Appendix 10 - Analysis of Zaporizhzhya, Unit 1 Fire on January 27, 1984

A10.1 Plant Characteristics

Zaporizhzhya is a six unit nuclear power plant site located near Energodar, Ukraine.[A10-4,5] All six units are of the VVER-1000 design. At the time of the fire described here, Ukraine was a part of the former Soviet Union. Plant construction on Unit 1, begun in 1980, was in its last stages when a severe cable fire occurred on January 27, 1984. As a result, the plant's initial operations were delayed until late 1984 (November[A10-4] or December[A10-5]). The plant began commercial operations in April 1985.[A10-4] At the time of the fire, some of the cable penetration seals were not installed yet, and there were other penetration seals that had been reopened for inspection. The other units at the site began operations between 1985 and 1995.

A10.2 Chain of Events Summary

On January 27, 1984, Unit 1 was in the last stages of construction and apparently the reactor was not activated yet. At 17:15, a fire was reported at elevation 13.2m of the Control Building. It was later postulated that a failure in the terminal box No. 114 had caused the fire. The features of the box and the nature of the initiating fault are not clear from the available information. The reports postulate that a loose item had fallen into the box.

The fire propagated via cables coming out of the terminal box and into a cable shaft where it started to burn its way up the cable risers. The fire eventually spread through practically all elevations of the control building. In response to the fire, the operators tripped the electrical system, including the DC power system.

All attempts to put the fire out in the initial stages failed. Two operators even tried to crawl under the smoke and approach the fire with hand held extinguishers, but they had to pull back because of the heavy smoke. Plant personnel and off-site fire brigades were summoned to support fire suppression efforts. Using a stairwell for positioning themselves, the fire brigade sprayed water at different points of the Control Building. However, since the fire brigade personnel were not familiar with the building layout, and because of the heavy smoke in the building, they were ineffective at fighting the fire in some locations, and the fire continued to propagate. In the end, over 115 fire fighters participated in the fire fighting effort.

Until 19:25, about 2 hours after ignition, the fire had remained confined to the cable shaft. At this point fire barriers failed and the fire propagated into areas adjacent to the cable shaft on four separate elevations (16.0, 19.0, 21.0 and 24.0 m). At elevation 16.0 the deluge system was activated (it is not clear whether this was done manually or automatically) and that controlled the fire on that level. The fire on elevation 20.0 m was stopped by the sprinkler system on that level. Although by 21:00 the fire at elevation 16.0 was declared extinguished, the fire continued to propagate to elevations 19.0 m and 24.0 m. On elevation 19.0 m, the fire was stopped by a sprinkler system. Despite the impact of fixed suppression systems at different elevations, the fire continued to propagate and by 21:40 it reached elevations 28.3 m and 41.0 m.

At 24:00 the fire was declared as out and the fire pump was stopped. However, at 01:15 on January 18, plant personnel noticed a cable fire at the 20.4 m elevation. This was apparently a re-ignition of the previously suppressed fire on this level. The fire pump was restarted and fire water was sprayed inside the impacted cable shafts and in cable chase areas. The fire fighting continued for another 11 hours and finally after more than 17 hours from the discovery of the fire, the fire was declared as completely extinguished.

A10.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A10-1] and [A10-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On January 27 1984, Unit 1 was in the last stages of construction. Some of the cable penetration seals were not installed yet and there were other penetration seals that were reopened for inspection. At this stage of construction, the automatic fire suppression system and fire detectors inside cable trays and cable shafts were not yet activated. The dry-pipes of the deluge system for cable trays and cable shafts were temporarily connected to a fire water system that required manual activation.	Construction often presents unique fire hazards and construction phase fires are often discounted in fire PRAs. In this case, the fire appears to offer valuable lessons despite the fact that the plant was still under construction. It does not appear that the fact that construction was ongoing had a significant impact on the fire's progression. In particular, it would appear that despite reports of incomplete fire barrier penetration seals, the fire did remain confined to the initially impacted cable shaft for two hours or more before spreading to adjacent areas.
00:00	At 17:15, a fire was observed at elevation 13.2 m of the control building. It had started in or near terminal boxes No. 112 and 114. As a result of incident investigation, it was concluded that the fire may have been caused by a short in 112-114 terminal box at elevation 13.2m. The short circuit may have started in a cable (it was suspected that something had dropped inside the terminal box).	This event can be classified as a self ignited cable fire. In fire PRAs for U.S. plants, the possibility of occurrence of self ignited cable fire is considered to be very unlikely. It is also interesting that the reports cite that the fault likely started inside the box and that the fire propagated to the cables outside the box. However, the condition of the cable penetrations into the terminal box are not known.
--	The fire propagated into a cable shaft	Vertical cable risers are recognized as a potential fire hazard in fire PRAs.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	As soon as the shift supervisor received news about the fire, he ordered the control room operators to initiate isolation of electrical devices.	Plants in the former Soviet Union typically require by procedure that power be isolated before fire fighters attack fires in electrical equipment. Since the plant was not in operation this likely had little or no real impact.
00:20	At about 17:35, a supervisor and his assistant crawled under the smoke towards the fire on elevation 13.2m and tried to extinguish the fire with hand held extinguishers. Their attempts were futile. Because of the heavy smoke, they had to retreat to safety.	In this case, the fire brigade had already been notified of the fire and called out. Hence, the attempts by operators to extinguish the fire would not have delayed the later response by trained fire fighters. However, the event illustrates that early intervention by un-trained or ill-equipped personnel may not be successful.
00:23	At 17:38 fire brigade arrived at the plant.	In a U.S. plant the primary fire brigade is on site, and a more rapid response would typically be assumed.
--	A fire pump was started manually.	
00:45	By 18:00, using the stairwell for positioning themselves, the fire brigade sprayed water at different points of the control building. However, since the fire brigade personnel were not familiar with building layout and because of the heavy smoke in the building, they failed to be effective and fire continued to propagate. At this time fire fighting was taking place from the cable spreading room for the 3rd train, half of the 2nd train cable shafts and the 2nd train cable spreading room.	
01:45	Until about 19:00, the fire fighting activities were neither systematic nor effective. It is stated in one report that the fire fighters often did not know whether the water they were spraying was directed at the fire or not.	The potential for fire fighters to spray water indiscriminately is recognized, but typically discounted in fire PRAs. Such behavior could lead to collateral damage to electrical equipment. In this case, a lack of adequate pre-fire planning and lack of fire brigade coordination were clearly contributing factors. The fact that primary fire brigades in US plants are made up of plant personnel would reduce the likelihood of similar behavior in the event of a fire.
02:10	Starting 19:25, plant personnel started from the lower elevations systematically looking for actual fires, so that fire fighting activities would be focused on actual fires.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
02:10	Until 19:25, the fire remained confined to the cable shaft and affected the cables there up to elevation 16.3 m. However, at this point propagation to adjacent areas apparently began.	Fire resistant construction of the cable shaft boundaries was the main reason for the fire to remain confined up to this point. Despite reports of incomplete barrier seals, the fire did apparently remained confined for up to two hours.
--	At elevation 13.2, the fire brigade fought the fire manually. At elevation 16.0 the deluge system was activated and that controlled the fire.	
02:15	By 19:30, the fire resistant barriers of the cable shaft failed and the fire propagated into new areas. It was discovered that the fire had propagated to elevation 20.0 m where it was stopped by the sprinkler system.	This is a case where a fire barrier may have been overwhelmed by the fire. In fire PRAs for U.S. plants it is common to assume that fire barriers will last for their full fire duration rating (typically three hours) and that fire of a duration that would exceed the rating are very low likelihood.
02:25	At 19:40, the chief engineer ordered the operators to trip 6kV boards BA, BB and BD (associated with safety trains 1 and 2) from the control room.	
02:45	At 20:00 plant personnel tripped the electrical system, including the DC power system at elevation 41:00m.	
03:45	By 21:00, the fire at elevation 16.0 was declared extinguished.	
03:45	By 21:00 (approximately), the fire propagated to elevations 19.0m and 24.0m of the Control Building. On elevation 19.0m, the fire was stopped by the sprinkler system on that floor.	
04:25	By 21:40 the fire propagated to elevations 28.3m and 41.0m of the Control Building.	
06:45	At 24:00 the fires were declared out and the fire pump was stopped.	
08:00	At 01:15 on January 18, 1st and 2nd safety trains were lost.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
08:00	At 01:15, plant personnel noticed cable fire at 20.4 m elevation. The fire pump was restarted. Water was sprayed inside the cable shafts and in cable chase areas. The power system was tripped.	This is one of the few incidents where fire re-flash well after initial extinguishment has been reported (some cases of re-flash immediately following suppression attempts have been reported). The main cause of the re-flash is postulated to be deep seated fire in the cable bundles that got exposed to fresh air. The possibility of re-flash is not considered in a fire PRA, however, given the apparent rarity of such events this may not be a significant oversight.
17:50	The fire was finally declared as completely out by 11:10 on January 18, 1999. More than 115 fire fighters were involved in this effort.	

Equipment Damaged:

- An electrical junction box (source of the fire)
- Large quantity of electrical cables

Damaged Areas

- Cable shafts and a large area of the control building were affected by this fire.

Impact on Core Cooling

- Safety related equipment was affected by this fire. The plant was in the last stages of construction. From the available information, it is not clear whether or not core cooling function was necessary. Had the fire occurred during plant operations, the impact on plant operations would have been severe.

Radiological Release

- No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

- There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

- The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

- There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A10.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events of the fire incident is compared to the elements that make up a typical PRA fire scenario. Entries are made only if specific information was provided by the available sources. No attempt was made to postulate a possible progression of the chain of events no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element/Issue	**Incident - Zaporizhzhya, January 27, 1984**	**Fire PRA Insights**
Presence of combustible / flammable materials	Cables were the primary sources of combustible for this fire incident. Materials in the initiating junction box also played a role in very early fire behavior.	It is claimed that the construction companies had used non-fire resistant cables and plastic materials inside the electrical junction boxes that contributed to the fire. In fire PRA it is assumed that a plant is constructed per set specifications. The possibility of manufacturers' error in using the wrong materials is assumed to be very unlikely.
Presence of an ignition source	A failure or foreign object in the electrical panel is suspected to be the main cause for fire ignition.	This is, in effect, a self ignited cable fire since there was no external fire exposure source.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	See above.	
Fire growth within the combustible or component of original ignition	Fire apparently established itself quite readily within the junction box.	The fire grew outside the initial junction box and spread via cable entering the top of the box.
Fire propagates to adjacent combustibles.	Fire propagated to other cables and continued to propagate for a long time..	Fire spread was apparently slow but steady during the initial growth period though no specific estimates are available. There is conflicting information however regarding how quickly the fire actually spread, in particular, in the time between 2 and 4 hours after ignition.
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information is provided regarding hot gases. However, given that the fire occurred in various compartments and cable shafts, hot gases should have played an important role in the propagation of the fire from one compartment to the other.	Clearly, a very dense smoke layer did form in the compartment of fire origin that prevented initial attempts to attack the fire. Smoke formation is commonly recognized a potentially delaying effective fire fighting activities.

Fire Scenario Element/Issue	Incident - Zaporizhzhya, January 27, 1984	Fire PRA Insights
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	In part because of incomplete penetration seals, the fire had the opportunity to propagate into other compartments. Smoke had a major impact on the fire fighting activities. Attempts were made by the operators to crawl under the smoke and extinguish the fire. But their efforts proved to be futile. Outside fire brigade members, because they were not familiar with the plant, had difficulties in fighting the fire in smokey condition. From the information provided, it can be inferred that the entire control building was affected by smoke.	The actual role of the incomplete penetrations may be overstated in the available reports since the fire apparently remained confined to the initial area for up to two hours. Some penetrations may have been overwhelmed by the fire. Fire PRAs generally consider fires of sufficient intensity so as to overwhelm a fire barrier as highly unlikely. In a fire PRA, smoke movement is not explicitly modeled. These events demonstrates it is important to include some consideration of smoke spread as part of the fire PRA analysis and include the propagation paths and their impact on recovery actions and fire fighting.
Local automatic fire detectors (if present) sense the presence of the fire	From available information it is inferred that fire detectors were already installed but were not activated yet.	The fact that the plant was still under construction was a factor in this event that would not be typical of an operating plant.
Alarm is sounded automatically in the control room, locally and / or other places	n/a	
Automatic suppression system is activated (if present)	From the information provided, it is inferred that fixed automatic water systems were present and functional at least in certain parts of the Control Building. The sprinkler and deluge systems controlled the fire in at least one and possibly two locations.	
Personnel are present in the area where fire occurs	Personnel were present at all parts of the plant where fire had propagated.	This fire was manually detected.

Fire Scenario Element/Issue	Incident - Zaporizhzhya, January 27, 1984	Fire PRA Insights
Control room is contacted or fire alarm is sounded	The fire was reported to the control room promptly upon discovery, but time of initiation is uncertain.	
Fire brigade is activated	Plant and outside fire brigades were activated to fight this fire. A total of 115 fire fighters participated in this incident.	There was no apparent delays in calling out the fire brigade.
Fire suppressant medium is properly applied	Water streams were applied at several different locations. From the available information it is inferred that the automatic sprinkler and deluge system at certain locations were successful to control the fire for that area.	From one report it appears that fire fighters were initially spraying water somewhat indiscriminately and were not certain where the fire actually was. Such behavior is commonly considered and dismissed as unlikely in fire PRAs.
Automatic fire suppression system is activated	See above	
Fire is affected by the suppression medium	The fires were ultimately affected by the water systems. It was brought under control at several locations and was declared extinguished by midnight. However, the fire re-flashed and the fire fighters had to start the fire pump again and continued to fight the fire until 11:00 the next day, when it was finally announced as completely out.	Fire fighting was not very effective apparently due to uncertainty as to where the fire actually was (see comments above).
Fire growth is checked and no additional failures occur	The fire growth could not be checked for a long time. It was thought that the fire had been brought under control at several points in the path of its growth. While fire fighting efforts seemed to be at least partially effective, fire growth continued for several hours. Contributing factors include combustibility of the cables, configuration of the cables (vertical risers) and the shape and inaccessibility of the compartments.	This is an incident where despite all the efforts of the fire fighters, the fire remained unchecked for a long time. In fire PRAs, the possibility of a fire lasting for several hours, while fire fighting efforts are seemingly effective, is deemed to be very unlikely. That is, it is commonly assumed that once fire fighting activities begin, the fire will be quickly brought under control.

Fire Scenario Element/Issue	Incident - Zaporizhzhya, January 27, 1984	Fire PRA Insights
Fire is fully extinguished and fire brigade declares it as out	The fire was declared as out at midnight. However, it re-flashed inside a cable shaft. It took the fire fighters another 11 hours to completely extinguish the fire.	The possibility of re-flash is not explicitly modeled in fire PRAs. However, it can be argued that since the models used are based on actual fire occurrence data, it empirically includes the possibility of re-flash. This event points out that if one were to model fire suppression in great detail should include the possibility of re-flash in that model.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	A large number of cables were lost. The available information does not provide sufficient information about the type of electrical circuits, equipment and systems that were affected.	
Cable failure impacts equipment outside the fire location	Several kilometers of cables were replaced, electrical panels were replaced. Cable failure had certainly impacted equipment outside the fire areas. However, the available information does not specify which cables and equipment were affected. Because of the extensive damage, the fire delayed plant startup.	In this case because the plant was still under construction the operation impact was apparently minimal. However, from the severity of the fire as described in the available sources and given that the fire damaged a large set of cables, it is inferred that if the fire had occurred during power operation, core cooling capability would have been affected severely.
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	All three safety trains were affected either directly or indirectly because of operators' decision to switch off 6kV bus to minimize the hazards during fire fighting.	From the information provided, it can be inferred that all three safety trains were lost in this fire incident. Thus, if the fire had occurred after reactor activation, core cooling would have been severely jeopardized.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	No clear information available.	
Operators attempt to control the plant properly and bring the plant to a safe shutdown	n/a	
Structural failures (if occurred) may jeopardize availability of equipment	n/a	

Fire Scenario Element/Issue	Incident - Zaporizhzhya, January 27, 1984	Fire PRA Insights
Water when sprayed over electrical equipment may fail the exposed equipment	No information on this phenomenon.	As noted above, the fire fighters did spray water somewhat indiscriminantly. However, there are no reports of any damage. Given that the areas contained primarily cables, this is not unexpected (i.e., cables should not be vulnerable damage as a result of wetting).
The cooling effect of CO_2 may adversely impact equipment	n/a	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The plant was under construction.	As noted above, construction is widely recognized as presenting unique fire hazards and construction fires are routinely dismissed in fire PRA analyses. In this case, in the judgement of the authors, the fire behaved much as it likely would have had the plant been in operation. The one possible exception is with regard to fire spread through incomplete penetration seals as noted above.

A10.5 Incident Analysis

The root cause of this fire incident can be attributed to an electrical fault leading to a self-ignited cable fire. While the actual nature of the fault remains unclear, the available reports cite that the most likely explanation is that a fire started inside a terminal box due to either an external object shorting across bare terminals or a self ignited cable fire. The fire then propagated from the terminal box to associated cables entering the top of the box and from there into a cable shaft.

Self ignited cable fires can be regarded as rare occurrences. It is common to assume that the potential for such fires is tied to the specific characteristics of the cables, cable manufacturing practices and cable installation practices. In fire PRAs for the plants in the U.S. it is assumed that self ignited cable fires are implausible if IEEE-383 qualified low-flame-spread cables are used. In the case of Zaporizhzhya, the qualification standards of the cables and terminal boxes is not clear. Hence, this incident neither refutes nor confirms these assumptions.

It appears that the fire propagated rather slowly at first, but steadily. Some of the information reported for the time period between 2 and 4 hours after detection indicates that the fire may have spread more quickly during this period, but the information is somewhat contradictory. The cable risers in the cable shaft where the fire began were the main path for fire propagation. In many regards, this fire followed a "classical" initiation and spread behavior as commonly assumed in a PRA fire scenario. That is, the fire started quite small, propagated to adjacent cables, propagated to nearby cable trays and cable risers, and then spread unchecked until suppression efforts were begun. Hence, in this regard, a fire PRA would have likely postulated the potential development of a fire in the impacted compartment, at least up to the point that other fire areas became involved.

Initial attempts by operators to fight the fire were unsuccessful because they did not have proper gear to deal with the smoke. Subsequent efforts by the fire brigade were also hampered by smoke because fire fighters could not clearly identify areas of active burning. The fire fighters were initially somewhat ineffective in their attacks due in large part to the heavy smoke buildup. Other contributing factors include a lack of adequate pre-fire planning and unfamiliarity of fire fighters with the plant. Ultimately the fire managed to propagate upward to practically all Control Building elevations. This incident demonstrates the potential impact of smoke on fire fighting activities. In fire PRA, the impact of smoke on the fire fighters is not generally modeled explicitly. It is commonly assumed that once fire fighters arrive on-scene, they will quickly and effectively control and suppress the fire. It is quite common to base manual fire suppression times on the response time of the fire brigade without explicit consideration of the conditions they might encounter upon arrival.

Lack of fire brigade training and pre-fire planning is another interesting insight of this incident. From the available sources, the importance of this factor is not clear. In fire PRAs conducted in the recent years in the U.S., the training of the fire brigade is often reviewed in some level of detail (see for example Reference 10-3). In this case, there are also reports that fire fighters were spraying water despite the fact that they had no clear idea of where the fire actually was burning. The potential for misdirected suppression is considered, but commonly dismissed, in fire PRAs. This incident illustrates that the potential for such actions does exist and provides some indication of the circumstances under which this might be anticipated. That is, for fire PRAs careful consideration of the training of on-site fire brigades is confirmed to be both appropriate and important. Furthermore, it would also be appropriate to consider the level of cooperation, coordination and pre-fire planning that goes into interactions with off-site fire brigades that might be called upon to support fire fighting efforts at the plant.

The available reports cite that incomplete and unsealed penetrations were a factor in the fire spread. However, from the available information, it can be inferred that at least some nominally intact fire barriers were overwhelmed by the fire. This is inferred from the fact that the fire remained confined to the cable shaft for over two hours before propagating to various adjacent spaces. Hence, it is likely that many of fire barriers were intact and confined the fire, but that continued burning eventually overwhelmed some elements of the barriers and allowed the fire to propagate to adjacent areas. In fire PRAs for U.S. plants it is common to assume that all fire barriers are properly designed and installed to withstand the fire threats likely to be experienced in most areas. Furthermore, cables are not generally considered a high-hazard fuel source, so the likelihood that a cable fire would overwhelm a rated fire barrier would be assumed very small. It would be common in such cases to assign a small random failure probability to the barrier, typically on the order of 0.01 per demand. The applicability of the experience here to U.S. plants is unclear because of likely differences in Soviet versus U.S. barrier qualification and monitoring practices.

This is one of the few incidents where a long-term fire re-flash has been reported. There are other cases where initial attempts to suppress a fire have been unsuccessful and a fire has re-flashed immediately upon removal of the suppressant. This is particularly true in cases where hand-held gaseous extinguishers are used to fire electrical fires. However, this case is unique because of the time involved. In this case, over one hour after the fire was initially declared out reports were received that the fire in one area had re-ignited. It is likely that the main cause of the re-flash was deep seated burning in the cable bundles and exposure to fresh air. The possibility of re-flash is not considered in a typical fire PRA. However, it can be argued that since the models used in fire PRAs are based on actual fire occurrences, it empirically includes the possibility of re-flash. This event points out that if one were to model fire suppression in great detail should include the possibility of re-flash in that model.

This event offers little insight into the impact of a fire on plant operations and operator actions because the plant was still under construction and was not in operation. However, it can be inferred from the available reports that had the plant been in operation, the impact on plant operations would have been severe. All three safety divisions were lost during the fire. Hence, it is likely that core cooling functions would have been severely challenged.

A10.6 References

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A10-4 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A10-5 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 11 - Analysis of Kalinin, Unit 1 Fire on December 18, 1984

A11.1 Plant Characteristics

Kalinin is nominally a four unit nuclear power plant site located in Tver Volga, Russia.[A11-3,4] All four planned units are VVER-1000 type nuclear power plants. Units 1 and 2 have been in operation since the mid-1980's, Unit 3 is under construction, and construction has been suspended on Unit 4.[A11-4] At the time of the fire, Russia was a part of the former Soviet Union. Plant construction on Unit 1 began in 1977, and the first criticality was achieved in April 1984. First power operations began in May of 1984, but commercial operations did not commence until June of 1985. The fire described here occurred in December 1984, approximately seven months after initial power operations but before commercial operations had commenced. Construction on the sister unit, Kalinin 2, had been underway for approximately two years but had not been completed at the time of the fire.

Typical of Soviet-designed reactors, the unit has two turbine generators and two control rooms. A main control is responsible for reactor operations while the second "central control room" is responsible for the power generation side of the plant. Also note that the Kalinin design includes three safety trains.

A11.2 Chain of Events Summary

On December 18, 1984, at 18:28, while Kalinin Unit 1 was producing power, a service water pump was being restarted after a major repair. Sparks became visible on the cover of the pump and "unknown sounds" came from the direction of the pump (as reported by workers in the area who had apparently been working on the pump). Later it was determined that on startup, the service water pump started to turn in the wrong direction (likely due to a phase reversal on the power supply connections). This caused the electrical control system to fail. An additional breaker failure caused a breaker cubicle fire and a 6 kV cable fire in the turbine building.

A machinist and electrician working in the service water pump area tried to trip the pump using the emergency switch, but the pump would not trip. They called the control room and asked operators to trip the pump from there. The control room operators were not able to trip the pump either. After this the workers observed arcing in the motor and the cable connection to the motor started burning near the wall. Since the associated power feed breaker did not open, the electrician called the Central Control Room that controls the electrical distribution system and asked operators there to de-energize the safety power train. The 6 kV power train was tripped and the service water pump stopped. However, by this point a fire had started inside the breaker cubicle for the service water pump. The workers tripped the associated transformer, opened the cubicle door and applied CO_2 onto the fire. They were apparently successful at suppressing the fire in this cubicle.

However, at 18:28 the turbine building personnel noticed a fire burning in a cable tray at -4.0 m elevation under Turbine B. A fire had ignited on a 6 kV cable at several locations along the cable. The available reports state that it is suspected that the 6 kV cable had manufacturing defects and was damaged because of improper cable pulling practices. Thus, its insulation had weakened or was damaged and was susceptible to failure. From this one can surmise that the combination of the damaged insulation and the overload condition resulting from the pump and breaker problems combined to cause a self-ignited cable fire in the subject cable.

Plant personnel started the fire fighting process immediately and called for the off-site fire brigade. At 18:37 the fire brigade arrived on the scene and a full scale fire fighting effort started. By 20:12 (1 hour 46 minutes after the first alarm in the control room) the fire was considered under control and by 21:20 the fire was declared to be completely extinguished.

The automatic fire suppression systems functioned as designed although it was apparently ineffective. The fire fighting was done in severe smoke conditions using SCBAs. To vent the heavy smoke from the turbine building, several windows were broken. The hydrogen was drained from the generator and the 6 kV buses were de-energized.

A11.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A11-1] and [A11-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On December 18, 1984, the unit was operating at power.	
00:00	At 18:28:36 the control room received an alarm.	
--	Service water pump NTN-3 was being put back on line after a major repair. Sparks became visible on the cover of the pump and unknown sounds came from the direction of the pump.	Electrical fires are typical of the fire sources postulated in a fire PRA. The exact mechanism of initiation is not considered, but rather, fires are postulated based on statistical analysis of past fire experiences.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The machinist and electrician who were on the scene tried to trip the pump using the emergency switch, but the pump did not trip. They called the control room to trip the pump from there. The control room operators were not able to trip the pump either. After this they observed several arching in the motor and the cable connection to the motor started burning near the wall.	The breaker for the service water pump was later found to be in the test mode. This reduced the opportunity for mitigating the ignition processes before the fire could occur. Such details are not generally modeled in a typical fire PRA. The fire occurrence frequency is based on all recorded fire events and therefore, in theory includes human errors leading to fires.
--	The electrician called the Central Control Room asked them to isolate the safety power train. The 6kV power train tripped on protective breaker opening. It is not clear whether the operators tripped the breaker or it tripped on over-current.	
--	Fire was noticed inside the breaker cubicle for the service water pump. The technicians tripped the transformer and opened the breaker cubicle and applied CO_2 into the cubicle.	
00:00	At 18:28 fires were discovered in the cable trays at -4.0m elevation of the Turbine Building under turbine B. Fire had ignited at several places on a 6kV cable. It was later determined that the motor of Service Water Pump NTN-3 had rotated backwards. This had caused the electrical control system to fail, and lead to a demand for breaker trip. The breaker failed to open and this led to overcurrent condition in the 6kV cable. It was also suspected also that the 6kV cable had manufacturing defect and was damaged because of improper cable pulling practices.	In this incident, effectively there were three ignitions -- the service water pump, switchgear cubicle and 6kV cable. On the cable itself there were several ignition points. Thus, multiple simultaneous fire took place in this incident. Fire PRAs do not generally address multiple fires. It is assumed that all fires occur independent of each other and therefore their simultaneous occurrence is very unlikely.
00:02	The generator tripped offline.	
--	Plant personnel started the fire fighting process.	
--	The security personnel were notified.	
--	The automatic fire suppression systems in the turbine building functioned as designed.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:09	At 18:37 the fire brigade arrived at the scene.	
--	The fire fighting was done in severe smoke conditions using SCBAs. To remove smoke windows had to be broken.	Smoke hampering of fire fighting activities is often considered, but typically discounted, in fire PRAs. In this case, fire fighting may was hampered by the smoke.
--	The hydrogen was drained from the generator and 6kV bus bars were tripped.	This successful action potentially prevented a much more severe fire.
01:46	By 20:12 the fire was brought under control.	This is a relatively long fire in comparison to fires commonly postulated in fire PRAs. The possibility that a fire might burn for more than about 30 minutes is considered remote.
02:52	By 21:20 the fire was declared as completely extinguished	

Equipment Damaged

- 6 kV switchgear
- Service water pump motor
- Electrical cables below turbine B

Damaged Areas

- The switchgear and pump fires were localized to equipment of origin. The cable fire inside the Turbine Building affected a large number of cables.

Impact on Core Cooling

- Available sources do not specify the impact on core cooling functions.

Radiological Release

- No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

- There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

- The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

- There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A11.3 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events of the fire incident is compared to the elements of a typical PRA fire scenario. Entries are made only if specific information was provided by the available sources. No attempt was made to postulate a possible progression of the chain of events no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	Incident - Kalinin 1, December 18, 1984	Fire PRA Insights
Presence of combustible / flammable materials	The combustibles that were affected in this incident included the motor winding of service water pump NTN-3, the breaker cubicle serving the service water pump, the 6kV cables under Turbine B.	These are common combustibles that are considered in fire PRAs
Presence of an ignition source	The ignition source for was electrical overload aggravated by a breaker that failed to open.	Self-ignited cable fires are considered in fire PRAs but are judged to be unlikely events.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The following three fires occurred: - The service water pump motor threw some sparks (minor) - Switchgear cubicle serving the pump caught fire - 6kV power cable under Turbine B caught fire at several locations.	Simultaneous occurrence of several ignitions at different parts of the plant is not modeled by current fire PRA methodologies.
Fire growth within the combustible or component of original ignition	The service water pump stopped sparking as soon as the power was cut off from it. The switchgear fire was quickly suppressed by technicians at the scene and did not propagate. However, the cable associated with the pump caught fire did spread to other nearby cables.	The fire under the turbine was the only fire that saw significant propagation. Hence, while multiple fires did occur due to a common cause, only one really had any substantial impact on the plant.
Fire propagates to adjacent combustibles.	The cable fire in Turbine Building propagated to adjacent combustibles and grew to a considerable magnitude.	
A hot gas layer forms within the compartment of origin (if conditions may allow)		
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Large quantities of dense smoke were emanating from the cable fire in the Turbine Building.	There are no reports of any adverse fire effects in areas other than the turbine building.

