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Operating Experience Feedback Report

Assessment of Spent Fuel Cooling

U.S. Nuclear Regulatory Commission

Office for Analysis and Evaluation of Operational Data

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ABSTRACT

This report documents the results of an independent assessment by a team from the Office for Analysis and Evaluation of Operational Data of spent-fuel-pool (SFP) cooling in operating nuclear power plants. The team assessed the likelihood and consequences of an extended loss of SFP cooling and suggested corrective actions, based on their findings.

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ABBREVIATIONS

AEOD	Analysis and Evaluation of Operational Data (NRC Office for)
BNL	Brookhaven National Laboratory
BWR	boiling-water reactor
CDF	core damage frequency
CFR	*Code of Federal Regulations*
ECCS	emergency core cooling system
EDO	Executive Director for Operations
GDC	General Design Criterion/Criteria
HVAC	heating, ventilation, and air conditioning
INEL	Idaho National Engineering Laboratory
LOCA	loss-of-coolant accident
LOOP	loss-of-offsite power
NBF	near-boiling frequency
NRC	Nuclear Regulatory Commission (U.S.)
NRR	Nuclear Reactor Regulation (NRC Office of)
NSSS	nuclear steam supply system
PNL	Pacific Northwest Laboratory
PRA	probabilistic risk assessment
PWR	pressurized-water reactor
RCS	reactor coolant system
RHR	residual heat removal
SFP	spent-fuel pool
SRP	Standard Review Plan

EXECUTIVE SUMMARY

As directed by the Executive Director for Operations, the Office for Analysis and Evaluation of Operational Data (AEOD) performed an independent 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.

The AEOD staff conducted six site visits to gain an understanding of each licensee's SFP physical configuration, practices, and operating procedures. During these visits, they found great variation among the designs and capabilities of SFPs and systems at the nuclear plants on these sites.

In November 1992, Mr. Donald Prevatte and Mr. David Lochbaum submitted a defects and noncompliance report on the Susquehanna SFP to the U.S. Nuclear Regulatory Commission (NRC). The AEOD staff interviewed Mr. Prevatte and Mr. Lochbaum to better understand 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 SFPs.

AEOD reviewed the applicable SFP regulations, the applicable acceptance criteria in the NRC Standard Review Plan, and the applicable Regulatory Guides. Because the criteria evolved and each reactor was licensed over time, the criteria varies for evaluating these SFP designs.

The AEOD staff performed independent assessments of the electrical systems, instrumentation, heat loads, and radiation from which they determined the typical SFP configurations and potential problems.

Utilizing a previous Susquehanna risk analysis, Idaho National Engineering Laboratory (INEL) performed model refinements that resulted in better estimates of near boiling frequency (NBF). Although INEL performed no quantitative estimates of core damage, the analysis provided qualitative insights for identifying improvements to SFPs that may lessen the risks of events.

Findings from these assessments are as follows:

- From reviewing more than 12 years of operating experience, the staff determined that loss of SFP coolant inventory greater than 1 foot occurred at a rate of about 1 event per 100 reactor years. Loss of SFP cooling with a temperature increase greater than 20 °F occurred at a rate of approximately 3 events per 1000 reactor years. The consequences of these actual events were not severe. However, these events resulted in loss of several feet of SFP coolant level, some of the events have lasted longer than 24 hours. The primary cause of these events was human error.

- During review of existing SFP risk assessments, the staff found that after correction for several problems in the analyses, the relative risk produced by loss of spent fuel cooling is low when compared with the risk of events not involving SFP. The likelihood and consequences of loss of SFP cooling events are highly dependent on human performance and individual plant design features.

- The staff determined that utilities' efforts to reduce outage duration have resulted in full core off-loads occurring 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.

Actions recommended by AEOD based on these assessments are as follows:

- The need for corrective actions at each plant 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, should be evaluated.

- The need for improvement to configuration controls related to the SFP to prevent 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.

- 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 and 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.

1 INTRODUCTION

Several instances occurred in recent years in which the adequacy of SFP cooling systems were questioned. For example, Mr. David Lochbaum and Mr. Donald Prevatte, former Susquehanna Steam Electric Station plant contractors, submitted a report (Ref. 1) in accordance with Part 21 of Title 10 of the *Code of Federal Regulations* (10 CFR Part 21) (Ref. 2) on the adequacy of SFP cooling at the Susquehanna plant. In addition, the agency corresponded with Mr. Lochbaum and Mr. Prevatte on this topic, and reviewed and responded to a 10 CFR 2.206 petition from them. As a result of the issues raised with respect to SFPs, on February 10, 1996, the Executive Director for Operations (EDO) requested that the Office for Analysis and Evaluation of Operational Data (AEOD) perform an independent study of the likelihood of, and consequences of, an extended loss of SFP cooling (Ref. 3). On February 29, 1996, AEOD sent the EDO a plan and schedule (Ref. 4) for performing this independent study.

The 10 CFR Part 21 report filed by Mr. Lochbaum and Mr. Prevatte postulated loss of SFP cooling that resulted in boiling of the SFP, failure of the emergency core cooling system (ECCS) and of other equipment that was due to steam releases and condensation of SFP vapors, reactor core heatup and damage, spent fuel heatup and damage, and large offsite radioactivity releases.

AEOD completed the independent assessment, during which the staff—

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

- Assessed more than 12 years of operational experience for both domestic reactors and foreign reactors with designs similar to those in the United States.

- Performed six site visits to gather information on SFP physical configuration, practices, and procedures; and conducted interviews with Mr. Lochbaum and Mr. Prevatte to better understand their 10 CFR Part 21 report.

- Reviewed applicable SFP regulations, applicable acceptance criteria in the NRC Standard Review Plan (SRP) and applicable Regulatory Guides.

- Performed independent assessments of electrical systems, instrumentation, heat loads, and radiation to better understand their effects on SFP cooling.

- Contracted with Idaho National Engineering Laboratory (INEL) to review existing risk analyses and to use risk assessment techniques to evaluate the risk of losing SFP cooling and coolant inventory.

In order to accomplish the stated goals in the 7-month schedule, AEOD utilized existing agency SFP data and analyses. AEOD worked closely with the Office of Nuclear Reactor Regulation (NRR) throughout the assessment to be able to use current SFP information. Specific analyses and specific sites were assessed for generic applicability to other plants.

2 SPENT FUEL COOLING

A survey of SFPs indicates that a wide variety of configurations exists. This section provides simplified general descriptions of SFP configurations; the descriptions may not apply to any specific SFP but are considered to be typical or "generic" PWR and BWR SFPs. Since most plants were built before the NRC issued specific regulatory guidance for SFPs, diverse designs would be expected. For purposes of this study and this report, loss of spent fuel cooling is considered to include two subcategories: the loss of SFP coolant inventory and the loss of SFP cooling. Potential problems with SFP coolant inventory and SFP cooling that can lead to loss of spent fuel cooling and the potential consequences of loss of spent fuel

cooling are discussed. Once the problems are identified, possible approaches to prevention and response to loss of spent fuel cooling situations are described.

2.1 System Description

Figure 2.1 shows a generic PWR SFP and Figure 2.2 shows a generic BWR SFP. SFPs are constructed of reinforced concrete, several feet thick, with a stainless steel liner to prevent leakage and maintain water quality. The pools are designed to survive seismic events although the cooling system may not. For BWRs, the SFP is generally located within the reactor building. For PWRs, the SFP is located outside the containment but adjacent to it in a separate fuel handling building or within the auxiliary building. Typically, SFPs are about 40 feet deep and vary in width and length. The fuel is stored in stainless steel racks and submerged with approximately 23 feet of water above the top of the stored fuel. The water in the SFP of a BWR is demineralized water; whereas PWRs use borated water. In addition to cooling, SFP water inventory provides radiological shielding for personnel in the fuel pool area and adjacent areas. Each plant generally has Technical Specification requirements for water level and reactivity of the spent fuel stored in the SFP.

Each plant has a source of high purity water to fill the SFP, referred to in nuclear power plants as make-up. The preferred sources are usually the refueling water storage tank for PWRs and the condensate storage tank for BWRs. The normal make-up is through a connection from the water source to the suction of the SFP cooling system pumps or a water source. The make-up rates among plants have a wide range. Local valve operations are needed to initiate SFP make-up. Plants also have alternate methods to provide make-up if normal make-up is unavailable and may include the service water system and the fire water system.

SFP coolant inventory is cooled by a dedicated cooling system. As shown in Figures 2.1 and 2.2, SFP coolant is pumped through heat exchangers where sensible heat is transferred to an intermediate cooling system, which finally rejects heat to the plant's ultimate heat sink. The SFP cooling system takes suction from the SFP through a skimmer or strainer at such an elevation that a water level change in the SFP would cause the pumps to lose suction and prevent further SFP coolant inventory loss through a break in the SFP cooling system piping. The SFP cooling return lines either discharge near the top of the SFP or are arranged to distribute coolant flow around the bottom of the fuel in the SFP. With a few exceptions, SFP cooling piping, which extends deep into the SFP, is equipped with antisiphon devices (usually drilled holes) to prevent loss of SFP coolant inventory should a system misalignment or pipe break create an inadvertent siphon flow path. SFP pumps, heat exchangers, and intermediate cooling systems are single train or redundant, depending on the plant's SFP design. Many plants have the capability to align the residual heat removal (RHR) system to remove heat from the SFP in the event that the normal SFP cooling system is unavailable. Each plant has a nonsafety-related system that is used to purify and clarify the SFP water. This system is often integrated with the normal SFP cooling system. The system is typically made up of filters, ion exchangers, and other supporting equipment.

Most plants have leak detection systems to determine if leakage is occurring from the SFP liner, spent fuel shipping cask pool, or from other portions of the fuel pool or reactor cavity structure. The leak detection system is usually made up of several channels that can be monitored individually or are designed in such a way that leakage empties into drains that can be monitored and returned to either sumps, liquid radioactive waste, or other cleanup or collection systems. The SFP leak detection system can usually be isolated if necessary to attempt to reduce SFP leakage.

