that this scenario is not a problem. According to the NRR survey assessment, however, eight multiunit sites may be susceptible to this scenario.

Loss of SFP Cooling

Figure 3 also presents potential causes of loss of cooling to the SFP. Cooling can be lost because of loss of SFP cooling flow or because of an ineffective SFP heat sink. Losses of SFP cooling system flow can occur as the result of several mechanisms, including loss of electric power to the SFP cooling pumps, pump failure, loss of suction caused by loss of level, flow blockage, or diversion in the SFP cooling system. Losses of heat sink can occur as the result of operation with less than the required SFP cooling system complement or with heat loads in the SFP in excess of the SFP cooling system design capability.

Loss of SFP Cooling System Flow. All SFP cooling pumps are electrically powered. Loss of electric power to these pumps results in loss of SFP cooling system flow. Loss of electric power can occur because of losses of off-site power (LOOPs) or human error in electrical alignments. Most SFP cooling system pumps can be loaded on available on-site power sources. The NRR survey assessment found that four SFPs did not have the capability to be cooled by systems that could be powered by on-site power sources.

The likelihood of an extended loss of SFP cooling as the result of loss of electric power to the pumps is fairly low because of the combination of available on-site power, the existence of workable procedures for power restoration, the general knowledge of the plant operations staff of the need to restore power, and the time available to restore power.

For other than loss of electric power, failure of both SFP cooling pumps is unlikely. Except for situations in which a full core has been transferred to the SFP relatively soon after plant shutdown, a single SFP cooling pump generally provides sufficient cooling.

Losses of SFP coolant can result in losses of cooling flow when the level drops below the suction intake of the SFP cooling pumps. Thus such losses of inventory will be accompanied by a loss of SFP cooling.

Flow can also be lost because of blockage or diversion; for example, foreign material could clog a filter or strainer in the SFP cooling system. If flow blockage were to occur during a full core off-load, implementation of a backup cooling process might be required to prevent adverse conditions from developing in the SFP.

Ineffective SFP Heat Sink. SFP cooling system heat exchangers are usually cooled by the component cooling water system or the service water system. An ineffective SFP heat sink can occur as the result of misalignment of cooling water sources, failure of the cooling water source, heat exchanger fouling, and insufficient heat exchanger capacity, among others.

Current practice of full core off-loads a short time after shutdown has greatly increased the heat load in the SFP. Any degradation in the heat removal of the cooling system at these times could result in heatup of the SFP. Errors in the calculated heat load or assumption of nonconservative ultimate heat sink temperatures could mislead operators.

Consequences of Loss of SFP Cooling. An extended loss of SFP cooling would result in heatup and boiloff of SFP coolant inventory and eventual uncovery of the stored fuel in the unlikely event that no corrective actions were taken. This would result in high levels of radiation in the SFP area and deny personnel access. Clad failure and radiation release could be the final outcome; however, loss of cooling poses less hazard than loss of inventory because loss of cooling does not pose the immediate threat of fuel uncovery. No fuel damage is likely until the fuel is uncovered.

During an extended loss of SFP cooling, water vapor may be generated either by direct boiling or evaporation from the SFP. Various SFP equipment and ventilation configurations may allow the water vapor to condense and accumulate in locations that could affect other equipment. All the potential impacts that apply to the situation described previously for loss of SFP coolant inventory leading to generation of steam and water vapor, which is transported to other parts of the plant, apply to the extended loss of SFP cooling.

Preventing and Responding to SFP Events

No systems are available for automatic response to a loss of SFP coolant inventory or loss of SFP cooling.

Consequently operator actions form the basis for preventing and responding to a loss of spent fuel cooling.

Preventing a loss of SFP coolant inventory as the result of gate seal failures or cavity seal failures relies on correct installation and testing of the seals and testing and control of the air supply for the inflatable seals. Better seal performance could be achieved by seal replacement at intervals consistent with manufacturers' recommendations or when inspection of seals shows evidence of aging, cracking, or tearing.

The response to loss of inventory events depends, first of all, on timely discovery of the event by the operator. The rate of loss of SFP coolant inventory can vary greatly, depending on the cause; for example, water level drop from a reactor cavity seal failure can be quite rapid. The reduction in level during these events is usually discovered either by direct observation by operations staff in the spent fuel area or by alarm actuation in the control room. Reliable and accurate instruments and annunciators can alert the operator to an SFP event. If the operators are aware of an SFP event in a timely manner, the large volume of water in the SFP will usually allow sufficient opportunity for the operators to diagnose and correct the problem.

Response to loss of SFP cooling requires effective instrumentation, procedures, and training. Most operating situations would allow a relatively long time to respond to such an event; however, following a full core off-load, the SFP could heat up to near boiling in a few hours. Operators would attempt to restore cooling either by correcting any problems with the SFP cooling system or by initiating operation of backup cooling systems, if available.

As with prevention and response to SFP coolant inventory events, prevention and response to loss of SFP cooling are also largely dependent on configuration control and human performance. The primary concern is to maintain electric power to the equipment involved in SFP cooling.

OPERATING EXPERIENCE

Operating experience with SFP loss of coolant inventory and loss of cooling was reviewed. The primary source of information was licensee event reports (LERs) from 1984 through early 1996, screened from the Sequence Coding and Search System. In some cases, events before 1984 were included because of sparse data for some types of events. Additional information sources included event notifications made in accordance with 10 CFR 50.72, NRC Inspection Reports, NRC regional morning reports, NRC preliminary notifications, and industry communications. More than 700 separate sources of information were reviewed. This screening process resulted in about 260 events related to SFPs. Table 1 is a summary of these SFP events listing the number of events of each type under the two main categories (loss of SFP coolant inventory and loss of SFP cooling). Table 1 indicates that numerous precursor events were found during the study. These precursor conditions represent potential losses of SFP coolant inventory or loss of SFP cooling given the condition that did occur plus other postulated failures.

The operating events obtained in this study provide a reasonable representation of experience with SFPs. During discussions with operations staff, however, a number of additional events were discovered that provide insights into problems with SFPs. Although these events have been included in this study, they were not initially captured by the study's event review process, primarily because some relevant events are below the reporting threshold required by NRC regulations.

Table 1 Spent Fuel Pool (SFP) Events

Type of event	Actual	Precursor
SFP coolant inventory	**38**	**55**
Connected systems	20	12
Gates and seals	10	8
Structure or liner	8	35
SFP cooling	**56**	**22**
Cooling flow	50	20
Heat sink	6	2

Loss of SFP Coolant Inventory

About 38 events involved actual loss of SFP coolant or refueling water. About 55 other events were precursor events. Table 2 provides details about loss of SFP coolant inventory events. Figures 4 and 5 provide an overview of the SFP loss of coolant inventory events for which level drops and duration times could be quantified. These figures show that SFP losses of coolant inventory have been infrequent. Several events have lasted more than 12 h, however, and about 10 events have resulted in level decreases of more than 1 ft before the event was terminated. The low number of events found with smaller level changes may be due to a lack of reporting of such events.