Fire Scenario Element	Incident - Kalinin 1, December 18, 1984	Fire PRA Insights
Local automatic fire detectors (if present) sense the presence of the fire		
Alarm is sounded automatically in the control room, locally and / or other places	Operators did promptly activate the fire brigade upon initial reports of a fire.	
Automatic suppression system is activated (if present)	The automatic fire suppression systems activate as designed, but did not extinguish the cable fire.	In this case, a gaseous suppression system failed to either control or extinguish the fire. The design characteristics or the system are not, however, known so this failure cannot be clearly extrapolated to other cases.
Personnel are present in the area where fire occurs	Plant personnel were present in the service water pump and switchgear area and in the Turbine Building	Personnel did detect the fires and reported promptly to proper authorities (the main control room). In one case (the switchgear) these personnel apparently suppressed the fire as well.
Control room is contacted or fire alarm is sounded	Control room was contacted by the mechanical and electrical technicians who were at the service water pump area and were trying to startup a pump for the first time after a major repair. The contacted the control room to open the breaker for the pump but control room efforts failed. They later contacted the electrical control room and asked for the associated switchgear to be tripped, which was done successfully.	
Fire brigade is activated	The plant personnel and the plant fire brigade fought the fires.	The fire brigade was activated quite early in the incident and apparently responded within a short time period (several minutes). This is consistent with typical PRA assumptions regarding fire brigade response times.
Fire suppressant medium is properly applied	The fire brigade applied the fire suppressant properly.	There are no reports of collateral suppression damage.
Automatic fire suppression system is activated	Automatic fire suppression system is activated as designed.	While the system activated it was apparently ineffective.

Fire Scenario Element	**Incident - Kalinin 1, December 18, 1984**	**Fire PRA Insights**
Fire suppressant medium is properly applied to where the fire is.	The brigade had to work in dense smoke conditions. However, no fire brigade errors are noted.	The impact of heavy smoke on fire fighting effectiveness is not explicitly modeled in most fire PRAs.
Fire is affected by the suppression medium	With the help of the fire brigade the fire was brought under control in one hour and 46 minutes after the initial alarm in the control room and it was declared as completely out at 2 hours and 52 minutes after initial alarm.	Typical assumptions assume that fires will be very quickly suppressed once fire fighting begins. In this case the fire continued to burn despite active fire fighting efforts.
Fire growth is checked and no additional failures occur	The fire was brought under control in one hour and 46 minutes after the initial alarm in the control room	
Fire is fully extinguished and fire brigade declares it as out	Fire was declared as completely out at 2 hours and 52 minutes after initial alarm.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	There was apparently substantial fire damage, but the damage was confined to non-safety systems and equipment. Windows were broken intentionally to help in ventilating the Turbine Building to minimize the amount of smoke.	Actions outside the established procedures are not credited in a fire PRA. For example, in case of heavy smoke in a compartment, credit would not be given to the possibility of breaking windows to ease the density of the smoke.
Cable failure impacts equipment outside the fire location	The available sources do not provide information regarding this matter. There was apparently little damage to safety systems or components.	
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	no information	
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	no information	

Fire Scenario Element	Incident - Kalinin 1, December 18, 1984	Fire PRA Insights
Operators attempt to control the plant properly and bring the plant to a safe shutdown	no information	
Structural failures (if occurred) may jeopardize availability of equipment	None reported	
Water when sprayed over electrical equipment may fail the exposed equipment	no information	
The cooling effect of CO_2 may adversely impact equipment	n/a	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	None reported	

A11.5 Incident Analysis

This particular event was included in the current review largely because, from a classical fire protection engineering standpoint, the fire was rather severe. The fire burned for nearly two hours, produced copious amounts of smoke, required several fire fighters working in somewhat harsh conditions to suppress, and apparently caused some substantial physical damage to the plant. However, the operational impact of this fire was apparently modest, and plant operators appear to have responded appropriately to the fire incident. This again illustrates that not all large or prolonged fires will lead to significant nuclear safety challenges.

This observation is fully consistent with current PRA methods. Many fire areas are routinely screened from a fire PRA on the basis of minimal potential for operational impact. This commonly includes the screening of, in particular, turbine halls which are widely known to present severe fire hazards from a classical fire protection standpoint. This event provides confirmation of the general validity of this approach. In this case, there was apparently no safety significant equipment threatened by the fire, and a fire PRA would have likely concluded that even a prolonged fire would represent a very small risk contributor, provided of course that the fire remained confined to the turbine hall as it did in this case.

It is also interesting that in this incident there were, effectively, three fires at three different locations of the plant caused by the same root failure. The three locations are as follows: the service water pump itself, a switchgear cubicle, and a 6 kV cable. The common link was association with the same electrical circuit. Of the three fires, the most serious was the self-ignited cable fire in the turbine building. For the cable, there were actually several ignitions along the length of the cable, although all were in the turbine building. Thus, multiple, simultaneous fires took place in this incident. Fire PRAs do not address multiple fires. It is assumed that fires occur independent of each other and therefore simultaneous occurrence is very unlikely.

This case also involves a self-ignited cable fire. Such fires are commonly considered in fire PRAs, but are typically dismissed for newer plants and in cases where cables are certified as low flame spread per the IEEE 383 testing standard. This particular event confirms the potential for self-ignited cable fires in a very general context, but neither confirms nor refutes the assumptions regarding low flame spread cables.

A11.6 References

A11-1 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A11-2 Soloviev, P.S. "Accidents and incidents in nuclear power plants", Obninsk,1992.

A11-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A11-4 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 12 - Analysis of Maanshan, Unit 1 Fire on July 1, 1985

A12.1 Plant Description

Maanshan is a two unit nuclear power station located near Herng Chuen, Taiwan. Both units are 890 MWe Westinghouse design, pressurized water reactors. Unit 1, where this fire incident occurred, started commercial operation in July 1984. The sister Unit 2 began commercial operation in May of 1985, just two months before the subject fire in Unit 1.

A12.2 Chain of Events Summary

While operating at power, a turbine blade failure occurred on July 1, 1985 at Unit 1 [ref. A12-1]. As a result of the imbalance, the turbine shaft came to a halt within a few seconds. The vibration caused by the loss of turbine balance, broke the generator seal allowing hydrogen to escape and seal oil to spill inside the turbine building. Both the hydrogen and the seal oil ignited starting fire inside the turbine building. The fires caused significant damage and the plant remained shutdown for repairs close to 11 months.

The heat detectors in the turbine building responded to the fire and the automatic carbon dioxide fire suppression system activated. The system was apparently ineffective. The local fire brigade was summoned and arrived about 1 hour after the turbine failure. The fire fighters experienced some difficulties and additional delays due to a failed fire protection system valve. Water was sprayed on the fire starting about 1 hour after turbine failure. The fire was apparently so intense that the fire fighters had to keep some distance. The fire was declared as completely extinguished about 10 hours after turbine failure.

The turbine failure also led to reactor trip. Although some electrical cables and motor control centers were affected, no safety related equipment were affected and there was apparently no adverse interference with reactor shutdown and core cooling capabilities.

A12.3 Incident Analysis

In this incident a relatively severe turbine building fire occurred because of turbine blade failure. However, despite a severe and prolonged fire causing extensive physical damage, the incident did not have an adverse effect on plant safety. The plant was shut down reportedly with little or no real challenge to nuclear safety. This incident confirms the conclusion that is often reached in fire PRAs; namely, that the turbine building can often be screened out as risk insignificant. This is a case where this conclusion would have been valid, although the actual risk significance of the turbine hall is plant specific depending on what equipment (including cables) is housed within or passes through that area.

The incident is included in this study because it does represent a major turbine building fire incident of a similar nature to others considered in this review (e.g., Narora and Vandellos). That is, a turbine blade failure leading to release of both hydrogen and oil and a resulting fire. As in other cases the fire was apparently severe and lasted for several hours. This incident does serve to illustrate that there are two quite distinct criteria for judging the severity of a fire incident. In the classical fire protection engineering sense, this fire was quite severe. However, from a nuclear safety standpoint, the fire had a very minimal impact.

A second aspect of this fire that is of interest is the apparent ineffectiveness of the carbon dioxide fire suppression system. While the system did actuate as designed, it was ineffective at either suppressing or controlling the fire. It is not, however, known how the system was designed. For example, CO2 systems are commonly designed as total room-flooding systems, but may also be used to protect locally against fires involving fixed sources. Given a space with the volume of a typical turbine hall, it would be quite unusual to provide a total flooding system. Hence, it is likely that the system was either provided as "point" protection, or was designed to protect specific zones within the larger turbine hall. Given these uncertainties it appears inappropriate to draw conclusions from this aspect of the incident.

A12.4 References

A12-1 W. Wheelis, , "User's Guide for a Personnel Computer Based Nuclear Power Plant Fire Data Base," NUREG/CR-4586, SNL/USNRC, August 1986.

Appendix 13 - Analysis of Waterford, Unit 3 Fire on June 26, 1985

A13.1 Plant Description

Waterford 3 is a single unit pressurized water reactor (PWR) located near Taft, Louisiana. Unit 3 is the only nuclear power unit on the site (Units 1 and 2 being separate conventional units). The unit is rated at 1104 MWe and started commercial operation in September 1985. The fire being reviewed here occurred on June 26, 1985, after initial power operations had begun but prior to the commercial operation date [Ref. A13-2].

A13.2 Chain of Events Summary

On June 26,1985 the plant was operating at power, when a fire occurred in one of the main feedwater pumps. An electrician notified the control room that smoke was emanating from main feedwater pump A. An operator was dispatched to the scene and reported back to the control room that the pump was on fire. Control room operators tripped the cited pump, started reducing reactor power and declared an unusual event was underway.

Five minutes after the initial report of a fire, the control room was notified that the fire was actually in main feedwater B, rather than pump A as previously reported. As a result the control room operators immediately tripped the turbine, which in turn caused the reactor to trip. Since both main feedwater pumps were secured, the steam generator level dropped below the emergency feedwater system setpoint.

The fire brigade was activated upon confirmation of the fire. They used a local hose station and water streams to fight the fire and managed to extinguish it in about 10 minutes. The fire was limited to a small portion of the outer wrapping of insulation on the feedwater piping and was attributed to design and fabrication error.

A13.3 Incident Analysis

In most senses this fire was relatively small and, overall, the challenge to nuclear safety during the incident was relatively minor (a reactor trip with all safety systems available). The interesting aspect of this incident is that operator/personnel error led to an initial report identifying the wrong pump as the one on fire. As a result, the unaffected pump was first tripped, and eventually both main feedwater pumps were tripped. Although only non-safety related trains were involved in this incident, it provides an interesting insight into the possibility of indirect impact of fire on multiple train availability. That is, a fire for various reasons, may lead to unaffected trains being taken out of service. In this case the cause was operator error.

In this incident, the operator actions would be classified as an error of commission. That is, rather than failing to take a desirable action, the operator in this case took an action that was undesirable. Fire PRA methodologies are capable of identifying conditions where an operator action may exacerbate the situation (i.e., errors of commission). However, currently such scenarios are seldom considered in either general or fire PRAs. More likely is that a fire analysis of this scenario would have assumed a random failure probability for the unaffected pump, commonly a very low value. Human reliability methods currently applied are widely recognized as providing poor treatment of errors of commission.

A13.4 References

A13-1 W. Wheelis, "User's Guide for a Personnel Computer Based Nuclear Power Plant Fire Data Base," NUREG/CR-4586, SNL/USNRC, August 1986.

A13-2 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

Appendix A14 - Analysis of Fort St. Vrain Fire on October 3, 1987

A14.1 Plant Characteristics

Fort St. Vrain is a single unit High Temperature Gas-cooled Reactor (HTGR). The power rating of the plant is 1,250 Mwe provided by one turbine generator. Plant construction began in 1968, commercial operation began in 1979, and the plant was permanently shutdown in 1989. [Ref. A14-3].

A HTGR reactor uses graphite as a moderator and helium gas for heat removal from the core. Fort St. Vrain had two main cooling (helium) loops. The helium, after passing through the core, flowed through the two steam generators (one per cooling loop). Motive power for the helium was provided by two steam driven circulators for each loop. The steam for the circulators comes from the discharge of the high pressure turbine of the turbine-generator. The steam is passed through the steam generators once more for superheating before it is taken to the intermediate and low pressure turbines.

The control room is located at the north end of the Turbine Building (see Figure A14-1). It is isolated from the open part of the Turbine Building by doors. The control room has four doors: 1) the west door on the south wall opens directly into the turbine area, 2) a double door, also on the south wall, is labeled in Reference [A14-1] as "non-opening", 3) an east facing door next to the south wall that opens into a corridor type area that includes a door into the turbine area, and 4) a door on the east wall that opens into the locker room in Building 10.

A14.4 Incident Summary

On October 2nd, 1987 the plant was coming out of a long outage and was in the midst of its initial power ascension. As part of this process, the operators closed a hydraulic valve in the turbine building, when they noticed a drop in hydraulic oil pressure. An inquiry into the causes of this drop discovered that a filter bowl (canister) had failed and high pressure oil (about 3,000 psig) was spraying (close to 15 feet distance) onto hot exposed steel. The petroleum based hydraulic oil ignited starting the fire. The temperature of hot surfaces were above the auto-ignition point of the oil. The equipment operator who discovered the fire initially succeeded in extinguishing the fire using a portable dry-chemical extinguisher. However, since he did not close the valve feeding the failed filter, the oil continued to spray and re-flashed (re-ignited). By this time the size of the fire was relatively large (estimated as 8' x 3').

Plant fire brigade was called on immediately. An outside fire department was also asked to respond. A reactor operator was dispatched to the Reactor Building to close the two control valves for the hydraulic system to cut off the supply of oil to the failed filter. This operator managed to close one of the two valves immediately. The handle for the other valve was missing and therefore, some delay occurred in cutting off the oil from the fire. As soon as the oil was cut-off, the fire was extinguished and the operators managed to close off and isolate the failed filter and activate the available hydraulic system train.

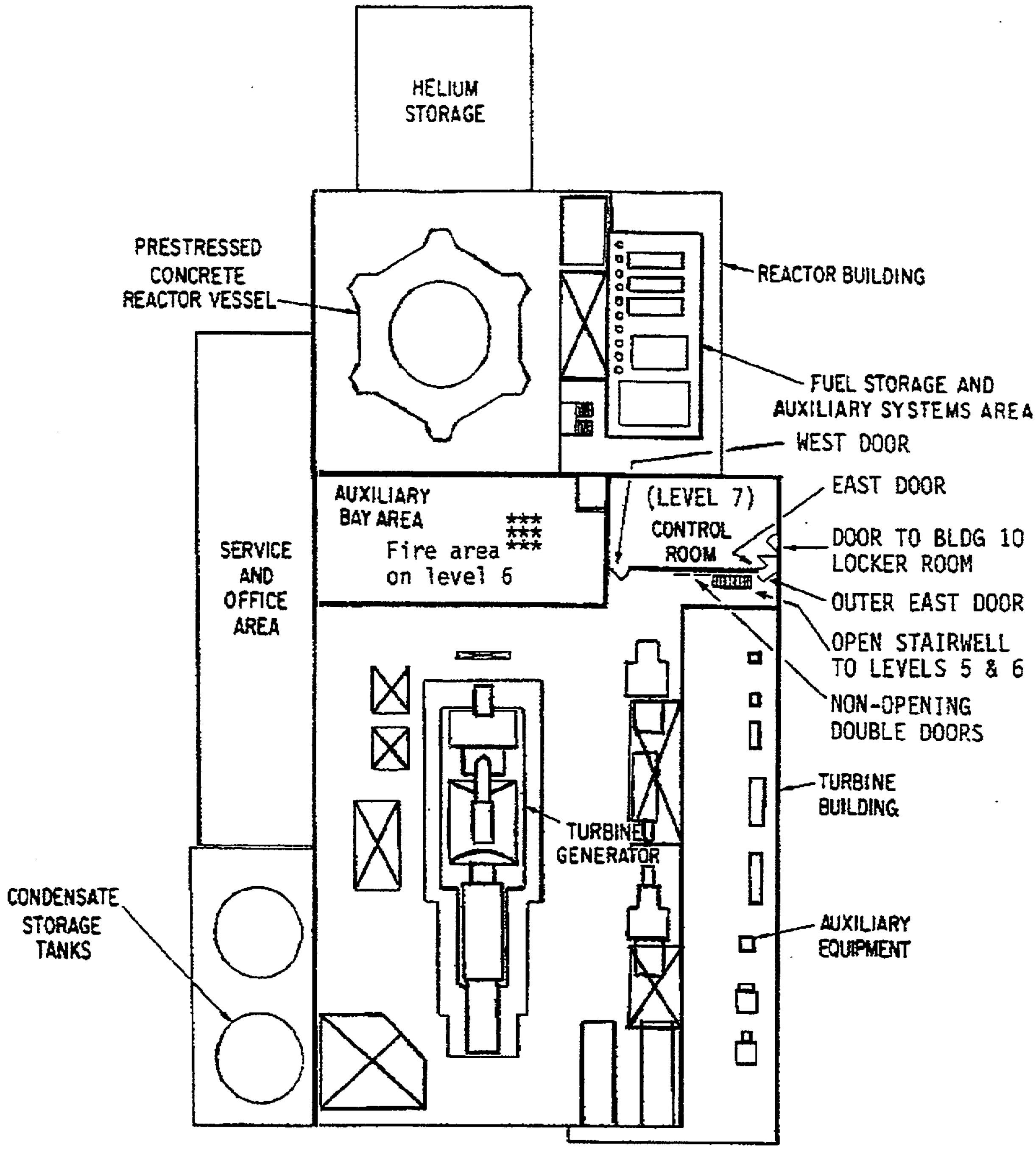

Figure A14-1: Plan view of the reactor building and turbine building including fire area on Level 6 and control room on level 7 (from Reference A14-1).

The damage caused by this fire was limited to the immediate area of the fire at the north end of the turbine building. Several cables were damaged that had some effect on the control room. Valves, instruments and structural elements were affected by the fire. However, there was minor impact on plant shutdown and reactor cooling capability.

The fire had some impact on control room habitability. Apparently large quantities of smoke were generated from burning oil and cables, that affected the initial fire fighting efforts. The cables damaged by the fire caused the control room ventilation system to shift to radiation emergency mode. Also, cable damage caused loss of electric power at the fire location rendering electric motor driven smoke ejectors useless. In this mode, the system shifts to suction from the turbine building. It therefore, drew some smoke from the turbine building into the control room. The operators, within two minutes of ventilation system shift, turned the ventilation system into the purge mode. However, smoke continued to enter the control room because positive pressure in the room could not be maintained due to frequent use of the door between the control room and the turbine building. The operators had to prop open the door separating the control room and Building 10 to allow fresh air to be drawn into the control room.

The control room was equipped with a piped-in Breathable Air System that provided fresh air via a common air supply header and individual masks for operators. Although the system was designed for 6 masks, only three were available during the incident and there were six operators in the control room. Scott Air Pacs were also available to the operators to make up for the shortage of masks.

A14.3 Detailed Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [14-1] and [14-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On October 2, 1987, the plant was coming out of a long outage and was in the process of power ascension.	

Prior to the incident	The audible alarm of the fire detectors located in the control room were turned off because of too many nuisance alarms.	In fire PRA such plant specific conditions are expected to be discovered during the plant walkdown. Typically an overall fire detection and suppression model is used to encompass all possible ways that detection and suppression is delayed or failed.
Prior to the incident	At 23:50, control room operators noticed that after activation of a major hydraulic valve hydraulic oil system pressure did not recover back to its normal 3,000 psi pressure.	In fire PRA, credit is seldom given to operators using indirect methods for discovering an adverse condition. This type of behavior is difficult to quantify.
Prior to the incident	At 23:51, a turbine equipment operator was dispatched to identify the causes for oil pressure drop.	
Prior to the incident	At 23:55, the turbine equipment operator reported that there was oil flowing into the catch basin under the turbine. This is located at level 5 of the turbine building. The oil was coming from a failed filter bowl of the hydraulic oil system at level 6. The oil was spraying out of the bowl for a distance of about 15 feet onto 20" diameter hot reheat piping and 2 associated reheat check valves..	
--	The equipment operator noticed a fire	
00:00	At 23:59, the equipment operator reported a fire at level 6 involving the sprayed oil. The ignition source was later found to be exposed hot steel parts of relief valves that could not be insulated. The auto ignition temperature of the oil was 620F. The hot surfaces of exposed reheat piping were between 680 and 690 F.	The fire source/cause is relatively common for a turbine hall fire, leaking lube oil, but PRA fire modeling rarely considers high pressure spray fires and would generally treat such fires as pool fires only.

--	The turbine equipment operator, who happened to be a member of plant fire brigade, discharged one bottle of dry chemical fire extinguisher at the fire, which extinguished the flames. He could not however reach an isolation valve to stop the flow of oil to the filter. The fire re-ignited. This time it was larger than the previous fire. The dimensions of the fire are estimated in one report as 8 feet by 3 feet. The equipment operator had to retreat from the area because of heavy smoke.	As mentioned above, in fire PRA under some methods an overall statistical probability model is used to account for all possible ways that fire detection and suppression may be delayed or failed. The possibility of failing to put a fire out in the initial stages of a fire fighting scenario is included in the overall suppression time. However, other methods might have given substantial credit to initial suppression efforts that may not be appropriate for this situation (a rapidly developing oil fire). Also note that the fire itself prevented the operator from shutting down the oil flow locally. As a result, oil continued to feed the fire. A typical fire PRA would not have credited this action because it required actions near the fire source.
00:01	At 00:00 (October 3rd) a reactor equipment operator was dispatched to level 1of the reactor building to manually close two control valves on the hydraulic oil supply to the entire system to stop the flow from the ruptured filter bowl. He managed to close one valve immediately and since the handle was not attached on the other valve, had to leave the area, find a wrench and then close that valve as well. He completed this task at 00:13.	A quality fire PRA, as part of the human actions analysis, would conduct a walkdown of the actions and potentially discover a missing valve handle. This incident demonstrates the importance of conducting such walkdowns. Consideration of the possible need to shut down the oil flow system from this remote location is, however, a subtle point that might easily be missed in a fire PRA.
00:02	At 00:01, the operators decided to start lowering the speed of recirculator D in anticipation of its shutdown because of hydraulic oil valve closure.	
00:04	At 00:03, outside fire department was contacted for assistance.	
--	Smoke leaked into the control room under the door opening into the turbine building.	
--	The equipment operator who had discovered the fire, went back to the fire area after donning fire brigade protective clothing and SCBA. He attacked the fire with a hose using a fog nozzle.	
00:05	Fire brigade arrived on the scene and attacked the fire using hoses from a different angle than the equipment operator who had discovered the fire.	
--	The smoke hampered the initial fire fighting efforts. Also, loss of electric power caused by the fire rendered the use of electric motor driven smoke ejectors useless.	

00:07	At 00:06, the "C" circulator tripped because of internal causes. Given the circulator "D" was coasting down, effectively the second reactor cooling loop was completely tripped.	
00:09	At 00:08, loop 1 circulators shut down because of loss of power to instruments caused by the fire.	It is interesting to note that a loss of instrument power is cited as the cause for loss of the loop 1 circulators. In a fire PRA, systems may be credited with continued operation even if the associated instrument circuits are lost.
00:09	Cable faults caused by the fire, shifted the control room ventilation system to minimum makeup mode from the Turbine Building. This allowed smoke from the Turbine Building to enter the control room.	In a quality fire PRA, the failure modes of a ventilation system should be studied. If such a study is undertaken, the possibility of ventilation system drawing smoke into the control room would be discovered. This is, however, a rather subtle aspect of the fire that might easily be missed in a PRA.
00:10	At 00:09, the operators initiated a manual scram because of indicated loss of primary and secondary cooling flow.	
00:11	At 00:10, the control room ventilation was manually shifted to purge mode to clear the light smoke entering the room. Air masks from a central Breathable Air System were distributed among the operators. However, an insufficient number of masks were available and operators had to share the available masks.	In fire PRA, in case of smoke in the control room it is conservatively assumed that the room is inhabitable. Therefore, lack of availability of sufficient number of working breathing masks would not be explicitly addressed, but the analysis may have assumed evacuation instead. Only a detailed fire risk analysis of the control room would identify such problem areas.
--	The door between the control room and building 10 was propped open to allow fresh air to enter the room and clear the smoke.	In a typical fire PRA no credit is given (conservatively) to the possibility of taking actions outside the normal procedures. As mentioned above, in the case of smoke in the control room., it is assumed that the operators will leave the room.
00:13	At 00:12, the operators placed the "B" (motor-driven) feed pump into operation.	The actions require to accomplish this recovery are not discussed.
00:14	At 00:13, the reactor equipment operator in the Reactor Building succeeded in closing the second hydraulic oil valve shutting off the source of oil to the fire.	
00:16	At 00:15, the fire was extinguished, but heavy smoke remained in the turbine building.	
00:26	At 00:25, Platteville Fire Department arrived on site	In this case, the fire was out before the off-site fire brigade arrived. The estimated response time is 23 minutes.
--	Smoke cleared from the control room.	

00:31	An ALERT was declared.	
00:41	At 00:40, certain phone lines to the plant were found to be lost because of fire damage to the cables.	In fire PRA, the availability of communication system is not explicitly modeled. Loss of the phone system would impact the possibility of contacting personnel who are not on-site. In a typical human action analysis in a fire PRA the possibility of calling in off-duty operators is not taken into account. Since most accident scenarios are modeled assuming an average number of operators in the plant, this omission is conservative.
01:31	At 01:30, the hydraulic oil isolation valve that had been engulfed in the fire was closed.	
01:36	At 01:35, the reactor equipment operator was dispatched to open one of the two hydraulic oil control valves from the Reactor Building.	
01:46	At 01:45, the Loop 2, Group 1 hydraulic header was returned to service. No leaks were discovered.	
01:59	At 01:58, the Technical Support Center was declared operational.	
03:51	At 03:50, the Forward Command Post was declared operational.	
06:03	At 06:02, it was verified that two independent safe shutdown paths were available and normal cooldown mode was being used.	
08:16	At 08:15 downgraded from ALERT.	

<u>Equipment Damaged</u>

- Electrical cables
- Instruments
- Valves
- Snubbers
- Fire detectors
- Offsite phone lines

<u>Damaged Area</u>

As shown in Figure A14-1, the fire occurred at the north part of the turbine building close to the control room. The fire itself was approximately 9 feet by 12 feet at its maximum. The area where the temperature was above 300^0F was estimated as 19 feet square at the base of the fire and covered and area of 53 feet by 35 at an elevation 17 feet above the base of the fire.

Impact on Core Cooling

Although normal cooling capability was affected and apparently lost for a short time during the fire, it was soon restored when the fire was extinguished. At no time during the fire was the core in any danger of overheating.

Radiological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A14.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in reaching a specific insight.

Fire Scenario Element	**Incident - Fort St. Vrain, October 3, 1987**	**Fire PRA Insights**
Presence of combustible / flammable materials	Petroleum based hydraulic oil of the hydraulic system was the main source of combustible material.	A common source for turbine buildings that would be considered in a PRA.
Presence of an ignition source	Hot exposed steel parts of relief valves that could not be insulated are deemed to be the ignition source. The temperature of the exposed steel was between 680 and 690F and auto-ignition temperature of the oil 620F.	These would be captured in a PRA
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The hydraulic oil, under close to 2800 psi pressure, was sprayed out of a failed filter bowl (canister). The oil spray arced 15' and came into contact with exposed hot steel and caught fire.	PRA fire modeling would typically consider a pool fire rather than a high pressure spray fire due to limitations of the commonly applied models.

Fire growth within the combustible or component of original ignition	The fire spread rapidly over the sprayed oil and created an 8'x3' fire. It propagated to nearby cables and started a fire in IEEE 383 qualified and non-qualified cables.	As with other turbine hall oil fires, the fire grew quickly. This should be captured in a PRA given the fuel source. IEEE 383 qualified cables were burning. This confirms the general assumption used in fire PRAs that qualified cables can sustain fire.
Fire propagates to adjacent combustibles.	Fire spread to adjacent cables was progressing towards Train B safety related cables. Cables were certainly damaged in this fire that had some impact on the control board in the control room.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	Although, given the large open areas of the Turbine Building perhaps only a relatively cool hot gas layer formed under the ceiling. Reference A14-4 indicates that hot gases were trapped between large structural beams of the Turbine Building and caused some deformation and damage to structural elements. However, per Appendix B of Reference A14-2 the high temperature region (300F) above the fire and below Floor 7 is approximately 53x35 feet.	Modeling of hot layer development in a very large open space is problematic for existing fire models.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke entered the control room because a cable failure caused by the fire put control room ventilation system into radiation release emergency mode. In this mode the control room HVAC draws air from the Turbine Building. This caused smoke to be drawn into the HVAC system and into the control room. Also, the west door was used extensively during the course of the fire. Frequent opening of that door caused loss of positive pressure in the control room and allowed the smoke enter the room through that door. Loss of electric power at the fire area rendered the use of electric motor driven smoke ejectors useless.	Turbine building fires are modeled in fire PRAs. In the case of Fort St. Vrain, a quality fire PRA would identify the potential for a turbine building fire affecting the control room. The west door would certainly be identified as the potential pathway for propagation of smoke into the control room. Although current methodologies are clearly capable of handling the scenario, given the level of detail employed in a typical fire PRA, it is doubtful that the analysts would identify the possibility of control room HVAC switching to radiation emergency mode and drawing from the turbine building. It is also not clear what the nature of the cable fault was leading to this switch in modes. This may be evidence of a cable failure induced spurious operation, but this cannot be established.

Local automatic fire detectors (if present) sense the presence of the fire	There were local fire detectors in the fire area that activate as designed. However, the operators would not have learned about the fire from the detectors because the main fire protection panels are located in a room separate from the control room with a closed door. Furthermore, the audible alarm in the control room was turned off because of nuisance alarms that had occurred prior to the fire. The fire was detected because of low pressure noticed by the operators in the hydraulic oil system.	If the operators were not alert to hydraulic oil pressure level, given that the audible fire detector alarm was silenced, it is possible that the fire would have remained unnoticed for an extended period of time. Plant specific conditions, such as those mentioned here (alarm in a separate room, annunciator turned off), would likely be identified during the plant walkdown and a degraded credit allowed for automatic detection.
Alarm is sounded automatically in the control room, locally and / or other places	See above	
Automatic suppression system is activated (if present)	There were no automatic suppression systems in the area.	
Personnel are present in the area where fire occurs	An equipment operator was dispatched to check the situation as soon as low hydraulic pressure was noticed.	
Control room is contacted or fire alarm is sounded	The equipment operator immediately contacted the control room about the oil spill and fire, and then returned to initiate an attack on the fire.	The operator in this case acted properly in reporting the fire. This, no doubt, helped to mitigate the extent of the fire and contributed to the final prompt suppression.
Fire brigade is activated	Fire brigade was activated practically immediately and they were on the scene within a few minutes. Local volunteer fire department was notified and they arrived at the plant withing a few minutes.	Fire brigade response is considered in PRA and this brigade responded as quickly or more quickly than is typically assumed.
Fire suppressant medium is properly applied	The equipment operator who discovered the fire managed to extinguish the fire initially by a dry-chemical portable extinguisher. However, since he was not able to close the valve to isolate the failed filter bowl, the fire flared up again and this time it was too strong to be handled by a portable extinguisher. The manual fire brigade was able to quickly extinguish the fire.	The actions of the fire operator on the scene undoubtably helped to control the fire and limit fire damage. However, in a fire PRA it is commonly assumed that once initiated fire fighting efforts will be successful.