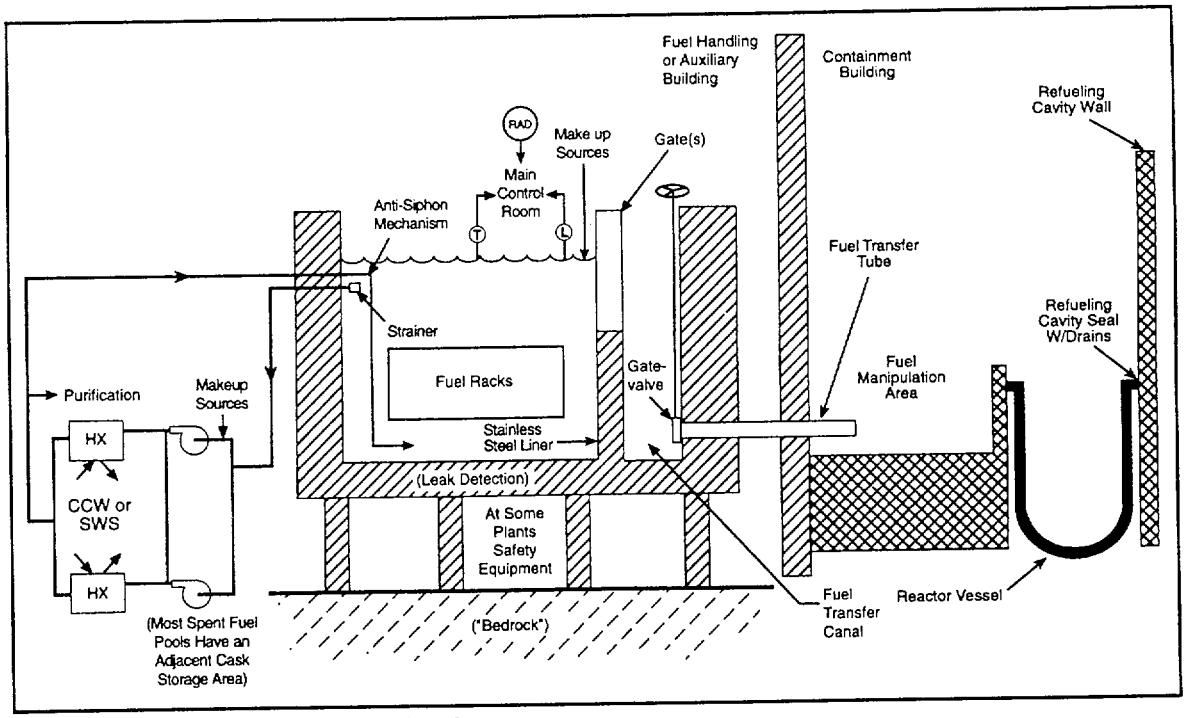

Figure 2.1 PWR Spent Fuel Cooling Systems

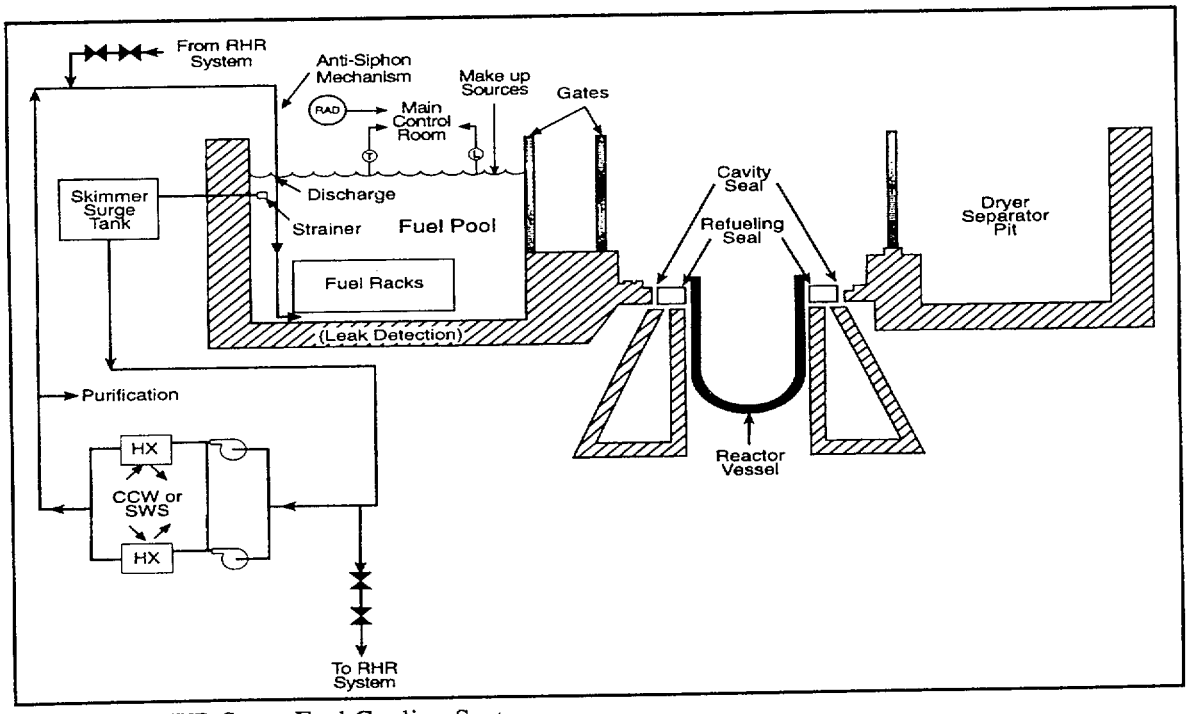

Figure 2.2 BWR Spent Fuel Cooling Systems

Spent Fuel Cooling

During refueling operations, the refueling cavity above the reactor is filled with water to equal the water level in the SFP. Fuel is moved from the SFP to the reactor via transfer canals in BWRs or transfer tubes in PWRs. For BWRs, the movable gates that separate the SFP and the transfer canal from the reactor cavity are several feet wide and extend approximately 24 feet down to provide an opening for fuel to be moved in a vertical position. Removal and replacement of the gates requires use of the plant traveling crane because of their size and weight. Thus, during refueling, a loss of water from the refueling cavity resulting in a drop in water level would also lower the water level in the SFP. Replacement of the gates to isolate the leak would be a major time-consuming operation.

For PWRs, the transfer tube provides for movement of the fuel in a horizontal position. The opening provides a much smaller flow path from the SFP to the reactor cavity than the movable gates of a BWR. Also, a gate valve at the SFP end of the transfer tube can be closed fairly quickly to stop the flow path from the SFP to the reactor cavity.

Refueling cavity seals are installed between the reactor vessel flange and the bottom of the reactor cavity to maintain a leak-proof volume during refueling operations. Both PWRs and BWRs have drains in the refueling cavity area to allow draining of the cavity when the refueling is complete. Some plants have leak detection systems to monitor the cavity seal.

BWRs and PWRs have indicators for temperature, level, and radiation instrumentation in the SFP area. Analog meters are generally not provided in the control room for SFP level and temperature, but at certain sites, some SFP parameters are available on the computer in the control room. SFP radiation values are generally available on analog meters in the control room. Control room annunciators for SFP parameters generally have more than one function (e.g., low SFP level and high SFP level) for each annunciator, and local conditions usually need to be investigated to determine the cause of SFP annunciator actuation. SFP instrumentation is discussed in more detail in Section 6.2 of this report.

Some SFPs have a separate pool for spent fuel shipping cask operations. Typically, these areas are separated from the main SFP by movable gates. At most sites, this area is open to the SFP only during cask operations. The spent fuel shipping cask pool usually has a drain system to allow raising and lowering of the water level.

Based on the SFP descriptions in Section 2.1, the discussion in Section 2.2 describes potential scenarios that can lead to loss of spent fuel cooling caused by (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 2.3 is a schematic classification of the types of events that could lead to loss of spent fuel cooling.

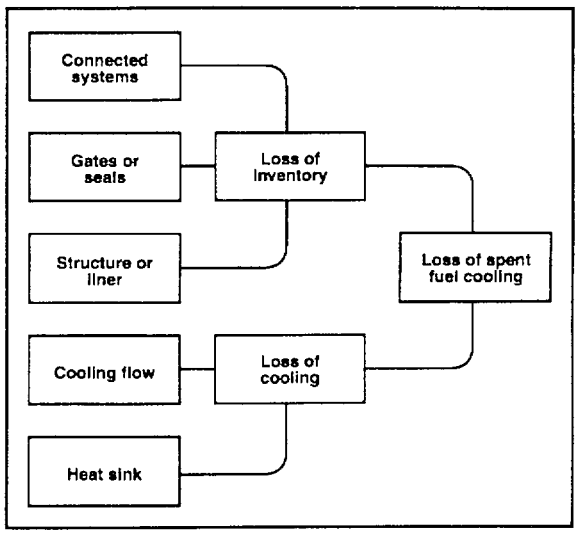

Figure 2.3 Loss of Spent Fuel Cooling

2.2 Loss of Spent-Fuel-Pool 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.

2.2.1 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 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 owing to a pipe break or a configuration control problem, would be limited by antisiphon devices. However, siphoning can occur if the antisiphon devices are incorrectly designed, are plugged, or otherwise fail. NRR determined through a recent survey of all power reactors (Ref. 5) 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 tc the spent fuel shipping cask pool drains. For these situations in many designs, the extent of the inventory loss is limited by internal weirs or drain path elevations, which maintain the water level above the top of the stored fuel in the SFP.

2.2.2 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 Figures 2.1 and 2.2, both PWRs and BWRs have seals that keep water above the vessel in the refueling cavity during refueling. BWRs usually require two seals to keep refueling water above the reactor vessel; in Figure 2.2 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 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, which use gaskets to seal between mating surfaces, and permanent seals, which 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 varied 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 in evaluating the vulnerability to loss of SFP coolant inventory caused by failed inflatable seals. Many seal failures will result in only limited water 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 that 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 be immediately uncovered, SFP cooling water would be lost because the SFP pumps would trip on loss of suction; and

the remaining SFP coolant inventory would heat up to near boiling within a few hours. Also, because of the 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 a cavity seal or gate seal failures to a level that would continue to provide radiation shielding sufficient to allow operator actions would be more likely to be able 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. During the NRR survey assessment, the staff found that five SFPs have fuel transfer tubes that are lower than the top of the stored fuel without interposing structures.