Table 2 Loss of Spent Fuel Pool Coolant Inventory Events

Type of event	Actual	Precursor
Connected systems	20	12
Configuration control	16	2
Siphoning	3	[illegible]
PWR transfer tube	1	[illegible]
Piping	0	[illegible]
Piping seismic design	0	[illegible]
Gates and seals	10	8
Cavity seals	0	6
Gate seals	10	2
Pool structure or liner	8	35
Liner leaks	7	1
Load drops	1	32
Pool seismic design	0	2

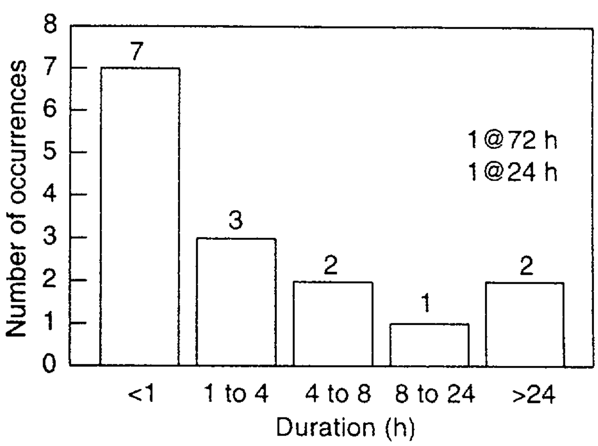

Fig. 4 Loss of spent fuel pool inventory duration.

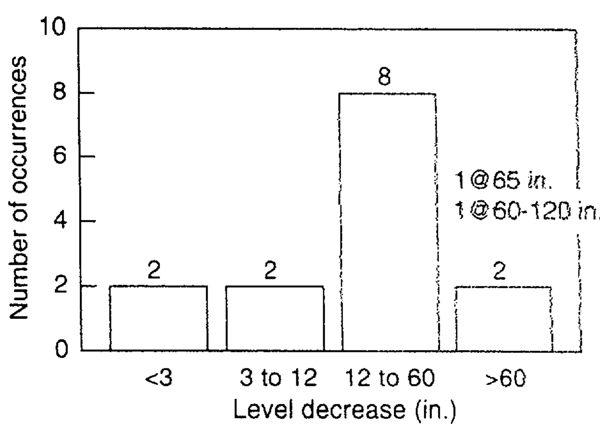

Fig. 5 Loss of spent fuel pool inventory levels.

With the use of the number of events found during this study over a period of about 12 years for which level drops could be quantified, the frequency of loss of inventory events in which loss of more than 1 ft occurred can be estimated to be on the order of 1/100 RY.

Connected Systems. The majority of losses of SFP coolant inventory through connected systems were due to configuration control problems. These connected systems include the SFP cooling and purification system, a spent fuel shipping cask pool, sources of makeup, the fuel transfer tube(s) (in PWRs), the fuel transfer canal (in BWRs), and, during refueling, the reactor.

Configuration control. Sixteen loss of SFP coolant inventory events were due to configuration control errors. These events are about equally distributed between BWRs and PWRs. Two recent configuration control events are described here.

At Cooper Station on October 31, 1995, about 10 000 gal of refueling water was inadvertently lost from the refueling cavity and transferred to the plant's low-level waste system.[4] At the time, the full core had been placed in the SFP, the reactor refueling cavity was filled with refueling water, and the refueling gates were open. A cable from a remote video camera came in contact with and caused a submerged valve to open. Because this valve is part of the main steam line plug, this valve opening allowed refueling water to flow to the main steam line drains. About 30 min after the valve was opened, the SFP surge tank low-level alarm alerted the operations staff to an ongoing loss of water. Although the operations staff started to add water, the makeup was not sufficient to avoid tripping both SFP cooling pumps on low suction pressure. One SFP cooling pump was restarted in about 3 min with no observed increase in SFP temperature. About 40 min later, the source of the inventory loss was identified, and the valve was closed. This event resulted in reduction of about 1 in. in the refueling cavity and SFP. More than 23 ft of water was above the fuel in the SFP. This was a fairly slow drainage rate.

At Millstone Unit 2 on July 6, 1992, about 10 000 gal of SFP water was drained to the reactor coolant system (RCS). At the time of the event, the unit had been shut down for about 37 days, and the full core had been placed in the SFP. A loss of normal power resulted in loss of SFP cooling. During the response to the event, the operations staff decided to align the shutdown cooling system to provide cooling to the SFP. During the alignment process, however, a flow path was created that permitted flow via a gravity drain from the SFP to the RCS. The SFP level dropped about 14 in. On the basis of available reported information, at least 23 ft of water was above the fuel because no Technical Specification violation was reported. A 4 °F temperature rise occurred before SFP cooling was restored.[5]

Siphoning. Although reported operating experience with siphons (both actual events and precursor conditions) is very sparse (three actual events), losses of SFP coolant inventory have occurred because of siphoning problems. One event at River Bend on September 20, 1987,[6] involved plugging of a single (nonredundant) vertical vent pipe acting as an antisiphon device. In this event, the SFP coolant loss caused by siphoning was masked by the SFP low-level annunciator being in the alarm condition as the result of other ongoing plant work. The event lasted about 0.5 h. This event was terminated when a radiation alarm occurred coincident with a high level in the tank receiving the SFP water. This event resulted in loss of SFP level of between 5 and 10 ft, one of the largest level decreases found in the study. Further, it is not clear how far the level would have fallen had no operator action occurred.

In another event at San Onofre Unit 2 on June 22, 1988,[7] about 9 000 gal of SFP coolant drained from the SFP to the reactor cavity through the SFP purification system because of lack of siphon protection in that system. This event lasted about 5.5 h. The licensee stated that this condition would be corrected by providing siphon protection. The licensee determined that the minimum amount of water above the top of the active fuel in the SFP would be about 13 ft if the operations staff failed to respond to two alarms.

Another event at Davis Besse on February 1, 1982,[8] involved a temporary pump used to fill the SFP, which created a siphon path when the pump was secured. In this event, about 21 ft 9 in. of SFP coolant remained above the fuel.

One precursor event was reported in which antisiphon holes in the two SFP cooling return lines were absent, even though 0.5-in. holes were previously thought to exist. Also, further investigation indicated that the 0.5-in. holes would not have been adequate to stop a siphon given postulated failures.

PWR transfer tube. Only one actual event was found in which the transfer tube actually leaked while closed. In this event the SFP end of the transfer tube was open, and the flange on the containment end of the transfer tube leaked. AEOD was informed during some site visits that minor leakage through transfer tubes had occurred.