Fire suppressant medium is properly applied to where the fire is.	Using fogging nozzles, the fire brigade attacked the fire from two sides and put out the fire as soon as a reactor operator closed the control valves to the two oil headers.	The was no report of collateral damage due to fire suppression activities.
Fire is affected by the suppression medium	Fire was affected by the water but was not brought under control until the oil supply was cut from the Reactor Building.	See note above regarding suppression effectiveness
Fire growth is checked and no additional failures occur	Fire growth was checked by the fire brigade attacking the fire from two sides.	
Fire is fully extinguished and fire brigade declares it as out	The fire was fully extinguished as soon as the supply of the oil from the two oil headers were cut off by manually closing two control valves in the Reactor Building.	The fire duration in this case is typical of the fires postulated in a PRA.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	Hydraulic valves, cables, instrumentation and some structural related items sustained damage from the fire.	The damage would likely have been captured in a fire PRA, in particular, the damage to cables. Valves are commonly assumed invulnerable to direct fire damage.
Cable failure impacts equipment outside the fire location	Several cables failed from direct impact of the fire. Control room ventilation system shifted to radiation emergency mode because of this. One primary circulation loop train was apparently lost due to loss of associated instrumentation.	The ventilation mode switch may be evidence of a spurious operation, but this cannot be verified. The loss of a circulation train due to instrumentation failures would not typically be postulated, but a plant specific review of circuit design may have revealed this vulnerability.
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	There are no indications of direct fire damage to equipment needed for safe plant shutdown. The operators had to trip the hydraulic oil system and close off the headers to stop release of oil into the fire. This in turn disabled several components needed for shutdown.	This is a case where safe shutdown equipment was rendered inoperable, in effect, through manual actions taken to fight the fire (shutting of the oil supply valves). This type of action could be easily missed in a fire PRA.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	The first message that led to the discovery of the fire was loss of oil pressure. After that several failures occurred that did not cause much limitation for the operators to maintain safe reactor shutdown condition.	The operators appear to have performed well in this incident despite the fact that some smoke got into the control room, and there was some difficulty with the breathing air supply system (not enough masks).

Operators attempt to control the plant properly and bring the plant to a safe shutdown	See above	
Structural failures (if occurred) may jeopardize availability of equipment	Although some structural elements were affected by the fire, there were no failures of structures.	
Water when sprayed over electrical equipment may fail the exposed equipment	no information	
The cooling effect of CO_2 may adversely impact equipment	no CO2 systems were involved	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The audible fire detector alarm was turned off in the control room.	This condition would likely have been detected during PRA plant walkdowns.

A14.5 Incident Analysis

In this fire incident a relatively severe turbine building fire took place (approximate damage $2.5 millon per Reference A14-4) that impacted control room habitability. In many regards, the fire was quite typical of those considered in a typical fire PRA. The fuel source (oil), the reason for its exposure (a piping failure), and its ignition mode (hot surfaces) are quite typical of turbine hall fires. The fire propagated to adjacent cable tray containing IEEE 383 qualified and non-qualified cables. The fire severity and duration are also quite typical of the scenarios postulated in a fire PRA analysis.

One significant insight that may be gleaned from this incident is that under special circumstances, a turbine building fire may be important to plant safety via its effect on other parts of the plant. In this case it affected the habitability of the control room. This ultimately was not a serious challenge to the nuclear safety of the plant in this case, but illustrates the potential for such challenges to arise. Smoke entered the control room via two pathways. The fire failed cables that caused the ventilation system for the control room to shift to a mode where the system takes air from the turbine building. There was a door between the control room and the turbine building that was used frequently causing the ventilation system fail to establish a positive pressure in the control room. Using current fire PRA methods it is possible for both pathways to be discovered. Of course, it will require a detailed analysis of the ventilation system to discover the situations as it occurred at Fort St. Vrain.

It must be added that it is common in fire PRAs, in case of smoke in the control room, to conservatively assume that the room is un-inhabitable. In this incident, there were an insufficient number of breathing masks connected to a piped fresh air system to service the six operators present (3 masks). This initially caused the operators to share the available masks implying that they were working in an uncomfortable environment. At some point portable air packs were made available to alleviate this situation. In a fire PRA the lack of sufficient breathing masks would not be explicitly addressed. Only a detailed fire risk analysis of the control room would identify such problem areas.

Other events of note during this incident include the silencing of the audible fire detector alarm in the control room, and a missing valve handle causing a delay in shutting off a key valve. In a quality fire PRA, during the walkdown, the analyst is expected to look for such plant conditions. This incident demonstrates the importance of conducting detailed walkdowns.

In the case of the valve handle, it is quite likely that the analyst would miss this problem since it was associated with a secondary shutdown valve (the primary valves being local near the fire source) and because in terms of the manipulation of plant equipment and systems, the analysis will commonly focus on plant control and recovery actions rather than actions that might be needed to mitigate a fire. Hence, this particular item would be easily missed in a fire PRA. It is also interesting to note that shutdown of the oil system also led to loss of some additional plant equipment. Again, this would be an easily missed action, although the consequence would be anticipated given the action.

The telephone system was partially failed during this incident. Although, the impact on the outcome of this incident was minimal, it brings out an interesting point. In fire PRA, the availability of communication system is not explicitly modeled. Loss of phone system would impact the possibility of contacting personnel who are not on-site. In a typical human action analysis in a fire PRA the possibility of calling in off-duty operators is not taken into account. Since most accident scenarios are modeled assuming an average number of operators in the plant, this omission is conservative.

Finally, the fact that the ventilation system for the control room switched operating modes due to cable damage may be evidence of a spurious operation due to cable failure. This cannot, however, be verified based on the available information. Verification would require access to, and analysis of, the plant HVAC control circuit diagrams and cable routing details. Given that the plant has been shut down for over a decade, this is considered unlikely, and in any case, such an analysis is beyond the scope of this review. The likelihood and impact of spurious operations is a current area of debate for fire PRA.

A14.6 <u>References</u>

A14-1 Attachment to the letter addressed to Mr. Robert O. Williams, Jr., Vice President of Nuclear Operations, Public Service Company of Colorado, from L.J.Callan, Director of Division of Reactor Projects, U.S. Nuclear Regulatory Commission, October 30, 1987.

A14-2 "Preliminary Report on the Impact of the FSV October 2nd Fire", Fort St. Vrain Nuclear Generating Station, Public Service Company of Colorado, October 30, 1987.

A14-3 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A14-4 Schmalz, Gregory D. "Lessons Learned from the Fort St. Vrain Turbine Building Fire", Fire & Safety '94, Barcelona, Spain, December 5-7, 1994.

Appendix 15 - Analysis of Ignalina, Unit 2 Fire on September 5, 1988

A15.1 Plant Characteristics

Ignalina is a two unit nuclear power plant located near Visaginas, Lithuania, which at the time of the fire discussed here was a part of the former Soviet Union. The two units are both RBMK-1500 type reactors. The power rating of each unit is 3,950 MWt and about 1,250 MWe provided by two turbine generators one at 550 and the other at 700 MWE. Construction of both units began in 1974. Unit 1 began initial power operations in either October[A15-5] or December[A15-4] 1983. Unit 2, where this fire incident occurred, began initial startup in December 1986.[A15-5] The units started commercial operation in May 1985 and December 1987 respectively.[A15-4] A planned third unit on the site was canceled.[A15-4]

RBMK reactors use graphite as a moderator and boiling water for cooling the core. The generated steam is dried in the steam drum or steam separator before it is directed towards the turbine generators. Core cooling is composed of two parts, a Left Hand Side (LHS) and a Right Hand Side (RHS). These two sections of the core are not fully independent from one another. There is some interaction between them, and this includes the cooling functions as well. Each side of the core is serviced by separate core cooling loops, each with its own steam drum and main coolant pumps (four per side). The feedwater from the condenser is pumped into the steam drum, which serves as the source of water for the main coolant pumps as well.

The core for an RBMK reactor includes special reactor protection rods that travel inside dedicated cross shaped channels and are isolated from the rest of the systems entering the core. In the case of Ignalina Unit 2 there were 12 such rods. The channels are cooled by a separate water cooling system. Pumps CP-21 and CP-22, mentioned in the discussions below, belong to the cooling system for these channels.

Room 209, where the fire occurred, is a cable spreading room in Unit 2, located under the Main Control Room and computer room at elevation 5.9m (measured from the local grade). Ionization type smoke detectors and a water based fixed suppression system were provided for that room. At the time of the fire, fire resistant coating was not applied to the cables at Ignalina but such coatings have been applied since.

A15.2 Chain of Events Summary

On September 5, 1988, Ignalina Unit 2 was at 100% power when, at 00:52:39, the Main Control Room received a fire alarm from room 209. The exact cause of the fire was never conclusively determined. However, it is suspected that the fire started in one of the 220VAC cables in the lowest of a stack of cable trays. There were apparently no external fire sources identified. The lowest tray housed 31 cables including at least one 220 VDC cable. It is suspected that the fire started due to overheating caused by a short circuit in one of the cables. The postulated root cause for the short circuit is damage inflicted to the cable during plant construction and a slow deterioration of the cable after that. It is possible that the cable had deteriorated because of thermal cycling, thermal overload, undue mechanical tension or vibration. Inadequate circuit protection devices are also thought to have facilitated the overheating of the cables and thus the possibility of an ignition.

The automatic fire suppression system in room 209 activated within a short time of the alarm (either a sprinkler or deluge system). The fire brigade was called and plant personnel made an attempt to check the room but could not enter because of dense smoke. Within three minutes of notification, the fire brigade arrived at the plant with five fire engines and smoke removal apparatus.

Over the course of the fire incident several pumps related to core cooling and various plant instrumentation systems were lost affecting the core's LHS. Despite the losses, however, the operators managed to establish feedwater flow to the affected steam drum and facilitated the natural circulation of the coolant through the core. All systems associated with the core's RHS remained functional throughout the fire. Operators took some precautionary measures to ensure that the two sides of the reactor would not adversely interact given the losses to the LHS related systems.

Cable faults caused numerous electrical power system failures. Instrumentation and control cable faults caused supply breakers for normal and essential (non-safety) 6kV buses to open. Cable damage also prevented proper alignment of two of the six diesel generators to these buses. This led to the unavailability of the LHS reactor protection coolant pumps. Later, one of the diesel generators started and properly connected to one of these buses, and one of the reactor protection coolant pumps started. The power to the affected buses was restored within about 40 minutes from the first fire alarm and the operators managed to regain normal control of the reactor and its cooling functions at that time.

The fire also caused a partial loss of reactor core monitoring instrumentation systems. The indications for 4 out of the 12 reactor protection channels were lost. At about 10 minutes after the fire alarm, the operators de-energized control rod drive mechanisms to prevent any spurious movement of the rods.

The fire brigade attempted to enter room 209 to fight the fire directly but they were forced to retreat because of the dense smoke. At about 22 minutes into the incident, the smoke removal apparatus was activated. The fire brigade managed to enter room 209 about 16 minutes later, or 38 minutes after the fire alarm. They found the fire completely extinguished by the automatic fire suppression system. The fire had damaged 646 cables for a length of about 5 meters. Of these, 506 cables were associated with control and instrumentation circuits and 106 with power distribution systems. Cables in the upper-most cable trays were also found damaged by the fire.

Apparently the cable faults caused by the fire in room 209 led to failures in the Reserve Control Room as well. The Reserve Control Room is the back-up for the Main Control Room and it contains a control panel that can duplicate a large number of safety related controls and instrumentation available in the Main Control Room. For example, the level control signal for the LHS steam drum was restored from the Reserve Control Room about 40 minutes after the first fire alarm. Since by this time the feedwater flow had been established, but level control was apparently not functioning, the level was found to be above the measurable scale.

After the fire was extinguished, diesel generator #8 developed an oil leak and had to be tripped. Power to one of the buses was lost again which led to loss of one reactor protection cooling pump. These failures occurred from causes independent of the fire.

A15.3 <u>Incident Progression and Implication for Fire PRA</u>

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [A15-1] through [A15-3]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, such events are included within the sequence of events based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	On September 5, 1988, Unit 2 was at 100% power (i.e., the turbine generators were producing 550 MWE and 700 MWe). The fire detectors and fire suppression system for room 209 were in the automatic mode. The ventilation system of room 209 was operational Main coolant pump 12 was on stand-by.	
00:00	At 00:52:39 on September 5, 1988, the Main Control Room received a fire alarm from room 209. The exact cause of the fire could not precisely be determined during the accident investigation although a self-ignited cable fire is suspected.	Given the conclusions of the fire investigation, this incident demonstrates that self ignited cable fires can occur, even in a relatively low voltage circuit (220VAC in this case). The fire experience in US nuclear power plants contains only a few minor self-ignited fire events. In fire PRAs, such fires are commonly considered, but only for cables that are not qualified as low flame spread per standards implemented for the nuclear industry beginning in 1975 (IEEE-383). Given the differences that likely exist in cable characteristics and electrical circuit design features between US and Soviet-designed plants, the Ignalina experience may not be directly relevant to U.S. plants.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:00	At 00:52:49, a second fire alarm was received from room 209 in the Main Control Room. This alarm was also automatically transmitted to the plant fire brigade. At the same time, the automatic fire suppression system in room209 was activated automatically.	The fixed fire detection and suppression systems did activate as designed.
00:01	At 00:53:00, the fire brigade was called.	
--	A senior engineer and another member of the plant staff checked the situation from the corridor next to room 209, but could not enter the small entrance area to room 209 because of dense smoke.	
00:03	The fire brigade arrived at the plant with five fire engines and apparatus for removing smoke from a compartment. Upon arrival, they called for additional help and equipment.	As is typical of plants in the former Soviet Union, fire fighting is primarily provided by an associated fire brigade located near the plant but off-site.
00:03	At 00:55:55, the Control Room received oil level alarms for main coolant pump 14 (serving LHS) and the pump tripped automatically. This caused the power level to reduce to 2,830 MWt (60%). Cable faults in the circuits for oil level indicators and alarm are suspected to be the cause of the trip.	This is apparently a spurious trip signal caused by fire damage to instrumentation circuits. Some fire PRAs would not assume loss of a system given fire damage only to associated instrumentation circuits, although practice does vary from analyst to analyst.
00:04	At 00:56:25, main coolant pump 13 tripped because of cable faults related to the oil system and reduction in oil flow to the bearings. Loss of this second main coolant pumps led to automatic reactor trip. The automatic reactor trip led in turn to the startup of all six diesel generators associated with this unit.	This is the second system to be failed by the fire.
00:04	At 00:57:00, turbine generator #3 tripped on low steam drum level. Reactor coolant pressure was at 55kgf/cm^2 (780psi)	
00:04	At 00:57:15, turbine generator #4 tripped on high level in low pressure heater #4.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:06	At 00:58:31, main coolant pump 11 tripped because of cable faults. With loss of all main coolant pumps, natural convection became the motive force of coolant flow through left hand side of the core.	This is the third system failed by the fire.
00:06	At 00:59, level control of steam drum, feedwater control valves and main coolant pump valves, all associated with the LHS, were lost. Plant personnel established feedwater flow to the affected steam drum.	
00:06	At 00:59:14, cable faults caused numerous electrical power system failures. Instrumentation and control cable faults led to the opening of supply breakers of normal 6kV buses BA and BB and essential (non-safety) buses BV and BU. Cable damage also tripped Transformer 5 and prevented it from taking up the loads for these buses. Diesel generator #7, because of bus failures, did not connect to bus BU. Because of this, reactor protection system pump CP-21 failed to operate. Diesel generator #8 started and supplied power to BV to 2MW load. Since BV was powered, the reactor protection system cooling pump CP-22 began operation.	These are cases where instrumentation and control faults apparently led to spurious trip signals being sent to various supply power systems and breakers. See note above.
00:07	At 01:00, there was a partial loss of reactor neutron monitoring instrumentation. The indications for 4 out of the 12 reactor protection channels were lost.	
00:10	At 01:03:20, operators de-energized the control rod drive mechanisms to prevent any spurious signals from causing a control rod to move. Main coolant pump 24 (serving the RHS) was tripped by the operators to minimize the possibility of adverse interaction between the two sides of the reactor. Main coolant pump 22 was left in service.	De-energizing of the CRD system is an interesting precautionary measure taken by plant operators. Whether or not this was a procedure-based action is not clear. It does illustrate that operators were cognizant of the spurious actuation possibility and took actions to mitigate their potential impact.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:12	About 01:05, the fire brigade tried to enter room 209 to fight the fire but was unable because of the dense smoke.	This indicates a transit time from the plant entrance to the location of the fire of about 9 minutes (see 00:03). This is relatively fast in comparison to typically assumed response time from fire PRAs. Smoke hampering fire fighting efforts is commonly recognized as a potential issue but is also commonly considered unlikely based on fire brigade training.
00:18	At 01:11, the monitor for LHS feedwater flow was lost. The operators energized buses BA and BU from a working auxiliary transformer. This initiated the operation of one reactor protection system pump.	
00:22	At 01:15, smoke removal equipment was activated in Unit 2 corridors.	It is not clear if this was portable or fixed equipment. One must infer from the 10 minute time period from initial attempts to access the fire area to the time smoke removal was initiated that this involved the placement of portable smoke removal blowers.
00:27	At 01:20, an attempt was made to start main coolant pump 12, but it did not start.	
00:38	At 01:30, the fire brigade entered room 209. The brigade could not find a fire in the room. The water supply to the fire suppression system for the room was therefore stopped. It was concluded that the fire was extinguished by the automatic fire suppression system. 646 cables for a length of about 5 meters was found damaged by the fire. 506 cables were associated with control and instrumentation circuits and 106 were associated with power distribution systems. The ceiling of the room was found partially damaged.	In this case, the fire suppression system actuated and performed as designed. The time of detection and fire suppression system activation imply a very prompt system response, typical of what would be assumed in a fire PRA. It is interesting, however, that despite proper and successful operation of the fire suppression system, substantial damage was observed. It is commonly assumed that once a fire suppression system activates, further damage will be mitigated. In this case, the event clearly shows that fire damage continued to cause system losses well after the suppression system activated.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:40	The level control signal for LHS steam drum was restored from the Reserve[1] Control Room. The level was found to be above the measurable scale.	Note that this event indicates that a "partial abandonment" of the MCR was exercised. Operators were working from both the main and reserve control rooms to control the plant. From the information provided in the available sources, it can be inferred that the Main Control Room and Reserve Control Room were not completely independent and some of the failures caused by the fire in room 209 rendered some indicators and control functions on both control panels unavailable. For U.S. plants, potential interactions or dependencies between the control room and remote shutdown capability are explicitly addressed through the Appendix R analysis. It is common for current PRAs to rely on these deterministic assessments to assure remote shutdown independence, but confirmation of these assumptions was raised as a potential unaddressed risk issue in the Fire Risk Scoping Study (SNL) and was a common point of technical concern raised in the USNRC-sponsored IPEEE reviews.
00:45	At 01:38, in order to prevent spurious withdrawal of the rods, the drivers of the rods were mechanically blocked and the blocks were de-energized.	Recall that earlier in the event the CRD system had been electrically de-energized. Apparently operators did not fully trust this action and took additional measures to prevent rod withdrawl.
00:47	At 01:40, diesel generator #8 was manually tripped because of an oil leak from a flange. Power to bus BV was lost which led to pump CP-22 of the reactor protection system to trip.	This represents an independent event (failure) in that the loss of the diesel generator cannot be attributed to causes related to the fire. Diesel generator #8's oil system developed a leak and the operators had to shut it down. In this case, the impact of this event may not have been detrimental to the capability to provide core cooling. In fire PRAs, the possibility of occurrence of independent events is modeled explicitly through the use of internal events model.
--	Per Reference A15-2 "Shutdown key" on Reserve Control Room panel was lost.	

Notes: (1) The Reserve Control Room is a back-up of the Main Control Room. For Soviet-designed plants, the Reserve Control Room generally contains a control panel that can duplicate a large number of the safety related control and instrumentation functions in the Main Control Room.

Equipment Damaged

– Electrical cables (646 cables for a length of about 5 meters was found to be damaged by the fire. 506 cables were associated with control and instrumentation circuits and 106 were associated with power distribution systems.)

Damaged Areas

– Cable Spreading Room under the Main Control Room and Computer Room.

Impact on Core Cooling

– Safety related equipment were affected by this fire. Cooling capability for one half of the core was affected.

Radiological Release

– No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

– There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

– The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

– There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A15.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against a typical fire scenario which is expressed in terms of a list of elements. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Ignalina 2, September 5, 1988**	**Fire PRA Insights**
Presence of combustible / flammable materials	Electrical cables were the main source of combustibles for this fire incident.	Cable fires are commonly considered in fire PRAs

Fire Scenario Element	**Incident - Ignalina 2, September 5, 1988**	**Fire PRA Insights**
Presence of an ignition source	An electrical fault was apparently the source of ignition in this incident. The fire was concluded to have been ignited in a 220VAC cable servicing a valve motor. It was suspected that some of the cables were damaged during construction and they further deteriorated due to overheating, vibration or mechanical tension. Also, the inadequate response of circuit protection systems were suspected to be a contributor to the ignition of the cable.	The ignition was apparently exacerbated by physical damage to the cables and inadequate circuit protection. In fire PRA, fire initiation is handled as a statistical process and the exact mechanism of ignition is rarely considered.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Fire investigators concluded that this was a self-ignited cable fire. The exact cause of cable failure and ignition of the cables could not be conclusively determined.	Self-ignited cable fires are considered, in particular, for older plants that still contain significant quantities of cable that has not be certified as low-flame-spread per IEEE-383
Fire growth within the combustible or component of original ignition	From the information provided, it can be inferred that fire established itself quite rapidly.	It is commonly assumed in fire PRA that cable tray fires will develop slowly over the period of several minutes at the least. This fire appears to have grown more quickly than this, although differences in U.S. versus Soviet cable materials may have played a role so extrapolation to US plants may be inappropriate.
Fire propagates to adjacent combustibles.	From the timing of the events, it can be concluded that the fire propagated to other combustibles (trays above the ignition tray) nearby in a short time.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	Clearly, a hot gas layer did form in the fire room, but it is not clear if any damage was cause by the gas layer rather than direct fire involvement.	A common finding in fire PRAs (based on fire modeling) is that hot gas layers are not sufficiently hot so as to cause fire damage. Rather, fire damage is typically predicted to be limited to trays directly in the fire or fire plume. This incident appear to nominally support the validity of these findings.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	The fire remained in the compartment of origin and no damage outside the compartment was reported.	
Local automatic fire detectors (if present) sense the presence of the fire	The ionization type smoke detectors did actuation, apparently within a short time of fire initiation.	Fire detectors performed as designed

Fire Scenario Element	Incident - Ignalina 2, September 5, 1988	Fire PRA Insights
Alarm is sounded automatically in the Control Room, locally and / or other places	Alarms were sounded automatically in the Control Room and at the associated but fire brigade station. In fact two alarms were received at the initial stages of the fire, one from the smoke detectors and a second flow alarm on the fire suppression system.	
Automatic suppression system is activated (if present)	The fixed automatic water system of room 209 activated as designed.	The suppression system apparently actuated nearly simultaneous with the initial fire detection by smoke detectors. This is an indication of very prompt suppression system response.
Personnel are present in the area where fire occurs	Personnel could not enter the room because of dense smoke and low visibility.	Given these conditions a PRA would not typically credit any fire intervention actions by anyone other than the fire brigade. This event confirms the validity of this practice.
Control Room is contacted or fire alarm is sounded	The fire initiation time for this incident is measured from the moment that the Control Room received a fire alarm from room 209.	
Fire brigade is activated	Plant fire brigade was activated within a short time of the initial alarm in the Control Room. In addition to the Control Room, the fire alarm sounded in the fire station as well. Five fire engines arrived at the plant within 3 minutes of the alarm. Additional equipment and personnel were requested as well.	The fire brigade arrived on-scene very promptly. Typical PRAs would assume a somewhat longer brigade response time, particularly for brigades not physically located on-site.
Fire suppressant medium is properly applied	Water from the automatic fire suppression system sprayed on the fire. Fire fighters did not apply any suppressants but after clearing smoke, found the fire extinguished when they entered the room.	Fire suppression systems are typically designed to provide fire control rather than extinguishment. It is interesting to note that in this incident the fire suppression system worked as designed and apparently suppressed the fire completely. However, despite the successful operation, extensive damage was sustained. Even cables in the uppermost cable trays were damaged by the fire that apparently started in the lowest tray.

Fire Scenario Element	Incident - Ignalina 2, September 5, 1988	Fire PRA Insights
Automatic fire suppression system is activated	The automatic fire suppression system activated as designed.	See note above.
Fire suppressant medium is properly applied to where the fire is.	The fire brigade did not conduct any manual fire fighting.	
Fire is affected by the suppression medium	The fire was affected by the automatic suppression system. The fire was fully extinguished in less than 38 minutes after it was initiated.	
Fire growth is checked and no additional failures occur	The fire growth was checked by the automatic fire suppression system. However, a large number of cables (646 cables) were damage for a length of about 5 meters.	In fire PRA it is common to assume that if the fixed suppression system activates, any subsequent damage will be mitigated (prevented). In this case damage continued well after the suppression system activated.
Fire is fully extinguished and fire brigade declares it as out	The fire was extinguished by the automatic fire suppression system and declared as out about 38 minutes after the first fire detector alarmed in the Control Room. No manual fire fighting was necessary.	
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	A large number of cables were lost. No other equipment were affected directly by the fire or smoke. There was some structural damage to the ceiling.	See note above regarding damage timing versus suppression activation.
Cable failure impacts equipment outside the fire location	Cable failure certainly impacted equipment outside the fire area. The impact was mainly on the systems serving the LHS: part of the neutron monitoring instrumentation was lost, the main coolant pumps were lost, and feedwater flow control was lost.	The reported failures apparently include cases where control or instrument cable failures did lead to the generation of spurious trip signals for various electrical supply systems. (See note in previous table above.)

Fire Scenario Element	Incident - Ignalina 2, September 5, 1988	Fire PRA Insights
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Three of the four main coolant pumps for the left hand side of the core were tripped. As a consequence the reactor tripped. Feedwater flow control and steam drum level were lost. The power to several buses were lost. The reactor protection system cooling pumps were also affected. Overall a large number of equipment serving the left hand side of the core were affected. However, the core was not in any imminent danger of severe overheating.	This fire did present the operators with the loss of a number of important safety systems. However, the operators responded appropriately to recover the plant to a safe shutdown state.
Operators in the Control Room receive messages and respond to the information displayed on the control board or received verbally from the plant	The operators used the Main Control Room and the Reserve Control Room to monitor the condition of the reactor and core cooling systems. There was partial loss of neutronics related instrumentation. No specific information is provided regarding the adequacy of the information on the control board in the Main Control Room, reliance on Reserve Control Room readings and interaction with field operators.	This is one of the few fire incidents where an attempt was made to use the alternate shutdown panel. However, some interaction was experienced between the main panel and the alternate shutdown panels (i.e., the Reserve Control Room). In fire PRAs for US plants it is typically assumed that the analysis conducted as part of Appendix R compliance has resolved the potential interaction issues. Some attention is given to this issue in fire PRAs as part the response to the issues raised in Sandia Fire Risk Scoping Study. However, no probabilistic analysis of the potential interactions is conducted.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	Operators were able to control the plant properly. The systems serving the right hand side remained available throughout the fire. The left hand side cooling was achieved by natural circulation and feedwater flow into the steam drum.	There were not significant operator errors noted.
Structural failures (if occurred) may jeopardize availability of equipment	The ceiling of the cable spreading room was found partially damaged.	
Water when sprayed over electrical equipment may fail the exposed equipment	No information	
The cooling effect of CO_2 may adversely impact equipment	Not applicable	

Fire Scenario Element	Incident - Ignalina 2, September 5, 1988	Fire PRA Insights
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	Main coolant pump 12 was on stand-by at the time of the event and could not be started.	

A15.5 Incident Analysis

The fire incident at Ignalina 2 can be considered as a classic case of relatively modest cable spreading room fire that ignited on its own, propagated to adjacent cables, was detected in a short time, and was extinguished by the automatic suppression system that functioned as designed. The fire remained confined to its compartment of origin, and damage was apparently limited to one stack of cable trays. The cables affected by the fire belonged only to a limited number of systems and components, and core cooling and reactor monitoring was never completely lost in this incident. Despite the available components and systems, the set of cable faults experienced in this incident made it difficult for proper control of the reactor core parameters and core cooling for the LHS. This is a scenario that is commonly postulated in fire PRAs.

One interesting aspect of this fire is that while the suppression system functioned as designed, and even extinguished the fire (the design basis for a typical automatic suppression system is to control the fire and not necessarily extinguish it completely), extensive damage was sustained. Furthermore, additional equipment losses were recorded well after the fire suppression system had actuated. This incident demonstrates that it may not be proper in a fire PRA to assume that activation of a fixed suppression system would stop any further damage from occurring. However, it must be added that a direct extrapolation of this incident for refuting the above mentioned assumption may be premature. The characteristics of the cables used at Ignalina would have influenced the propagation of the fire, apparently despite fire suppression system activation. It is not clear what correspondence (or lack thereof) there might be between cables used in the U.S. and those used in the Soviet designed plants.

This incident also demonstrates that self-ignited cable fires can occur. Furthermore, such fires can happen in relatively low voltage circuits (220VAC in this case). Fire PRAs treat fire ignition possibility through a statistical analysis of relevant fire incidents. For self-ignited cable fires, the fire experience in the nuclear power plants in the U.S. contains only a few minor incidents. For cases where the cables are certified as low-flame-spread (per IEEE 383) it is common to dismiss self-ignited cable fires as of extremely low probability. This incident neither supports nor refutes this aspect of fire PRAs given the differences that likely exist in cable characteristics and electrical circuit design features between US and USSR plants.

It is also interesting that in this event, operators acted from both the main and reserve control rooms. From the information provided in the available sources, it can be inferred that at the time of the fire the Main Control Room and Reserve Control Room at Ignalina were not completely independent. This is because some of the failures caused by the fire in room 209 rendered some indicators and control functions on both control panels unavailable. In fire PRAs for US plants, the Appendix R compliance analyses are commonly cited as ensuring the independence of the alternate shutdown capability. Verification of independence, rather than assuming independence, has been raised as a potential risk issue in both the SNL Fire Risk Scoping Study and in the USNRC-sponsored reviews of the IPEEE submittal. Again, given that the electrical design practices of the Soviet plants is likely substantially different from that of the US, the Ignalina experience may not be directly applicable to US plants.