2.2.3 Pool Structure or Liner

Finally, inventory loss could occur directly owing to SFP liner leakage or gross failure of the SFP structure. The impacts of a dropped heavy (a load weighing more than one fuel assembly) load or a seismic event are potential causes of gross failure, although SFPs are designed to survive seismic events. Radiological and structural response and makeup capability for dropped light loads (those weighing no more than a fuel assembly) are bounded by analyses of a fuel handling accident. On the other hand, dropped heavy loads have the potential to exceed the design basis of the fuel pool structure and the make-up system. Thus, heavy load control programs have been instituted to evaluate the potential effect of a dropped heavy load or to implement special controls on the design and operation of heavy load handling equipment.

2.2.4 Consequences of Loss of Spent-Fuel-Pool Coolant Inventory

For a large loss of SFP 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 make-up capacity, the fuel could become uncovered and heat to the point of clad damage and release of fission products. Extremely high radiation fields would also result around the SFP area if the fuel were uncovered.

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 were taken, the final consequences would be similar to loss of SFP coolant inventory described in the first paragraph of Section 2.2.4.

Loss of SFP coolant inventory events for which corrective actions are taken before severe consequences occur can potentially cause 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 affect 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, further exacerbating the loss of inventory.

Where the SFP area atmospheric water vapor can be transported to areas which 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. In these units, the fuel pool atmospheric water vapor from the unit refueling can be transported to areas housing safety equipment when the unit is operating at or near full power. 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 Section 7.2 of this report. Most plants have sufficient flood protection, ventilation, and equipment separation to prevent this scenario. However, according to the NRR survey assessment, eight multiunit sites may be susceptible to this scenario.

2.3 Loss of Spent-Fuel-Pool Cooling

Figure 2.3 also presents potential causes of loss of cooling to the SFP. Cooling can be lost by loss of SFP cooling flow or because of an ineffective SFP heat sink. Losses of SFP cooling system flow can be due to several mechanisms, including loss of electrical power to the SFP cooling pumps, pump failure, flow blockage, loss of suction caused by the loss of water level, or a diversion in the SFP cooling system. Losses of heat sink can be due to operation with less than the required SFP cooling system complement or with heat loads in the SFP that exceed the capability of the SFP cooling system design.

2.3.1 Loss of Spent-Fuel-Pool Cooling System Flow

All SFP cooling pumps are electrically powered. Loss of electrical power to these pumps results in loss of SFP cooling system flow. Loss of electrical power can be due to losses of offsite power or human error in electrical alignments. Most SFP cooling system pumps can be loaded on available onsite power sources. During the NRR survey assessment, the staff found that four SFPs could not be cooled by systems that could be powered by onsite power sources.

The likelihood of an extended loss of SFP cooling caused by loss of electrical power to the pumps is fairly low owing to the combination of available on-site power, the existence of workable procedures for power restoration, and the plant operations staff knowing that they need to restore power and the time available to restore the power.

For other than loss of electrical 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.

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

Flow can also be lost because of a 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.

2.3.2 Ineffective Spent-Fuel-Pool 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 because of misalignment of cooling water sources, failure of the cooling water source, heat exchanger fouling, or insufficient heat exchanger capacity, among other causes.

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 heating the SFP. Errors in the calculated heat load or assumption of nonconservative ultimate heat sink temperatures could mislead operators.

2.3.3 Consequences of Loss of Spent-Fuel-Pool Cooling

An extended loss of SFP cooling would result in heat up and boil off of SFP coolant inventory and the 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 having to prohibit personnel access to the area. 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 uncovering the fuel. No fuel damage is probable 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 effects that apply to the situation described in Section 2.2.4 for loss of SFP coolant inventory leading to generation of steam and water vapor being transported to other parts of the plant apply to the extended loss of SFP cooling.

2.4 Preventing and Responding to Spent-Fuel-Pool Events

No systems automatically respond to a loss of SFP coolant inventory or a loss of SFP cooling. Consequently, operator actions form the basis for preventing and responding to a loss of spent fuel cooling.

Both a gate seal and cavity seal must be correctly installed and tested in order to prevent a loss of SFP coolant inventory. And in the case of an inflatable seal, the air supply must be properly tested and controlled to prevent loss. 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, a drop in the water level 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 a SFP event. If the operators become quickly aware of a SFP event, the large volume of water in the SFP will usually allow sufficient opportunity for the operator 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 problem 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 is also largely dependent on configuration control and human performance. The primary concern is to maintain electrical power to the equipment involved in SFP cooling.

3 OPERATING EXPERIENCE

The staff reviewed operating experience with SFP loss of coolant inventory and loss of cooling, using, as the primary source of information, licensee event reports from 1984 through early 1996 that were screened from the Sequence Coding and Search System. In some cases, events before 1984 were included. 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. Foreign operating experience is discussed in Section 3.5 of this report. After reviewing more than 700 separate sources of information, the staff found about 260 events related to SFPs. Table 3.1 is a summary of these SFP events and lists the number of events of each type under the two main categories: loss of SFP coolant inventory and loss of SFP cooling. The table shows numerous precursor events found during the review. These precursor conditions represent potential losses of SFP coolant inventory or loss of SFP cooling given the condition that occurred plus other postulated failures.

Table 3.1 Spent Fuel Pool Events

Type of Event	Actual	Precursor
SFP 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

The operating events found during the review provide a reasonable representation of experience with SFPs. However, during discussions with operations staff, the staff learned about a number of additional events that provide insights into problems with SFPs. While these events have been included in this report, they were not initially captured by the event review process, primarily because some relevant events are below the reporting threshold required by NRC regulations.

3.1 Loss of Spent-Fuel-Pool Coolant Inventory

About 38 events involved actual loss of SFP coolant or refueling water. About 55 precursor events occurred. Table 3.2 provides some details about loss of SFP coolant inventory events. Figures 3.1 and 3.2 provide an overview of the SFP loss of coolant inventory events in which the water level dropped and for which duration times could be quantified. These figures show that SFP losses of coolant inventory have been infrequent. However, several events lasted more than 12 hours and about 10 events resulted in water level decreases of more than 1 foot 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 3.2 Loss-of-Coolant Inventory Events

Type of Event	Actual	Precursor
Connected Systems	20	12
Configuration Control	16	2
Siphoning	3	1
PWR Transfer Tube	1	1
Piping	0	1
Piping Seismic Design	0	7
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

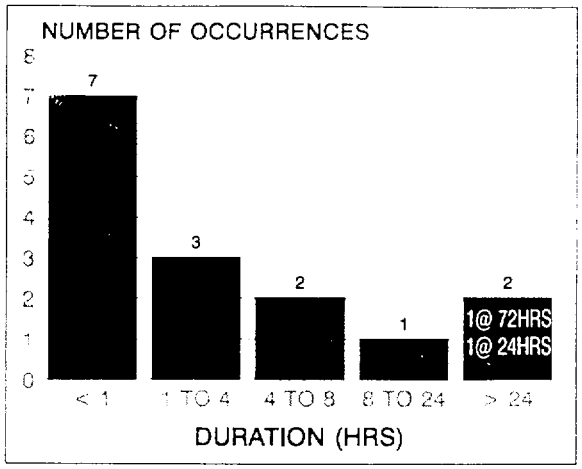

Figure 3.1 Loss of Inventory Duration

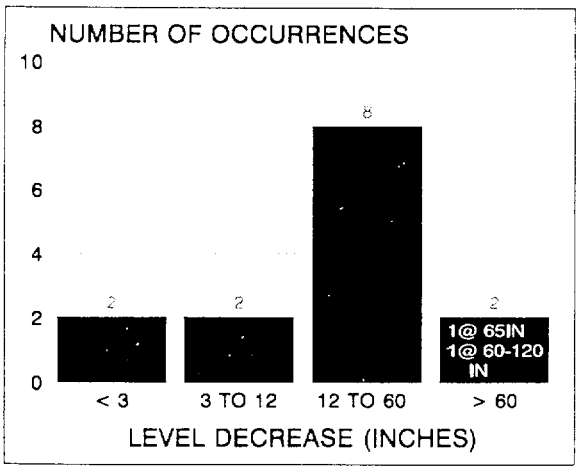

Figure 3.2 Loss of Inventory Levels

Using the number of events found during this review over a period of about 12 years for which the decrease in the water level could be quantified, the frequency of loss of inventory events in which loss of more than 1 foot occurred can be estimated to be on the order of less than 1 event per 100 reactor years.

3.1.1 Connected Systems

The majority of losses of SFP coolant inventory through connected systems was due to configuration control problems. These connected systems include the SFP cooling and purification system, a spent fuel shipping cask pool, sources of make-up, the fuel transfer tubes (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 gallons of refueling water were inadvertently lost from the refueling cavity and transferred to the plant's low-level waste system (Ref. 6). 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. The valve was part of the main steam line plug. This allowed refueling water to flow to the main steam line drains. About 30 minutes after the valve was opened, the SFP surge tank low-level alarm alerted the operations staff to an ongoing loss of water. While the operations staff started to add water, the make-up was not sufficient to avoid tripping both SFP cooling pumps on low suction pressure. One SFP cooling pump was restarted in about 3 minutes with no observed increase in SFP temperature. About 40 minutes later, the source of the inventory loss was identified and the valve was closed. This event resulted in reducing the water level about 1 inch in the refueling cavity and SFP, a fairly slow drainage rate. More that 23 feet of water was still above the top of the fuel in the SFP.

At Millstone Unit 2 on July 6, 1992, about 10,000 gallons of SFP water was drained to the reactor coolant system (RCS). At the time of the event, the unit had been shut down 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. However, during the alignment

process, a flow path was created that permitted flow via a gravity drain from the SFP to the RCS. The SFP water level dropped about 14 inches. According to the information reported, at least 23 feet of water was above the top of the fuel because no Technical Specification violation was reported. A 4 °F temperature rise occurred before the SFP cooling was restored (Ref. 7).

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, (Ref. 8) involved plugging of a single (nonredundant) vertical vent pipe acting as an antisiphon device. In this event, the SFP coolant loss was due to siphoning, but was masked by the SFP low-level annunciator being in the alarm condition because of other ongoing plant work. The event lasted about one-half hour. This event was terminated when a radiation alarm occurred coincident with a high level in the tank receiving the SFP water, alerting personnel to the coolant loss. This event resulted in a loss of between 5 and 10 feet of the SFP water level, one of the largest level decreases found in the study. Further, how far the level would have fallen had no operator action occurred is not clear.