One site (Oconee Units 1 and 2) has a fuel transfer tube with piping penetrations at a level of 6 ft below the top of the spent fuel in the SFP. This penetration is used during operation of the Oconee Standby Shutdown Facility. This facility has a mission time of 72 h. Water is taken from the SFP through the transfer tube via the penetration and injected into the reactor coolant pump seals for cooling. In this design, continued use of SFP coolant inventory for reactor coolant pump seals could have caused radiation doses in the SFP to reach high levels such that makeup to the SFP would be impossible. This problem has been corrected by adding remote makeup capability to the SFPs.

Piping and piping seismic design. No actual events were found where SFP system piping actually leaked and thus caused a loss of SFP coolant inventory. A variety of seismic piping design problems have been reported, however. The most prevalent type of problem involves use of the nonseismic SFP purification system for purification of the large sources of refueling water in both BWRs and PWRs. Failure of the nonseismic SFP purification system while connected to the refueling water source could cause loss of this source as makeup to the SFP as well as compromise these sources as ECCS sources. In addition, other minor piping seismic design problems were discovered and reported.

Gates and Seals. Large losses of SFP coolant inventory have occurred through SFP gate seals. Also, there is a potential for large losses of SFP coolant inventory through reactor cavity seals.

Refueling cavity seals. At least two rapidly developing leaks have been caused by inflatable reactor cavity seals. In both cases the SFP was isolated from the reactor cavity by the closed fuel transfer tube before the event. At Haddam Neck on August 21, 1984, the seal failed, and about 200 000 gal of water was drained to the containment building in about 20 min. At Surry Unit 1 on May 17, 1988, with all the fuel in the SFP, the seal failed, and about 25 800 gal was drained to the containment in about 0.5 h. In the case of Surry, the instrument air supply to the containment was isolated, and a backup nitrogen supply was used to reinflate the seal. Problems resulted when the inflatable seal deflated enough to result in leakage. Although the SFP was not connected to the reactor cavity in both of these cases, these events and an additional four events discussed later are precursors that indicate the possibility of failure of the cavity seals and consequent loss of inventory. Review of individual plant-specific geometry is required to evaluate each plant's vulnerability to this type of event.

This study found four additional events in which cavity seals failed tests before flooding the refueling cavity or in which leaks developed in the seals following refueling. These events indicate that testing of inflatable seals is important in ensuring their operability. These events further emphasize the need to be aware of potential failures. Most of these events involved design problems. Only one event was caused by failure to maintain an adequate air supply to the inflatable seal. One event involved a gasket-type (noninflatable) seal, which leaked during the draining operation following the refueling.

Gates. The second most prevalent type of loss of SFP coolant inventory (10 events) was leaking fuel pool gates. The majority of these leaks were caused by failure to maintain the air supply to the gate seals. In one case there was a failure to completely inflate the seal. The majority of the air supply events were due to human error. Three of these events involved failed or disconnected level instrumentation, and most of these events occurred at PWRs. Leaks were generally large, involving tens of thousands of gallons of water and two or more feet of SFP level decrease. Level drop rates ranged from fractions of a foot per hour up to several feet per hour. These rates seem a reasonable pace to deal with; in fact, the operations staff responded and restored levels effectively in these events.

One event, at Hatch on December 2, 1986, resulted in the fuel pool level dropping about 5.5 ft.[9] This event resulted from isolating the single air supply to the transfer canal's six gate seals. The seals partially deflated, which resulted in a path for SFP water to go to the gap between the two unit reactor buildings and into areas of both units' reactor buildings. When the source of the leak was discovered, the air source was restored, and the leak was stopped. The event lasted about 24 h, however. During this time the SFP level was low, and makeup was performed several times without attempts to determine the cause. The leak detection alarm was miscalibrated, and a drain valve was left open, which defeated or impaired the ability to detect a leak from the transfer canal gates. Subsequent corrective action included alternate air supplies for alternate gate seals such that inner seals were supplied from one unit and outer seals were supplied from the other unit, and a degree of redundancy was established.

Pool Structure or Liner. No events involving major SFP leakage have been reported; however, some events involved small leaks or potential leaks.

Liner. Seven events involved leaking from the fuel pool liner. These events generally involved relatively small leak rates (less than about 50 gal/day). One event involving small tears in a PWR refueling cavity seal was also reported. The events appear evenly spread out over the review period. Thus operating experience suggests that occurrence of SFP liner leakage is relatively low; however, Salem reported a PWR design problem in which the SFP liner could buckle and leak at temperatures above 180 °F.[10] This site is one that apparently does not have liner drainage isolation capability. Subsequent licensee analysis determined that the liner would not fail. The NRC is currently evaluating the licensee's analysis.

Load drops. Only one event was found during the operating experience review in which the fuel pool liner was punctured by dropping a load into the SFP. This event at Hatch Unit 1 on December 28, 1994, involved a core shroud bolt that was dropped. An approximately 0.7-gal/min leak resulted, which was contained between the fuel pool liner and the concrete structure. The fuel pool level was restored and maintained with normal makeup.[11]

There were no other examples of loads actually being dropped and damaging the SFP; however, many situations (more than 30) involved loads heavier than allowable being moved or potentially moved over the SFP. Less than about 20% of these events involved actual downward motion or drops of objects (usually fuel assemblies) into the SFP. Although not judged safety significant by themselves, these events represent continuing precursors to potential SFP puncture events. They indicate that movement of loads heavier than allowed over the SFP is continuing, even though the NRC has taken steps to reduce the problem.

Pool seismic design. Only two conditions were found that were related to seismic design problems with SFPs. One condition was related to block walls in the fuel-handling building, which could collapse during a seismic event. The walls were replaced. The other condition involved only the fuel racks.

SFP Makeup Capability. Only two events found during the operating experience review involved potential loss of SFP inventory makeup capability. No actual losses of makeup capability were found. One event involved a small accumulation of marine life in the service water pipe used for makeup to the SFP. Had the accumulation of clams gone undetected, it may have blocked the pipe. Another seismic Class I source was available. One event involved a 2-min loss of an electrical bus needed to supply makeup water to the SFP. Operating experience indicates that losses of all makeup capability are not very likely.