A15.6 References

A15-1 Section IV, "Analysis of the Event: Partial Loss of the Control Room Unit 2 Due to Fire in Cable Room, 1988", in English

A15-2 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A15-3 Soloviev.P.S. "Accidents and incidents in nuclear power plants", Obninsk,1992.

A15-4 *1999 World Nuclear Industry Handbook*, Nuc. Eng. Int., 1999.

A15-5 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 16 - Analysis of Oconee 1 Fire on January 3, 1989

A16.1 Plant Characteristics

Oconee is a three unit nuclear power plant located near Seneca, South Carolina. All three units are nearly identical 860 MWE Babcock and Wilcox design, pressurized water reactors. Unit 1 started commercial operation in July 1973. Each reactor has four reactor coolant pumps (RCPs). At Unit1, two of the pumps are powered by an Auxiliary Power System 6.9kV switchgear designated as 1TA and the other two by another Auxiliary Power System switchgear designated as 1TB. The following design/control features played a role in the fire incident being reviewed.

Per the technical specifications, reactor cooldown should be less than 50°F per 30 minutes. Main coolant loop pressure is maintained by controlling the sprays and heaters of the pressurizer. The normal pressurizer spray is fed from one of the cold legs of the main coolant loops. If control of the pressure via the pressurizer is not possible, the operators can use one of the following three methods:

- The Power Operated Relief Valve (PORV) of the pressurizer can be used to relieve main coolant into the Quench Tank.
- An auxiliary spray is available for the pressurizer using the high pressure injection system.
- By throttling open the Turbine Bypass Valve, steam from the steam generators can be dumped into the main condensers.

The plant, for normal operation, is controlled by the Integrated Control System (ICS). One of the features of the ICS is to automatically, upon loss of all reactor coolant pumps and availability of main feedwater function, swap the feedwater flow from the main feedwater nozzles to the auxiliary nozzles and to increase steam generator level to 50%. These actions facilitate establishing of natural convection cycle in the main coolant loop.

A16.2 Chain of Events Summary

On January 3, 1989, Unit 1 was being brought up to power after a trip that had occurred a few days earlier. It had reached 26% power at 19:16 when the 6.9kV Switchgear (1TA) failed explosively and caught fire. The precise cause of this incident could not be established in later investigations. As a result of the switchgear failure, the main turbine and two reactor coolant pumps tripped initiating a reactor transient.

The operators immediately started reactor power reduction. Average reactor temperature was 575°F at the beginning of the incident. Initially core cooling was maintained by the two operating reactor coolant pumps and main feedwater flow through the steam generators. Two high pressure injection pumps were started by the operators to compensate for contraction of the water in the main coolant loop as it was cooling down due to the power reduction. When the power dropped to 4%, the operators tripped the reactor.

Meanwhile, fire alarms were received in the control room. The fire brigade was activated to respond to the fire. Later, off-duty shift personnel were called in to assist in the fire fighting effort. Two initial attempts by the fire brigade to suppress the fire using carbon dioxide and dry chemical fire extinguishers failed to put the fire out. Control room operators de-energized the DC power bus in order to isolate the impacted 1TA switchgear from all electrical sources. It was then decided to apply water to the fire using a fog nozzle. To further protect the fire fighters, the other train of non-safety 6.9kV switchgear (i.e., 1TB), located near 1TA, was also de-energized. The water fog was used on the fire and at 20:15, about one hour after the switchgear failure, the fire was declared as completely extinguished.

Tripping of 1TB (to protect the fire fighters) caused the remaining reactor coolant pumps to trip. The Integrated Control System (ICS) is designed, under these conditions, to raise the water level in the steam generators to 50% and swap the feedwater nozzles from main to auxiliary. Due to fire damage to signal cables, the ICS failed and the operators had to execute these two actions manually. However, in doing so the operators forgot to close the main feedwater valve. This further accelerated the rapid cooldown process that was already underway. Furthermore, since the operators focused on in-core thermocouple readings to monitor reactor temperature, they did not properly monitor the rate of cooldown at different points of the main coolant loop.

Cold leg temperature dropped to about 426°F in about one hour. The shift engineer and shift supervisor determined that the temperature in parts of the reactor may have dropped faster than 100°F in one hour, which means that they may have entered the Thermal Shock Operation Region (overcooling).

Because operators had started the high pressure injection system, reactor pressure reached 2355 psig for a short time. Later, the pressure reached 2385, also for a short time. Operators then stopped the high pressure pumps to control the high pressure condition. These two pressure spikes, combined with the possibility of operating in thermal shock region, could have endangered the integrity of the main vessel if the conditions had persisted for an extended time.

At some point in the incident smoke did find its way into the main control room. The extent of the smoke and the path by which the smoke found its way into the control room are not described in the available sources. It is not clear if the smoke had any impact on operator performance, although one report cites this (rather in passing) as a contributing factor to the errors that led to the overcooling transient.

A16.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available source [Ref. A16-1]. If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	Unit 1 had in the days before the fire tripped and was being brought back to power. The reactor had reached 26% power level at the time of the fire. Units 2 and 3 were operating at 100% power.	
00:00	At 19:16, 6.9kV auxiliaries were manually transferred from the startup transformer to the main transformer (1T). Differential alarms were received in the control room on two of the three phases on 1T.	
00:00	Switchgear 1TA failed explosively and caught fire. The causes of this event could not be established in later investigations. Two scenarios were suspected -- arcing at "plug-in" connections or a fire in the DC control circuits inside the switchgear that caused high voltage parts to arc and fail explosively. Main turbine and two reactor coolant pumps tripped as a result.	This incident involved and explosive fault in a switchgear panel. Typical fires modeled in a fire PRA involve an initial ignition that grows over time. In this case, the fault was energetic and ignited a substantial fire.
00:01	Fire alarms were received in the Control Room, which was followed by telephone calls reporting of a fire and an explosion at 6.9kV switchgear 1TA. The switchgear was de-energized.	Detection of the fire was very prompt as would be consistent with a typical PRA. Fire PRA will typically assume prompt detection given fixed detection systems.
--	The fire brigade was activated to respond to the fire.	There were no delays in declaring the fire and initiating a response.
--	Reactor ran back to 14% power.	
00:13	At 19:29, the DC control power was removed at 1DIA and 1DIB buses to completely isolate 1TA switchgear from power sources.	
--	Smoke entered the Control Room. The available information [Ref. A16-1] does not elaborate on how smoke entered the control room nor how dense it was. If the operators had to don breathing apparatus, this would likely have been mentioned in reports. Since it isn't mentioned, this is taken to indicate that the smoke density was low.	Smoke propagation is not explicitly addressed in fire PRAs. This incident demonstrates that a fire outside the Control Room can lead to smoke inside the Control Room. In Reference [A16-1], it is stated that the smoke may have had some impact on operators' performance. However, no details are provided.

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
00:17	At 19:33, carbon dioxide was applied to the burning switchgear. It did not put the fire out.	PRAs typically assume that once initiated, fire fighting efforts will be successful. The two failed fire suppression attempts demonstrate that the availability and application of a fire suppressant does not necessarily lead to fire extinguishment. Rather, the effectiveness of the fire suppression system or method is important. Fire fighting is a decision-making process involving the selection and application of fire suppressants, and this decision making process is not explicitly modeled in current PRAs
00:25	At 19:41, dry chemical extinguisher was applied. This also failed to extinguish the fire.	
00:29	At 19:45, the shift supervisor declared an Unusual Event.	
00:39	At 19:55, operators started reactor power reduction. Average reactor temperature 575F.	
00:40	At 19:56, two high pressure injection pumps were started by the operators to compensate for the shrinkage of the water in the main coolant loop as it was cooling down because of power reduction.	
00:41	At 19:57, Technical Support Center and Operational Support Center were activated.	
--	Shift supervisor asked for off-duty shift personnel to be called in to assist in the fire fighting effort.	
00:42	At 19:58, a suction valve on the High Pressure Injection system from the Borated Water Storage Tank opened automatically and a reactor coolant loop injection valve throttled open.	
00:43	At 19:59, decision was made by fire brigade leaders and shift supervisors to use water to fight the fire.	Here again fire fighting is seen as a progressive exercise in decision making. See note above.

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
00:44	At 20:00, reactor power had decreased to 4% of full power and the reactor was tripped manually. The two remaining reactor coolant pumps were also tripped manually in preparation to de-energize 1TB switchgear. At 20:00, the operators de-energized 1TB switchgear to allow for the fire fighters use water on the fire.	With the de-energizing of 1TB, effectively two opposite trains of a system, albeit a non-safety system, were temporarily out of service. This demonstrates that it is not necessary for the fire itself to cause all system trains to fail. In the course of fire fighting, equipment may be de-energized possibly leading to the unavailability of redundant trains. Current fire PRA methodologies include provisions for analyzing the actions that should be taken by fire brigade. In that analysis, such special condition as that discussed here may be discovered and modeled properly.
00:44	The Integrated Control System (ICS) that controls the normal plant operation was affected by the fire because of signal cable failure. Upon loss of reactor coolant pumps and main feedwater available, the ICS is designed to raise steam generator levels to 50% and swap feedwater nozzles from main feedwater to auxiliary feedwater to facilitate natural circulation in the main coolant loop. It failed to implement these two actions.	Failure of the ICS was a direct result of fire damage to the associated signal cables. This would have likely been predicted in a fire PRA.
00:48	At 20:04, reactor pressure reached 2,355 psig, the set point for Reactor Protective System. The Turbine Bypass Valve was throttled to 10% open by the operators.	
00:49	At 20:05, the operators manually increased steam generator levels to 50% and swapped feedwater from main feedwater nozzles to the auxiliary nozzles. However, the main feedwater block valves were left open (in error), which further enhanced the rapid cooldown process. Turbine bypass valves closed automatically.	An error of omission occurred at this point in the chain of events. In fire PRA such errors are modeled as an integral part of the event tree and fault tree models developed for the internal events analysis. The human error probability assigned to these events is generally includes consideration of the conditions that fire imposes on the operators. However, it is common to assume that actions in the main control room are not impacted by fires in other plant areas. The fire in this case created the need for a manual operator response, but it is not clear whether or not the fire directly increased the likelihood that failures might then result.
--	The high pressure injection system caused the main coolant loop pressure to reach 2395 psig.	

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
00:50	At 20:06, apparently due to internal system control features the high pressure injection valve first opened fully, then closed completely. Operators stopped the high pressure pump 1A because of the increasing pressure and placed the pump in the automatic mode.	
00:54	At 20:10, plant personnel determined that the requirements for "Thermal Shock Operating Region" has been met. A control room operator tried to establish high pressure injection auxiliary pressurizer spray to depressurize the reactor, but his efforts were not successful. Later, a containment entry was made and the isolation valve for this spray path was found closed.	Failure of the auxiliary spray capability was caused by an independent failure (i.e., not related to the fire). This failure had an impact on the chain of events, and demonstrates the importance of such events. In fire PRA, independent failures are modeled explicitly using the event trees and fault tree of the internal events model.
00:54	The high pressure injection pump 1A was started.	
--	A second rapid pressure increase of the main coolant loop took place. The pressure reached approximately 2300 psig.	
00:59	At 20:15, water fog was used and the fire was declared as completely extinguished.	This fire was of relatively long duration in comparison to typically modeled PRA fire scenarios. In this case, there was a substantial delay in the application of effective suppression methods.
00:59	Cold leg temperature reached 426F. Given a drop of more than 100°F per hour from the average temperature of 575°F in the main coolant loop augmented by two pressure spikes, there was a threat of thermal shock.	Thermal shock is generally considered in internal events PRAs. However, it is often eliminated from the sequence models because multiple random equipment failures reduce the likelihood of such an event. Fire PRAs commonly rely on these same internal events models. Fire can act as a common threat to several items whose simultaneous random failure probability may be very low. Elimination of low-frequency sequences in the internal events analysis may have implications for the fire analysis.
01:47	At 21:03, 1TB switchgear was re-energized	
02:03	At 21:19, the Technical Support Center was established.	
02:04	Cold leg temperature reached 398F	

Relative Time (hr:min)	Event or Step Description	Fire PRA Implications
02:34	At 21:50, members of the Technical Support Center determined that Thermal Shock Operating Region (TSOR) was not reached. However, recommended, after reactor coolant pump restart, to maintain the reactor in a three hour soak period to allow vessel and other reactor parts to reach a steady state condition.	

Equipment Damaged

- 6.9kV switchgear.
- Electrical cables (including ICS cables)

Damaged Areas

- The damage was limited to a switchgear and electrical cables nearby.

Impact on Core Cooling

- Core cooling was maintained at all times during the incident. The reactor was subjected to rapid cooldown and may have entered thermal shock operating region.

Rediological Release

- No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

- There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

- The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

- There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A16.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire incident is compared against the elements that make up a typical fire PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Presence of combustible / flammable materials	Switchgear cabinet contents and electrical cables around the switchgear were the available combustibles.	
Presence of an ignition source	Electrical equipment were the source of ignition.	
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The exact cause of ignition could not be determined. Arcing at the connectors or a DC circuit related component fire may have led to the energetic failure of the switchgear.	In this case, the initial fault was energetic in nature and the fire, in effect, bypassed the typical fire initiation and growth stages assumed in a PRA. It would appear that the entire switchgear panel was engulfed in fire almost instantaneously.
Fire growth within the combustible or component of original ignition	1TA switchgear failed explosively and its internal components caught fire.	
Fire propagates to adjacent combustibles	Cables near the switchgear caught fire.	This is a case where a fire starting inside an electrical panel did propagate out of the panel. Some PRA methods discount this possibility, and this was a topic of debate with regard to application of the EPRI *Fire PRA Implementation Guide* to the IPEEE analyses (see report body for further discussion).
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information provided	
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	From Reference [A16-1] it can be inferred that some smoke found its way into the control room.	This event demonstrates that smoke can propagate to other locations. In fire PRA smoke propagation is generally not modeled in detail.
Local automatic fire detectors (if present) sense the presence of the fire	The fire detectors activated within a short time of switchgear failure.	
Alarm is sounded automatically in the control room, locally and / or other places	Fire alarm did sound in the control room.	
Automatic suppression system is activated (if present)	No information provided. It is inferred that the switchgear area was not protected by a fixed automatic suppression system.	

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Personnel are present in the area where fire occurs	No information is provided although personnel did report an explosion in the switchgear room to the MCR.	
Control room is contacted or fire alarm is sounded	The control room was contacted by telephone, about the fire in a short time after switchgear failure.	
Fire brigade is activated	Fire brigade was activated immediately upon receiving news about the fire.	
Fire suppressant medium is properly applied	Two attempts to suppress the fire were made with portable CO_2 and dry chemical extinguishers, but it was not successful. The fire re-flashed in both cases. The power to 1TA was completely de-energized (including the DC power). The power to the adjacent switchgear 1TB was also de-energized by the operators to allow for the use of water with fogging nozzles.	The failure of initial fire suppression efforts is not typically considered in a fire PRA. A PRA would have assumed a very high probability of suppression and no further damage based on the initial fire brigade response time.
Automatic fire suppression system is activated	It is inferred that there was no fixed fire suppression system.	
Fire suppressant medium is properly applied to where the fire is.	No collateral damage due to fire suppression was reported.	
Fire is affected by the suppression medium	The fire was finally extinguished by the use of water in about one hour.	
Fire growth is checked and no additional failures occur	No information is provided regarding fire growth and extent of fire damage. It is inferred that the fire remained limited to the switchgear of origin and cables adjacent to the switchgear itself.	
Fire is fully extinguished and fire brigade declares it as out	Using water, the fire was completely extinguished in about one hour.	This fire was relatively long (about one hour) compared to fires typically modeled in a fire PRA (10-30 minutes).
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	Switchgear 1TA was lost, as it was the source of the fire. Fire damaged cables near the switchgear.	The impact of fire damage would likely have been predicted in a fire PRA.

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Cable failure impacts equipment outside the fire location	Switchgear failure and de-energization led to the unavailability of several components needed for normal reactor cooling and power operation. Cable failure led to failures of certain functions of ICS.	
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Loss of 1TA switchgear led to tripping of two reactor coolant pumps. The reactor power level started decreasing. At a certain point ICS had to adjust steam generator level to 50% and swap feedwater nozzles from main to auxiliary. It failed to do so because of cable damage.	
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	The instrumentation was not affected in this incident. In-core thermocouple readings were the focus of the operators. Adequate attention was not given to cold leg temperature. Because of this the operators did not realize that rapid cooldown is underway and there is a potential for the reactor entering the thermal shock operating region.	It is not clear how much the operators were influenced by the fire and its effects (i.e., failures and smoke in the control room). In fire PRA, operator errors are modeled explicitly. Methodologies exist that attempt to model the influence of complex set of events on human error probability. However, it is interesting to note that this incident, since it occurred in non safety related switchgear with no safety related cables and equipment affected, would be considered as an insignificant risk contributor and would be screened out in the initial stages of the analysis.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	Operators took the steam generator levels to 50% and swapped the feedwater nozzles, but forgot to close a main feedwater valve. This omission added to the overcooling scenario. The operators started high pressure injection system to makeup the water in the main coolant loop that had shrunk. HPI activation led to pressure spikes (twice) over the course of the incident.	Operator errors are modeled in fire PRAs. The available report attributes the error, at least in part, to the presence of smoke in the control room, although the actual role of the smoke remains unclear. Most PRAs assume that in-control room actions are not impacted by fires outside the control room.
Structural failures (if occurred) may jeopardize availability of equipment	No structural damage was reported.	

Fire Scenario Element	Incident - Oconee 1, January 3, 1989	Fire PRA Insights
Water when sprayed over electrical equipment may fail the exposed equipment	Switchgear 1TB was de-energized to allow for the use of water on the burning switchgear.	PRAs would not typically consider that nearby equipment will be de-energized to facilitate fire fighting.
The cooling effect of CO_2 may adversely impact equipment	Reference [16-1] does not indicate occurrence of such a phenomenon.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	Several independent failures occurred in the course of this fire. An isolation valve inside the containment had been left closed that prevented the use of auxiliary pressurizer spray. A push button was stuck on the control board that caused a device to cycle several times. The yoke bearing of a feedwater valve experienced a mechanical failure. The feedwater control valves experienced calibration drifts.	In this incident several independent failure occurred. In fire PRA, an important element of calculating the core damage frequency for a fire scenario is the proper accounting of independent failures that may occur in tandem with the fire. This incident demonstrates that such failures can occur and may influence the chain of events.

A16.5 Incident Analysis

The most important insight from this incident is that a fire in non-safety-related area led to a potential challenge to reactor safety. The fire occurred in a non-safety switchgear that is not co-located with any safety related cables or equipment. In a fire PRA this fire scenario would generally be considered as risk insignificant, and would likely have been screened out from detailed analysis because of the lack of any threats to safe shutdown equipment.

The significance of this incident also lies in the actions that the operators took in the control room in that they caused an overcooling transient that had the potential to cause a thermal shock. It is not clear whether or not the mistake made by the operators (i.e., failure to close the main feedwater valve) was influenced by the fire itself. However, by failing the ICS, the fire did put the operators in a position where they had to take additional manual control actions, and it was while they were taking these actions that the mistake occurred. Reference [16-1] also states that some smoke did enter the control room and implies that this was, at least in part, the reason that mistakes were made. The smoke ingress aspect of the incident is not well described in the available information; hence, it can not be determined whether or not there was any actual discernible impact on control room habitability.

In fire PRA, operator errors are modeled explicitly. Methodologies exist that attempt to model the influence of complex set of events on human error probability. In fire PRAs it is widely assumed that fires outside the control room will not impact operator actions that take place within the control room. In this case there may have been such an influence, although the evidence for this is inconclusive. The chain of events experienced during this fire incident (i.e., a fire in a non-safety area of the plant leading to a complex chain of events with operator interactions and mistakes) would not typically be identified as a risk significant scenario in a typical fire PRA.

In this incident the most significant operational impact was the overcooling transient coupled with high reactor pressures. The possibility of thermal shock of the main vessel has been addressed in some internal event PRAs. Fire PRAs commonly use the same event sequences as those used in the internal events analysis. However, often in the internal events analysis, the analysts make simplifying assumptions based on the likelihood of a given chain of events. In fire conditions, the likelihood of a given chain of events may be significantly greater than that calculated in internal events analysis. However, if the chain of events is eliminated during the internal events process, the fire analysis may not recognize that chain of events as a potential risk scenario. The fire versus internal events difference lies in the fact that fires can simultaneously impact several items including, in particular, cables. In the internal events analysis, the same equipment would be failed as a result of random factors that are not correlated. Sequences involving multiple random failures quickly become probabilistically insignificant. In this incident, the fire damage caused two of the four reactor coolant pumps to trip, failed parts of the Integrated Control System (ICS), and affected the control room operators to an undetermined extent.

This incident also demonstrates that even with rapid detection, fire fighting can be a prolonged process and that the application of a fire suppressant does not necessarily lead immediately to either fire control or fire extinguishment. In this case two initial suppression attempts were ineffective, and the fire ultimately burned for over an hour. In many current fire PRAs fire duration is based primarily on the manual fire brigade response time. This approach may not be a proper representation of the potential chain of events that may occur. Earlier PRA methods had commonly utilized generic fire duration probability curves based on historical experience. These curves would inherently capture this type of behavior, but are not amenable to plant-specific adjustments. This issue is discussed further in the body of this report.

It is also interesting to note that the neighboring switchgear (1TB) was purposely de-energized in order to facilitate fire fighting and protect fire fighters from electrical hazards. With the fire-induced loss of 1TA and de-energizing of 1TB, two opposite trains, albeit non-safety trains, of a system were taken out of service. This demonstrates that equipment may be lost from causes other than direct fire damage in a fire incident. That is, actions taken to support fire fighting may also lead to the intentional isolation of redundant trains and this may have unanticipated consequences. A parallel example of such a condition lies in the so called self-induced station blackout (SISBO) that has been incorporated in the procedures of a few power plants. The SISBO procedure instructs the operators to intentionally isolate as-yet unfailed equipment. This is done to isolate the adverse effects of a cable fire. Current fire PRA methodologies include provisions for analyzing the actions that should be taken by the fire brigade and are nominally capable of dealing with these kinds of actions. However, other than SISBO type scenarios, actions such as manual isolation of an unaffected train are rarely identified or considered. This is discussed further in the body of the report.

A final aspect of this incident that is of interest is the explosive nature of the initial electrical fault. It has been observed that certain electrical faults will be manifested as an energetic release of electrical/thermal energy. In this case, a 6.9kV switchgear faulted with an explosive release of energy substantial enough to have been heard in other areas of the plant. This is not the typical fire modeled in a fire PRA. Typical fire PRAs will assume a fire that ignites, grows within the initial fuel package, and then exposes and potentially spreads to adjacent combustibles. In this case, the initial fire initiation and growth behavior was essentially by-passed, and a rather substantial fire was apparently ignited as a result of the fault. There are no clear indications as to how extensive the initial fire actually was. However, the fire did clearly propagate and caused damage to cables outside of the originally involved panel. This has been an area of methodological debate, in particular, associated with the IPEEE process. See the body of the report for further discussion.

A16.6 References

A16-1 Licensee Event Report # 26989002, "Fire in 1TA Swtichgear Due to Unknown Cause", Oconee Nuclear Station, Unit 1, Event Date 01/03/89.

Appendix 17 - Analysis of H. B. Robinson, Unit 2 Fire on January 7, 1989

A17.1 Plant Description

H. B. Robinson, Unit 2 is a 665 MWE Westinghouse design, pressurized water reactor located near Hartsville, Southern Carolina. Unit 2 is the only nuclear unit on the site. The plant started commercial operation in March 1971.

A17.2 Chain of Events Summary

At the time of this incident the plant was in a refueling outage. At 22:30, on January 6, 1989, as part of an air test of the main generator, a maintenance crew erroneously connected the instrument air header to the main generator hydrogen manifold using a rubber hose. This allowed the bulk hydrogen supply, which is at 120 psig, to be directly connected to the 95 psig station compressed air system. The configuration was such that hydrogen flow to the generator was blocked, but flow into the Station Air System was not. Hence, hydrogen spread into the plant's general purpose compressed air system.

At the time this hose connection was established the Station Air compressor was out of service and the Station Air System was connected to the Instrument Air System. The Station Air System was in greater demand because air-driven tools were being used throughout the plant. This caused the majority of the hydrogen to migrate into the Station Air System.

Approximately one hour after the connection had been made, it was noticed that generator pressure had not increased. At approximately the same time a small fire was discovered in an air junction box inside the turbine building, on the turbine deck. The fire was extinguished quickly and no damage was noticed. Approximately three hours after the connection was made, a contract worker reported that flames were coming out of his air operated grinder. Upon this discovery, all work that could cause a spark was stopped and the use of the air system was prohibited.

Samples of the air were taken at several locations. The hydrogen concentration was discovered to range from 50% to 150% of lower explosive limit. The hydrogen had migrated into the entire system at practically all plant locations, including the auxiliary building and the containment. No further fires apparently occurred, and the system was eventually purged of hydrogen.

A17.3 Incident Analysis

This incident is of interest to the current review because it illustrates a somewhat unique point, namely, that unexpected fire sources can arise during a refueling outage. In this case, at least two minor fires occurred, and there was clearly an inherent potential for more, and perhaps more serious, fires. Only a few shutdown fire PRAs have been conducted. The typical methodology follows the same process as that used in an at-power fire PRA. It is unlikely that a typical fire PRA of any type would have identified an error of this type as a possible contributor to fire risk. In this event flammable gas was introduced into a system and areas of the plant that are normally void of such gases. Also, it created a condition where several, potentially severe fires could have occurred at the same time at different locations of the plant. The possibility of multiple fires is not addressed in fire PRAs.

A17-4 References

A17-1 Licensee Event Report # 26189001, "Hydrogen Introduced Into the Instrument Air System", H. B. Steam Electric Plant, Unit 2, Event Date 01/07/89.

Appendix A18 - Analysis of Calvert Cliffs, Unit 2 Fire on March 1, 1989

A18.1 Plant Description

Calvert Cliffs is a two unit nuclear power station located near Lusby, Maryland. Both units are 850 MWe Combustion Engineering PWRs. Unit 2 started commercial operation in April 1977.

A18.2 Chain of Events Summary

On March 1, 1989, Unit 2 was operating at 100% power. At 16:45 a fire was discovered in a control panel in the Main Control Room. An operator was in the process of verifying a repair on the over-speed trip mechanism of the Auxiliary Feedwater Pump trip/throttle valve actuator. As part of this procedure, the operator put the hand switch for the valve in the "shut" position. The shut position indicating light flickered and a buzzing noise was heard on the control panel. The operator repeated the action with the same result. The operators opened the panel cover and discovered a fire at the hand switch. Using a hand-held Halon extinguisher, the operators put out the fire in 1-2 minutes. In the meantime, a 10amp fuse in the associated circuit blew. Since the fire was extinguished quickly, the control room supervisor did not call out the fire brigade.

When the fire was discovered, a turbine building operator was called to reset the throttle valve. In the attempt to reset the valve, that operator discovered that a solenoid associated with the valve was smoking. There were no visible flames. The solenoid stopped smoking apparently when the 10amp fuse blew. The fire in the main control room panel caused some damage to wires nearby. No other damage was noted from this incident. This incident did not cause a significant safety hazard and its impact was limited to an isolated part of a safety related system. The lack of damage can be at least in part attributed to the immediate response of the operator whose actions had led to the fire being initiated.

A18.3 Incident Analysis

This incident caused very limited damage and had no real impact on plant safety. Hence, the fire was not severe from either a classical or nuclear safety perspective. It is included in this review because this is one of only a very few incidents in the U.S. lending insight into multiple fire ignitions in a single incident. In this case there was a small fire in the main control room, and an incipient fire (the smoking solenoid) in the auxiliary feedwater pump room. Once again, the common link in the fire is a common electrical circuit. In fire PRAs, the possibility of simultaneous fires in two different compartments is not generally addressed. See further discussion in the body of this report.

A18.4 References

18-1 Licensee Event Report # 31889004, "Auxiliary Feedwater Pump Trip Circuitry Fire in Control Room Due to Maintenance Error", Calvert Cliffs, Unit 2, Event Date 03/01/89.

Appendix 19 - Analysis of Shearon Harris Fire on October 9, 1989

A19.1 Plant Description

Shearon Harris is a 900 MWE, Westinghouse design PWR located in New Hill, North Carolina. The plant started commercial operation in May, 1987.

A19.2 Chain of Events Summary

On October 9, 1989, the plant was operating at full power. At 23:05, a turbine generator and main power transformer differential relay tripped and started a chain of events that led to fires at three locations involving one main transformer and the main generator. As a result of the relay trip, the main generator output breaker also tripped. This in turn caused a turbine trip and a reactor trip. The auxiliary feedwater system actuated as designed. However, the turbine driven pump failed to operate properly. Motor driven auxiliary feedwater pumps were used. The operators closed the main steam isolation valves to limit the cool-down rate.

The initial cause of the event was multiple ground faults in a bus duct near the "B" main power transformer. Reference [A19-1] states that the cause of the ground faults is thought to be aluminum debris carried into the duct by the forced air ventilation system used for cooling the bus duct. The debris is suspected to have entered the ventilation system as a result of two damper failures, one that occurred on February 27, 1988 and a second during the summer of 1989. The ground fault caused arcing over a fifty foot length of the bus. The arcing reduced the dielectric strength of the air. The air, per the design of the system, entered the bushing box of the transformer. This caused ground faults in the bushing box, which led to a crack in the low voltage bushings. The bushing crack, in turn, led to a spill of oil and ignition of a fire at the transformer (the first fire).

The faults in the main transformer bushing box and the "A" bus duct, caused the voltage of the generator neutral to become elevated. A current transformer was mounted around the neutral conductor, and was isolated from the neutral conductor by insulating tape. The insulation resistance of the insulating tape was apparently insufficient to withstand the elevated neutral voltage, and an electrical breakdown occurred causing the neutral conductor to short to ground. The arcing caused by this short burned holes in generator related piping, which in turn allowed generator hydrogen to escape and catch fire (the second fire). The oil in the main generator housing above the hydrogen fire was subsequently ignited (the third fire).

At 23:09, the Control Room was notified of a fire at the "B" main power transformer, and an oil fire on the second level of the turbine deck underneath the main generator. The site fire brigade was activated immediately. The fire fighters also noted a hydrogen fire on the second level of the turbine deck underneath the main generator. The deluge system at the main transformer activated as designed.

Off-site fire departments were also contacted shortly after the initiation of the incident to assist in the fire fighting efforts. Later, the prompt notification of outside fire departments was credited as having limited the damage caused by the fires.