In another event at San Onofre Unit 2 on June 22, 1988 (Ref. 9), about 9000 gallons of SFP coolant drained from the SFP to the reactor cavity through the SFP purification system because that system lacked siphon protection. This event lasted about 5.5 hours. 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 active fuel in the SFP would be about 13 feet if the operations staff failed to respond to two alarms.

Another event at Davis Besse on February 1, 1982 (Ref. 10), involved a temporary pump used to fill the SFP that created a siphon path when the pump was secured. In this event, about 21 feet 9 inches of water remained above the fuel.

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

Pressurized-Water Reactor 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 has occurred.

One site (Oconee Units 1 and 2) has a fuel transfer tube that has piping penetrations at a level 6 feet 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 hours. 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 such high levels that make-up to the SFP would be impossible. This problem has been corrected by adding remote make-up capability to the SFPs.

Piping and Piping Seismic Design. No actual events were found during which SFP system piping actually leaked, causing a loss of SFP coolant inventory. However, a variety of seismic piping design problems have been reported. The most prevalent type of problem involves use of the nonseismic SFP purification system for purifying 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 make-up to the SFP as well as compromise these sources as ECCS sources. In addition, other minor piping seismic design problems were discovered and reported. Seismic analysis is discussed in Section 7 of this report.

3.1.2 Gates and Seals

Large losses of SFP coolant inventory have occurred through SFP gate seals. Also, potentially large losses of SFP coolant inventory could be lost through reactor cavity seals.

Refueling Cavity Seals. At least two rapidly developing leaks were due to inflatable reactor cavity seals. In both these 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 gallons of water were drained to the containment building in about 20 minutes. At Surry Unit 1 on May 17, 1988, with all the fuel in the SFP, the seal failed and about 25,800 gallons were drained to the containment in about one-half hour. 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 in the inflatable seal deflating enough to cause leakage. While in both these cases, the SFP was not connected to the reactor cavity, these events and an additional four events discussed in the rest of Section 3.1.2 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 vulnerability to this type event.

The staff found four additional events in which cavity seals failed tests before the refueling cavity was flooded or where leaks developed in the seals following refueling. These events indicate that testing of inflatable seals is important in ensuring their operability. The events further emphasize the need to be aware of potential failures. Most of these events involved design problems. Only one was due to failure to maintain an adequate air supply to the inflatable seal. One event involved a gasket type (noninflatable) seal that 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 due to failure to maintain the air supply to the inflatable gate seals. In one case, the seal did not completely inflate. The majority of the air supply events was due to human error. Three of these events involved failed or disconnected level instrumentation. Most of these events occurred at PWRs. Leaks were generally large, involving tens of thousands of gallons of water, and a decrease of 2 or more feet of SFP water level. The decrease in water level rates ranged from fractions of a foot per hour up to several feet per hour. These drop rates can be dealt with and, in fact, in these events, the operations staff responded and restored level effectively.

One event, at Hatch on December 2, 1986, resulted in the fuel pool level dropping about 5.5 feet (Ref. 11). This event resulted from isolating the single air supply to the transfer canal's six gate seals. The seals partially deflated. This deflation resulted in a path for SFP water to go to the gap between the two unit reactor buildings and into areas of each unit's reactor building. When the source of the leak was discovered, the air source was restored and the leak was stopped. However, the event lasted about 24 hours. During this time, the SFP level was noted to be low and make-up 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 supplies for alternate gate seals so that inner seals were supplied from one unit and outer

seals were supplied from the other unit, establishing a degree of redundancy.

3.1.3 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 gallons per 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 (Ref. 12) a PWR design problem in which the SFP liner could buckle and leak at temperatures above 180 °F. This site is one of the sites 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. A core shroud bolt was dropped in this event at Hatch Unit 1 on December 28, 1994. An approximate 0.7-gallon-per-minute leak resulted between the fuel pool liner and the concrete SFP structure. The fuel pool level was restored and maintained with normal make-up (Ref. 13).

No other examples were found of loads actually being dropped that damaged the SFP. However, more than 30 situations involved loads heavier than allowable that were moved or could have potentially been moved over the SFP. Less than 20 percent 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 agency has taken steps to reduce the problem.

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

3.1.4 Spent-Fuel-Pool Make-up Capability

Only two events found during the operating experience review involved potential loss of SFP inventory make-up capability; no actual losses were found. One event involved a small accumulation of marine life in the service water pipe used for make-up 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-minute loss of an electrical bus needed to supply make-up water to the SFP. Operating experience indicates that losses of all make-up capability are not very likely.

3.1.5 Impact on Safety Equipment

Several events were reported that involved flooding caused by SFP overflow. These events had the potential to affect 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.

Two conditions were reported in which problems within the SFP could potentially lead to failure of important safety equipment. The licensee for Susquehanna Unit 1 submitted one report of a potential effect on safety equipment that was due to boiling of the SFP on

November 17, 1992 (Ref. 14). 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 loss-of-offsite power (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 affect safety-related equipment in the reactor building. The licensee event report stated that the postulated events were beyond the plant's design basis. These conditions were postulated by Mr. Lochbaum and Mr. Prevatte in the 10 CFR Part 21 report and were addressed in a June 1995 letter from the NRC to Pennsylvania Power and Light Company (Ref. 15).

The second report was a licensee event from WNP 2 issued May 28, 1993 (Ref. 16), which describes a circumstance in which, under operating conditions at the time of discovery while the local manual service water valve was closed, a postulated LOCA would render emergency SFP make-up 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, causing failure of ECCS equipment needed to mitigate the ongoing LOCA. The LOCA is postulated to make the local manual SFP make-up valve inaccessible. In this postulated scenario, the normal nonsafety make-up source is also assumed to be unavailable. Subsequent licensee investigation indicated that the local manual valves in the service water lines for make-up to the SFP could be opened when required after a LOCA.

3.2 Spent-Fuel-Pool Cooling

Fifty-six events found during the operating experience review involved actual losses of SFP cooling. There were 22 precursor events, which when coupled with additional failures or postulated events, could result in losses of SFP cooling. Table 3.3 gives a summary of the numbers and types of loss of SFP cooling events. Figures 3.3 and 3.4 give 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. However, some events lasted for significant periods, and four events resulted in temperature increases of more that 20 °F. The low number of events with small temperature increases may be due to a lack of reporting of such events.

Table 3.3 Loss of 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

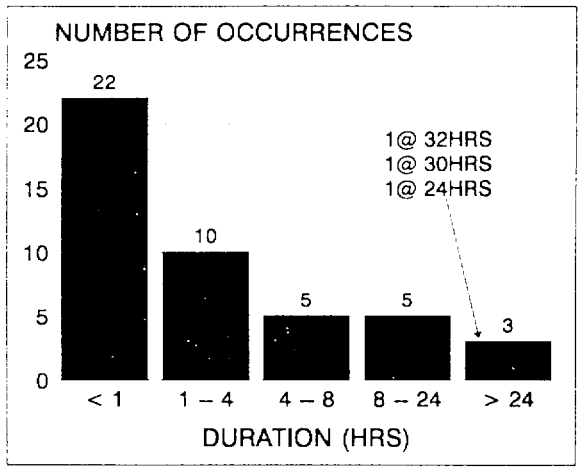

Figure 3.3 Loss of Cooling Duration

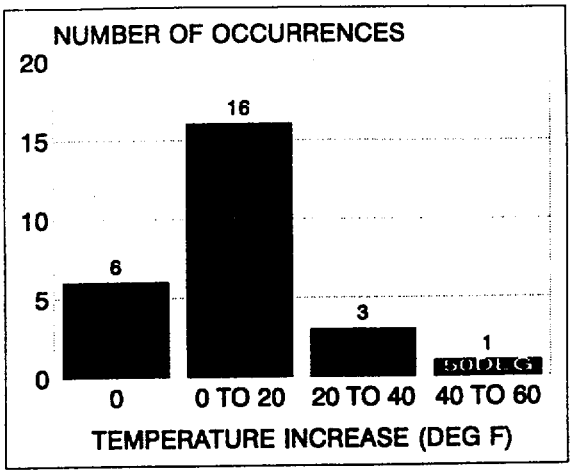

Figure 3.4 Loss of Cooling Temperatures

Using 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 events per 1000 reactor years.

3.2.1 Loss of Spent-Fuel-Pool Cooling

The dominant cause of the actual loss of SFP cooling events was loss of electrical 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 electrical power, the time for which cooling was not available ranged from a few minutes with no accompanying temperature increase to 8 hours with an associated temperature rise of 20 °F. Most plants have alternate sources of power available for SFP cooling pumps. No attempt was made during the event review to determine if alternate power was available in each event. The primary causes appeared to be human error and administrative problems in 22 of the 39 events. The events appeared evenly distributed between BWRs and PWRs.

Five events involved failure of one SFP cooling pump while 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. While events with the potential for common-cause, common-mode failure have been reported, none have occurred.

In four events, SFP cooling was lost owing to loss of SFP coolant inventory and consequent tripping of the SFP cooling pumps on loss of suction. In one flow blockage event, a rubber boot blocked an SFP cooling pump strainer. About 6 hours was required to remove the blockage. Although engineered safety features actuations have resulted in losses of SFP cooling, these losses resulted in almost no temperature increase and generally lasted for only short periods. They did not appear to present a threat to long-term cooling.

No actual events involving insufficient cooling 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 also occurred. This issue surfaced at Millstone Unit 1 (Ref. 17). 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.

3.2.2 Ineffective Heat Sink

The second leading cause of loss of SFP cooling was loss of SFP heat exchanger cooling. Of these 6 events, almost all were caused by human error. These events lasted from some very short periods to about 13 hours with temperature increases ranging from zero to 40 °F.

3.3 Spent-Fuel-Pool Instrumentation Experience

Several events involved losses of SFP coolant inventory or SFP cooling, in which associated instrumentation was inoperable or failed before or during the events. In one event, a shared annunciator window was illuminated because of an instrumentation problem when the loss of inventory occurred. Since the window was already illuminated, the operations staff was not alerted to the loss-of-coolant inventory event when it began. While relatively few of these instrumentation problems occurred, they raise concerns about how SFP instrumentation is treated and regarded. Section 6.2 of this report discusses SFP instrumentation.