Impact on Safety Equipment. Several reported events involved flooding as the result of SFP overflow. These events had the potential to effect equipment in other portions of the plant. In some of the events, actual flooding took place when the SFP overflowed into the ventilation system or the reactor building. None of these flooding events was serious. They were all caused by human error. There were two reports of conditions in which problems within the SFP could potentially lead to failure of important safety equipment. One report of a potential effect on safety equipment as the result of boiling of the SFP was submitted by Susquehanna on November 17, 1992.[12] It describes a condition in which a loss of SFP cooling is postulated to occur subsequent to a design-basis accident such as a loss-of-coolant accident (LOCA) or a LOOP. The design-basis accident is postulated to prevent makeup to the SFP. Subsequent boiling of the SFP is postulated to create an environment that could be transported to safety-related equipment in the reactor building. The LER stated that the postulated events were beyond the plant's design basis. These conditions were postulated in the Susquehanna 10 CFR 21 report and were addressed in a June 1995 letter from the NRC to Pennsylvania Power and Light Company.[13]

The second report was an LER from Washington Nuclear Plant Unit 2, issued May 28, 1993,[14] which describes a circumstance in which, under operating conditions at the time of discovery (local manual service water valve closed), a postulated LOCA would render emergency SFP makeup capability inoperable. Subsequent evaporation of SFP inventory and tripping of SFP cooling pumps were postulated to result in SFP boiling. The evaporated and boiled water is postulated to condense and flood the ECCS pump rooms, which causes failure of ECCS equipment needed to mitigate the ongoing LOCA. The LOCA is postulated to make the local manual SFP makeup valve inaccessible. In this postulated scenario, the normal nonsafety makeup source is also assumed to be unavailable.

Subsequent licensee investigation indicated that the local manual valves in the service water lines for makeup to the SFP could be opened when required after LOCA.

SFP Cooling

Fifty-six events found during the operating experience review involved actual losses of SFP cooling. There were 22 precursor events that, when coupled with additional failures or postulated events, could result in losses of SFP cooling. Table 3 provides a summary of the numbers and types of loss of SFP cooling events. Figures 6 and 7 provide an overview of the loss of SFP cooling events for which temperature increase and duration could be quantified. These figures indicate that the losses of SFP cooling are infrequent. Some events have lasted for significant time periods, however, and four events have resulted in temperature increases of more that 20 °F. The low number of events found with small temperature increases may be due to a lack of reporting of such events.

Table 3 Loss of Spent Fuel Pool (SFP) Cooling Events

Type of event	Actual	Precursor
Cooling flow	**50**	**20**
SFP pumps	39	8
Configuration control	1	0
Loss of pump suction	4	0
Flow blockage	1	0
Single SFP pump failure	5	12
Heat sink	**6**	**2**

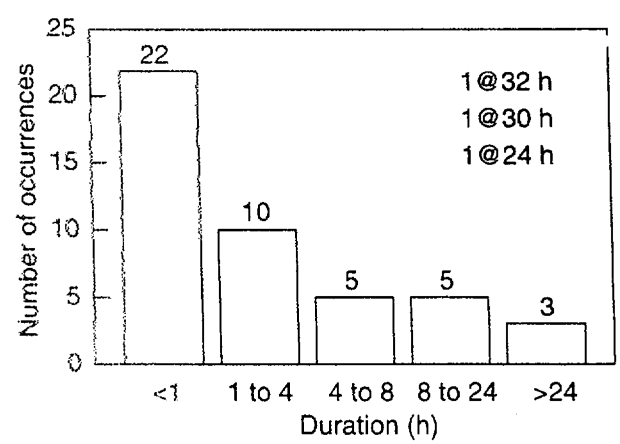

Fig. 6 Loss of spent fuel pool cooling duration.

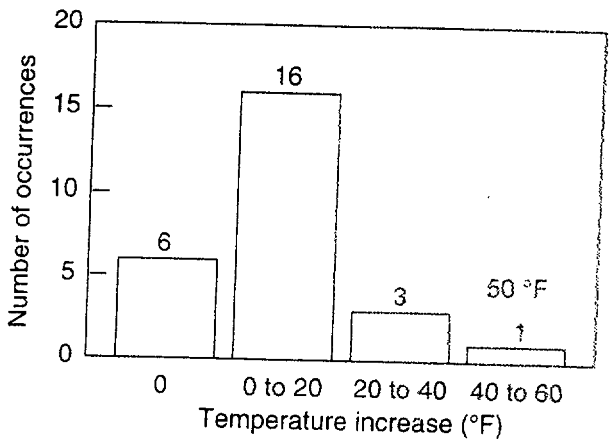

Fig. 7 Loss of spent fuel pool cooling temperatures.

With the use of the number of events found during this study over a period of about 12 years for which temperature and duration could be quantified, the frequency of loss of SFP cooling events in which a temperature increase of more than 20 °F occurred can be estimated to be on the order of about 2 to 3/1000 RY.

Loss of SFP Cooling. The dominant cause of the actual loss of SFP cooling events was loss of electric power to the SFP cooling pumps. Thirty-nine of the loss of cooling events were due to loss of power to the SFP cooling pumps. For these losses of electric power, the time for which cooling was not available ranged from a few minutes with no accompanying temperature increase to 8 h with an associated temperature rise of 20 °F. Most plants have alternate sources of SFP cooling pump power available. No attempt was made during the event review to determine if alternate power was available in each event. The primary causes appear to be human error and administrative problems (22 of the 39 events). The events appear evenly distributed between BWRs and PWRs.

Five events involved failure of one SFP cooling pump, whereas the second pump remained operable. During these events the second SFP cooling pump was adequate to cool the SFP. Because these events did not result in an actual loss of SFP cooling, they are not counted in the overall total for this category. Although events with the potential for common-cause common-mode failure have been reported, none have occurred.

Four events were found in the study in which SFP cooling was lost because of loss of SFP coolant inventory and consequent tripping of the SFP cooling pumps on loss of suction. The only flow blockage event was caused by a rubber boot that blocked an SFP cooling pump strainer. About 6 h was required to remove the blockage. Engineered safety feature actuations have resulted in losses of SFP cooling; however, these resulted in almost no temperature increase and generally lasted for only short periods. They did not appear to have presented a threat to long-term cooling.

No actual events involving insufficient cooling have occurred; however, several conditions were reported in which full core off-loads were performed with insufficient evaluation of the heat loads or SFP cooling system during the off-load. Errors in the calculated heat load and nonconservative ultimate heat sink temperature assumptions have also occurred. This issue surfaced as the result of a situation at Millstone Unit 1.[15] For Millstone Unit 1, the licensee determined that during prior refueling outages the SFP cooling system would not have been capable, by itself, of maintaining pool temperature below the 150 °F design limit under certain postulated conditions, including a single active equipment failure.

Ineffective Heat Sink. The second leading cause of loss of SFP cooling, although there were significantly fewer events, was loss of SFP heat exchanger cooling. Of the six events, almost all were caused by human error. These events lasted from some very short periods of time to about 13 h with temperature increases ranging from 0 to 40 °F.

SFP Instrumentation Experience

Several events have involved losses of SFP coolant inventory or SFP cooling, where associated instrumentation was inoperable or failed before or during the events. In one event a shared annunciator window was illuminated as the result of an instrumentation problem when the loss of inventory occurred. Because the window was already illuminated, the operations staff was not alerted to the loss of coolant inventory event when it began. Although there have been relatively few of these instrumentation problems, they raise concerns about how SFP instrumentation is treated and regarded.