As noted above, the auxiliary feedwater system actuated automatically in response to the incident. However, the turbine driven auxiliary feedwater pump tripped shortly after it started. The cause of the trip was later determined to be a spurious over-speed trip signal from the tachometer. No link between the failure of the auxiliary feedwater pump and the fire has been established, and this appears to have been an independent (random) failure event.

At 23:35, an alert was declared and the Technical Support Center (TSC) was activated. By 00:13 October 10 (a little over 1 hour after initiation of the event), the oil fire at the generator housing was extinguished. Also, the fire at the main power transformer was believed to be under control by the deluge system. The hydrogen fire underneath the generator was also considered under control.

By 01:45, a small residual oil fire at the main transformer was extinguished using portable dry chemical extinguisher. By this time, all three fires were considered extinguished. By 02:45 (2 hours and 40 minutes after incident initiation) walk-downs were completed to verify that all three fires were extinguished. Fire watches were posted at the fire locations and the main generator was purged with carbon dioxide.

A19.3 Incident Analysis

The fires in this incident were of relatively long duration, about 1 hour 45 minutes total, and were relatively severe from a classical fire protection perspective. However, from a nuclear safety perspective, the overall impact of the fires was relatively modest. The plant did trip automatically, and an auxiliary feedwater pump did fail, apparently a random failure. However, the operators responded appropriately to the situation and properly controlled the plant shutdown including proper control of the cool-down rate. This incident again demonstrates that not all fires that are severe from a classical fire protection standpoint are severe from the nuclear safety perspective. As noted elsewhere in this report, this is fully consistent with the findings of current fire PRA studies.

The incident is of interest to the current review primarily because it is one of the few incidents in the U.S. that involves multiple fires occurring concurrently. The incident demonstrates that multiple fires may occur simultaneously at different areas of a plant. As seen in other such incidents, one of the common links was a common electrical system. However, the secondary hydrogen fire was apparently the result of damage caused by the failure of the current sensor on the generator neutral cable so there are multiple contributing factors, rather than simply a common electrical system that becomes overloaded. Concurrent multiple fires are not addressed in current fire PRAs. As discussed in detail in the body of this report, current fire PRA methods could, at least in theory, predict the potential impact of multiple fires if the locations and characteristics of the individual concurrent fires could be established. However, there is currently no basis for identifying the frequency or characteristics of multiple fire incidents.

A19.4 References

A19-1 Licensee Event Report # 40089017, "Electrical Fault on Main Generator output bus Causing Plant Trip and Fire Damage in Turbine Building", Shearon Harris Nuclear Power Plant, Event Date 10/09/89.

Appendix 20 - Analysis of Vandellos, Unit 1 Fire on October 19, 1989

A20.1 Plant Characteristics

Vandellos Nuclear Power Plant Unit 1, which is currently decommissioned, was a gas cooled, natural uranium fueled, graphite moderated reactor located 140 km South of Barcelona, Spain. It shared the site with Vandellos, Unit 2, a pressurized water reactor. Vandellos, Unit 1 started commercial operation in May 1972 and has not been operated since the October 19, 1989 fire incident described in this appendix. The rated thermal power of Unit 1 was 1750 MWt. It used a concrete pressure vessel and CO_2 as the primary coolant. Each unit had two turbine generators, rated at 250 MWe each. There were four steam driver turbo-blowers for primary circuit coolant (i.e., CO2) recirculation. After shutdown, one blower could provide sufficient cooling.

A20.2 Chain of Events Summary

At 21:39 on October 19, 1989, while the plant was operating at partial power level (about 80%), the high pressure section of turbine No. 2 ejected 36 blades. The turbine blade failure was later attributed to stress corrosion phenomenon. The blade ejection altered the balance of the turbine leading to high vibration and excessive friction around the turbine shaft. This in turn caused the shaft to come to a full stop within a few seconds. Vibration also caused the seals around the generator to fail allowing hydrogen gas to escape. According to available reports, the escaped hydrogen is thought to have ignited on the hot surfaces of the shaft. Available reports also state that a hydrogen deflagration did occur, but apparently caused no significant damage.

The ejected blades also cut through turbine lube oil lines. All oil pipes feeding the bearings of the high pressure side of the turbine and one pipe for the bearing located between the two low pressure turbines were broken spilling the lube oil. Hot surfaces caused by the excessive shaft friction are thought to have served as the ignition sources for the oil as well. The oil supply system, upon loss of oil pressure in the bearings, started all four oil pumps and transferred, in 55 seconds, close to 4,500 liters (more than 1,100 gallons) of oil to the broken pipes. A total of about 12,000 liters (more than 3,000 gallons) of oil spilled into the turbine building from the severed pipes during the course of this incident.

The control room became aware of the incident almost immediately because of the loud noise caused by blade failure, the reported hydrogen deflagration and observations made through a window from the control room that overlooked the turbine hall. At 21:40, a minute after blade ejection, the external fire brigade was called. At 21:54, 14 minutes after being notified, the off-site fire brigade arrived. It took them until 04:00 on October 20 (more than 6 hours from ignition) to extinguish the fire using hose streams.

Of the four coolant loops of the reactor, two (numbers 3 and 4) failed because of fire-induced cable failures. In addition to the turbo-blowers, the fire caused the shutdown heat exchanger (a defense in depth feature) to fail as well. Core cooling capability remained available through steam generators No. 1 and 2, their associated feedwater pumps and turbo-blowers. However, the control of feedwater flow proved to be difficult. The control air supply was lost because hot gases under the ceiling of the turbine building damaged the copper piping of the air system (this was presumably due to failure of solder joints in the piping). Operators, using SCBAs and hand held lighting, entered darkened and smoke filled valve rooms to manually adjust the flow control valves.

The turbine lube oil, as it was burning, cascaded down to the lower floors of the turbine building and created a pool of burning oil underneath the turbine. A part of the oil flowed down along a wall and behind a large (2m diameter) pipe from the circulating water system. A rubber expansion joint was located on the pipe near the location where burning oil was flowing down along the wall. The joint was directly exposed to the flames and softened. It eventually ruptured at the point that was closest to the wall. The rupture allowed seawater to spill into the basement of the turbine building. The joint itself, because of water flow, did not burn.

Water from the broken pipe joint collected in the basement of the turbine building. A sufficient amount of water escaped to cause a large pool to form. The building sump pumps did not activate because the cables feeding the pumps were damaged by the fire. The water also entered the reactor building's lowest elevation through an open door and through piping and cable penetrations. The water in the reactor building and turbine building basements eventually reached a depth of 81cm (about 32 inches).

The sprinkler system in the turbine building activated as designed. However, it did not control the fire because there were no sprinkler heads near where the fire occurred. It is interesting to note that, despite the proper operation of the sprinkler system protecting the hydraulic oil tank, the fire overwhelmed the sprinkler system and the tank was completely destroyed.

Smoke entered other areas of the plant and activated the suppression systems in areas where there were no actual fires burning. Smoke also entered the control room. Self contained breathing apparatus (SCBA) were issued to control room operators. However, the SCBAs were not used (apparently the smoke level never reached a point where operators felt the SCBA was needed). Portable fans were brought in to clear the smoke and provide fresh air into the control room.

The fire ultimately damaged 90% of Turbine Generator No. 2 and 10% of Turbine Generator No. 1 as well as numerous cables and the one pipe joint.

A20.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [A20-1] through [A20-4]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	Stress corrosion eroded the strength of turbine blades. The blades were not inspected specifically for this phenomenon.	
Prior to the incident	The door between basement of Turbine and Reactor Buildings was left open. This was apparently in violation of administrative control requirements.	Often a small probability is assigned to the likelihood of a door being open that is administratively required to be kept closed. This event points to the importance of inspecting the plant in a detailed walkdown, as part of fire PRA, where the existing conditions are observed and recorded carefully. However, the possiblity of the door being left open might still be judged small if the door happened to be closed at the time of the walkdown.
Prior to the incident	The plant was operating at 400 MWE output. Turbine Generator Number 1 at 190 MWe and Number 2 at 210 MWe.	
00:00	At 21:39 on October 19, 1989, Turbine No. 2 ejected 36 blades from wheel number 8 because of stress corrosion phenomenon. This led to high vibration of the turbine (located on elevation +16.0m), and friction around the shaft, which caused the shaft to come to full stop within a few seconds of blade failure. The friction energy caused the shaft to reach red hot temperature range. A vibration alarm (>180micron) and Turbine Generator No. 2 trip annunciation was received in the control room. The control room had a window overseeing the turbine generators. A flash was seen in the control room and the shift operator manually tripped the reactor. Fire was observed in the high pressure turbine housing and in the generator vent at the excitor side. Fire alarms (audible and luminous) were received in the control (the exact time of the alarm is not known)	In a typical fire PRA, ignition of oil fire in turbine building is assumed to occur from an arbitrary cause. The specific causes are generally not addressed explicitly. However, it is commonly assumed that oil is released, ignited and a large fire ensues.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The vibration (actually a jump) caused the generator's terminals and the seals to fail and allowed 5m³ of hydrogen to escape. The escaped hydrogen ignited on the hot surfaces of the shaft and deflagrated. An eyewitness described hydrogen burning as a fire ball leaving the bottom of the generator, traveling horizontally towards the bottom of the turbine. The eyewitness noted that the fireball took a spiraling (scrolling) movement as it went from the generator towards the turbine. The deflagration was very short and it only charred (not burnt) the areas where it touched. The instrumentation within the area were tested after the fire and were found in working condition. However, the deflagration did damage a movable ceiling at elevation +16.0 meters.	Two types of fires occurred - a deflagration of hydrogen gas and a large oil fire. In a typical fire PRA, only one type of fire is postulated. Since, extensive damage is often postulated for turbine building fire scenarios, lack of consideration of simultaneous occurrence of a deflagration and a fire is of minimal consequence. In this particular case the hydrogen fire apparently caused no significant damage.
--	The ejected blades cut through turbine oil lines. All oil pipes feeding the bearings on the high pressure side of the turbine and one pipe for the bearing located between the two low pressure sections were broken. Hot surfaces caused by shaft stoppage served as the ignition sources for the oil as well. The oil supply system, upon loss of oil pressure in the bearings, started all four oil pumps that sent the oil from the storage tank to the broken pipes. Per the design feature of the oil system, it was impossible for the control room to manually stop the oil pumps when they started on low oil pressure. This eventually led to 11,000 liters (about 3,000 gallons) of oil being pumped out through the open pipes.	The oil fire was ultimately the fire of most significance. In a typical fire PRA the specific details of oil fire is generally not considered. This event points out that the analysts cannot assume that the quantity of oil involved in the fire is limited to the oil within the turbine. Under special conditions, the entire contents of the oil storage tank may have to be postulated at a location away from the oil storage tank itself.
--	A cascade of burning oil poured to the lower elevations of the turbine building. Oil also poured on cable trays, causing part of the flow to be diverted horizontally. In all cases the oil was burning as it was flowing about. Eventually the bulk of the oil dropped down to the lowest elevation floor, formed a burning pool and flowed towards the floor drain. The pool fire damaged all of the equipment in its pathway to the drain.	In this case the fuel (oil) was quite mobile and spread readily. In a typical fire PRA, fires are assumed to occur in a particular location. Hence, this aspect of the fire may not have been captured in a typical fire PRA. Severe oil fires occurring in various areas of the turbine building would likely have been postulated as noted above, but each scenario would likely have considered a relatively confined fire.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:01	Within 55 seconds of blade failure, close to 4,500 liters (more than 1,100 gallons) of oil were spilled from the broken pipes that fueled the fire (see note 1). (See 00:06 below - eventually 12,000 liters (more than 3,000 gallons) of oil was ejected from the broken pipes.)	Even by the standards of a typical fire PRA turbine hall fire scenario, this is a very large quantity of burning oil. Some fire PRAs do consider catastrophic loss of the turbine hall. However, other fire scenarios would typically involved more limited fires.
00:01	At 21:40, the external fire department was called by radiotelephone to respond to the fire and the plant management and reserve personnel were notified (per procedures). The plant maintained a fire brigade of plant personnel who were trained and certified in fire fighting techniques. A 5-member team was on site for every shift. If the fire brigade had to be activated, the reserve personnel would be called in to look after the plant while the brigade is focused on the fire.	
--	The oil fire propagated to other combustibles -- some of the cables in the lower elevation of the turbine hall and the hydraulic oil in its storage tank. The insulating material of cables were PVC.	
--	A part of the oil went down against a wall, behind a 2 meter diameter pipe from the circulating water system. A rubber (reinforced by a metallic mesh) expansion joint was located at this same location. The expansion joint was 2m in diameter (as was the pipe), 40cm long and 1.5cm thick. The joint became directly exposed to the flames and softened. It eventually broke from water pressure at the part that was closest to the wall opening a vertical gash in the joint of about 2 meters long (this is about 1/3 of the circumference of the joint). The area of the break is estimated to be about 2,000 cm^2 (310 in^2) The opening allowed seawater to spill into the basement of the turbine building. Burning oil collected on top of the pool created by the spilled water. The expansion joint, because of water flow, did not burn. The normal flow rate through the circulating water pipe is 12m^3/s (about 190,000 gpm) at about 18°C temperature.	This event, failure of the expansion joint, would not typically be captured in a fire PRA. The location of the joint with respect to the oil pipes and the turbines led to the possibility of direct flame impact. In a typical PRA, the chain of events leading to a breach in the integrity of a water carrying system is not considered. As mentioned above, in a typical turbine building fire analysis, it is postulated that the fire is large and damages all those items that are susceptible to fire. However, large water-filled pipes and associated equipment are not generally considered vulnerable to fire damage because of the large heat capacity of the water inside the pipe. This event directly contradicts this common assumption, at least in the case of flexible rubber expansion joints. Failure of the pipe joint did lead to significant flooding of two buildings. PRAs would not typically consider a large flood concurrent with a fire.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The sprinkler system in the turbine building activated as designed. However, it could not control the fire because there were no sprinkler heads near where the fire had started. The sprinkler system inside the turbine building only covered the oil storage tanks (lubricating and hydraulic oils) and big motors. The rest of the Turbine Building had fire detectors only. At the hydraulic oil tank, the fire suppression system was an open head (deluge type) system. This system was activated by heat detectors with one alarm level. The detector did activate, the fire water pump did start and valves to feed the sprinklers did open. At the lubricating oil tank, the sprinklers heads were also of open (deluge) type. The system activated on heat, optical and smoke detectors that were arranged in two alarm levels. At the first alarm level, the fire water pump was started and a permissive signal was given for opening the isolation valve of the concerned area from the control room. At the second alarm level, pump operation would be confirmed and the valve would open automatically, thus allowing fire water to spray from the open heads.	The fixed fire suppression systems did actuate as designed but covered only select areas of the building. They were apparently ineffective at either controlling or extinguishing the fires. In conducting a fire PRA, as part of the detailed analysis, the characteristics of the fire protection system for each fire area is studied. Such systems are commonly credited with suppressing fires quickly and effectively (on the order of 95% reliability or higher). This incident illustrates the need to consider both the system design and the fire threats that it may face in assessing system effectiveness. Note that if only manual fire brigade actions are postulated, the likelihood of a large fire in the turbine hall would be postulated to be significant.
--	As noted above, water from the ruptured expansion joint and the fire suppression systems collected in the basement of the turbine building. Although, there is no eyewitness confirmation, it is inferred in the available reports that the burning oil floated on top of this water spreading the fire further.	Occurrence of major flooding as a result of fire is not postulated in a typical fire PRA. Although, theoretically speaking, current methodologies can accommodate the proper identification of such events, in a typical fire PRA the progression of the event scenarios is not carried through to such level of detail to allow for the identification of additional external event phenomena.
--	The sump pumps in the turbine building did not activate because the cables feeding the pumps were damaged by the fire.	Cables for a system such as sump pumps would not typically be identified in a fire PRA. Hence, the potential for loss of these pumps would not typically be captured by a fire PRA analysis.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The water also entered the reactor building lowest elevation because of an open non-water tight door. There were also cable and pipe penetrations in the wall separating the two buildings that would have allowed the water through. The flood depth reached 81cm at elevation +3.50m of the turbine and reactor buildings.	See note on fire and flooding above.
--	Smoke entered the control room through the ventilation system. The control room is located at +28.20m elevation of the electrical/control building, next to the Turbine Building The control room was about 50m from the fire itself. SCBAs were provided for the operators, but they did not use them.	Propagation of smoke and its impact on plant personnel is typically addressed using conservative and simplified models. The possibility of smoke egress into the control room is often not considered, unless there are clear indications that this could be possible. If a fire PRA were to be conducted of Vandellos 1 prior to the incident, given that the control room ventilation communicates with the turbine building, the analysts would likely have postulated the possibility of smoke inside the control room. Actually, it would have conservatively been assumed that the control room would become inhabitable.
00:06	In a few minutes, the three oil transfer pumps, transferred all the oil in the storage tank into the severed oil piping. A total of about 12,000 liters (3,000 gallons) of oil spilled into the turbine building from the severed pipes and caught fire (note 1).	
--	The cables for non safety 5.5kV switchgear DG2A that provided power to condenser, feedwater and vacuum pump loads was lost.	
00:07	At 21:46 Turbo-Blower No. 4 (provides primary coolant flow) failed because of cable failure. The cables to safety related 5.5 kV switchgear DS4A, that powers Turbo-Blower No.4 was lost. A 10m length of cable tray, located in the lowest level of the turbine building, was damaged from direct exposure to fire. It is suspected that cable fire contributed heavily to smoke generation during the fire.	The cable trays were doused with burning oil. In a typical PRA cables are assumed to be exposed to external fires. In this case a PRA would have likely postulated a pool fire on the floor below the cables. The observed damage would likely have been covered in fire PRAs as part of a postulated large fire. However, this incident points out that the typical fire propagation calculation methods may not be valid for such a scenario.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:10	At 21:49 Turbo-Blower No. 3 and the feedwater pumps for heat exchangers no. 3 and 4 failed because of cable failure. The cables to safety related 5.5 kV switchgear DS3A, that powers Turbo-Blower No. 3 was lost. As for DS4A, 10m length of cable tray was damaged at the lowest level of the turbine building.	
00:10	Electric cables of the power supply for the shutdown heat exchanger was lost.	
--	Power to the safety and normal lighting was lost. Battery powered emergency lighting remained functional.	Loss of lighting is not typically explicitly postulated in a fire PRA. This incident points out that for human action analysis and human error probabilities, severe performance shaping factors may have to be postulated.
--	Per Reference [A20-3], none of the cable failures led to spurious actuations or instrumentation drift on the control board.	It is not known whether or not the potential for spurious actuations did, in fact, exist. In particular, since the damaged cables were all in the Turbine Building, it is not clear what portions of the impacted instrument and control circuits were threatened. Hence the implications of this "negative" finding regarding spurious operations are not clear.
00:15	At 21:54, outside fire brigade arrived. Up to 30 fire fighters came to the site to help in putting out the fire. Outside fire fighters were not familiar with the plant and feared radiological exposure. To alleviate these problems, a member from the available plant personnel was assigned to each fire fighting team.	In typical fire PRAs, the impact of external fire brigade on the progression of the fire is combined with the plant brigade in an overall manual fire fighting model. In this incident, the external fire brigade did not have any adverse effects on the fire. However, the training and familiarity of external fire brigades with plant layout and special conditions may need to be taken into account when it is assumed that a large turbine building fire will eventually be brought under control.
--	Fire fighters used hose streams to attack the fire. They attacked the fire from elevation +9.00m and +16.00m. The fire fighters had to work in total darkness using hand-held flashlights. There were no additional failures attributed to the fire fighting activities.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	Smoke was pumped into other areas of the plant by the ventilation system. In the reactor building this activated the suppression system at certain locations. The air intake of the reactor building ventilation was in the turbo-generator area of the Turbine Building, above elevation +16.0m. Also, the doors between the turbine and reactor buildings at elevation +3.50m and +9.00m were not tightly closed.	The spread of smoke to areas remote from the fire points out that some special attention is warranted in the human error probability evaluation. Plant conditions may be degraded by movement of smoke, and therefore, human error probabilities taken directly from the corresponding internal events PRA may not be applicable. It is also interesting that this incident involved spurious actuation of a fire suppression systems in areas remote from the fire. In the U.S. reliance on smoke detectors for fire suppression actuation is no longer common (due largely to adverse spurious actuation experience). No damage due to suppression activation was reported.
--	Hot gases accumulated under the floors and the ceilings. Some equipment damage occurred near +9.00m ceiling at areas not reached by the flames. No damage were noted at elevations below the ceiling level. Copper pipes of the control air system melted under the ceiling and caused failure of automatic control of feedwater control valves.	The loss of the control air system piping integrity would not be captured in a typical fire PRA. Fire PRAs typically focus on cables, and may not consider the loss of other equipment. Some special attention to solder-joint air control supply piping in fire PRAs may be warranted if, for example, the operation or failure of air-operated valves is risk important.
--	Although the main part of the fire was only 10 meters from the lubricating oil tank at elevation 9.00m, the combined effect of sprinkler system and fire brigade hose streams managed to protect the tank from catching fire.	
--	The hydraulic oil tank was entirely destroyed by the fire, despite the presence of and successful operation of the sprinkler systems. This tank was located at elevation +3.50m, under the high pressure side of the turbine. It was doused by the burning oil raining down from the elevations above this point. The access to the area became impossible for the fire fighters during the first hour. Therefore, the tank did not benefit from the fire fighting activities.	This incident points out that a fixed suppression system may be overwhelmed by the fire. An important basic assumption underlying fire PRA methodology is that all fire protection systems are properly designed and will be effective against postulated fire threats. This incident points out that, at least in such areas as the Turbine Building where large concentration of combustible materials exist, this underlying assumption may not be valid in all cases.
--	From live broadcasts of the fire on TV and radio, many plant personnel heard about the event and came to the plant to help.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:30	The ventilation system for the control room was stopped to prevent further smoke ingress. Portable fans were brought to the control room to clear the smoke and bring in fresh air from non-smokey areas of the plant. Operators remained in the control room at all times from the beginning of the fire and did not have to wear breathing apparatus. No equipment failures occurred because of the smoke in the control room.	Smoke in the MCR was apparently not severe given that operators never felt the need to don their SCBAs. In a fire PRA conservative assumptions are made if smoke is assumed to enter the control room. This would typically lead to MCR abandonment. However, it is also rare for a fire PRA to postulate that smoke from fires outside the control room would actually enter the control room.
--	Operators did not need to take any actions within the areas impacted directly by the fire. However, the operators had to take actions at other parts of the plant that were either without a functioning lighting and/or engulfed in smoke. Also, the public address system was not functioning as a result of the fire.	Fire PRAs will typically make conservative assumptions with regard to operator actions. Actions that require entry into a smoke-filled room would not typically be credited. By the same token, most fire PRAs do not explicitly consider potential smoke spread, and would commonly assume that areas not directly involved in the fire could be safely entered for manual actions. Hence, it is likely that a fire PRA would have given credit to many of the cited manual actions that were taken.
01:54	Beyond 23:33 no additional electrical faults appeared.	It can be concluded that the effective fire duration was about 2 hours. This brings up an interesting issue about the duration of a fire. From PRA standpoint, when the fire stops to propagate such that no additional failures of safety related equipment would occur, the severity of the fire, given the typical compartmentilization of the plant, becomes of secondary importance to the risk model. Attention to such detail, of course, is non-conservative and may not be warranted for most fire scenarios of a PRA.

Time (hr:min)	Event or Step Description	Fire PRA Implications
02:00	In the first two hours of the incident, the feedwater and condenser pumps were used in an on/off mode of operation (i.e., the pumps were run at full flow or stopped). Operators were able to regain controlled auxiliary feedwater flow to main heat exchangers No. 1and 2 by manually adjusting the flow control valves at the valve location at elevation +9.00 of the reactor building which was filled with smoke. The operator had to use an SCBA to be able to approach the valve. Although there were no specific written procedures for the actions taken by the operators at those valves, the operators' experience (over 15 years) in plant operation and periodic training were considered as key contributors to the success of valve manipulation operations. The operators knew the proper position of the valves to stabilize water levels in the turbo-blower's condensers and in the heat exchanger. During the periodic training (administered for one week once per six weeks), manual adjustments to the automatic control of the system was always covered.	See note above about operator actions and smoke spread. In a typical fire PRA, no credit is given to operator actions beyond established procedures. Clearly, this event demonstrates that the assumptions regarding non-proceduralized actions as used in fire PRAs are conservative.
03:51	At 01:30, the fire was declared under control. The damage was later estimated to be 90% of Turbine Generator No. 2. The other turbine generator did not sustain any damage.	
04:21	At 02:00, the intense spraying on the fire stopped.	
06:21	At 04:00, fire was declared as completely extinguished	

Note 1 - There is some inconsistency between two sources regarding the total quantity of oil spilled and spill rate. A second source reports that 6000 liters spilled in the first 6 minutes and a total of 15,000 liters burned during the fire.

<u>Equipment Damaged</u>

- Turbine Generator No. 2
- Turbine auxiliary equipment
- Electrical cables, that led to failure of:
  - Turbo-Blowers No. 3 and 4
  - Feedwater pumps to heat exchangers No. 3 and 4
  - Turbine building sump pumps
  - Control air to valves
  - Shutdown heat exchanger
  - Area lighting in many parts of the plant
  - The public address system
  - Condenser control valves

Damaged Areas

- About 90% of Turbine Generator 2 was damaged. Smoke propagated into the control building and the control room. Flooding occurred at the lowest elevation of the Turbine Building and Reactor Building.

Impact on Core Cooling

Core cooling was maintained at all times. At no time during the fire, did core cooling functions stop. Fuel cladding, the primary envelope and the containment were not adversely affected by the fire. Core cooling capability remained available through steam generators No. 1 and 2 and associated feedwater pumps and turbo-blowers. Two turbo-blowers remained fully functional (i.e., blower speed control remained available). Only one blower is needed to provide sufficient core cooling. However, the control of feedwater flow proved to be difficult. Control air supply was lost. In the first two hours, the feedwater flow control was achieved using the system in an on/off mode of operation (i.e., full flow or stopped). This caused the pressure and temperature of CO_2 in the primary circuit to oscillate around a large range. The range, although outside the normal operating values, remained within the authorized limits. The flow control valves for the steam generators were locally (manually) adjusted after the second hour. A previous computer simulation of the event found that if the remaining two turbo-blowers had been lost and complete shutdown of the feedwater pumps had occurred, core damage was estimated to ensue at about 70 hours after the initiation of these additional failures. The long time period is mainly due to the thermal inertia provided by the gas-graphite reactor design. Given this time period, some substantial recovery actions could have likely been accomplished to prevent core damage (as demonstrated by other events covered by this review).

Rediological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were no injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A20.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared to the elements that make up a typical fire PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

<u>**Fire Scenario Element**</u>	<u>**Incident - Vandellos 1, Oct. 19, 1989**</u>	<u>**Fire PRA Insights**</u>
Presence of combustible / flammable materials	Turbine lubricating oil and hydrogen were the primary combustibles in this event. Cable insulation was a partial contributor to the combustible load. Hydraulic oil also caught fire.	
Presence of an ignition source	A turbine blade ejection event was the root cause of the fire, but ignition was attributed to hot surfaces created by the severe vibration of the shaft that led to shaft stoppage from friction.	
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Blade ejection led to double ended break of several oil pipes and generator seal failure. Oil and hydrogen ignited on hot shaft surface.	In a typical PRA, only those sources of ignition that are present at all times are considered. The possibility of an accident creating an ignition source is not generally modeled. However, since the frequency of fire initiation is based on a statistical analysis of the fire events, the impact of unusual conditions leading to fire ignition is covered by those frequencies to the extent experienced by the fire events. Given this understanding, a current fire PRA would consider oil/hydrogen fires as a result of turbine failure.
Fire growth within the combustible or component of original ignition	Hydrogen deflagrated through its vapor cloud and dissipated rapidly. Oil started burning and flowing downwards. It created a burning pool of fire under the turbine and along various cable trays.	The mobile nature of the oil would not be explicitly modeled in a typical fire PRA. For example, the oil cascading onto cable trays directly would not typically be captured. Rather the fires wold likely be postulated to be an oil pool on the floor. Several such fire locations would be postulated individually.
Fire propagates to adjacent combustibles	The fire propagated to cables inside cable trays where the oil had fallen. Cascading oil also caused the hydraulic oil storage tank to catch fire.	See note above regarding the mobility of the initial fuel. Fire PRAs typically considered fire source that remain where they initiate.
A hot gas layer forms within the compartment of origin (if conditions may allow)	Hot gas layer formed under the ceilings and caused damage at elevation +9.00m.	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke propagated to other parts of the plant and caused initiation of automatic suppression system. Smoke entered the control room. Mitigative steps were taken to minimize the impact of smoke on the operators. The operators did not have to leave the control room.	This event verifies that suppression systems outside the fire area may become activated from smoke ingress into other parts of the plant depending on the system design (in this case actuation by smoke detectors). Such scenarios are typically considered in fire PRAs conducted for U.S. plants as part of a deterministic survey of various fire related issues.
Local automatic fire detectors (if present) sense the presence of the fire	Automatic fire detectors sounded an alarm inside the control room in a very short time after fire ignition.	
Alarm is sounded automatically in the control room, locally and / or other places	The control room became aware of the fire almost immediately because of the noise caused by blade ejection and by visual observation through a window overlooking the turbine hall.	
Automatic suppression system is activated (if present)	Sprinkler and deluge systems inside the Turbine Building were activated as designed. However, there were no coverage in some of the areas where fire occurred and therefore, it could not control the fire.	
Personnel are present in the area where fire occurs	Personnel were present in the turbine building when the event started. There were eyewitness accounts of how hydrogen gas deflagrated and how oil cascaded down to a lower floor.	
Control room is contacted or fire alarm is sounded	Control room personnel became aware of the fire almost immediately because of the window between the control room and the turbine building and the loud noise caused by blade ejection.	
Fire brigade is activated	Outside fire brigade was called within one minute of fire ignition. A 30 person team responded and applied water hose streams to the fire.	
Fire suppressant medium is properly applied	Hose stream was used to fight the fire. The sprinkler system had only partial coverage of the building	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
Automatic fire suppression system is activated	Automatic sprinkler and deluge systems were activated but, because of lack of coverage in the area of fire proved to be ineffective in controlling the fire. In the case of the hydraulic oil system, since the fire fighters did not train their hose streams on them, despite the sprinkler system, the tank was destroyed by the fire.	This event demonstrates the importance of special conditions influencing the effectiveness of fire suppression system. One of the objectives of walkdowns conducted as part of fire PRA is to identify special conditions under which the suppression system may fail to be effective. In a fire PRA it is assumed that the fire protection system is properly designed to handle all possible fire scenarios of the area. The possibility of the suppression system being overwhelmed is not considered.
Fire suppressant medium is properly applied to where the fire is	There is no evidence in the available sources that the fire fighting efforts led to additional damage or complications, including areas where spurious actuations were observed.	
Fire is affected by the suppression medium	It took about 4 hours for the fire brigade to control the fire, and another two hours to extinguish the fire	This is a rather long fire in comparison to fire typically postulated in a fire PRA.
Fire growth is checked and no additional failures occur	At about 2 hours after the start of the fire no additional failures were observed.	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire	The burning oil cascaded down to the lower elevations of the turbine building. It caused the failure of cables in cable trays underneath the turbine and it caused the failure of a rubber expansion joint on a 2m diameter circulating water pipe. The rubber failed from softening under high temperature conditions and led to water spilling into the basement of the turbine building. Heat damage breached the control air piping and led to loss of control air pressure. Smoke from fire initiated automatic suppression systems outside the immediate fire area. Smoke propagated to other parts of the plant including the control room through the ventilation system that interacted with the turbine building. Some minor structural damage was later noticed that was attributed to hydrogen explosion.	In fire PRA the possibility of secondary effects, such as flooding caused by expansion joint failure, is not typically considered. Large water-filled pipes are commonly assumed to be invulnerable to fire damage. This event demonstrates that in fire PRA the analysts should focus attention on the specific chain of events that may ensue given a fire's propagation. The loss of the control air piping also would not typically be considered in a fire PRA. Smoke propagation is modeled in fire PRAs using simplified assumptions. At Vandellos, if a fire PRA was conducted prior to this incident, the possibility of smoke entering the control room and other buildings would have been predicted from the information obtained during plant walkdown.
Cable failure impacts equipment outside the fire location	Cable failures caused the failure of No. 3 and 4 heat exchangers (led to turbo-blower failure) and failure of control air system that led to the failure of remote control capability of the flow control valves to No. 1 and 2 heat exchangers. Cable failure caused the failure of the sump pumps and therefore the water from the suppression system and circulating water system water flooded the basement of the turbine building. Per Reference [20-3], no spurious activation of equipment was observed.	The control and power cables of such non-safety related components as drain pumps are not traced in a fire PRA. Although, in this case flooding had minimal effect on the core cooling functions and recovery actions, this incident points out that lack of knowledge about non-safety related components has the potential for indirectly affecting the analysis.