3.4 Ventilation Events

The staff reviewed about 59 SFP area heating, ventilation, and air conditioning (HVAC) events. Portions of HVAC systems would be needed if a postulated loss of spent fuel cooling with consequent boiling and fuel failure were to occur. The summary of the 59 events is in Table 3.4.

Table 3.4 HVAC System Problems

Type of Event	Number
Fuel Moved Over SFP / HVAC Inop	15
Dampers	12
Building Breaches	9
Loads Moved Over SFP / HVAC Inop	5
Inefficient Filters	5
HVAC Radiation Monitor	4
Unable to Maintain Pressure	4
Heaters Inop	3
Insufficient Flow	2
Total	59

Most reported HVAC events had little impact on SFP equipment related to SFP cooling. For example, the most prominent type of event, moving fuel or other loads over the SFP with the HVAC inoperable, is not important to SFP cooling equipment. Events related to breaches of buildings are events during which doors were opened or panels were removed when they should not have been. Indication was generally received by the operations staff, and the problem was corrected relatively rapidly.

Lower-than-required flow was not a major problem with SFP equipment performance. Generally, flows were near the required amount. Likewise, negative pressure problems generally did not involve significant deviations from requirements.

Problems with radiation monitors that actuated SFP HVAC were generally identified quickly. Repair or compensatory action was generally taken in a timely manner. Filter efficiency problems were generally minor.

Two types of conditions involving dampers and HVAC heaters are potential problem areas. In the case of dampers, events indicate that sometimes the problem is difficult to identify and sometimes difficult to repair quickly. Heaters may be required to maintain relative humidity within filtering systems. Without the heaters, charcoal may lose ability to filter. However, the staff found relatively few heater problems.

3.5 Review of Foreign Operating Experience

During a review of foreign operational experience, the staff found about 24 separate events that were related to SFPs. Table 3.5 is a list of the types and numbers of events found. Generally, these events were consistent with U.S. experience.

Nine losses of SFP heat sink events occurred. In eight of these events, raw service water flow was lost at one plant over a period of about 1 year. The raw service water system cools the

intermediate cooling water system, which cools the SFP heat exchanger. In one event, component cooling water cooling was lost to the SFP heat exchanger. Two losses of SFP cooling were due to loss of electrical power to the pumps. These losses occurred at one site within a short period. They occurred during periods when a significant amount of electrical equipment (including 1 of 2 diesel generators) was out of service for maintenance or inspection.

Table 3.5 Events at Foreign Plants

Type of Event	Number
Loss of Heat Sink (8 at 1 site)	9
Inventory / Configuration Control	3
Loss of Cooling / Electric Power (1 site)	2
Pool Liner Leakage	2
Neutron Poison	2
Refueling Cavity Seal	1
Seal Deflation / Loss of Air	1
Heat Exchanger Leakage	1
Sever Inventory Loss / Pump Leakage	1
Fuel Assembly Dropped on Pool	1
Water in HVAC Ducts / High SFP Level	1
Total	24

One of the three events involving loss of SFP coolant level was due to configuration control. This event also resulted in loss of SFP cooling caused by tripping of the SFP cooling pump and was caused by cavitation when the level dropped.

SFP liner leakage at weld seams occurred at two sites. In one case, the amount of leakage was acceptable and repair was not made. At the other plant, weld seam repair was performed.

One event involved a generic design problem with SFP heat exchangers and resulted in a leak in one SFP heat exchanger. This leak developed after 7 years of operation and led to redesign of all similar types of SFP heat exchangers. No actual SFP heat exchanger failures were found in the review of U.S. operating experience.

One event involved a severe loss of SFP level caused by SFP pump seal leaks that were due to lack of maintenance. These leaks had existed for some time. Also, the operations staff knew about the loss of level but had not treated it as important. The problem received little attention, although corrective actions should have been taken to comply with procedures. The level dropped from about 34 feet to about 18 feet above the fuel.

One event involved a loss of SFP level because compressed air was lost to the gate seal between the SFP and the transfer canal. The gate between the SFP and the fuel transfer canal was closed for work on the fuel transfer machine. Water passed through the fuel transfer tube to the containment. The fuel transfer tube could not be shut because the fuel transfer machine could not be moved to clear the isolation valve. Tools left in the machine when the area was vacated because of incoming water from the SFP were blocking movement of the transfer machine. Air was reconnected to the seal but excess air pressure caused the seal to burst, increasing the flow rate to about 26,000 gallons per hour. The operations staff was able to close off an area in the containment. This closure limited the volume needed to be made up. About 211,000 gallons of make-up water were needed to equalize the levels in the containment area, the fuel transfer canal, and SFP. Adding this volume of water took about 7 hours. One event involved loss of refueling water at a BWR when the rubber bellows seal between the drywell and the refueling cavity failed.

3.6 Operating Experience Review Findings

Losses of SFP or refueling water inventory are dominated by events involving system or SFP configuration control problems that were due to human error. The second most prevalent cause of loss of SFP inventory is leaking inflatable

gate seals that were generally due to 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 was due to 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 agency has taken steps to reduce this problem.

The most prevalent type of loss of cooling events involved loss of electrical power to the SFP cooling pumps that were generally due to human error. The few losses of SFP cooling that were due to loss of SFP heat exchanger cooling were also generally due to 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.

While conditions have been reported that suggest the possibility of SFP boiling affecting other plant equipment important to safety, operating experience does not provide insights 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. This study captured relatively few of these instrumentation problems, but they represent concerns about how SFP instrumentation is treated and regarded.

Some ventilation events (damper problems, 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 make-up capability are not very likely.

4 OBSERVATIONS FROM THE SITE VISITS AND INTERVIEWS

The staff conducted six site visits 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. Two more trips were taken to conduct interviews. Mr. Prevatte and Mr. Lochbaum were interviewed to better understand their concerns as documented in the 1992 Susquehanna 10 CFR Part 21 report, and to apply the generic implication of those concerns to the industry. The following observations are from the site visits and the interviews. These observations are a cross-sampling and representative of the nuclear power industry.

Each site visit included a tour of the SFP, its associated equipment, the spent fuel building, and the control room to see the SFP indications. This allowed the AEOD engineers the opportunity to see the physical arrangement of the equipment in relation to other equipment and to the rest of the plant. The tours were conducted by licensee personnel who were highly knowledgeable about the configuration and equipment. In-depth discussions were conducted with the licensees on the procedures

and practices utilized for the SFP activities and the analyses that have been performed for the SFPs. Discussions were held with control room operators, outage planning engineers, probabilistic risk assessment (PRA) engineers, systems engineers, maintenance engineers, nuclear engineers, and electrical and instrumentation engineers.

No two SFP physical configurations were the same with respect to the locations of the SFP pump rooms, heat exchangers, and local equipment control panels. Most pumps and associated equipment are located below the level of the SFP. Most SFP cooling pumps are provided safety-related power. Switchgear rooms were not in the vicinity of the SFPs. Very little equipment other than refueling equipment is located in the SFP area. Generally, no equipment important to safety that could be damaged by the inadvertent boiling of the pool is within the pool area. The pools are divided into distinct areas that are used for specific purposes, such as cask loading.

Water level and temperature sensors are located in the pools. A very visible scale generally denotes pool level. The water level sensor is aligned with a vertical plate indicator. Power to this sensor and to the temperature sensor is generally safety related, but the sensors themselves are not safety related and do not have redundant instruments.

All the plants visited had once-through HVAC systems so that SFP atmosphere is not recirculated to other parts of the plant. Most plants had the capability to isolate the SFP area.

Several radiation monitors were in each SFP area. Some of these monitors are local alarms set on certain radiation levels for personnel evacuation. The rest of the radiation monitors are part of the plant's radiation monitoring system.

In the case of inadvertent draindowns, system leaks, and overflow of the SFP, the adjacent rooms and other pathways for water to escape are a concern. Most of these pathways are plant specific, and it is hard to determine from observations the path that water would take.

Local control panels usually have the SFP parameter indications and manual controls. The manual controls for the valves exist in various locations.

The control rooms have annunciators for the water level and temperature located on the main control boards. Few licensees have analog meters for both temperature and level. If one meter exists, the preferred parameter is the SFP temperature. The rest of the alarms are grouped into one annunciator labeled "SFP Trouble." This trouble alarm would include flows, loss of power, and inlet/outlet heat exchanger pressure. Radiation alarms are in a separate annunciator and are part of the plant radiation monitoring system. Radiation monitors do have analog readings in the control room, but they are located in the back panels.

Most activities related to the SFP are covered by procedures, especially the refueling activities. Procedures exist for logging operator rounds and using the specific refueling tools. Operators use procedures for aligning the make-up paths, and for reconnecting the SFP equipment after load shed and signals of engineered safety features activation. However, reconnecting the SFP pumps to the electrical supply is not usually covered in the top level of emergency procedures. Procedures for responding to all the SFP annunciators are in the control room. Before a refueling outage, the workers are trained in the general SFP activities and their specific tasks. Additional reactor operator assistance is present in the control room during refueling outages.

Operator rounds to record the SFP parameters are conducted at least once every 12-hour shift. Most utilities make the rounds twice per shift. With the recent trend toward shorter outages, SFP activities are now generally in the critical

path of the outage schedules. Outages have been shortened from 90 days to a target of about 20 days for some utilities. These shorter outages have forced utilities to perform SFP activities more efficiently and to do more work before the refueling outages begin. Outage scheduling and planning include more attention and detail to the SFP activities.

Although utilities are doing a good job of analyzing the SFP heat loads and heat up rates, the results of these analyses are not always given to the control room operators. These results 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.

During the site visits, the engineers identified events in which 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. Little attention is paid to the antisiphon devices. Very few sites performed testing or had analysis on the efficacy of the antisiphon devices.

There is a large variation in utility practice 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.