Effect of Shortening Refueling Outage Times

Review of operating experience has shown that, in an effort to minimize refueling outage times, many plants perform full core off-loads early in their outages. The effect of such practices is to reduce the time available to recover from a loss of SFP cooling event. AEOD discussions with the engineering manager of

Nine Mile Point Unit 2 provided good insight into the effect this practice has on reducing the time available until boiling begins.

Figure 8 shows the history of full core off-loading times at Nine Mile Point Unit 2. Figure 9 shows the ranges of calculated times available to initiate boiling at Nine Mile Point Unit 2. For operation with the SFP gates out, the licensee's conservative calculations estimated that the time to initiate boiling reduced from 51 h during the first refueling outage to 24.2 h during the fourth refueling outage. For operation with the SFP gates installed, the licensee's conservative calculations estimated that the time to initiate boiling reduced from 17.6 to 8.4 h. Similarly, during a visit to the South Texas plant, AEOD learned that calculations

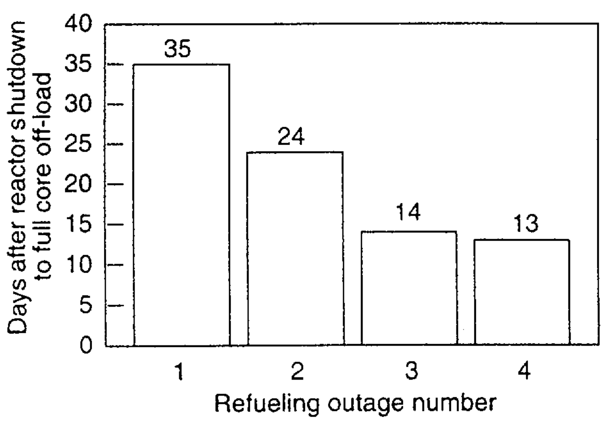

Fig. 8 History of full core off-loading at Nine Mile Point Unit 2.

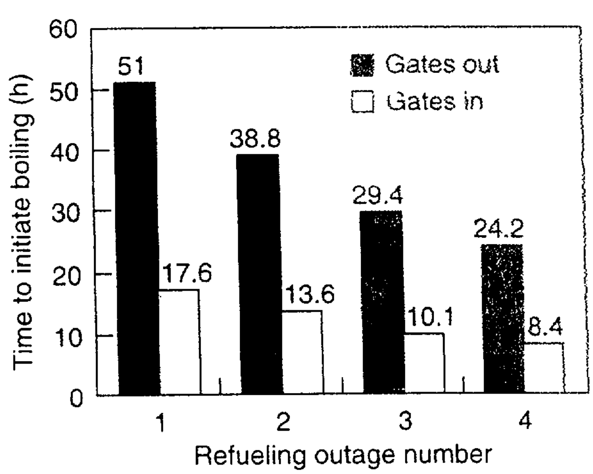

Fig. 9 Times available to initiate boiling at Nine Mile Point Unit 2.

performed for the most recent refueling outage estimated that the initiation of boiling could begin approximately 5 h after SFP cooling is lost. A recent survey assessment performed by NRR indicated that, if a full core had to be off-loaded during midcycle, boiling could begin about 2 to 3 h after losing SFP cooling.

Operating Experience Review Findings

Losses of SFP or refueling water inventory are dominated by events involving system or SFP configuration control problems caused by human error. The second most prevalent cause of loss of SFP inventory is leaking inflatable gate seals, generally caused by loss of air to the seals because of human error. Losses of inventory from SFP gates caused by leaking inflatable gate seals have generally been of greater magnitude than those caused by configuration control problems. Loss of inventory because of configuration control problems is more easily controlled by the operations staff than leaks from gates; however, configuration control problems seem to have taken longer to diagnose.

Pool leakage events do not appear to have caused problems with long-term losses of spent fuel cooling. Inadvertent movement of heavier than allowed loads over SFPs is continuing, even though the NRC has taken steps to reduce this problem.

The most prevalent type of loss of cooling event involved loss of electric power to the SFP cooling pumps, generally caused by human error. The few losses of SFP cooling caused by loss of SFP heat exchanger cooling were also generally caused by human error. Both types of events resulted in losses of about the same time frame and associated temperature rises. The events were evenly distributed between BWRs and PWRs.

Whereas conditions have been reported suggesting the possibility that SFP boiling affects other plant equipment important to safety, operating experience does not provide insight into what is apparently a very complex issue. Operating experience provides only limited insight into instrumentation problems. Several loss of level events have taken place while level instrumentation was inoperable or level annunciators were already actuated for other reasons. Relatively few of these instrumentation problems have been captured by the AEOD study. They represent concerns about how SFP instrumentation is treated and regarded.

Some ventilation events (damper problems and heater problems) could be potential areas of concern when coupled with postulated SFP events that could lead to radiation release.

Foreign operating experience appears to be consistent with that from U.S. plants. Operating experience suggests that losses of makeup capability are not very likely.

OBSERVATIONS FROM THE SITE VISITS AND INTERVIEWS

Six site visits were conducted to gain understanding of the licensees' SFP physical configurations, practices, and operating procedures. Site selection was a cross-sampling of the industry that included BWRs and PWRs, large and small architect–engineer designs, shared and single pools, old and new designs, and all four nuclear steam supply system vendor designs. The sites visited were North Anna, South Texas Project, Susquehanna, Three Mile Island, River Bend, and Calvert Cliffs. In addition to the site visits, one trip was made to Pennsylvania Power and Light headquarters. The following observations are from the site visits and the interviews. These observations are a cross-sampling and are representative of the nuclear power industry.

In general, utilities are doing a good job of analyzing the SFP heat loads and heatup rates; however, control room operators are not always being made aware of the analysis and results. This information could prove to be critical in worst-case refueling outage conditions (e.g., full core off-load and a very short outage schedule). Some of the utilities are performing risk analysis as part of the outage planning.

Some utilities have used lessons from operating experience and have done a very good job in correcting problems through better analysis, good operator aids, training, and procedure revisions. Some utilities have a good system to evaluate industry experience.

The site visits identified events where connected systems could have caused loss of SFP coolant inventory. Many events, such as draindowns, are not being reported through the standard mechanisms that would allow for the standard analysis of the events. Therefore the actual frequency of draindowns is higher than is typically assigned in the risk analysis. The site visits also identified that little attention is paid to the antisiphon devices; very few sites performed testing or had analysis on the efficacy of the antisiphon devices.

A large variation in utility practice exists regarding full core off-loads versus fuel shuffles. One plant that had been performing full core off-loads now plans to do fuel shuffles instead. Another plant that had intended to do fuel shuffles now routinely does full core off-loads.

The newer designs have more of the better features, such as safety-related power, analog control room meters, more parameter indicators in the control room, more sources of water, and generally better qualified equipment. Some older plants, however, have made improvements by adding indicators or annunciators in the control room and supplying safety-related power to the SFP equipment. All of the sites visited are including the SFP system in the equipment covered by the Maintenance Rule.