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Operators initiated a reactor shutdown almost immediately after the fire. Some defense in depth equipment were lost to the fire. Core cooling was achieved through the use of two remaining turbo-blowers and feedwater flow to the steam generators.	More than one safety train was affected by the fire. See further notes above.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	Operators apparently responded properly to the incident. Some smoke did enter the control room. However, the control boards were not adversely affected by this fire. The operators remained inside the control room at all times. They had SCBA units available to them, but did not use them.	In a fire PRA, if the control room is postulated to be filled with smoke, no credit would be given to further operator actions from the control room. In this incident, the operators remained in the room and continued to take proper actions to maintain core cooling despite some smoke ingress. By the same token, it is rarely assumed that smoke from fires outside the control room would actually enter the control room, let alone in quantities sufficient to cause abandonment. Most abandonment scenarios derive from fires that start in the control room itself. Hence, a fire PRA would likely not have postulated abandonment for this particular fire scenario.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	The operators manually adjusted the flow control valves of the functioning heat exchanger, by donning SCBA and walking through darkened and smoke filled compartments.	The operators took actions under environmental conditions that in a typical fire PRA would not be given any credit for. In particular, actions in smoke-filled rooms would not typically be credited. By the same token, smoke spread is rarely considered explicitly, and a typical fire PRA would assume that areas not involved in the actual fire would be accessible. Hence, it is likely that a fire PRA would have credited many of the actions taken by operators.
Structural failures (if occurred) may jeopardize availability of equipment	Hydrogen deflagration had some impact on the movable ceiling at elevation +9:00m.	
Water when sprayed over electrical equipment may fail the exposed equipment	No evidence of water damage to electrical equipment is provided.	

Fire Scenario Element	Incident - Vandellos 1, Oct. 19, 1989	Fire PRA Insights
The cooling effect of CO_2 may adversely impact equipment	Only water was used or was activated for fire fighting.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The only pre-existing condition was the fact that the door between the turbine and reactor buildings that was left open. The door was not water tight and there were piping and cable penetration that would have allowed water through into the reactor building regardless of the position of the door. Hence, this had minimal impact on the development of the incident.	Fire PRAs would have assigned a very low probability to this door being left open based on the existence of administrative controls requiring that the door be kept closed.

A20.5 Incident Analysis

The Vandellos, Unit 1 fire incident is considered a major fire from the classical fire protection perspective. The fire also presented a modest challenge to nuclear safety. The fire caused extensive damage, failed several key safe shutdown related components, created an adverse environment for the operators in the control room and in other areas of the plant, and ultimately led to the permanent shutdown of the plant.

The root cause of the fire is failure of a turbine wheel and blade ejection caused by stress corrosion of the blades. The configuration of turbine oil pipe routing with respect to the turbine blade trajectories influenced the severity of the incident in that the ejected blades severed the oil piping at several points. Also, the design of the lube oil pumps, which auto-started on loss of oil pressure, contributed to the very large quantity of oil released into the turbine building in a very short time period. Operators were unable to stop these pumps from the main control room, and presumably, manual local shutdown was not possible due to the fire and/or short time period involved with the oil discharge (the total inventory was apparently discharged within about six minutes). In a typical PRA, fire initiation is modeled using statistical analysis of actual incidents. The actual configuration of the systems that may or may not influence the occurrence rate or initial severity of a fire is not explicitly taken into consideration.

Two ignitions took place in this fire incident – an oil fire and a hydrogen deflagration. Since the hydrogen fire did not cause much damage, outside of superficial charring of cables and equipment, it did not have any serious contribution to the overall incident. In a typical fire PRA, the possibility of multiple, simultaneous of concurrent fires is not modeled. A hydrogen deflagration event, and the associated pressure effects, are also not typically considered. However, it must also be noted for areas such as a turbine building where large quantities of flammable materials are present, in fire PRAs it is often conservatively assumed that the fire would affect the entire building. This would inherently encompass this scenario.

In a typical fire PRA, fire-induced damage is limited to failure to function or spurious actuation of active components. Other types of potential failure are not typically considered in fire PRAs. For example, in this incident, the rupture of an expansion joint of a water-filled pipe from direct exposure to flaming oil led to the flooding of the basement of the reactor and turbine buildings. In this case flooding of the basements had little impact on the progression of the events and core cooling function. However, a typical fire PRA would consider the likelihood of failure of a water-filled component (e.g., expansion joint) to be invulnerable to fire damage; hence, the potential problems associated with flooding concurrent with a fire would not be captured in a typical PRA (with the possible exception of flooding due to fire water discharge). A second example is the heat-induced loss of the control air piping and loss of control air pressure. A typical PRA would not currently consider this potential. This could be an important aspect of some scenarios, if for example, air operated valves are involved in the scenario (either their failure on loss of air or reliance on their operation for plant shutdown). In this case, it is presumed here that the piping was probably of a soldered copper type, and the heat caused failure of the solder joints. Other types of piping would not likely be vulnerable to similar fire damage. A third example is the loss of plant lighting systems. The fire apparently caused loss of lighting in several areas of the plant. This is cited as a specific complicating factor in the fire fighting response and in operator actions taken locally. A typical fire PRA would not trace lighting cables nor consider the potential impact of their loss. In this case, emergency lighting was available. Fire fighting efforts in the turbine hall were apparently impacted significantly, but a number of local operator actions were successfully taken, including in some darkened areas.

In a typical fire PRA, the control and power cables for sump or drain pumps are usually not traced because these pumps have no direct reactor safety function. This incident points out that even those non-safety grade systems that require control and power circuits may become unavailable from the fire itself, and that their loss may complicate a fire incident. This could have implications for events involving the release of significant quantities of fire fighting water, or situations where a water-filled pipe may be vulnerable to failure (e.g., direct flame impingement on an expansion joint as in this case). The loss of sump pumps may lead to flooding problems that would not be captured in a typical fire PRA.

The need to consider the effectiveness of a fixed fire suppression system is mentioned in most fire PRA methodology documents. However, specific guidance on how to accomplish an effectiveness assessment is lacking, hence, effectiveness assessments are often not incorporated into actual analyses. Certainly, the phenomena that would lead to degradation of the effectiveness of a suppression system are difficult to identify, analyze and quantify in terms of suppression reliability. Typical PRAs will assume that if the suppression system actuates, then the fire will be controlled and/or suppressed and that any subsequent damage would be prevented. While exceptions exist, this is commonly given a high reliability - on the order of 95% success rates or higher. In this incident, the suppression systems did not cover those areas where the fire occurred (i.e., the general turbine building sprinklers) and/or were inadequate to deal with the fire that occurred (i.e., in the case of the deluge system for the hydraulic oil tank). Fire-induced damage continued well after actuation of the suppression systems. This possibility is not covered in typical fire PRA methodologies and applications. This incident also reiterates that a fire duration on the order of several hours is possible.

Smoke entered several important areas of the plant, including the control room. Operators managed to function properly and maintain core cooling functions with available equipment. While SCBA equipment was available in the control room, it was never used indicating that only a modest amount of smoke must have made its way to the control room. Control room ventilation was shut down to prevent further smoke ingress and portable fans were brought in to provide ventilation. Other actions were successfully undertaken that required operators in SCBA to enter smoke-filled compartments in order to manipulate certain valves manually. The situation with regard to current PRA practice is somewhat dichotomous. On one hand, a typical fire PRA would assume that the presence of smoke in an area would prevent operator actions in that area. This incident illustrates that this fire PRA assumption may be conservative since operators did take actions successfully in smoke-filled areas using SCBA equipment. On the other hand, fire PRAs rarely give explicit consideration to the potential for smoke spread to areas not directly impacted by the fire. In particular, operator actions in areas that are not actually involved in the fire are widely credited without explicit consideration of potential smoke spread paths. Performance shaping factors are often applied in these cases, although not universally, to reflect an increased likelihood of failure for actions taking place outside the main control room. Hence, current PRA practice contains elements with the potential to introduce both conservative and optimistic assumptions. Overall, the "trick" would appear to be to achieve a proper balance between the two.

Smoke also caused the activation of fire protection systems in other parts of the plant where fire had no direct impact. The suppression system actuations in these areas had no known impact on plant equipment. However, this points out that the spurious activation of fire suppression systems due to smoke migration, an issue included in the scope of Generic Issue 57, is possible. Spurious suppressant discharge has a potential to cause secondary equipment damage, may divert suppressants from areas where they are actually needed to fight the fire and may also create hindrances or distraction for the operators. In this case the systems were apparently actuated on smoke detection alone. This is now a rarely encountered configuration for plants in the U.S., largely due to adverse spurious operation experiences of the 1980's.

A20.6 References

A20-1 E. Pla, "Fire at Vandellos 1: Causes, Consequences and Problems Identified"

A20-2 "Fires in Turbine Halls and Nuclear Power Plant Safety", ASSET/IRS Activity, International Atomic Energy Agency, Vienna, Austria, December 11-13, 1991.

A20-3 Personal communication between Mr. E. Pla of International Atomic Energy Agency and Dr. M. Kazarians, 1999.

A20-4 "Fires in Turbine Halls and Nuclear Power Plant Safety - ASSET/IRS Activity", International Atomic Energy Agency, Vienna, December 11-13, 1991.

Appendix 21 - Analysis of Chornobyl, Unit 2 Fire on October 11, 1991

A21.1 Plant Characteristics

The Chornobyl plant site is located near Pripyat Ukraine. At the time of the fire incident addressed in this Appendix, Ukraine was a part of the former Soviet Union. The plant site originally had four units. Unit 4 was destroyed in an April 1986 reactor accident.[A21-7] The three remaining units were brought back online after the Unit 4 accident, and after implementation of several improvements including upgraded fire protection systems and cable protection. This appendix discusses a fire that occurred in Unit 2 about five years after the Unit 4 accident.

All four units are RBMK-1000 type reactors. This type of reactor has a vertical channel, boiling water, graphite moderated, light water cooled core with two turbine-generators per unit. Turbine-Generators No.3 and No.4 serve the Unit 2 reactor. The thermal power rating of Unit 2 is 3,200 MWt and each turbine-generator is rated at about 500 MWE power. Unit 2 started commercial operation in 1979 and was apparently was shut down permanently following the fire described here.[A21-7] The only currently operating unit is Unit 3.

Each reactor unit is cooled by two independent loops; each cooling half of the reactor and providing steam to a separate turbine-generator. Each loop includes four coolant pumps and one separator drum for drying the steam before it enters the turbine. The condensate from the turbine condensers flows back via five main feedwater pumps (for use during power operation) or three emergency feedwater pumps (for use during an emergency) to the separator. The main circulating pumps of the main coolant loop take suction from the separators.

A21.2 Chain of Events Summary

On October 11, 1991, Unit 2 was in the process of start-up after a two-month shutdown when a steam leak was discovered on Turbine-Generator No. 4. The reactor was at about 50% power (1,570MWt) and Turbine-Generator No. 3 output was at 425 MWE. The operators tripped Turbine-Generator No. 4 and attempted to take the generator off the gird by closing the valves to the turbine which caused the automatic opening of the 330kV air-operated breaker between the generator and the grid. However, before the field operators could open the isolator that de-energizes the air breaker, a short circuit in the control cable for the 330kV air breaker caused the breaker to close spuriously and re-connect the grid to generator No. 4.

It was later determined that the short was caused by mechanical damage to a section of cable insulation about 120 mm long in an underground duct. Cable pulling practices during construction in 1977 were thought to be the cause of insulation failure. Cable tests were carried out periodically during operation, but the defect was not discovered in any of those tests. The short occurred between the conductor that carried the control signal for breaker control and the conductor that carried the indication signal that the breaker is closed. Both conductors were located inside the same cable.

The closure of the breaker, in effect, turned the generator into a motor. However, the breaker closure was such that the generator started to turn in an asynchronous mode. Its speed reached 3,000 rpm in about 30 seconds. Due to the asynchronous operation, the alternator rotor overheated causing damage to the alternator rotor windings. Displacement of the rotor windings produced out of balance forces during the acceleration of the rotor and damage to the bearings and seals. This led to the release of hydrogen from the generator cooling system and release of oil from the turbine lube system. Both materials ignited on hot surfaces and started a large fire in the Turbine Building near Turbine-Generator No. 4.

Upon the initiation of the fire, operators tripped the reactor manually and started cool-down procedures. The shift supervisor ordered rapid cool-down of the reactor (30°C/hr) using the steam dump valve discharging into the steam suppression tank. The makeup for the Steam Drum Separator was provided by a main feedwater pump.

The fire brigade was called almost immediately. They arrived at the plant within 5 minutes. A total of 63 people including both plant personnel and off-site fire fighters were ultimately engaged in fighting the fire.

There was one error of omission made by the operators in response to the fire. The circuit breakers for Turbine-Generator No.3 were left closed even after the reactor had been tripped. Therefore, after the reactor trip this generator also received power from the grid and rotated, in this case in synchronous mode, like a motor. The generator remained in this condition for close to 20 minutes but did not suffer any observable damage. Ultimately this error had no impact on the progression of the event.

The steel roof supports located above Turbine-Generator No. 4 deformed from high temperature and collapsed. This is attributed to the build-up of hot gases under the ceiling, the lack of smoke discharge capability and insufficient cooling of the steel structure. The fire brigade's hose streams did not have enough pressure to reach the ceiling. This led to the collapse of the roof over Turbine-Generator No. 4 within about 20 minutes. The generator was completely destroyed by the collapse of the roof. Main feedwater and emergency feedwater pumps and their electrical boards were also affected. As a result, three out of five main feedwater pumps and one out of three emergency feedwater pumps were damaged. Thus, multiple safety trains were rendered unavailable in this incident.

The failure of the roof structural elements and the impact of fire on these elements caused release of radioactive aerosols into the atmosphere from contamination that was deposited during the April 1986 accident at Unit 4. The total radioactive material released from this event was about 1.4×10^{-3} Ci, which is less than daily admissible level. No other radiological release or undue contamination occurred as a result of the fire.

Initially, the makeup water was provided by a main feedwater pump. A flow control valve failed to adjust the flow and caused a high level condition in the steam drum. This in turn caused the main feedwater pump to trip. Later, the steam dump valve failed partially open because of a mechanical failure causing depressurization of the reactor coolant loop. All high pressure feedwater capability was eventually lost. Some of the pumps and their associated control valves were damaged by the debris from falling roof elements and the rest were de-energized to allow for fire fighting activities in the vicinity of their associated electrical panels.

At about 1 hour into the incident, the water level in the Steam Dump Separator dropped to the emergency set point. However, none of the main and emergency feedwater pumps were available to provide water to the separator. Although the operators were successful in starting one main feedwater pump, the electrical supply to all main and emergency feedwater pumps were removed, at about 1.5 hours, to allow the fire fighters continue their efforts in the vicinity of the associated electrical equipment. At about 2 hours, the operators started the seal water supply system to the main circulating pumps to provide makeup to the reactor. This can be regarded as a change in the core cooling and coolant makeup strategy.

About 3 hours after the incident started, the water level in both Steam Drum Separators dropped below the measurable range. Due to the decrease in reactor pressure and low temperature of the feedwater, the water had contracted and the level in Steam Drum Separator had dropped. The reactor pressure eventually decreased to the level where the low pressure feedwater injection from the clean condensate storage tank could be activated. Water level was regained when the low pressure pump was started. Thus, the operators lost control over the coolant flow rate through the core. For a time they relied on the seal water to provide the core cooling, but had no clear idea of the rate of coolant entering the reactor. The water level in the Steam Drum Separator was restored only after a feedwater pump was re-activated.

About 3.5 hours after the fire started, it was declared under control. At about 6 hours, the fire was completely extinguished. Reference A21-7 cites that Unit 2 was shutdown (permanently) in October of 1991. While not stated explicitly, one can infer that the unit was permanently shutdown due to the extensive damage realized during the fire.

A21.3 <u>Incident Progression and Implication for Fire PRA</u>

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (Reference [A21-1] through [A21-5]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	The unit was in the process of start-up after a two-month shutdown. The reactor was at about 1,570MWt, with Turbine-Generator No. 3 at 425 MWe. Turbine-Generator No. 4 had to be tripped because of a steam leak and it was coasting down. Its rotational speed was 50 rpm when the incident started. Two main feedwater pumps and 6 main circulating pumps were operating.	
Prior to the incident	At 19:46, on October 11, 1991, the operator switched off the Turbine-Generator No. 4 from the grid. This was achieved by closing the valves to the turbine and automatic opening of the 330kV air-operated breakers 1, 2 and 3 between the generator and the grid. The operator in the Central Control Room (the control room that controls plant connection to the grid) instructed a field operator to open the isolator TP-4GT to de-energize the air breaker. He had to walk 150m to verify the position of the breaker before he could de-energize the breaker.	
00:00	At 20:10, Turbine-Generator No. 4 had coasted down in the range of 50 to 200rpm, before the field operator could reach his destination and open the isolator, a short circuit in the control cable for the 330kV air breaker caused the breaker 2 to close spuriously and re-connect the grid to generator No. 4. The short was caused by a mechanical damage to about 120 mm of cable insulation thought to have been caused during the cable pulling operation through an underground duct during construction in 1977. Cable tests were carried out periodically and the defect was not discovered. Because of poor or damaged insulation, a short occurred between the wire that carries control signal for breaker control and the wire that carries the signal that the breaker is closed. Both wires were located inside the same cable. The operator in the Central Control Room noticed that the 330kV breaker was switched on.	This event demonstrates that spurious actuation of a device can occur from a short between two wires inside a cable. This type of event is often postulated in fire PRAs as a consequence of fire damage to control cables. This case is somewhat unique because the failure led to the fire rather than resulting from the fire.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The operators in the Unit Control Room and Central Control Room felt vibration of the building and noticed severe vibration of Turbine-Generator No.4. Almost at the same time, both operators discovered the fire in Turbine-Generator No. 4. The closure of the breaker, in effect, turned the generator into a motor (sometimes referred to as "motorizing" of the generator). It started turning in an asynchronous motor regime. Its speed reached 3,000 rpm in about 30 seconds. The alternator rotor overheated and resulting in damage to the alternator rotor windings. Displacement of rotor windings produced out of balance forces during the acceleration of the rotor. Severe vibration took place that led to rotor displacement. The forces of this event led to damage in rotor components, bearings (numbrs 10 to 14) and generator seals. Hydrogen and oil were released that caught fire.	
00:00:40	At 20:10:40, the oil fire affected generator bus bar and caused a 120,000 amp short circuit of all 3-phases. The generator protection system activated and opened the generator circuit breaker 2. However, because of the short in the control cable, breaker 2 closed again in 0.25 sec. The breaker cycled once more at a period of about 0.2 second. At this point the air pressure became insufficient to allow further action of the air-operated breaker. The grid circuit breaker, located 200km away, opened by actions of the grid protection system, which disconnected the generator from the grid. The duration of these actions was estimated as about 1.18 second.	
00:01	At 20:10:52, the reactor was tripped manually. According to the procedures, the operators immediately initiated emergency oil removal process from the turbine and purging of the generator hydrogen with nitrogen.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The generator circuit breakers on Turbine-Generator No.3 were left closed. This generator also received power from the grid and rotated, in this case synchronous, motor mode. Although, the generator remained in this condition for close to 20 minutes, it did not suffer any observable damages.	This is an error of omission in that an erroneous configuration of plant equipment went unnoticed for a long time. One possible cause for this may be operators' pre-occupation with dealing with the fire damage, reactor shutdown and core cooling. Although this element of the event was not important to plant safety, it demonstrates that it is possible for operators to fail to monitor a condition that could potentially cause adverse consequences because other events are in progress. The possibility of occurrence of overlapping scenarios is not explicitly addressed in typical fire PRAs.
00:01	Loss of vacuum occurred on both main condensers.	
00:01	Manual fire fighting activities using portable and fixed equipment were initiated and fire suppression systems activated as designed. Turbine oil sprinkler and area sprinkler systems were activated manually.	None of the references indicate the effectiveness of the suppression systems. Since it took a long time and the efforts of a large number of fire fighters to put the fire out, it is inferred that the fire overwhelmed the suppression systems and manual actions were necessary.
00:01	The fire brigade was called in.	
00:03	At 20:13, the control room shift supervisor ordered rapid cooldown of the reactor (30°C/hr) using steam dump valves discharging into the steam suppression tank.	
00:04	Two main feedwater pumps were operating. At 20:14, operators tripped one of the two pumps.	
00:06	At 20:16, the fire brigade arrived on the scene of the fire. A total of 63 people from the fire brigades and plant personnel were ultimately assigned to fight the fire.	
00:08	At 20:18, the operators tripped the turbine-generator oil pumps and started manually draining the oil in the lubricating oil tanks which are located outside the turbine building. An oil spill occurred as a result of this activity, but not in the vicinity of the fire.	Plant personnel were perhaps lucky that the oil spill did not contribute to the fire. This part of the event demonstrates that it is possible for personnel actions to influence the spread and severity of the fire. In fire PRA, actions taken by plant personnel that may aggravate the severity of the fire is not addressed.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:10	At 20:20, high level in the Steam Drum Separator tripped the operating main feedwater pump. The high level was caused by a failure in the main feedwater discharge valve to modulate properly.	This is a case where an event (failure) has occurred independent of the fire. In fire PRA, such independent failures or events are routinely included in the core damage frequency evaluation of fire scenarios using event trees and fault trees.
00:13	Fire brigade begins the fire fighting activities.	The response time of the fire brigade is quite typical of the times assumed in fire PRAs. Given that the brigade is largely an off-site unit, this is, in fact, a relatively prompt response.
--	The fire brigade aims water streams towards the ceiling. However, it later becomes evident that because a large number of equipment (including two sprinkler systems) drew water from the fire water system, its pressure had dropped and the hose streams did not reach the ceiling. Because of dense smoke in the turbine building, the fire fighters could not tell whether their water streams were reaching the ceiling.	Specific causes for the failure of manual fire fighting is generally not modeled in a fire PRA. This specific scenario (i.e., insufficient pressure in the system because of water over use) is typically not addressed in a fire PRA. Simplistic, perhaps conservative, models are used that is intended to cover a wide range of failure scenarios.
00:20	At 20:30, the steel roof supports located above Turbine-Generator No. 4 deformed from high temperature and collapsed. This is attributed to lack of smoke discharge capability and insufficient cooling of the steel structure. Attempts to cool the ceiling and structural elements failed because of lack sufficient pressure in the fire hoses for the water to reach the full height of the building. It must be noted that roof collapse occurred despite the upgrades in 1986, when combustible components of the roof were replaced with fire resistant elements, and the fixed fire fighting systems were improved.	This event demonstrates that a severe turbine building fire may cause catastrophic structural damage, even with proper fire protection measures. The relatively short time from fire initiation to collapse of the roof (20 minutes) is somewhat unexpected. In this case, the fire grew very quickly and must have been quite severe. However, in fire PRA it is relatively common to consider catastrophic loss of the turbine building without explicit consideration of the timing of that loss. Hence, most modern full-scope fire PRAs would nominally capture this potential.
00:20	Debris from the ceiling fell over Turbine-Generator No. 4. The generator was completely destroyed from the collapse of the roof. Main feedwater and emergency feedwater pumps and their electrical boards were affected. As a result 3 out of 5 main feedwater pumps and one out of three emergency feedwater pumps were damaged.	Multiple safety trains were rendered unavailable in this event. Such failures are the focus of all fire PRAs.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The roof materials caught fire and released radioactive materials from contamination deposited during the April 1986 accident. From this part of the event, one can infer that a portion of the roof structure was combustible (Reference [A21-3]) and that excessive heat caused them to ignite. This may have contributed to the structural collapse.	
00:28	At 20:38, the Steam Dump Valve failed partially open because of a mechanical failure. This caused the level in the Steam Dump Separator to drop.	This is another case of an independent failure that occurred during the course of the fire. (See note above).
00:30	At 20:40, because of debris falling from roof and impact of fire, control of main feedwater pumps 2, 3 and 4 and their associated control valves were lost. Hot metal debris and electrically active wires prevented operators from reaching control cabinets to restore a feedwater pump.	
00:50	The level in the Steam Dump Separator reached emergency set point. However, none of the main and emergency feedwater pumps were available to provide water to the separator.	
01:05	At 21:15, operators were successful in starting one main feedwater pump (No.1).	
01:10	At 21:20, the operating main feedwater pump had to be stopped based on high water level in Steam Drum Separator.	
01:30	At 21:40, the electrical supply to all main and emergency feedwater pumps were removed to allow fire fighters to continue their efforts in the vicinity of pump motors and control cabinets. This left the reactor cooling system without make-up water.	This incident demonstrates that direct fire damage may not be necessary for a set of equipment to become unavailable. One cause for equipment unavailability is intentional tripping of the equipment as part of fire fighting activities. This type of scenario is not generally considered in a fire PRA.
--	Operators initiated reactor coolant system pressure decrease by opening steam relief valves into the pressure suppression tank.	
02:00	At 22:10 the operators, initiated reactor cooling through an auxiliary system that is normally used to supply main circulating pump seals cooling.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
02:51	At 23:03, water level in both Steam Drum Separators dropped below the measurable range. Because of decrease in reactor pressure and low temperature of the feedwater, the water had shrunk and the level in Steam Drum Separator had dropped. The reactor pressure decreased to the level where the low pressure feedwater injection from the clean condensate storage tank could be activated. The operators, per Reference A21-6, had no previous experience with this type of operation.	Similar to a few other fire events, operators in this case have gone beyond the well established written and practiced procedures. In fire PRA, no credit is given to such actions and it is conservatively assumed that operators would not deviate far from set procedures.
03:03	At 23:15, the water level in the right Steam Drum Separator increased to above the measurable level.	
--	The operators maintained the makeup and core cooling using the seal water system and regained control of the Steam Drum Separator level by 23:45.	
03:31	At 23:41, the fire is declared under control.	
03:35	At 23:45, water level in the left Steam Drum Separator increased to above the measurable range.	
03:48	At 23:58, the level in both steam drums reached normal range.	
06:10	At 02:20 on October 12, the fire was completely extinguished.	

Equipment Damaged

- Generator
- Five main feedwater pumps
- Three emergency feedwater pumps

Damaged Areas

- The turbine building sustained severe damage. The roof above the Turbine-Generator No. 4 collapsed. No effects outside the turbine building were noted.
- The plant apparently was permanently shutdown following the fire.[A21-7]

Impact on Core Cooling

- Some safety related equipment was affected by this fire. However, core cooling functions remained available at all times.

Radiological Release

– The disruption of roof structural elements and impact of fire on these elements caused release of radioactive aerosols into the atmosphere from contamination that was deposited during the April 1986 accident at Unit 4 (Reference [21-3]). The total radioactive material release from this event was about 1.4×10^{-3} Ci, which is less than daily admissible level. No other radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

– There were no reported injuries to plant or external fire brigade personnel caused by the fire. The fire fighters and plant personnel involved in fire fighting activities received radiation exposure that ranged from 0.02 to 0.17 rem, which did not exceed the two-week dose.

Public Impact

– The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

– Available sources do not indicate any radiological releases beyond the re-lofting of previously deposited contaminants as noted above. There was no significant, contamination or any other adverse environmental impact.

A21.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Chornobyl 2, October 11, 1991**	**Fire PRA Insights**
Presence of combustible / flammable materials	Turbine lubricating oil and generator hydrogen were the combustible materials that contributed to this fire.	
Presence of an ignition source	Hot surfaces of the turbine-generator and steam pipes or the heat generated by asynchronous operation of the generator may have served as ignition sources.	

Fire Scenario Element	Incident - Chornobyl 2, October 11, 1991	Fire PRA Insights
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	The fire ignited because of oil and hydrogen release from Turbine-Generator No. 4. The release occurred because the generator was inadvertently connected to the grid and rotated up to 3,000 rpm as an asynchronous motor. The generator breaker had closed because of a short between two wires from the breaker control circuit and breaker closure status signal. The short occurred because of mechanical damage to the cables inside a duct.	
Fire growth within the combustible or component of original ignition	The fire became large, apparently in a short time. Per Reference A21-6, the hydrogen flame was 6 to 8 meters high.	Turbine building are widely recognized in fire PRAs as presenting unique fire hazards. This incident confirms these assumptions and the potential for a very rapidly growing and severe fire to occur.
Fire propagates to adjacent combustibles.	The fire apparently caused parts of the roof to ignite although reports imply that ignition occurred only after the roof had collapsed. It is not clear whether or not any other aspects of fire spread were significant.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	The hot gas layer under the ceiling caused the roof to collapse over the turbines. Combustible elements of the ceiling and the roof may have caught fire contributing to the early collapse.	This is well beyond the typical hot layer effects characteristic of fires postulated by a PRA in most plant areas. However, for turbine buildings many PRAs will postulated total loss of the turbine building without specific consideration of the mechanisms of loss beyond postulating a severe fire.
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	From the available information it is inferred that the fire remained confined to the turbine building close to Turbine-Generator No. 4	
Local automatic fire detectors (if present) sense the presence of the fire	No information is provided regarding the presence of any fire detectors in the area.	