Responsibility for the SFP and its systems varies among licensees. While all have SFP system engineers, responsibility does not necessarily reside with the system engineer. The individual in charge of the various aspects of the SFP could reside in the Operations, System Engineers, Maintenance, or Nuclear Engineering organization. In some utilities, the responsibility is shared between groups. With shared arrangements, the possibility always exists that, if one does not know the other's responsibility, issues could be dropped inadvertently. Regardless of responsibility, when refueling starts, the Operation staff seems to have a very tight control of the SFP.

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. However, some older plants 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. Although not every plant used all the practices listed, some of the good practices observed in our visits 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 heat up 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 before 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 HVAC system for refueling.

The interviews with Mr. Prevatte and Mr. Lochbaum were very informative. They provided the details of their concern that the as-found Susquehanna SFP configuration did not meet the licensing basis. The 10 CFR Part 21 report that they filed does have potential generic implications, including—

- mechanisms to transport vapor to and create high temperatures in other parts of the plant
- electrical and instrumentation weaknesses in SFPs
- potential for multiunit sites with shared pools to have an increased SFP risk
- a lack of awareness for SFP issues

The 10 CFR Part 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 Part 21 report concerns, Pennsylvania Power and Light has improved the Susquehanna SFP design, modified its operation, improved emergency procedures, and improved operator training. A limited PRA showed that the net effect of these actions at Susquehanna would diminish the risk from SFP events.

5 REGULATORY REQUIREMENTS AND GUIDANCE

Regulatory criteria for the design of SFPs have evolved with case-by-case approval for the early plants to the existing criteria. Today, acceptance criteria are specified by the guidance in the Standard Review Plan, NUREG-0800 (Ref. 18); several Regulatory Guides; and the requirements in the General Design Criteria (GDC) of Appendix A to 10 CFR Part 50. Because of the evolution of the criteria and the different times that reactors were licensed, the criteria to evaluate the SFP designs among the operating facilities varies. Generally, the newer the plant, the closer the design is to the specified SRP criteria. Final acceptability of the SFP design, as described in the applicant's safety analysis report, is based on certain GDC and Regulatory Guides, and on independent calculations and staff judgement with respect to system functions and component selection. AEOD did not attempt to review any existing system against the criteria but did observe substantial variation in the designs.

The SRP provides the specific criteria from the applicable GDC and regulations and acceptable methods that can be used to meet the criteria.

Regulatory Requirements

Two sections of the SRP apply to the SFP: SRP Section 9.1.2, "Spent Fuel Storage," and SRP Section 9.1.3, "Spent Fuel Pool Cooling and Cleanup System." SRP Section 9.1.2 covers the acceptance criteria for the structural aspects of the pool for coolant inventory, reactivity control, and the monitoring instrumentation. SRP Section 9.1.3 covers the acceptance criteria for the SFP cooling system and coolant temperature control. Because the AEOD study dealt with the extended loss of SFP cooling, the AEOD study dealt more with the criteria in SRP Section 9.1.3 than Section 9.1.2.

In 1970, the U.S. Atomic Energy Commission, forerunner of NRC, developed Regulatory Guide 1.13, "Design Objectives for Light-Water Reactor Spent Fuel Storage Facilities at Nuclear Power Stations," to provide specific methods acceptable to the staff for preventing loss of water from the SFP, protecting fuel from mechanical damage, and providing capability for limiting the potential offsite exposures from a significant release of radioactivity from the fuel. The other applicable Regulatory Guides, Regulatory Guide 1.26, "Quality Group Classification and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants," Regulatory Guide 1.29, "Seismic Design Classification," Regulatory Guide 1.52, "Design, Testing, and Maintenance Criteria for Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants," and Regulatory Guide 8.8, "Information Relevant to Ensuring That Occupational Radiation Exposures at Nuclear Power Stations Will Be As Low As Is Reasonably Achievable," were not developed specifically for the SFP but have some guidance that applies to the SFP.

SFP overall design requirements are in Appendix A, GDC 2, 4, and 5. Criterion 2 states that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, and tsunami. Criterion 4 states that structures, systems, and components important to safety shall be designed to accommodate the effects of the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents. Criterion 5 states that structures, systems, and components important to safety shall not be shared among nuclear power units unless it can be shown that such sharing will not significantly impair their ability to perform their safety functions, including, in the event of an accident in one unit, an orderly shutdown and cooldown of the remaining units.

SFP requirements for fluid systems are in Appendix A, GDC 44, 45, and 46. Criterion 44 states that a system to transfer heat from structures, systems, and components important to safety, to an ultimate heat sink shall be provided. The system safety function shall be to transfer the combined heat load of these structures, systems, and components under normal operating and accident conditions. Criterion 45 states that the cooling water system shall be designed to permit appropriate periodic inspection of important components, such as heat exchangers and piping, to ensure the integrity and capability of the system. Criterion 46 states that the cooling water system shall be designed to permit appropriate periodic pressure and functional testing to ensure the structural and leak tight integrity of its components, the operability and the performance of the active components of the system, and the operability of the system as a whole and under conditions as close to design as practical, the performance of the full operational sequence that brings the system into operation for reactor shutdown and for LOCAs, including operation of applicable portions of the protection system and the transfer between normal and emergency power sources.

Fuel and radioactivity control requirements are in Appendix A, GDC 61, 62, and 63. Criterion 61 states that the fuel storage and handling, radioactive waste, and other systems that may contain radioactivity shall be designed to ensure

adequate safety under normal and postulated accident conditions. These systems shall be designed with a capability to permit appropriate periodic inspection and testing of components important to safety, with suitable shielding for radiation protection, with appropriate containment, confinement, and filtration systems, with a RHR capability having reliability and testability that reflects the importance to safety of decay heat and other RHR, and to prevent significant reduction in fuel storage coolant inventory under accident conditions. Criterion 62 states that criticality in the fuel storage and handling system shall be prevented by physical systems or processes, preferably by use of geometrically safe configurations. Criterion 63 states that appropriate systems shall be provided in fuel storage and radioactive waste systems and associated handling areas to detect conditions that may result in loss of RHR capability and excessive radiation levels and to initiate appropriate safety actions.

6 ENGINEERING ASSESSMENTS

In support of this study, AEOD performed engineering assessments of the electrical system, instrumentation, heat load, and radiation areas. The electrical assessment was to understand the type of power supplies for SFP cooling system components, such as pumps, valves, and instrumentation. The instrumentation assessment included gathering of information on the type of instrumentation used to monitor the system parameters and desirable enhancements to the instrumentation. The electrical and instrumentation assessments were based on a review of system design data for a sampling of plants and the results of the site visits.

The heat load assessment included independent calculations on heat up and boiling of the SFP resulting from complete loss of cooling for a typical PWR and a BWR. The calculations estimated the time to reach boiling conditions to determine if the time is consistent with the industry calculations. The radiation assessment presented the results of utility calculations on the radiation level that would exist for different SFP water levels. Detailed results of these assessments are discussed in Sections 6.1 through 6.4 of this report.

6.1 Electrical Assessment

The staff reviewed design features of spent fuel cooling systems of a representative sample of 14 plants to understand the type of electrical power supplies to the SFP cooling systems at these plants. The review included representative samples of BWRs and PWRs for vendors General Electric, Westinghouse, Combustion Engineering, and Babcock & Wilcox. The design features of electrical power supplies varied among different plant types and vendors, and sometimes even among plants designed by the same vendor.

The SFP pumps for approximately 80 percent of these plants have qualified and fully independent Class IE power supplies. For these plants, the normal source of power is the offsite grid system, and the emergency source is the diesel generators. Load shedding under LOOP conditions is initiated by undervoltage relays. After the diesel generators have energized the emergency buses, the emergency loads are automatically started by the load sequencer. The SFP pumps are not automatically started, but need to be manually started by the operator after all emergency loads are started.

The power supplies for the SFP pumps for the remaining plants reviewed are Non-Class IE. In the event of a LOOP at these plants, the SFP cooling function will be lost.

The information in the Final Safety Analysis Report and in other sources was insufficient to determine the type of power supplies for the system valves and instrumentation, (i.e., whether they are Class IE, qualified, and redundant).

The observations from the site visits were in general agreement with those from the review on the type of power supplies for SFP pumps. Most sites have Class IE power supplies for the SFP pumps and the system instruments, although the instruments themselves are not safety related.

6.2 Instrumentation Assessment

Review of the design features of SFP cooling system instrumentation for the same sample of 14 plants noted in Section 6.1 gave the team a general understanding of the type of instrumentation at these plants. In addition, the team visited six other plants to obtain instrument information. As in the case of electrical power supplies, the design features of instrumentation varied among different plant types and vendors, and sometimes even among plants designed by the same vendor. Notwithstanding these differences, this section describes the instrumentation features that are typical of the industry.

The results of the review are summarized in Table 6.1. Each plant had some type of instrumentation to monitor the SFP system performance, although the type and extent of instrumentation varied significantly among plants. The parameters monitored include SFP level, temperature, liner leakage, pump discharge pressure, and system flow. Indication, recording, or alarm functions of these parameters are provided either in the main control room or on a local panel. Typically, most instrumentation is on the local panel, and only important parameters are monitored in the control room. However, most local alarms initiate a common trouble alarm in the main control room and an operator is dispatched to investigate the cause of the trouble.

Each plant had level and temperature instrumentation. SFP level is monitored locally, but an abnormal level is alarmed in the control room. For half the plants, the temperature is indicated or recorded in the control room; for the other half, the temperature is on a local panel. For most plants reviewed, an abnormal temperature is individually alarmed in the control room. For other plants, the alarm is on the local panel that initiates a common trouble alarm in the control room.

Table 6.1 SFP Instrumentation Summary (14 plants)

Parameter	L[1]	T[2]	LD[3]	P[4]	F[5]
Plants monitored	14	14	11	11	3
Indicated (CR[6]/Loc[7])	5/10	6/6	0/8	0/8	0/1
Alarmed (CR/Loc)	11/7	12/3	3/3	5/3	2/0

1 Level
2 Temperature
3 Leak Detection
4 Pump discharge pressure
5 Flow
6 Control Room
7 Local

The SFP level sensor has a narrow range, typically 4 feet, covering high and low alarm setpoints and the minimum Technical Specification level. The control room level indicator provided by this sensor is good only for this narrow range. Therefore, the control room indicator cannot monitor a level below this range and becomes useless for lower level conditions expected in case of a gross loss of SFP coolant inventory event.