All the plants visited had examples of good practices. Some of the good practices observed in our visits, but not all in one plant, include:

- Using licensed reactor operators and training them for the refueling outages.
- Including SFP risk in the outage planning.
- Having SFP system power restored in the top-level emergency operating procedures.
- Forming a refueling team with formal structure.
- Providing classroom and simulator training in preparation for the outage.
- Producing user-friendly graphs of pool heatup rates from the analysis for use in the control room.
- Doing analysis beyond heat loads and heat rates, such as SFP risks in outage planning.
- Having strong command and control of SFP activities.
- Providing a second source of power for the SFP system.
- Having a mimic on the control board for the SFP system lineup.
- Utilizing a system diagram prior to making SFP system alignment changes.
- Having an effective program to learn from internal and industry operating experience.
- Refining the SFP risk model used in the outage planning down to the component level.

Three good design modification examples were found:

- Adding additional SFP indication to the control room.
- Adding safety-related power to the SFP instrumentation.

• Providing a dedicated heating, ventilation, and air conditioning system for refueling.

The interviews with the authors of the Susquehanna 10 CFR Part 21 report were very informative. They provided the details of their concern that the as-found Susquehanna SFP configuration did not meet the licensing basis. The report that they filed does have potential generic implications, including (1) mechanisms to transport vapor to and create high temperatures in other parts of the plant, (2) electrical and instrumentation weaknesses in SFPs, (3) potential for multiunit sites with shared pools to have an increased SFP risk, and (4) a lack of awareness for SFP issues.

The 10 CFR 21 report provided an impetus for the NRC and the nuclear industry to take a closer look at SFPs, which historically have not received much attention. In the efforts to address the 10 CFR 21 report concerns, Pennsylvania Power and Light Co. has improved the Susquehanna SFP design, modified its operation, improved emergency procedures, and improved operator training. A limited probabilistic risk assessment (PRA) found that the net effect of these actions at Susquehanna was to diminish the risk from SFP events.

RISK ASSESSMENT

Over the years, the SFP has not received the risk assessment attention that the reactor has because early analysis put the risk of an SFP accident an order of magnitude below a reactor event. Therefore the analyses done for the SFP were limited. In recent years, however, several issues have required that certain aspects of the SFP be studied further. INEL was contracted to review the previous SFP risk assessments and to utilize the insights to assess the current risk of SFP accidents. In addition to those risk insights, INEL used the AEOD operating experience review, engineering analyses, site visits, and site interviews to assess the likelihood of SFP events.

Risk Analysis for SFP Cooling at Susquehanna Electric Power Station

In October 1994, Battelle Pacific Northwest Laboratory (PNL) prepared a draft report. *Risk Analysis for Spent Fuel Pool Cooling at Susquehanna Electric Power Station*,[16] for NRC's Risk Applications Branch of NRR. The report presented the results of PNL's analysis of loss of SFP cooling events at the Susquehanna nuclear power plant, including estimates of the likelihood for loss of SFP cooling, the near-boiling frequency (NBF), and order of magnitude estimates of core damage frequency (CDF) attributed to SFP heatup events.

The PNL analysis addressed design-basis accidents that would cause mechanistic failure of the nonsafety-related SFP cooling system. The accident scenario postulated in the Susquehanna 10 CFR 21 report, an RCS LOCA, would result in deenergizing SFP power and could also induce hydrodynamic loading of systems and equipment associated with SFP cooling. In addition to addressing RCS LOCA, NRR had PNL analyze other initiating events: earthquakes, LOOP, and flooding. The PNL analysis did not consider major SFP coolant inventory losses from configuration control, gates, and seals to be credible events.

The results of the analysis indicated that the risk from SFP events was low compared with reactor events that did not account for any risk contribution from the SFP. The PNL study showed that, for the Susquehanna plant, the largest contributors to SFP risk emanated from extended LOOP and LOCA events. The analysis also showed that the improvements made at the Susquehanna station in response to the issues raised by the 10 CFR 21 report resulted in an NBF reduction of about a factor of 4 with a commensurate reduction of risk of about a factor of 4.

The results of the PNL study were integrated into NRR's Safety Evaluation, Susquehanna Steam Electric Station, Units 1 and 2, Safety Evaluation Regarding Loss of Spent Fuel Pool Cooling Issues.[13] The PNL analysis was used to augment the deterministic analysis of the Susquehanna plant. From their deterministic analysis, NRR found that "systems used to cool the spent fuel storage pool are adequate to prevent unacceptable challenges to safety-related systems needed to protect the health and safety of the public during design basis accidents."[13] On the basis of the PNL analysis, NRR indicated that "loss of SFP cooling events represented a low safety significance challenge to the plant [Susquehanna] at the time the issue [Part 21 report] was brought to the staff's attention."[13]

Although there may be large uncertainties associated with the absolute values and specific numerical results of the PNL analysis, much insight can be gained from the PNL analysis of the Susquehanna station: for example, the PNL analysis shows that the most significant risk reduction could be achieved from three strategies: (1) installing SFP level and temperature instrumentation in the control room, (2) enhancing SFP normal and off-normal procedures and training staff to be proficient, and (3) cross-tieing SFPs.

Risk Assessment

AEOD obtained technical assistance in the area of risk assessment from INEL. INEL reviewed the PNL Susquehanna PRA, assessed the adequacy of the risk analysis, and addressed the adequacy and reasonableness of the assumptions made. INEL extracted insights from the PNL Susquehanna PRA and the other relevant PRAs in industry to assist in generically assessing the likelihood of loss of SFP cooling. Information from the AEOD reviews of operating experience, interviews, site visits, and independent SFP analyses was used to refine the developed PRA model. The AEOD study provided quantitative estimates of the NBF and qualitative discussions about the risk of losses of SFP cooling. The following sections provide the results and insights obtained from these INEL efforts.[17]

Quantitative Results. INEL corrected modeling problems identified in the PNL study. The event and fault trees were refined to more accurately describe current Susquehanna plant operations. To refine the event trees, INEL staff visited Pennsylvania Power and Light Co. engineering offices and the Susquehanna station. The event and fault trees were quantified with the use of recent operating experience data supplied by AEOD. When performing the analyses, INEL also refined and updated the data and models that PNL had used to account for human performance.

In some cases the modifications and improvements resulted in increases in the NBF in the SFP, which, in turn, would result in increased estimates of risk. Correcting the initiating event frequencies for station blackout, LOCA, seismic events, configuration control errors, and seal failures would tend to increase the NBF. Counterbalancing this, the study identified possible sources of conservatism in the PNL study. Chief among them were the estimates of human performance associated with recovery and mitigation.