Fire Scenario Element	Incident - Chornobyl 2, October 11, 1991	Fire PRA Insights
Alarm is sounded automatically in the control room, locally and / or other places	No information is provided regarding alarms. However, the control room became aware of the fire in a very short time. The operators felt the vibration caused by generator rotor rotating as an asynchronous motor.	
Automatic suppression system is activated (if present)	From the available information it can be inferred that there were manually activated sprinkler systems at the turbine oil and the general area that were activated by plant personnel upon discovering the fire. However, no further information is given regarding the effectiveness of the systems. It can be inferred that they were overwhelmed, since it required a large number of people and a long time to put the fire out. Also, their combined activation with manual fire fighting activities caused the pressure in the fire water system to drop and starve the fire fighter from the capability to properly spray the ceiling to prevent its collapse.	The possibility of a suppression system being ineffective or being overwhelmed by the fire is not explicitly modeled in a fire PRA. PRAs commonly assume that if the system actuates it will be effective.
Personnel are present in the area where fire occurs	Personnel discovered the fire and were present in the turbine building at the time of the fire.	
Control room is contacted or fire alarm is sounded	Control room became aware of the fire in a very short time after ignition The vibration caused by generator No. 4 was felt in the control room.. The exact mechanism of informing the control room of the presence of a fire is not provided in the available sources.	
Fire brigade is activated	The fire brigade was called immediately upon discovery of the fire. They arrived at the plant in five minutes and began suppression efforts in about 13 minutes.	The fire brigade response is typical of the response times assumed in a fire PRA for an on-site fire brigade. Given that the brigade was made up of off-site personnel, the response time can be cited as quite fast compared to typical PRA assumptions.

Fire Scenario Element	Incident - Chornobyl 2, October 11, 1991	Fire PRA Insights
Fire suppressant medium is properly applied	Although not specifically mentioned in the available sources, in addition to the sprinkler systems that were activated manually, it is apparent that water and hose streams were used to fight the fire. Because there was excessive demand on the fire water system the hose streams did not have enough pressure to spray water on the structural elements of the ceiling.	
Automatic fire suppression system is activated	See the discussions above.	
Fire suppressant medium is properly applied to where the fire is.	There is no evidence that the hose streams were misapplied. The power to all main and emergency feedwater pumps had to be turned off to allow the fire fighting to continue around the pumps and control cabinets.	
Fire is affected by the suppression medium	The fire was brought under control in about 3.5 hours.	
Fire growth is checked and no additional failures occur	No additional failures caused by the fire were reported beyond the first half hour of the event.	In this case, the structural collapse of the roof apparently did the most serious damage. After this, there were few additional damage reports noted. (See related notes above).
Fire is fully extinguished and fire brigade declares it as out	The fire was declared as completely out about 6 hours after the event started.	This is a relatively long fire in comparison to fires considered in a typical PRA. However, as noted elsewhere, catastrophic loss of the turbine building is often postulated.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	The roof above generator No. 4 collapsed because of the failure of structural elements. The roof debris caused the failure of 3 out of 5 main feedwater pumps and one out of 3 emergency feedwater pumps. All feedwater capability was eventually lost because the power to the system had to be turned off to allow for fire fighting in the vicinity of the electrical cabinets.	

Fire Scenario Element	Incident - Chornobyl 2, October 11, 1991	Fire PRA Insights
Cable failure impacts equipment outside the fire location	No information is provided regarding this issue. However, the entire sequence of events started with a short in a cable caused by mechanical damage.	
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	The plant was scrammed immediately after the fire was discovered. Core cooling was established opening a Steam Dump Valve and makeup of water by one main feedwater pump. The feedwater capability was lost completely during this event, in part due to intentional shutdown of associated power busses. The operators had to use condensate seal water system for the main circulating pumps to add water to the core. To be able to accomplish this, reactor coolant system pressure had to be reduced by opening steam relief valves. The operators had no previous experience in providing makeup water in this manner. The control of the water level in the Steam Drum Separators was lost during the course of the event and was later regained when the seal water system was initiated.	Operator recovery actions were a key element of this incident. The operators took at least two different approaches for maintaining core cooling (use of feedwater and use of the seal water system). They also decided to implement the rapid cooldown (i.e., 30°C/hr) procedure. This last decision had implications in terms of loss of water level in the steam drums. Overall, the operators were successful in maintaining core cooling. At one point, for a duration of about 45 minutes, the water level in the Steam Drums was below its measurable level, thus the exact status of core cooling capability was not known to the operators. The operators relied on pump seal flow to provide coolant to the core. In PRA, small probability of success is typically assigned to the possibility of changing course in recovery strategy. Also, in fire PRA, core damage is assumed to occur if the water drops below a measurable level.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	No information is provided regarding this issue. Since the fire was in the Turbine Building, the affected cables likely had little impact on safety related instrumentation.	
Operators attempt to control the plant properly and bring the plant to a safe shutdown	The operators attempted several methods for rapid cooldown of the plant. Despite many difficulties in controlling the water from the feedwater systems and the water level in the Steam Drums, the operators managed to maintain core cooling at all times with the help of one main feedwater pump and seal water system for the main coolant loop recirculating pumps.	

Fire Scenario Element	Incident - Chornobyl 2, October 11, 1991	Fire PRA Insights
Structural failures (if occurred) may jeopardize availability of equipment	Structural failure occurred in this event and the debris caused the failure of main and emergency feedwater pumps.	
Water when sprayed over electrical equipment may fail the exposed equipment	The electrical equipment were de-energized to allow for the spray of water in the vicinity of the electrical equipment.	This is an aspect of the fire incident that would not be captured in a typical fire PRA. The possibility that redundant equipment might be taken out of service to facilitate fire fighting is not considered. This may be an artifact of Soviet fire fighting procedures that call for de-energizing equipment before fighting fires so the applicability to US plants is uncertain..
The cooling effect of CO_2 may adversely impact equipment	No information.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	At least two independent failures did occur during the event. The feed valve of operating main feedwater pump failed to modulate flow properly and the Steam Dump Valve stuck half open.	This demonstrates that independent failures can adversely impact the progression of a fire incident. In PRAs, independent events are an integral part of the event tree/fault tree models. In general the occurrence of more than one such failure in a single incident would be judged highly unlikely.

A21.5 Incident Analysis

The fire in the Chornobyl Unit 2 turbine building was clearly a severe fire from a classical fire protection standpoint because significant damage was inflicted on the turbine building structure, one generator, and several safety related pumps and equipment. Damage from the fire apparently led to a permanent shutdown of Unit 2.[inferred based on A21-7] The incident is also judged to have led to a significant nuclear safety challenge because the strategies employed by the operators for core cooling, were not according to an established procedure and perhaps could have led to adverse conditions for the core.

Operator recovery actions were a key element of this incident. The operators took at least two different approaches to maintaining core cooling (use of feedwater and use of seal water system) and decided to implement the rapid cool-down (i.e., 30°C/hr) procedure. This decision had adverse implications in that it led to a drop in water level in the steam drums and a depletion of the coolant inventory. Overall the operators successfully maintained core cooling. This was initially accomplished using the main feedwater pumps. After that option was lost (due to manual isolation of the operating pumps to facilitate fire fighting efforts) operators used reactor coolant pump seal flow. Thus, two different strategies were employed in maintaining coolant flow. At one point, for a duration of about 45 minutes, the water level in the Steam Drums was below its measurable level, thus the exact status of core cooling capability was not known to the operators. In PRA, a small probability of success is typically assigned to the possibility that operators will change course in their recovery strategy in the midst of an unfolding accident. Also, core damage would conservatively be assumed to occur if the water level drops below the measurable level.

At least two independent failures occurred that adversely impacted operator recovery efforts; failure of the feedwater flow control valve and failure of the steam dump valve in a partial open condition. The occurrence of independent failure events is an integral part of fire PRAs since such failure are included in the plant fault trees and event trees. However, the occurrence of two such failures during a single incident would generally be considered highly unlikely. This incident does illustrate that even unlikely events can occasionally occur, again, a concept consistent with the core basis of PRA which inherently deals with unlikely events.

The root cause of this incident was a short circuit between two wires inside a cable that resulted in spurious operation (closing) of a breaker circuit. The incident therefore demonstrates that spurious actuation of a device can occur from a short between two wires inside a cable. This case is somewhat unique in that the fire was a result of the short rather than a short resulting from fire damage to cables. Spurious equipment actuation is often postulated in fire PRAs as a consequence of fire damage to control cables. Current methods of analysis for this are, however, subject to considerable debate. See the body of this report for further discussion.

Another interesting factor in this incident is the fact that an erroneous alignment of plant equipment went unnoticed for a long time due to an operator error. Following the reactor trip, operators failed to isolate the second turbine generator from the grid. As a result Turbine Generator No.3 rotated in synchronous motor mode for close to 20 minutes. Ultimately this had little significance in this particular event. However, it must be noted that it was a spurious connection of generator 4 to the grid that led to the fire. Had this second generator also operated in an asynchronous mode, a second fire may have ensued.

The actual cause for the operators failing to notice the condition of this generator has not been established in any of the available documents. The most plausible apparent explanation is that the operators were pre-occupied with assessing and responding to the fire, implementing a reactor shutdown and maintaining core cooling (certainly these would appropriately be their top priorities). Although this element of the incident was ultimately not important to plant safety, it does demonstrate that fires can lead to adverse impacts on operator responses, even if those actions take place from the main control room. In this case operators failed to monitor a condition that could potentially cause adverse consequences beyond the original chain of events. In fire PRA methodology, it is commonly assumed that fires occurring outside the control room will not impact the reliability of operator actions that take place within the main control room. Also, the possibility of occurrence of overlapping scenarios or operator demands resulting from the fire is not explicitly addressed. In a fundamental sense, current methods do allow for the possibility of addressing such events in a fire PRA, this is simply not typical practice.

The available information sources indicate that the manually activated sprinkler systems activated as designed. Although, no information is provided about the effectiveness of those systems, it is noted that the pressure of the fire water system had dropped because of excessive demand on the system. Since the fire did cause extensive damage, and because it took a long time and the efforts of a large number of fire fighters to put the fire out, it may be inferred that the fire overwhelmed the suppression systems. The possibility of suppression system failing to control the fire because of the intensity of the fire is not generally modeled in a fire PRA. It is commonly assumed that if the systems actuate, they will control the fire. It is also commonly assumed that the activation of a fire suppression system will prevent any further damage from occurring. In this case, damage clearly continued to occur well after the suppression systems actuated. Again, the turbine building presents unique fire hazards as compared to other plant areas.

Roof collapse in the turbine building occurred despite upgrades made in 1986. The upgrades included replacement of combustible components of the roof with fire resistant elements, and the fixed fire fighting systems were improved. It would appear, however, that at least some combustible elements were left in place as the reports do cite that, at least after collapse and perhaps before the collapse, some elements of the roof did burn. (One might suspect, for example, that the roofs exterior sheathing was combustible.) The major structural supports were apparently steel, and the fire was sufficiently severe so as to cause failure of these steel structures. This incident demonstrates that a severe turbine building fire may cause catastrophic structural damage, even with fire protection measures in place. However, the specifics of the upgrades are needed to fully understand the reasons for the failure of the protective measures. It is also interesting to note that in this case the failure occurred in a rather short time, about 20 minutes. This is a further indication of that the fire was quite intense and grew rapidly following ignition.

Another human action that was noted in this event was that the electrical supply to all main and emergency feedwater pumps was intentionally removed to allow for the fire fighters continue their efforts in the vicinity of the associated electrical equipment. This incident demonstrates that direct fire damage may not be necessary for a set of equipment to be taken offline during a fire. Fire fighters are commonly reluctant to apply water to electrical fires due to personal safety concerns. In this case, the systems were taken off-line to alleviate such concerns and to facilitate fire fighting activities. Various incidents in the U.S. also demonstrate a reluctance on the part of fire fighters to apply water to energized electrical equipment (beginning with the Browns Ferry fire in 1975 and continuing through current events). This may have particular relevance in scenarios where redundant equipment is separated only by spatial separation within a single room. If the room fills with smoke, fire fighters may seek isolation of the redundant train power sources before applying water to the fire. This could delay fire fighting efforts and/or result in the isolation of the redundant train. This would not be considered in a typical fire PRA given current methods of analysis.

A21.6 References

A21-1 "Fires in Turbine Halls and Nuclear Power Plant Safety; ASSET/IRS Activity" Working Material, Report of a Consultants Meeting Organized by the International Atomic Energy Agency, Vienna, 11-13, December 1991.

A21-2 "Report of the ASSET Mission to the Chornobyl Nuclear Power Plant, Ukraine, 22-26 June 1992 - Review of the Root Causes of a Safety Significant Incident that occurred 11 October 1991 at Unit 2 - Loss of the Emergency Feedwater Supply due to a Fire in the Turbine Hall", IAEA-NENS/ASSET/92/A/03.

A21-3 Vasil'chenko, V.N., A.Ya. Kramerov, D.A. Mikhailov, and A.P. Nikolaeva, Analysis of the Accident in the Second Power-Generating Unit of the Chornobyl Nuclear Power Plant Caused by Inadequate Makeup of the Reactor Cooling Loop", Translated from Atomnaya Energiya, Vol 78, No.4, pp. 249-255, April, 1995, Plenum Press Corporation, 1995.

A21-4 Ovchinnikov, "Fire Protection of Nuclear Power Plants", A.E.Mikeev, Energoatomizdat, Moscow, 1990.

A21-5 Soloviev.P.S. "Accidents and incidents in nuclear power plants", Obninsk,1992.

A21-6 Shteinberg, Nicolai, J. Joosten and S. Routchkine, "Fire at Chornobyl 2", Fire & Safety '94, Barcelona, Spain, December 5-7, 1994.

A21-7 *Soviet-Designed Nuclear Power Plant Profiles,* USDOE, Office of Int. Nucl. Safety and Coop., Washington, DC, January 1999.

Appendix 22 - Analysis of Salem, Unit 2 Fire on November 9, 1991

A22.1 Plant Description

Salem is a two unit nuclear power plant site located near Salem, New Jersey. Unit 1 is a boiling water reactor and Unit 2, which is completely separate from Unit 1, is a pressurized water reactor. Unit 2 is rated at 3411 MWt and 1106 MWE. Unit 2, where the fire being reviewed occurred, started commercial operation in October 1981.

A22.2 Chain of Events Summary

On November 9, 1991, Unit 2 was operating at full power when a reactor trip occurred (References [A22-1] and [A22-2]). As a result of the trip, the main generator breaker opened. The Auto Stop Oil System was in test mode and as a result the turbine valves cycled open while the generator was disconnected from the grid (i.e., the turbine "re-started" without an appropriate generator load on the system). An over-speed condition took place, but the over-speed protection system failed to function properly and allowed the turbine's rotational speed to exceed 2500 rpm compared to the normal operating speed of 1800 rpm. The forces associated with this level of over-speed caused the blades to break apart and fragments were ejected from the turbine casing. Hydrogen gas escaped and caught fire because of seal failure caused by excessive vibration. The lube oil pipes were also severed causing release of the oil that also caught fire.

The following automatic fire suppression systems actuated promptly as designed.

- Deluge system protecting inboard generator bearing housing
- Deluge system protecting low pressure bearing housing
- Low pressure carbon dioxide system protecting the main generator excitor
- Wet pipe sprinkler system below the main generator pedestal

Per Reference A22-3, the entire sequence of events leading to turbine failure lasted 74 seconds. Fires had occurred by then and some of the automatic suppression systems had activated within that time frame. The automatic suppression systems managed to extinguish some of the fires.

The fire brigade happened to be outside the protected area at the time of fire. Withe the assistance of plant security, the brigade re-entered the plant proper promptly and managed to be on the scene within 5 minutes of fire ignition in full gear. With the help of plant fire brigade personnel, the fire was contained rapidly and was extinguished within 15 minutes. The damage caused by the fire in this incident was small compared to the damage done by the ejected blades. The turbine and exciter end of the main generator were found to be impacted by the fire.

Since the main turbine generator of Salem 2 is not enclosed, the hydrogen and smoke from the fire escaped directly into the atmosphere. The fire brigade did not need to be concerned with pocketing of hydrogen under ceiling structural elements.

A22.3 Incident Analysis

This incident is considered important because despite the potential for a very severe fire, only very limited fire damage was observed. In this case, catastrophic failure of a turbine occurred leading to a fire. In this sense, the event is similar to other turbine hall fires including some incidents covered by this same review (i.e., Narora, Maanshan and Vandellos). However, this event is somewhat unique in that the fire suppression system was adequate to control the ensuing fire, and coupled with brigade response, the fire was put out very quickly. There was some localized fire damage, and the costs for replacement of the failed turbine were extensive, but there was no impact on the safety related elements of the plant. The fire had no specific impact on the control room functionality nor the operators. This event illustrates the importance of rapid response to fires.

In this incident a main turbine-generator related system failure led to turbine disintegration. Fire was a consequence of that failure. In PRA, categories of external events are defined that include internal fires and turbine blade failures as two separate categories. In this incident both categories took place This incident demonstrates that when analyzing turbine failure (especially turbine blade ejection) in a general PRA, special attention should be given to the possibility of fire occurrence in the turbine building.

Finally, it is interesting to note that two independent events contributed directly to the initiation of the fires. First, the Auto Stop Oil System was in test mode and this created a condition where the turbine was, in effect, re-started without an appropriate load and this in turn led directly to the potential for an over-speed condition to occur. Second, the over-speed protection system failed to function allowing the over-speed condition to progress unchecked. PRAs rarely model the actual process of fire initiation, instead relying on statistical estimates of fire initiation based on past experience. Nominally, concurrent random failures tend to be considered low likelihood events. Nonetheless, current PRA practice would have captured the potential for such fires.

A22.4 References

A22-1 "Fires in Turbine Halls and Nuclear Power Plant Safety - ASSET/IRS Activity", International Atomic Energy Agency, Vienna, December 11-13, 1991.

A22-2 Licensee Event Report # 31191017, "Reactor/Turbine Trip on Low Auto Stop Oil Pressure Followed by Turbine/Gen. Failure", Salem Generating Station - Unit 2, Event Date 11/09/91.

A22-3 Braddick, Rita E., "The Role of Fire Protection - Salem Generating Station Turbine Failure", Fire & Safety '94, Barcelona, Spain, December 5-7, 1994.

Appendix 23 - Analysis of Narora, Unit 1 Fire on March 31, 1993

A23.1 Plant Characteristics

Narora Atomic Power Station (NAPS) is a twin unit pressurized heavy water reactor (PHWR) located in Utal Pradesh, India. Each unit is rated at 220 Mwe. Unit 1 started power operation in July 1989 and was declared as commercial in 1991. Unit 2 started power production in 1992. There are two turbine-generators, one per unit, housed in the same turbine building. The two units share the same control room, but separate control panels.

A23.4 Chain of Events Summary

On March 31, 1993, Unit 1 (NAPS-1) was operating at 185 MWe. Unit 2 (NAPS 2) was in cold shutdown but containment was pressurized. At 03:32, a turbine blade failure took place on the Unit 1 turbine-generator set that led to severe vibrations, rupture of oil lines and the release of hydrogen. These fuels ignited causing an explosion and fire in the Turbine Building. The reactor was tripped manually. A plant emergency was announced within a few moments of the accident and was not lifted until 22:45 of the same day, about 19 hours after the initiation of the accident.

Cool-down of the primary reactor cooling loop was initiated by manually opening small Atmospheric Steam Discharge Valves (ASDVs). The operators, observing the gravity of the situation, later opened the large ASDV valves to start a "crash" cool-down. In less than ten minutes all primary coolant recirculation pumps tripped and all safety related power sources were lost. This effectively placed the plant in a station blackout condition for Unit 1, and this condition persisted for 17 hours.

The oil-initiated fire propagated along cable trays inside the turbine building toward the Control Equipment Room. Apparently, the lack of proper fire barrier penetration seals allowed the fire to propagate to other areas as well. A large number of cable trays were damaged.

Within about 10 minutes, the operators manually started two diesel-driven fire water pumps. These pumps provided fire water and were later used to pump water into the steam generators. They operated for about 3.5 hours, when they both tripped simultaneously. Based on the information available, no clear cause for the pump trips can be established. There appears to be no direct link to any observed fire damage; hence, the trips were likely caused by an independent (random) common cause failure. One of the pumps was restored about 1.75 hours later (after the pumps tripped), although no details on how the pump was recovered are available.

A large quantity of smoke entered the Main Control Room from the Control Equipment Room and air supply diffusers. The operators for both units were forced to leave the Main Control Room at about 10 minutes after the blade failure and could not re-enter it for close to 13 hours. An attempt was made to take control of the plant from the emergency control room. Unit 2 efforts were apparently successful, but there was no power available to the Unit 1 side and therefore the Unit 1 control panel of the emergency control room had no functioning indications.

Thus, the operators had no indications of the condition of the reactor and were, in effect, "flying blind".

Fire fighting started about 20 minutes after blade failure in the area below the generator using water from fire hydrants and a fire tanker. Within about 1.5 hours the major part of the fire was extinguished. The rest of the fire was put out within another 7.5 hours, or about 9 hours after blade failure.

Members of Advisory Committee for Accident Management reached the site in about 30 minutes. and took charge of the situation. The guard house at the entrance of the turbine building was used as the command center for guiding the operations. The plant design had included an emergency back-up connection between the fire water system and the steam generators. A group of plant personnel were sent to the boiler room to check on the status of the valves to the fire water back-up circuit. The valves were opened manually to their 50% point. This established fire water flow into the steam generators that served as a heat sink for decay heat removal by maintaining natural-circulation cooling of the core.

Borated heavy water was added to the core to ensure sub-criticality. The Gravity Addition of Boron (GRAB) system was used for this purpose per established emergency operating procedures. GRAB was specifically designed to remain functional during a station blackout condition. Later, fire water hoses were also connected to the End-Shield Cooling System.

Some portion of the neutral bus ducts of the main generator and the vertical portion of the phase bus ducts below the generator melted because of the oil fire in the area. The turbine generator support structure and portions of the slab around the turbine generator set also suffered damage from intense heat. A number of glass window panes in the turbine building shattered.

At about 4.5 hours into the incident, the operators entered the primary containment of Unit 1 where they could read the primary loop instrumentation readouts directly. This lifted the "flying-blind" condition and restored the operators' ability to monitor reactor conditions.

A third diesel generator that serves both units was started and loaded about 5.5 hours into the incident. This allowed essential equipment to be energized. However, the shutdown cooling pump was not energized until about 17 hours into the accident. This point in the chain of events was used by Narora management to define the end of the station blackout condition.

A23.3 Incident Progression and Implication for Fire PRA

In this section, the conditions prior to the incident, the chain of events leading to ignition and the chain of events following the ignition are described in a chronological order as best as can be inferred from the available sources (References [A23-1] and [A23-2]). If the precise timing and the order of an event is not known, the time of occurrence is not specified. However, it is included at an order of presentation based purely on the judgement of the authors of this report.

Whether an event from the chain of events is typically included in a fire PRA is discussed where deemed appropriate. Lessons that may be gleaned from a specific event in the context of fire PRA are also provided.

Time (hr:min)	Event or Step Description	Fire PRA Implications
Prior to the incident	Unit 1 (NAPS-1) was operating at 185MWe full power level. Unit 2 (NAPS 2) was in cold shutdown but pressurized.	
Prior to the incident	One of three diesel engine driven fire water pumps was under maintenance and was inoperable.	
00:00	On March 31, 1993, at 03:31:40 a turbine trip signal was initiated, caused by fatigue failure of two turbine blades on the 5th stage of flow path 2 of the low pressure turbine. The initial failures resulted in breakage of 14 additional blades. The control room registered several alarms at the same time on the control panel for turbine and related auxiliaries. The specific parameters that initiated the turbine trip could not be identified.	In a typical fire PRA, ignition of a large fire in the turbine building is assumed to occur from an arbitrary cause. The specific causes are generally not addressed explicitly. However, it is assumed that oil is released, ignited and a large fire ensues.
--	Turbine blade failure led to turbine-generator imbalance, that led to the failure of bearing # 4 and later failure of bearings #5 and 6. Turbine imbalance led to frictional forces in the shaft.	
--	The vibration of turbine-generator caused the hydrogen seals of the generator to be "thrown out." A large quantity of hydrogen gas escaped from the generator and caught fire. A hydrogen explosion and fire took place. The hydrogen escaped into the bus ducts past the terminal and seal-off bushings. A hydrogen explosion caused damage to the bus ducts and excitation panels. The vibration also caused the oil pipes connected to the turbine to snap and spill the oil, which ignited and started a large fire in the turbine building.	Two types of fires had occurred -- an explosion of hydrogen gas and a large oil fire. In a typical fire PRA, only one type of fire is postulated. Since, extensive damage is often postulated for turbine building fire scenarios, lack of consideration of simultaneous occurrence of an explosion and a fire is of minimal consequence.

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	The control room personnel and other staff inside and outside the turbine building heard the sound of an explosion. The control room personnel felt vibration in the floor and a gush of hot and dusty air. A "huge" fire was observed at elevations +111.0m and +104.0m of the turbine building near the generator. The crane operator of turbine building crane was inside the crane cabin parked near the Unit 2 turbine and noticed a fire near the Unit 1 turbine-generator set with a bluish flame.	
--	The turbine trip initiated the opening of the unit transformer breaker, main generator breaker and field breaker and closure of start-up transformer breaker, as designed.	
00:00:38	A reactor trip was immediately, manually initiated upon turbine failure.	
00:00:40	Turbine-generator shaft stopped under friction caused by turbine imbalance (normal turbine coast down is 45 minutes).	
--	The control room received several reactor trip signals.	
--	The motor-generator set tripped.	
--	Cooldown of Primary Heat Transport (i.e., primary reactor cooling loop, the PHT) was initiated by manually opening small Atmospheric Steam Discharge Valves (ASDVs).	
--	The fire spread to control and power cables. Because of lack of separation between redundant trains, cable damage caused a station blackout (see Note 1). Control power supply cable trays on the mezzanine floor (+106.0m elevation) were severely damaged.	Multiple safety trains were affected by this fire. Impact on multiple trains in a fire incident is relatively rare. Current PRA methodologies would properly identify the possibility of occurrence of station blackout from a turbine building fire.
--	The diesel generators (2 for Unit 1) started automatically, but tripped because of loss of control power supply.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:05:45	Operators, upon observing the gravity of the situation, initiated a "crash" cool down of the primary coolant loop (the PHT) by opening the large Atmospheric Steam Discharge Valves. The Secondary Shutdown System (SSS) was initiated automatically because of crash cooldown.	Operators took the proper actions throughout the course of the event. Current PRA methodologies would properly identify the operator actions that had to take place. However, PRA methodologies put considerable emphasis on written, available emergency procedures. Little or no credit is given to actions outside written procedures.
00:06:47	All PHT pumps tripped. A complete loss of class IV supply was experienced.	
--	Control room staff noticed that PHT pressure is at 50kg/cm2(g) (about 700 psi) and that the fueling machine pump is running.	
00:07:04	Isolation of primary containment was noted.	
00:07:40	Complete loss of power supply systems (station blackout) on Unit 1 side of the plant was experienced. All Class I and II power supplies were lost.	
00:07:59	The breaker for motor-generator set MG-3 (of the control circuits) tripped leding to a complete loss of control power supply.	
00:08	Senior plant management were informed of the fire. Using the Unit 2 public address system, plant emergency was announced.	
--	Fire propagated along the cable trays towards the Control Equipment Room next to the Turbine Building. Lack of complete fire barriers allowed the propagation of the fire to other areas. A large number of cable trays, Emergency Transfer Relay (EMTR) panels and Line, Transformer and Generator (LTG) panels were damaged.	
--	Large quantity of smoke entered the Main Control Room from the Control Equipment Room and air supply diffusers. The operators for both units 1 an 2 had to leave the Main Control Room.	This is one of the few fire events where operators had to evacuate the Main Control Room. In fire PRAs, upon presence of smoke or other adverse conditions in the control room, it is assumed that the operators will not be able to function properly and will have to leave the control room.