A direct indication in the control room of SFP level and temperature would be desirable to minimize operator response time for events involving rapid loss of SFP coolant inventory or loss of SFP cooling. The present design feature of local indication with a trouble alarm in the control room for these parameters may prove to be insufficient for quickly responding to such events as full core off-load heat up caused by loss of inventory. Lack of direct indication in the control room will complicate diagnosis of

events. Typically an operator needs to be dispatched to determine the cause of trouble, which is time consuming. Developing trends for SFP level and temperature can be difficult because the control room operators have to depend on infrequent local operator rounds (typically once in 6 hours). The capability to develop trends for the parameters allows the operator the opportunity to react more quickly to developing problems. Therefore, a direct indication of SFP level and temperature in the control room, consisting of analog readings and annunciators, would be a desirable safety enhancement.

In most plants, SFP pump discharge pressure is used as an indication of adequate system flow. Only a few plants employ direct flow measurement. In all cases, the pressure or flow is indicated locally. An abnormal pressure or flow would be annunciated in the control room for most plants and on the local panel for others.

The SFP liners in almost all plants reviewed have with some form of local leakage detection. Abnormal leakage is alarmed only for a few plants, locally or in the control room. For other plants, an operator would periodically check the leakage detection system for any indication of abnormal leakage.

These plants have various radiation monitors in a system separate from the SFP cooling system. Local area monitors are provided for personal safety in case of a need to evacuate the area. The other monitors are part of the station radiation monitoring system. These monitors alarm in the control room through the annunciator system. In addition, the radiation monitors have analog meters and recording signals.

The newer plants have safety-related power to the SFP instrumentation, but the instruments themselves are not safety related. The older plants have neither safety-related power supplies for the instrumentation, nor instruments that are safety-related. The plants in general, new and old, have no redundancy for the SFP instrumentation.

6.3 Heat Load Assessment

The AEOD staff performed independent calculations on the heat up and boiling of the SFP resulting from a complete loss of cooling, calculating the SFP heat up rate, the time for the SFP water to reach the boiling point, and the time for the water to boil down to the top of fuel. The calculations were done for a typical PWR and a BWR, using simplified and generally conservative assumptions, under maximum heat load conditions.

The major assumptions and the results of the calculations are summarized in Table 6.2. For the typical PWR and BWR, the calculated heat up rates were 9.3 and 15.2 °F/hour, the times to reach the boiling point were 12 and 7.4 hours, and the time to boil down to the top of the fuel were 80 and 50 hours, respectively. The difference in values for the PWR and BWR cases were mainly due to the larger volume for

Table 6.2 SFP Heatup Calculations

	PWR	BWR
Plant (Data Source)	Surry	Limerick
Plant Rating, MWe	781	1055
Major Assumptions:		
Heat Load, BTU/hr	41 E6	38 E6
Water Volume, cubic feet	71,000	40,000
Water Volume above fuel	46,000	26,000
Initial SFP Temp., °F	100	100
Time after Shutdown, hours	100	216
Results:		
Heatup Rate, °F/hour	9.3	15.2
Time to Boiling Point, hours	12.0	7.4
Time to top of fuel, hours	79	50

the PWR (71,000 cubic feet versus 40,000 cubic feet for the BWR).

The calculations were based on maximum expected heat load under worst-case conditions, such as full core off-load and a back-to-back refueling scenario (for a dual unit site) with maximum expected inventory of spent fuel from previous refueling outages. The heat load assumed was 40.8 X E6 BTUs/hour for the PWR and 37.6 X E6 BTUs/hour for the BWR, as found in the Final Safety Analysis Report or licensee's calculation.

Operating experience has shown that, in an effort to minimize refueling outage time, many plants perform full core off-loads early in their outages. AEOD discussions with the engineering manager of Nine Mile Point Unit 2 provided good insight into the effect this practice has upon reducing the time available until boiling begins.

Figure 6.1 shows the time from reactor shutdown until completion of the full core off-load at Nine Mile Point Unit 2. As Figure 6.1 indicates, the period of shutdown until completion of the off-load decreased from

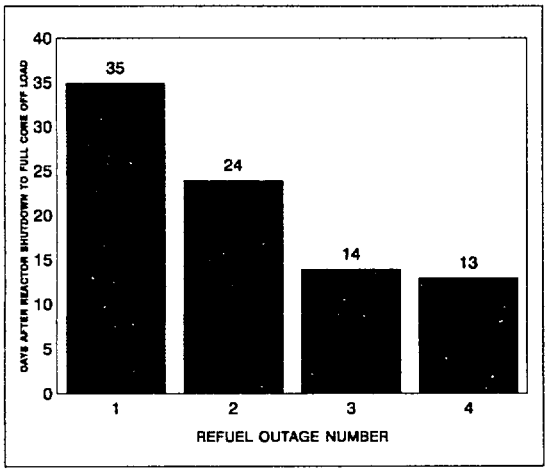

Figure 6.1 History of Full Core Offloading

35 days in the first outage to 13 days in the fourth refueling outage. Figure 6.2 shows the time to initiate boiling as a function of outage number with the refueling pool gates in and out. During the first four refueling outages the refueling pool gates were out at Nine Mile Point Unit 2. However, if maintenance work would have been required on the reactor vessel or appurtenances during those time it would have been necessary to have the refueling pool gates installed, thereby leading to shorter times to spent fuel boiling. Similarly, during a visit to the South Texas plant, AEOD learned that calculations performed for the most recent refueling outage estimated that the initiation of boiling could begin approximately 5 hours after the SFP cooling is lost. The NRR survey assessment of the South Texas plant also indicated that if a full core had to be off-loaded during midcycle, boiling could begin about 2 to 3 hours after losing SFP cooling.

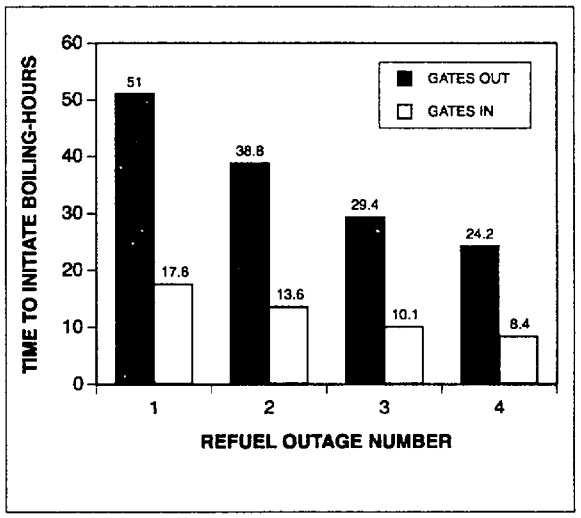

Figure 6.2 Reduced Time to Boil

Although the estimate of time to reach the boiling point and time to boiling down to the top of the fuel could vary among plants, the results of the AEOD calculation are indicative of the typical order of magnitude estimate for U.S. plants. These estimates are consistent with the estimates provided by several licensees.

6.4 Radiation Assessment

In addition to providing the vehicle to remove heat from the spent fuel, the water in the pool is relied upon to provide shielding for plant personnel. Loss of SFP coolant inventory with decreased SFP water levels can result in excessively high radiation fields that would prohibit entry into the SFP area. The shielding effect of the water in the SFP increases exponentially with increasing water level. Table 6.3 shows the results of several licensees' calculations that indicate the effectiveness of the water shielding associated with spent fuel.

As shown on Table 6.3, the radiation dose level at the surface of an exposed spent fuel bundle was estimated to be 250,000 rem/hr. The same bundle would produce a radiation dose level of 2.5 rem/hr with a shielding of 5 feet of water. The radiation dose level from the same bundle would decrease to less than 20 mrem/hr with a shielding of 8.5 feet of water.

Table 6.3 Radiation Shielding Estimates

Plant	Water Depth	Bundles	Rem/ hr
Susquehanna	0 inches	single	250,000
	5 inches	multiple	100,000
	5 feet	single	2.5
	8.5 feet	single	.02
Oconee	1 foot	multiple	900,000
TMI 1	6.5 feet	single	.007
North Anna	7 feet	single	<.05

Each of the plants visited had radiation detectors in the SFP areas with control room and local monitors and alarms. Discussions with plant staff indicated that the personnel were well trained and very knowledgeable of plant policies and regulatory aspects of radiation such as radiation control and health physics for ensuring that the exposure of personnel to radiation is maintained as low as reasonably achievable. However, little information was available to the operating staff for comprehending the radiation fields that would be present in the vicinity of the SFP during an accident. A comment expressed at several plants was that if things went bad the radiation monitors would go off and that was the signal to "clear out."

Recognizing the need to add water to the SFP during an accident from the standpoints of fuel cooling and personnel habitability, many plants do have remote "alternate" or "emergency" fuel pool make-up capability. Remote "alternate" or "emergency" fuel pool make-up capability is not a regulatory requirement; however, it does appear to be a matter of prudence. In a worst-case scenario, accessibility to the SFP area could become an important issue if local manual actions were necessary to connect a make-up source.

Discussions with plant personnel indicated that the information available to them about radiation doses was limited to individual bundles but did not address the entire pool. This appears to result from a mind-set in which the operating staff envisions a spent fuel accident to be one that involves the handling of a single bundle as a very credible event, whereas they may not envision a major loss of coolant inventory from the SFP as a credible event. At several plants the operators did not have ready access to information about the radiation doses from the SFP (versus an individual bundle) as a function of SFP water level even though engineering had already performed such calculations.

The plant staffs were all familiar with the SFP water-level requirements, however their responses were mixed when it came to addressing the minimum amount of water needed for shielding to enable habitability during a SFP accident. Operators indicated that water shielding requirements to allow access to the refueling and spent fuel areas were between 4.5 to 10 feet.

7 RISK ASSESSMENT

Over the years, the SFP has not received the risk assessment attention that the reactor has because early analyses put the risk of a SFP accident an order of magnitude below a reactor event. Therefore, the analyses done for the SFP were limited. However, in recent years 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 useful insights to assess the current risk of SFP accidents. In addition to those risk insights, INEL utilized the AEOD operating experience review, engineering analyses, site visits, and site interviews in assessing the likelihood of SFP events.