INEL performed the aforementioned refinements, including modifications of the initiating event frequencies using AEOD's operational event data base, to cover a full spectrum of loss of SFP inventory events, including catastrophic seal failure. The results of their analysis are shown in Table 4. The analysis found that the NBF for the Susquehanna plant after implementing the 10 CFR 21 improvements was 5×10^{-5}/year, which is approximately twice that found by PNL.

The dominant event initiators were LOOP and SFP inventory losses, including configuration control errors and seal failures. Because of the limited time and resources available, INEL did not extend the analysis to include a quantitative estimate of the CDF. Also, given the limited data available for development of estimates of event frequencies and the limited resources available for model development, more refinement is required before these estimates can be used as a basis for regulatory actions.

Table 4 Near-Boiling Frequencies (NBFs)

	INEL	PNL
Total NBF	5×10^{-5}	2×10^{-5}
LOOP[a]	3×10^{-5}	1×10^{-5}
Inventory losses	2×10^{-5}	1×10^{-6}

[a]LOOP, loss of off-site power.

Qualitative Results. The SFP PRAs that were done by PNL and INEL were specifically for the Susquehanna plant. Many features of the design and operation of Susquehanna are unique; consequently the results of the PNL and INEL analyses cannot be applied directly to other plants. Nonetheless, certain qualitative insights have been gained from those studies which may have generic applications. For example:

Effect of defueled unit upon operating unit. The analyses showed that, for a dual-unit BWR, it is possible for a problem with SFP cooling at a shutdown unit to affect the adjacent operating unit. The accident scenario postulated in the Susquehanna 10 CFR 21 report was found to be a credible event but less likely than other events.

Uncertainties of core damage frequency estimates. The task of estimating the NBF appears to be amenable to the use of PRA techniques; however, the task of estimating CDF is subject to very large uncertainties. PNL and INEL both acknowledged that the methodology used for this task provided only "order of magnitude estimates."

Effect of the Susquehanna 10 CFR 21 report. Comparison of the analyses that were done for the Susquehanna plant as it existed at the time of the 10 CFR 21 report and after corrective actions were taken revealed that the improvements made in the areas of instrumentation, accident response procedures, operator training, and shutdown operations reduced the estimated NBF.

Improvements in instrumentation consisted of providing reliable SFP level and temperature monitoring instruments in the control room.

Improvements in operations and accident response procedures involved:

- Ventilation system isolation.
- Installation of drains in the standby gas treatment system.
- Utilization of the RHR system of the operating unit to cool the SFP.
- Verification that removal of cask storage pit gates results in effective heat transfer between the SFPs.

Dominant accident sequences. For the Susquehanna plant, the PNL analysis found that the accident sequences that were the largest contributors to NBF were extended LOOP and LOCA. The extended LOOP is a dominant contributor because at the Susquehanna station the SFP cooling system pumps are not on the emergency buses. The original accident scenario raised in the 10 CFR 21 report did not appear to be a significant contributor to NBF. The INEL study found that the dominant contributors to NBF were LOOP and SFP inventory loss.

Deviation from the modeled plant design. Risk estimates from the SFP for the Susquehanna plant may be affected by changes planned for future refueling outages, which may represent major deviations from the models used by PNL and INEL. Some of those anticipated changes are:

- Operation without the SFP cross-tied for the future dry cask storage operations.
- Reduction of refueling outage from 55 to 35 days.
- Partial core off-loads taking place earlier in the outage.

Operating experience. INEL found that SFP inventory losses such as draindowns or pneumatic seal failures may be important contributors to NBF at the Susquehanna plant. In previous PRAs such events were either not modeled or their occurrence frequency was assumed to be very low: about once every 10 000 RY.

FINDINGS AND CONCLUSIONS

The following findings and conclusions are based on a review of operating events and interpretations of the available risk analyses. The conclusions are numbered, followed by paragraphs that describe the findings on which those conclusions are based.

Likelihood and Consequences of SFP Events

1. Review of more than 12 years of operating experience determined that loss of SFP coolant inventory greater than 1 ft has occurred at a rate of about 1/100 RY. Loss of SFP cooling with a temperature increase greater than 20 °F has occurred at a rate of approximately 3/1000 RY. The consequences of these actual events have not been severe; however, events have resulted in loss of several feet of SFP coolant level and have gone on in excess of 24 h. The primary cause of these events has been human error.

There have been two loss of SFP coolant inventory events with SFP level decreases in excess of 5 ft. These events were terminated by operator action with approximately 20 ft of coolant remaining above the stored fuel. Without operator actions, the inventory loss could have continued until the SFP level had dropped to near the top of the stored fuel, which would have resulted in radiation fields that could have prevented access to the SFP area. The events with the largest level decrease involved unavailable or inaccurate instrument readings. Ten other loss of inventory events resulted in level decreases between 1 and 5 ft. Operator response to one of the largest losses of SFP coolant inventory events (loss of 5.5 ft level in SFP) was deficient because several opportunities to diagnose and correct the problem were missed when makeup coolant was added to the system without evaluating the cause of the need for makeup. Two precursor events involved cavity seals that had rapidly developing leaks. In one case about 200 000 gal of water was lost in about 20 min. In the second case, about 25 800 gal was lost in about 30 min.

Several losses of SFP cooling have lasted in excess of 24 h; one had a maximum temperature increase of 50 °F to a final temperature of 140 °F. No reported approaches to boiling were found during the experience review period.

Whereas the operating experience review results are believed to be reasonably representative, discussions with operations staff revealed a number of additional events that did not reach the reporting threshold required by NRC regulations. Therefore they were not initially captured by the study's event review process.

2. Review of existing SFP risk assessments found that, after correction for several problems in the analyses, the relative risk as the result of loss of spent fuel cooling is low in comparison with the risk of events not involving SFP. The review determined that the likelihood and consequences of loss of SFP cooling events are highly dependent on human performance and individual plant design features.

The INEL risk assessment identified LOOP and loss of SFP coolant inventory as major contributors to NBF. LOOP was a major contributor largely because the analysis was based on the Susquehanna plant where the SFP cooling system is not connected to emergency power.

Human performance is the most important factor for both loss of spent fuel cooling event initiators and recovery actions. Problems with configuration control caused most of the SFP events. Lack of automatic functions for detection and recovery from SFP events places full reliance on operator actions. The results of risk assessments involving operator actions are sensitive to the level of administrative controls, instrumentation, procedures, and training provided to aid operator performance.

The impact of instrumentation, procedures, and training depends on plant-specific design features. The NRR survey of SFPs identified a wide range of plant design features and specific limitations at existing plants. Plants that have identified limitations relating to configuration control, instrumentation, procedures, and training could reduce the risk of SFP events by relatively modest improvements in these areas. Modest improvements to instrumentation and operations made by Susquehanna resulted in reduced risk.

3. The need for specific corrective actions should be evaluated for those plants where failures of reactor cavity seal or gate seals, or ineffective antisiphon devices, could potentially cause loss of SFP coolant inventory sufficient to uncover the fuel or endanger makeup capability.