7.1 Existing Probabilistic Risk Assessment

The INEL study included the review of three previous risk assessments that were relevant to SFPs: (1) NUREG/CR-4982, "Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82," (Ref. 19); (2) NUREG-1353, "Regulatory Analysis for the Resolution of Generic Issue 82, 'Beyond Design Basis Accidents in Spent Fuel Pools'" (Ref. 20); and (3) "Risk Analysis for Spent-Fuel-Pool Cooling at Susquehanna Electric Power Station," (Ref. 21).

7.1.1 NUREG/CR-4982, "Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82"

NUREG/CR-4982 documented an assessment performed in 1987 by Brookhaven National Laboratory (BNL) of the likelihood and consequences of a severe accident in the SFP. The authors concluded that the risk estimates are quite uncertain and could potentially, under the worst-case assumptions, be significant. The assessment identified potential mechanisms and conditions for failure of spent fuel cooling and subsequent release of fission products. Millstone Unit 1 and Ginna, two older designs, were the plants evaluated for the assessment. Frequency estimates for loss of SFP coolant inventory initiated by loss of cooling, missiles, and pneumatic seal failure were very low. However, the frequency estimates for loss of SFP coolant inventory caused by structural failure in a seismic event and heavy load drops were quite uncertain. In the case of seismic events, both the seismic hazard and structural fragilities contribute to the uncertainty range. For heavy load drops, human error probabilities, structural damage potentials, and recovery actions were the primary sources of uncertainties.

BNL assessed the conditions that could lead to failure of the spent fuel Zircaloy cladding if the cladding ruptured or a self-sustaining oxidation reaction occurred, and they estimated the SFP fission product inventory and the releases and consequences for the various cladding failure scenarios. Possible preventive or mitigative measures were qualitatively evaluated. The uncertainties in the risk estimate for a pool fire are large, and BNL identified areas where additional evaluations are needed to reduce uncertainty.

7.1.2 NUREG-1353, "Regulatory Analysis for the Resolution of Generic Issue 82, 'Beyond Design Basis Accidents in Spent Fuel Pools'"

NUREG-1353 was a value/impact and cost-benefit evaluation performed in 1989 that concluded that there were no cost-effective options to mitigate the risk beyond the licensing basis for SFPs. Previously, WASH-1400 (Ref. 22) considered SFP risks to be an order of magnitude below reactor risks. In 1989, the agency determined that SFPs required re-examination because more fuel was being stored in the pool than originally intended and new seismic concerns had arisen for the eastern plant sites. More fuel in the SFP increased the risk of fire propagation owing to the zircaloy cladding. A zircaloy cladding fire can occur at 1650 °F and such temperatures could be reached if the SFP lost all cooling and inventory. From this evaluation, PWRs were determined to be four times more susceptible to cladding fire than BWRs because of the configuration of their

storage racks. Risk from beyond design basis earthquakes to the SFP was no greater than damage to the reactor core from safe shutdown earthquakes.

7.1.3 "Risk Analysis for Spent Fuel Pool 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," 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 NBF, and order-of-magnitude estimates of core damage frequency (CDF) attributed to SFP heat-up events.

The PNL analyses addressed design basis accidents that would cause mechanistic failure of the nonsafety-related SFP cooling system. The accident scenario postulated by Mr. Lochbaum and Mr. Prevatte in their 10 CFR Part 21 report, an RCS LOCA, would result in de-energizing 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 find major SFP coolant inventory losses from configuration control, gates, and seals to be credible events.

The results of the analyses indicated that the risk from SFP events was low compared to 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 improvements that were made at the Susquehanna station in response to the issues raised by the 10 CFR Part 21 report resulted in a NBF reduction of about a factor of four with a commensurate reduction of risk of about a factor of four.

The results of the PNL study were integrated into NRR's Safety Evaluation, "Susquehanna Steam Electric Station, Units 1 and 2, Safety Evaluation Regarding Spent-Fuel-Pool Cooling Issues." 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." 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."

Although large uncertainties may be associated with the absolute values and specific numerical results of the PNL analyses, much insight can be gained from the PNL analyses 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-tying SFPs.

7.2 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 PNL PRA model. This 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 the insights obtained from these INEL efforts (Ref. 23).

7.2.1 Risk Assessment—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, the INEL staff visited Pennsylvania Power and Light engineering offices and the Susquehanna station. The event and fault trees were quantified, using recent operating experience data supplied by AEOD. 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, INEL 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 database, to cover a full spectrum of loss of SFP inventory events, including catastrophic seal failure. The results of their analysis are shown in Table 7.1. INEL found the NBF for the Susquehanna plant, after implementing the 10 CFR Part 21 improvements, to be 5E-5/year, which is approximately twice that found by PNL.

Table 7.1 Near-Boiling Frequencies

	INEL	PNL
Total NBF	5 E-5	2 E-5
LOOP	3 E-5	1 E-5
Inventory Losses	2 E-5	1 E-6

The dominant event initiators were LOOP and SFP inventory losses, including configuration control errors and seal failures. Because of limited time and resources, INEL did not 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, these estimates need further refinement before they can be used as a basis for regulatory actions.

7.2.2 Risk Assessment—Qualitative Results

The SFP PRAs 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 that have been learned from those studies may have generic applications. For example:

(1) **Effect of defueled unit upon operating unit.** The analyses showed that for a dual-unit BWR, a problem with SFP cooling at a shutdown unit could affect the adjacent operating unit. The accident scenario postulated in Mr. Lochbaum's and Mr. Prevatte's 10 CFR Part 21 report was found

to be a credible event, but less likely than other events.

(2) **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."

(3) **Effect of Mr. Lochbaum's and Mr. Prevatte's 10 CFR Part 21 Report.** Comparison of the analyses that were done for the Susquehanna plant as it existed at the time of the 10 CFR Part 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 the following:

- 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

(4) **Dominant accident sequences.** For the Susquehanna plant, PNL 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 busses. The original accident scenario raised in the 10 CFR Part 21 report did not appear to be a significant contributor to NBF. INEL found that the dominant contributors to NBF were LOOP and SFP inventory loss.

(5) 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 days to 35 days
- partial core off-loads taking place earlier in the outage

(6) **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; once every 10,000 reactor years.

8 FINDINGS AND CONCLUSIONS

The findings and conclusions presented in this section are based on review of operating events and interpretations of the available risk analyses. The conclusions are stated, followed by indented paragraphs giving the findings on which these conclusions are based. These findings and conclusions are grouped under the headings of (1) likelihood and consequences of SFP events, (2) prevention of SFP events, and (3) response to SFP events.

8.1 Likelihood and Consequences of Spent-Fuel-Pool Events

8.1.1 Loss-of-Coolant-Inventory Events

From review of more than 12 years of operating experience, the staff determined that loss of SFP coolant inventory greater than 1 foot has occurred at a rate of about 1 event per 100 reactor years. Loss of SFP cooling with a temperature increase greater than 20 °F has occurred at a rate of approximately 3 events per 1000 reactor years. The consequences of these actual events have not been severe. However, some events have resulted in loss of several feet of SFP coolant level and have exceeded 24 hours. The primary cause of these events has been human error.

- Two loss of SFP coolant inventory events occurred in which SFP level decrease exceeded 5 feet. These events were terminated by operator action when approximately 20 feet of coolant remained 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 resulting in radiation fields that would have prevented access to the SFP area. The events with the largest level of decrease involved unavailable or inaccurate instrument readings. Ten other loss of inventory events resulted in level decreases between 1 and 5 feet. Operator response to one of the largest losses of SFP coolant inventory events (loss of 5.5 feet of water level in SFP) was deficient because several opportunities to diagnose and correct the problem were missed when make-up coolant was added to the system without evaluating the cause of the need for make-up. Two precursor events involved cavity seals that precipitated rapidly developing leaks. In one case, about 200,000 gallons of water were lost in about 20 minutes. In the second case, about 25,800 gallons were lost in about 30 minutes.

- Several losses of SFP cooling continued for more than 24 hours; one had a maximum temperature increase of 50 °F to a final temperature of 140 °F. There were no reported approaches to boiling during the experience review period.

- While 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 and, therefore, were not initially captured by the study's event review process.

8.1.2 Possible Consequences of Loss-of-Coolant Inventory

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

- Risk assessment identified loss of offsite power and loss of SFP coolant inventory were the major contributors to near-boiling frequency. 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 is dependent upon plant-specific design features. The NRR survey of SFPs identified a wide range of plant design features and specific limitations at existing plants. Plants which 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. In fact, the modest improvements to instrumentation and operations made by Susquehanna resulted in reduced risk.

Assessment of operating experience determined that licensee efforts to reduce outage duration have resulted in full core off-loads occurring 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.

8.1.3 Need for Specific Corrective Actions

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.

- Risk assessment identified loss-of-SFP-coolant inventory was 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.

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

8.2 Prevention of Spent-Fuel-Pool Events

8.2.1 Configuration Control

The need for improvements to configuration controls related to the SFP to prevent 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.

8.2.2 Plant Modifications at Multiunit Sites

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.

- The Susquehanna 10 CFR Part 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. Specifically, there is the need to assess the potential for mechanisms to transport vapor to create high temperature in other parts of the plant that have critical plant equipment. The NRR survey identified

seven sites besides Susquehanna that have shared pools. Since the scenario involves the potential for many things to go wrong and because each configuration is different, these seven sites need additional assessment and evaluation.

8.3 Response to Spent-Fuel-Pool Events

8.3.1 Operator Response

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 and 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 the potential for near-boiling conditions within 5 to 10 hours if cooling to the SFP is lost. Current operator training and procedures do not typically include this information, or if the information is included 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 visited. Of the licensees that 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, the engineers and operators had knowledge and awareness of relevant SFP issues. Regarding backup sources for SFP coolant inventory and SFP cooling, discussions with the licensees revealed many ways that water could be provided to the pool that had not formerly been described and for which procedures do not exist.

8.3.2 Procedures and Instrumentation

The need to improve 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 develop trends of the SFP data and stop a developing problem before it becomes a serious event. In several events, SFP cooling was lost because power to the SFP pumps was lost. Most power supplies to the SFP pumps are safety related. For units that do not have safety-related power for the pumps, there is a need to assess whether having such power during accident conditions would assist them in reacting faster to an SFP event.

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