Review of the INEL SFP risk assessment identified loss of SFP coolant inventory as a major contributor to NBF, and review of operating experience and the site visits identified that problems with configuration control, seals, and antisiphon devices were contributors to large losses of inventory.

The INEL risk assessment identified that NBF is sensitive to individual plant-specific design features and human performance. Plant-specific design features that impact the NBF include pneumatic reactor cavity seals and gate seals and SFP geometry, which might result in draindown to near or below the top of the stored fuel.

Prevention of SFP Events

1. The need for improvements to configuration controls related to the SFP to prevent and/or mitigate SFP loss of inventory events and loss of cooling events should be evaluated on a plant-specific basis.

Operating experience shows that the most frequent cause of loss of inventory and loss of cooling is ineffective configuration control. Mistaken valve alignments have diverted water from the SFP and have isolated the air supply to pneumatic seals. Mistaken electrical alignments have resulted in loss of power to SFP system pumps and other equipment.

2. The need for plant modifications at some multi-unit sites to account for the potential effects of SFP boiling conditions on safe shutdown equipment for the operating unit, particularly during full core off-loads, should be evaluated on a plant-specific basis.

The Susquehanna 10 CFR 21 report brought to light the potential problem that, when two units have a common pool, the refueling of one unit when SFP cooling is lost could impact the operating unit. A specific need is the assessment of the potential mechanisms to transport vapor to create high temperature in other parts of the plant that have critical plant equipment. The NRR survey assessment identified seven sites in addition to Susquehanna that have shared pools. Because the scenario involves many things going wrong with each configuration different, more assessment and evaluations need to be performed on these seven units.

Response to SFP Events

1. The need for improved procedures and training for control room operators to respond to SFP loss of inventory and SFP loss of cooling events consistent with the time frames over which events can proceed, recognizing the heat load and the possibility of loss of inventory, should be evaluated on a plant-specific basis.

Refueling outages are getting shorter. Control room operators at some plants are not aware that early transfer of the entire core from the reactor to the SFP during a refueling outage results in significant heat loads in the SFP and potential for near-boiling conditions within 5 to 10 h if cooling to the SFP is lost. Current operator training and procedures do not typically include this information, or if the information is provided, it is not easy to interpret.

All licensees have to some degree work scheduling, training, and procedures that deal with the SFP activities during a refueling outage and during normal plant operations; however, the effectiveness of these efforts was not apparent at all the plants. Engineers and operators had knowledge and awareness of relevant SFP issues when the licensees had (1) a formal training structure consisting of classroom lectures for the workers involved in the refueling activities, (2) a schedule program that incorporated the SFP risks, and (3) detailed procedures for all the activities. Regarding backup sources for SFP coolant inventory and SFP cooling, discussions with the licensees during the site visits revealed many ways that water could be provided to the pool that had not been formerly described and for which procedures did not exist.

2. The need for improvements to instrumentation and power supplies to the SFP equipment to aid correct operator response to SFP events should be evaluated on a plant-specific basis.

Instrumentation available to the operators regarding the SFP parameters can be very limited. A single annunciator may be the only indication of SFP trouble. Some plants have SFP level or temperature indication readouts on control room back panels. All indications of the SFP parameters could easily be lost in a reactor accident because not all of these instruments have safety-related power. Plant operators make rounds to the SFP location, but the time between successive visits may be too long to adequately trend data and stop a developing problem before it becomes a serious event. The operating experience review found several events where SFP cooling was lost because of loss of power to the SFP pumps. Most power supplies to the SFP pumps are safety related, but for the units that do not have this capability, an assessment to provide power during accident conditions would assist them in reacting faster to an SFP event.

REFERENCES

1. U.S. Government Printing Office, Washington, D.C., *U.S. Code of Federal Regulations*, Title 10, Energy, revised periodically.
2. D. A. Lochbaum and D. C. Prevatte, Letter to T. Martin, U.S. Nuclear Regulatory Commission, Susquehanna Steam Electric Station, Docket No. 50-387, License No. NPF-14, 10 CFR Part 21, Report of Substantial Safety Hazard, November 27, 1992.
3. J. M. Taylor, U.S. Nuclear Regulatory Commission, Memorandum to the Commission, Resolution of Spent Fuel Pool Action Plan Issues, July 26, 1996.
4. U.S. Nuclear Regulatory Commission, Inspection Report 50-298/95-014, December 18, 1995.
5. Northeast Nuclear Energy Company, Millstone Unit 2, Licensee Event Report 50-336/92-012, *Partial Loss of Normal Power (LNP)*, January 7, 1993.
6. U.S. Nuclear Regulatory Commission, Information Notice 88-065, *Inadvertent Drainages of Spent Fuel Pools*, August 18, 1989.
7. Southern California Edison Co., San Onofre Unit 2, Licensee Event Report 50-361/88-017-01, *Spent Fuel Pool Drainage Due to the Failure to Implement Updated Safety Analysis (FSAR) Commitments*, January 2, 1990.
8. Toledo Edison Co., Davis Besse, Licensee Event Report 50-346/82-007, *Spent Fuel Pool Water Level Dropped Below TS Limit Due to Procedural Deficiency*, March 3, 1982.
9. U.S. Nuclear Regulatory Commission, Augmented Inspection Team Reports 50-321/86-41 and 50-366/86-41, January 8, 1987.
10. Salem Unit 1 and Unit 2, Event Notification 30528, May 22, 1996.
11. U.S. Nuclear Regulatory Commission, Morning Report II-94-0112, December 29, 1994.
12. Pennsylvania Power and Light Co., Susquehanna Unit 1, Licensee Event Report 50-387/92-016, *Voluntary Report—Spent Fuel Storage Pools*, November 17, 1992.
13. J. F. Stolz, U.S. Nuclear Regulatory Commission, Letter to R. G. Byram, Pennsylvania Power and Light Company, Susquehanna Steam Electric Station, Units 1 and 2, Safety Evaluation Regarding Loss of Spent Fuel Pool Cooling Issues (TAC No. M85337), June 19, 1995.
14. Washington Public Power Supply System, Washington Nuclear Plant Unit 2, Licensee Event Report 50-397/93-018, *Spent Fuel Pool Makeup Not Adequate to Mitigate Accident Conditions*, May 28, 1993.
15. Northeast Nuclear Energy Company, Millstone Unit 1, Licensee Event Report 50-245/93-011-02, *Spent Fuel Pool Cooling Capability*, July 25, 1996.
16. Battelle Pacific Northwest Laboratory, Draft Report under NRC Contract DE-AC96-76RLO 1830, *Risk Analysis for Spent Fuel Pool Cooling at Susquehanna Electric Power Station*, October 1994.
17. Idaho National Engineering Laboratory, *Loss of Spent Fuel Pool Cooling PRA: Model and Results*, Report INEL-96/0334, September 1996.