Time (hr:min)	Event or Step Description	Fire PRA Implications
00:10	Two diesel engine driven fire water pumps were started by the operating crew.	Recall that the third pump was out of service for maintenance. A PRA will not typically consider specific unavailability times for fire protection equipment as a part of the fire suppression assessment. Rather, suppression system reliability is based on generic overall system reliability estimates.
--	An attempt was made to take control of the plant from the emergency control room. However, there was no power supply to the Unit 1 side of the emergency control room and therefore Unit 1 control panels had no functioning indications.	This is one of the few fire incidents where the operators had to go to the emergency (reserve) control room. However, this event demonstrates that common causes can lead to failures for both control rooms. Because of complete loss of vital buses, the emergency control room was rendered useless. In PRA studies for U.S. plants independence of the remote shutdown station is commonly assumed by virtue of the deterministic Appendix R compliance analyses. However, confirmation of remote shutdown independence has commonly been cited as a point of potential technical concern during the IPEEE review process.
--	The operators had no indications of the conditions of the reactor and therefore were in "flying blind" operating mode.	This is perhaps the only fire incident where the operators have faced "flying blind" conditions. In a PRA it is generally assumed that core damage will ensue given a total loss of instrumentation.
00:20	Fire fighting started in the area below the generator using water from fire hydrants and a fire tanker.	By the time that fire fighting efforts had begun, severe damage had already been experienced. This is actually quite consistent with assumptions commonly made in fire PRA, that is, there is a competition between fire growth and damage and fire suppression. In this case, the fire was simply too severe and too fast growing for fire fighters to intervene before critical damage had been done.
00:30	Members of Advisory Committee for Accident Management reached the site and took charge of the situation. The guard house at the entrance of the Turbine Building was designated as the control center for guiding the operations.	
00:30	A quick radiation survey of the outside areas of the reactor building was conducted and no signs of abnormal radiation levels were noted.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
--	A group of staff members was sent to a boiler room to check the status of, and open, valves on a fire water back-up connection to the main coolant system. The valves were opened manually to the 50% point. This established fire water flow into the steam generators that served as a heat sink for decay heat removal by maintaining natural convective circulation cooling of the core.	The manual connection of the fire water system to the steam generators and use of diesel engine driven fire water pumps were the main method for providing core cooling in this incident. In a fire PRA, credit to the use of such core cooling method would be given only if a written procedure is available and the operators are trained in the implementation of the procedure. In this case, the connection did apparently pre-exist as a part of the plant design so one must presume that procedures for its use were available.
--	Borated heavy water was added to the core to ensure sub-criticality. Gravity Addition of Boron System (GRAB) was used for this purpose per established emergency operating procedure. GRAB is designed to be used during a station blackout condition.	
--	Some portion of the neutral bus ducts of the main generator and the vertical portion of the phase bus ducts below the generator melted because of the oil fire in the area.	
--	The turbine-generator support structure and a portion of the slab around the turbine-generator set suffered damage from intense heat. A number of glass window panes in the turbine building shattered.	
--	Fire brigades from nearby stations were summoned for additional help.	
--	More than 50 staff members from different sections of plant organization came to the site to help the Advisory Committee. Remaining staff members were asked to be on stand-by at a nearby community center.	
01:30	Major fires on the ground and mezzanine floors of the turbine building were extinguished.	This is interpreted as the time of fire being brought under control.
02:00	A radiation survey of the inside of the secondary containment was conducted and no signs of abnormal radiation levels were noted.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
03:50	The two operating diesel driven fire water pumps tripped. The cause for this failure is not known.	It seems that the cause for the failure of the diesel engine driven fire pump were linked (a common cause failure) and it was not related to the fire itself. In a fire PRA, the independent failure of equipment is postulated and the probability of occurrence of such events is included in core damage frequency calculations.
04:00	A radiation survey of the Reactor Building (primary containment) showed normal radiation levels.	
04:25	First entry into the Reactor Building (primary containment) was made by operating staff	
04:25	PHT pressure noted at the master gauge at Elevatoin +103.0m inside secondary containment.	
04:35	Fire water hose is connected to the End-Shield System.	
05:30	Inside the primary containment, fire water was connected to the suction side of the End-Shield Cooling System Pumps to provide cooling of the end-shields. Although the End-Shield Cooling System Pumps could not be used, the pressure in the fire water system was sufficient to push through past the pumps and provide cooling to the End-Shields (see Note 2)	Entry into containment is not typically credited in a fire PRA.
05:35	About 1:45 after they tripped, one of the two diesel driven fire water pumps was restarted. Cooling to end-shields provided in addition to putting fire water into the steam generators.	The steam generators remained without make-up water for about 1 hour 45 minutes. This demonstrates that the steam generators had sufficient capacity to allow for a lack of water make-up for an extended time. None of the incident reports indicate the capacity of the steam generator. The time to core damage after all make-up (primary and secondary) capability is lost is an important measure that is used in a PRA to establish the likelihoods of success or failure of operator recovery actions.
05:35	Diesel Generator #3 that serves both units was started using electrical power from Unit 2.	
06:00	Start up of Diesel Generator #3 allowed for Class Bus Q to be energized. From this point on, essential systems were started one after another.	

Time (hr:min)	Event or Step Description	Fire PRA Implications
07:00	Non-active high pressure process water pump (feedwater pump # 2) started.	
09:00	The fire was completely extinguished	There is a long time difference between the fire being brought under control and complete extinguishing of the fire. This is not modeled in a typical fire PRA and is not generally considered as an important contributor to the chain of events. In this case, the most critical damage occurred within the first 20 minutes of the fire.
13:10	Operators went back to the Main Control Room.	
17:00	One of the shutdown cooling pumps was started after 17 hours. This is considered by the plant operators to represent termination of the station blackout condition.	
17:05	Shutdown cooling pump # 2 was started.	
19:15	Plant emergency was lifted at 22:45.	
32:00	One End-Shield Cooling System Pump is activated to operate on its own power (see Note 2).	

Note 1: The original design basis accidents of the plant did not include station blackout. Hence, this event is considered as "Beyond Design Basis Accident".
Note 2: The use of fire water pressure to pass through the End-shield Cooling Pumps is inferred from the information provided in Reference [A23-1]. There may be some conflict in the exact timing of these actions given that other reports state that the first fire pump was not recovered until five minutes after this action was reported.

Equipment Damaged

- Turbine generator of Unit 1 and its accessories, bus ducts and excitation panels.
- Electrical cables, that led to the following:
  - Electrical power buses Class I and II (station blackout)
  - Automatic Liquid Poison Addition System (ALPAS)
  - Emergency D_2O injection
  - Circulation and cooling of moderator and end-shields
  - PHT circulation including shutdown cooling
  - Auxiliary feed to boilers
  - Loss of all indication on the emergency control panel outside the Main Control Room

Damaged Areas

The turbine building experienced severe fire damage. The turbine-generator, its support structure and portion of the slab around the turbine-generator set suffered damage from intense heat. A number of window glass panes of the turbine building were shattered. The fire propagated to the Control Equipment Room. Smoke entered the Main Control Room and rendered the room inhabitable.

Impact on Core Cooling

Core cooling was maintained at all times. At no time during the fire, core cooling function stopped. Fuel cladding, the primary envelope and the containment were not adversely affected by the fire. Core cooling capability remained available through secondary side cooling and natural convective recirculation in the primary side. The steam generators were supplied with fire water using diesel driven pumps.

Rediological Release

No radiological release or undue contamination occurred as a result of the fire.

Personnel Injury

There were no reported injuries to plant or external fire brigade personnel caused by the fire.

Public Impact

The health and safety of the public was not affected by the fire or its impact on the plant.

Environmental Impact

There were no radiological releases, contamination or any other environmental impact other than the smoke release into the atmosphere.

A23.4 Comparison of Fire Scenario Elements and the Incident

In this section, the chain of events in the fire event is compared against the elements of a typical PRA fire scenario. Entries are made only if specific information was available in the available documents. No attempt was made to postulate a possible progression of the event no matter how plausible it could be based on the physics of the fire process, unless it was deemed to be essential in concluding a specific insight.

Fire Scenario Element	**Incident - Narora 1, March 31, 1993**	**Fire PRA Insights**
Presence of combustible / flammable materials	Turbine lubricating oil and hydrogen were the primary combustibles in this event. Cable insulation was a partial contributor to the combustible load. Hydraulic oil also caught fire.	

Fire Scenario Element	Incident - Narora 1, March 31, 1993	Fire PRA Insights
Presence of an ignition source	The event, that is turbine blade ejection and severe vibration of the shaft, led to shaft stoppage from friction. It is assumed that this led to high temperature surfaces and served as the ignition source.	In a typical PRA, only those sources of ignition are considered that are present at all times. The possibility of an accident creating an ignition source is not generally modeled. Ignition is commonly treated probabilistically based on past experience.
Ignition of the fire and generation of heat (radiant and convective), smoke, and other gases	Blade ejection lead to imbalance of the turbine, that led to severe vibration. This led to breaks in several oil pipes and generator seal failure. Oil and hydrogen ignited on hot shaft surface.	
Fire growth within the combustible or component of original ignition	Hydrogen exploded inside bus ducts and caused damage to the ducts. Oil started burning and created a large fire inside the turbine building.	
Fire propagates to adjacent combustibles	The fire damaged cables inside cable trays that propagated to areas away from the turbine-generator.	
A hot gas layer forms within the compartment of origin (if conditions may allow)	No information provided	
Effects of fire (i.e., hot gas and smoke) propagate to an adjacent compartment (if pathways exist)	Smoke propagated into the Main Control Room and caused the operators to leave the room.	This is one of several events in this review that led to smoke in the main control room due to a fire elsewhere. This is the only event identified where this actually led to control room abandonment.
Local automatic fire detectors (if present) sense the presence of the fire	No information provided.	
Alarm is sounded automatically in the control room, locally and / or other places	The control room operators became aware of the fire in a short time because of the noise, a draft of hot air and many different system alarms.	
Automatic suppression system is activated (if present)	No information provided.	
Personnel are present in the area where fire occurs	Personnel were present in the turbine building who observed the occurrence of the explosion and the fire.	

Fire Scenario Element	Incident - Narora 1, March 31, 1993	Fire PRA Insights
Control room is contacted or fire alarm is sounded	Control room operators became aware of the fire almost immediately because of the noise, vibration of the building, draft of hot air into the room and many system alarms.	
Fire brigade is activated	Internal and outside fire brigades were called. Fire fighting started about 20 minutes after ignition. Outside fire brigades arrived about 30 minutes after ignition.	Note that most of the significant fire damage had already been done before fire fighting activities began. Scenarios such as this tend to dominate fire risk estimates.
Fire suppressant medium is properly applied	Hose streams were used to fight the fire. It took about 1.5 hours for the fire brigade to control the fire, and another 7.5 hours (total of 9 hours) to extinguish the fire	
Automatic fire suppression system is activated	No information.	
Fire suppressant medium is properly applied to where the fire is.	There are no indications of any collateral damage due to fire suppression activities.	
Fire is affected by the suppression medium	See above.	
Fire growth is checked and no additional failures occur	From Reference [23-1] it is inferred that all cable and equipment failures caused by the fire occurred in the first 30 minutes of the fire.	Although the major fire was announced as extinguished in 1.5 hours after ignition, it can be claimed that from fire PRA standpoint, the fire was checked in about 30 minutes after ignition.
Fire is fully extinguished and fire brigade declares it as out	Fire was declared as fully extinguished 9 hours after ignition.	The duration of fire can be considered as several hours. In fire PRA, typically the fire duration is in the order of several 10 minutes. This fire incident demonstrates and it is possible for the fire to last for several hours.
As heat and smoke are generated, equipment, cables and structural elements near the fire are affected by the fire.	The turbine-generator support structure and portion of the slab around the turbine-generator set suffered damage from intense heat. A number of window glass panes of the turbine building were shattered. A large number of cables were damaged. Smoke entered several areas including the control room.	

Fire Scenario Element	Incident - Narora 1, March 31, 1993	Fire PRA Insights
Cable failure impacts equipment outside the fire location	The following systems and equipment were failed: . Electrical power buses Class I and II (station blackout) . Automatic Liquid Poison Addition System (ALPAS) . Emergency D_2O injection . Circulation and cooling of moderator and end-shields . PHT circulation including shutdown cooling . Auxiliary feed to boilers . Loss of all indication on the emergency control panel outside the Main Control Room	A fire PRA would have likely identified the potential for loss of multiple and redundant equipment trains given the apparent lack of train separation.
Equipment failure perturbs the balance of plant operation and causes automatic systems to respond	Operators initiated a reactor shutdown almost immediately after the fire. All active components normally used for shutdown cooling were lost because of station blackout. Core cooling was achieved through the use of two diesel engine driven fire water pumps that injected water into the steam generators. Core cooling was then achieved through natural convective recirculation.	Multiple trains were affected by the fire. Impact on redundant trains is a rare occurrence. In fire PRA, proper methodologies are available to identify impact of fire on redundant trains and loss of vital systems.
Operators in the control room receive messages and respond to the information displayed on the control boar d or received verbally from the plant	The operators initiated atmospheric release of steam generators, monitored reactor parameters until they had to abandon the control room because of smoke.	In a fire PRA, if the control room is postulated to be filled with smoke, no credit would be given to proper operator actions from the control room. This incident, demonstrates the validity of this assumption.
Operators attempt to control the plant properly and bring the plant to a safe shutdown	The operators manually adjusted the flow control valves of the fire water pumps into the steam generators. The Gravity Addition of Boron (GRAB) system was activated manually. The system does not require electric power to function.	The operators took actions under time constraints that were in the order of half hour to one hour. In a fire PRA, the human error probability for actions that require such time windows is often close to those used in the internal events PRA.
Structural failures (if occurred) may jeopardize availability of equipment	In the turbine-generator area some structural damage took place and bus ducts melted from the heat. However, none of the structural failure impacted safety components or cables. The cables in the area caught fire and caused all safety related failures.	

Fire Scenario Element	Incident - Narora 1, March 31, 1993	Fire PRA Insights
Water when sprayed over electrical equipment may fail the exposed equipment	No evidence of water damage to electrical equipment were reported.	
The cooling effect of CO_2 may adversely impact equipment	Only water was used for fire fighting.	
Conditions may exist at the time of the fire that may aggravate the impact of the fire on plant systems	The only existing condition was the unavailability of the third diesel engine driven fire pump.	

A23.5 Incident Analysis

The turbine building fire at Narora Unit 1 caused an extended station blackout and extensive damage; hence, it is considered one of the major fire incidents in the nuclear power industry both from a classical fire protection standpoint and from a nuclear safety standpoint. The root cause of the fire is failure of a major equipment item (i.e. the turbine-generator) because of metal fatigue. Since the turbine generators are equipped with lubricating and hydraulic oil systems and the generators are filled with hydrogen, as is the case at several other sites, a catastrophic failure of the turbine generator set often leads to a severe fire. The impact of this fire on plant safety was aggravated by the lack of separation between redundant trains of cables.

In a fire PRA, the possibility of a large turbine building fire is often considered. It is common to model such fires by postulating that an oil spill occurs and is ignited. This, of course, is intended to cover a large spectrum of possible incidents, including blade ejection and turbine generator catastrophic failure. It is also interesting to note that in fire PRA the mechanism of ignition is rarely explicitly treated; however, in those cases where it is treated, only those sources of ignition that are present at all times are typically considered. In this incident, the imbalance in the turbine generator shaft caused the shaft to overheat presenting an ignition source that is not normally present in the plant. This was also seen at Vandellos, for example. The possibility of an accident creating an ignition source is not generally modeled. As mentioned above, in fire PRA an overall fire initiation frequency is used to represent a large spectrum of possible fire scenarios.

Two types of fires occurred at Narora Unit 1 during this incident; namely, an explosion of hydrogen gas and a large oil fire. In a fire PRA, only one type of fire is postulated in a given scenario. Since, extensive damage is often postulated for turbine building fire scenarios, the lack of consideration of simultaneous occurrence of an explosion and a fire would be expected to be of minimal consequence, provided that no ignitions or damage is observed outside the turbine building.

Multiple safety trains were affected at Narora, Unit 1. In particular, all primary and backup trains of safety related power were lost resulting in a station blackout. Current PRA methodologies properly identify the possibility of a fire impacting multiple trains by a thorough analysis of the location of cables important to plant safety. Therefore, in the case of Narora, a fire PRA should have correctly identified the possibility of occurrence of the station blackout from a turbine building fire, as was experienced.

Operators took the proper actions throughout the course of the incident. There were no significant operator errors identified. The alignment (done manually) of the fire water system to the steam generators and use of diesel driven fire water pumps were the main methods for providing core cooling in this incident. Current PRA methodologies do allow for properly identifying the appropriate operator actions. However, PRA methodologies put considerable emphasis on written, available emergency procedures. Little or no credit is given to the possibility of successful completion of actions that are outside written procedures. In this case since the fire water system connection apparently was pre-existing as a part of plant design, one can presume that there was a procedure in place for its use. However, this cannot be clearly established based on the available information.

This is perhaps the only fire incident where the operators have faced a "flying blind" condition (i.e., the operators had lost access to reactor and primary coolant loop instrumentation)[1]. The closest analogue is perhaps the 1975 Browns Ferry fire where plant personnel tapped into containment penetrations (on the outside of containment) to bypass damaged or suspect instrument cables and fed critical data on the reactor conditions to the main control room (see Appendix 3). Somewhat similarly in this case, operators overcame the problem by entering containment and tapping directly into instrument feeds or reading from master gauges. In a PRA it is generally assumed that the result of a complete loss of instrumentation is core damage, operator actions outside of the established procedures are not typically credited, and containment entry would not typically be credited. This incident demonstrates that typical PRA assumptions with regard to operator actions may be conservative.

This is the only fire incident identified in this review where operators had to evacuate the Main Control Room. In fire PRAs, upon the presence of smoke or other adverse conditions in the control room, it is assumed that the operators will not be able to function properly and will have to leave the control room. This incident demonstrates that smoke alone (i.e., there is no fire in the main control room and no direct fire damage to main control room circuits) can lead to main control room abandonment. It is also of interest to note that upon arrival at the emergency (reserve) control room, operators for Unit 1 were still unable to control the reactor because the station blackout had rendered the emergency control panels inoperable as well. This incident demonstrates the possibility of a common cause failure for the two control rooms. It should be noted, however, that regulatory requirements in the U.S. should preclude a similar occurrence.

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[1]The nearest similar incident is perhaps the 1975 Browns Ferry fire where operators and electricians tapped into instrument feeds through containment electrical penetrations in order to by-pass fire damaged cables.

Indeed, in fire PRAs it is somewhat common to assume remote shutdown independence based on the Appendix R analyses. However, verification of remote shutdown independence and potential control system interactions continues to be a point of methodological debate. For example, related technical concerns were commonly identified in the USNRC-sponsored reviews of the licensee IPEEE fire analyses.

In the course of the incident, the two diesel driven fire water pumps failed simultaneously well into the incident. No clear cause for this is established in the available reports, but it is inferred that the cause for the failure of both of the available diesel engine driven fire pumps were linked (a common cause failure) and that the failures were not related to the fire itself (i.e., not the result of fire damage). In a fire PRA, the independent failure of equipment is postulated and the probability of occurrence of such events are included in core damage frequency calculations. However, in the case of fire suppression systems, it is common practice to apply a generic system-wide reliability estimate rather than to consider specific mechanisms that might lead to system failure. This was somewhat aggravated by the maintenance outage of the third fire pump, although it is not clear if this pump would have survived while the other two failed. This incident demonstrates the potential importance of independent failure events and equipment outages to core damage frequency evaluation.

In this incident, there is a long time between the fire being brought under control and complete extinguishing of the fire. This is not modeled in a typical fire PRA and is not generally considered as an important contributor to the chain of events. Furthermore, from the available information about this incident, all key failures appear to have occurred within the first half hour of the incident. No additional failures were reported beyond this time. From a core damage modeling point of view, this demonstrates that extinguishing the fire quickly is an important factor. Beyond the first half hour in this case, the impact of fire fighting efforts had little or no apparent effect on the likelihood of core damage, perhaps other than the continued evolution of smoke that may have extended the abandonment time for the main control room. This is consistent with typical results of fire PRAs. PRAs commonly predict that fire damage that might occur very early in the incident is of the greatest risk significance.

The operators successfully took actions under time constraints that were on the order of a half hour to one hour. In a fire PRA, the human error probability for actions that require such time windows is often close to those used in the internal events PRA. That is, it is commonly assumed that the fire will not impact the longer term operator actions, provided those actions take place away from the fire itself. This event appears to be consistent with that assumption, despite the fact that the fire continued to burn for several hours.

A23.6 References

A23-1 International Atomic Energy Agency, Incident Reporting System, "Completed Station Blackout Due to Fire in Turbine Building at NAPS-1".

A23-2 J. S. Rao, "Role of Electrical Problems in the Failure of Narora Power Plant", Proceedings of the 1996 International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, Volume I, ISBN 0-7803-2795-0.

Appendix 24 - Analysis of Waterford, Unit 3 Fire on June 10, 1995

A24.1 Plant Description

Waterford 3 is a single unit pressurized water reactor (PWR) located near Taft, Louisiana. Unit 3 is the only nuclear power unit on the site. The unit is rated at 1,104 MWE and started commercial operation in September 1985. The fire being reviewed here occurred in one of the non-vital switchgear cabinets. There are two non-vital switchgear trains, A and B, and both are located in one room on the +15 feet elevation of the turbine building. The two buses are separated by a 10 foot high heat shield (a 1-foot thick, partial height, concrete block wall). The ceiling of the turbine building switchgear room is 25 feet above the floor, and the switchgear cabinets are 7 feet tall. There were 36 fire detectors in the room that annunciated on a fire protection board inside the control room, and there was no fixed fire suppression system in the switchgear room.

A24.2 Chain of Events Summary

On June 10, 1995, the unit was operating at 100% power. At 08:58 failure of a lightning arrester on a substation transformer (230kV/34.5kV) caused a severe electrical transient that, in combination with failure of a breaker, led to non-vital switchgear 2A failure and fire in the breaker cubicle for the startup transformer. This led to a reactor trip and a series of other non-safety related equipment trips, signal actuations and equipment activations. [Ref. A24-1].

All 36 fire detectors for the turbine building switchgear room alarmed to the control room indicating panel. However, the control room operators did not become aware of the fire detector alarms because there were other plant alarms sounding at the same time, the fire protection alarm board was in an area not readily visible to the operators and the fire detector alarm panel buzzer had been covered with tape. Hence, control room operators remained unaware of the fact that a fire had started in the switchgear room.

At 09:06 a.m., the control room received a report from an auxiliary operator, who happened to be a trained fire brigade member, that heavy smoke was coming out of the switchgear room. The shift supervisor asked if the auxiliary operator could observe flames or an orange glow. The response was that no flames could be seen but a large amount of smoke was coming out of the switchgear room. The auxiliary operator was instructed to confirm the presence of an actual fire and report back.

Two auxiliary operators donned self contained breathing apparatus (SCBA) and entered the switchgear room to verify the presence of a fire. The control room was notified that a fire was indeed in progress. This exchange of information took place about half hour after the arrival of the first fire alarms in the control room (i.e., approximately 09:30). The shift supervisor, at this point, announced the presence of fire and activated the fire brigade.

The fire brigade arrived on the scene and initially attempted to put the fire out using hand held extinguishers charged with carbon dioxide, Halon and dry chemical. All their attempts proved ineffective. The shift supervisor, according to plant procedures, assumed the leadership of the fire brigade and left the control room for the fire location.

The local off-site fire department was summoned at 09:41and they arrived at about 09:58 (17 minutes later). Upon arrival they recommended the use of water. However, the shift supervisor in consultation with other members of plant operations team decided to continue using non-water suppression media. Permission to use water was eventually given about 90 minutes after fire initiation (i.e., about 10:30). The fire was brought under control within four minutes after initial application of water and was declared extinguished about two and a half hours after initiation.

As noted, the fire was initiated inside of a switchgear panel. The fire propagated out of the top of the panel and ignited vertical cable tray risers above the panel. It can be inferred that the switchgear cubicle fire broke through the steel top of the panel and propagated to those cables. However, whether this was due to heat damage to the top panel or whether the top panel may have been damaged in the initial electrical fault cannot be established. In its progression, the fire jumped over a fire stop installed in the vertical section of the cable tray and continued its propagation. Cables in a 5-foot diameter column up to a height of about 10 feet above the panel top were damaged by the fire. The fire detectors immediately above the fire zone were also damaged by the heat.

The fire eventually reached a horizontal cable tray about 17 feet above the floor (10 feet above the top of the panel). The fire then propagated horizontally until it came to a fire stop installed in the horizontal cable tray about 8 feet from the junction with the vertical trays. From the available information it can be inferred that, for the horizontal segment of the cable trays, the flames were of limited height and/or limited duration. This is because the 6.9 kV power cables that were located a few inches above the burning 4.16 kV cables were not ignited and after the fire were found with only minor surface damage.

Two adjacent switchgear cubicles were also severely damaged by the fire. Four other nearby cubicles experienced exterior damage only. The investigators postulated that the radiative heat reflected from the shield wall separating the two switchgear trains caused the exterior damage to those four cubicles. None of the redundant train cubicles (on the opposite side of the shield wall) were damaged.

It is also interesting to note that, log records indicate erratic behavior of the A2 unit auxiliary transformer breaker that was involved in the fire. A few other erratic indications were also noted on the control board through the course of the incident. The records indicate that the transformer breaker first showed closed and then open. It can be inferred from this that breaker control circuit faults led to inaccurate indications on the sequence of events log.

A24.3 Incident Analysis

The non-vital switchgear fire at Waterford 3 had little impact on safety related functions. It does, however, provide important PRA lessons. Switchgear fires are considered one of the most likely fire scenarios in a nuclear power plant, and many fire PRAs have concluded that safety related switchgear are significant fire risk contributors. Non-safety related switchgear however, are not generally found to be risk significant.

This incident provides an interesting account of what can happen to the switchgear cubicles and the cables above it in the event of a switchgear fault and fire. In this case, three cubicles suffered extensive damage, and four experienced minor damage. Further, the fire propagated through the steel panel top into a vertical cable tray, about 10 feet up the vertical tray to a crossing horizontal tray and about 8 feet along the horizontal tray before being stopped by a raceway fire barrier. The potential for fires inside closed electrical panels to propagate outside of the panel has been a point of significant recent debate. This incident illustrates that under some conditions this potential clearly exists.

A second factor of interest is the fact that fire fighting was delayed considerably in this incident. The delay was caused by three nominally unrelated factors, two relating to decisions made by plant personnel during the incident.

One of these three factors was the decision made by the shift supervisor who insisted on direct observation of flames prior to declaring a fire and activating the fire brigade. It took close to half an hour (from the time of ignition) for two operators to don protective breathing apparatus, enter the room, seek out the source of the fire, verify the presence of flames, retreat from the room and report back to the main control room. This would not be captured in a typical fire PRA. Fire PRAs will almost universally assume that once there are clear indications of a fire underway (e.g., alarms, smoke), the fire brigade will be activated immediately. Indeed in most cases this is what happens observed. In this particular case the plant procedures apparently did call for plant personnel to verify the existence of flames before declaring a fire[1]. This illustrates the importance of a careful review of plant fire emergency response procedures to fire PRA.

The second factor related to the strategy used to fight the fire. Once the fire was declared and the fire brigade arrived on-scene, the fire brigade resisted using water on an electrical fire until multiple attempts to extinguish the fire using portable extinguishers proved ineffective. As a result, the fire was allowed to burn far longer than would typically be assumed in a fire PRA, and the observed damage was perhaps made worse than if prompt and effective fire suppression had been undertaken. Typical PRA practice assume that once the fire brigade arrives on scene, effective fire fighting will begin immediately. Delays caused by the decision to use ineffective fire suppressing agents are not modeled. This incident illustrates that this assumption may be optimistic. It must be noted that current fire PRA methodologies are fundamentally capable of incorporating the possibility of ineffectiveness of the fire suppression attempts and delays caused by management decision. For example, current methods already include the ability to assess fire brigade response based on time - likelihood of suppression distributions which could account for some chance that initial fire fighting attempts will be ineffective. However, there is currently no basis for quantifying such behaviors.

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[1]Based on discussions with cognizant USNRC/NRR staff.

The reasons for the failure of carbon dioxide, Halon and dry chemical in controlling the fire in this incident has not been reported. However, other incidents have illustrated similar unsatisfactory results for such efforts, in particular, when the fires involve energized electrical panels. In hind-sight, it also appears likely that the fire had already propagated to the overhead vertical cable trays before fire fighting was initiated (recall the fire had been burning for at least 40 minutes). This would place the fire well above the heads of the fire fighters. Under these conditions it is not surprising that the hand-held extinguishers were ineffective. These devices are designed to fight fires that can be readily approached. The very limited capacity and range of a hand-held gaseous or dry powder fire extinguisher made them poor choices in this particular case, and this was likely a contributing factor in their ineffectiveness in this particular incident.

The final factor contributing to the delay in declaring a fire emergency is the position of the fire protection annunciator panel and the suppressed sound of the alarm. The panel was not readily visible to the operators in the control room and the fire alarm buzzer had been covered with tape. Also, there were many other alarms in the control room that must have diverted the attention from the fire panel. It is important to note that the operators, even after receiving a verbal report of smoke in the switchgear room, did not approach the fire protection panel to verify fire detector conditions.

Such conditions may be addressed in a fire PRA but may well be overlooked. Current methodologies would likely have led to discovery of some of these conditions if exercised fully. In particular, a fire PRA walkdown would have considered the position of the fire annunciator with respect to the location of the operators and would have likely detected the condition of the buzzer. Of course, in such situations as tape over the buzzer, it is quite likely that the tape would be removed as a result of the discovery during the walkdown and the PRA analysts would assume lack of tape as the normal condition. However, this may be an optimistic assumption and a thorough analyst would likely attempt to discern the original reasons for the presence of the tape. Had, for example, plant operators been interviewed as a part of the PRA process, and had they stated that multiple false fire alarms had been a problem at the plant, then the PRA analyst would likely apply a judgmental factor to "degrade" the response time for fire detection and verification. This would, however, be highly dependent on the approach and knowledge state of the analyst. No clear or consistent guidance in this regard is currently available.

Another point of interest in this incident is the fact that a few erratic indications were noted on the control board through the course of the incident. This indicates that control circuits can fail erratically under fire conditions. The exact reasons for the observed behavior was not reported for this incident.

This incident also demonstrates two points related to cable fires and fire stops in cable trays. In this case the fire propagated out of the panel top, up a cable riser for about 10 feet, and along the intersecting horizontal tray for about 8 feet. Second, a fire stop in a horizontal cable tray can be effective in stopping the progression of the fire. In this case, the fire propagation in the horizontal tray ended at a raceway fire stop. Third, fire stops in a vertical cable tray may be ineffective. In this case the fire in the riser jumped past a fire stop and continued to propagate. It is not clear if propagation was delayed by the stop. Fire PRAs will often assume some credit for fire stops in cable trays limiting the extent of fire damage, although practices vary widely.

PRA practices with regard to panel fires vary widely. For example, the EPRI *Fire PRA Implementation Guide* (see report body for associated references) recommended that fires initiated in a closed and unventilated panel could not propagate out of the panel, and such sources could be screened. This was a point of considerable debate in the USNRC IPEEE review process. Indeed, the Waterford fire was one of the incidents cited as the basis for technical concerns regarding this practice. In this case, the fire did propagate out of a nominally closed electrical panel, along a vertical riser and into a horizontal cable tray. Ultimately, EPRI developed revised guidance and licensees were asked to reconsider the potential for fire spread outside of a closed panel for a range of panel types. While this resolved the concerns in the context of the IPEEE process, the more general methodological debate has not been fully resolved.

From the observations provided in the investigation report, it can be inferred that the flames on the horizontal segment of the cables were of limited height and/or limited duration. This is because damage to a tray immediately above was very limited and no propagation of the fire to the next higher tray was observed. The cable combustibility properties would clearly impact this behavior, and it must be noted that these aspects of the incident are not known. Given the age of the plant (construction began in 1974) it is quite likely that the cables used at Waterford are qualified as low flame spread per the 1975 IEEE-383 test standard. In fire PRAs, a large variation of fire propagation patterns are predicted depending on the severity of the exposure fire, cable material characteristics and the approach to estimating fire growth behavior. In some cases fire models are used to predict fire growth, and these models explicitly consider cable material flammability parameters. In other cases, fire spread is based on the results of past fire experiments applied to a given case. This practice has been criticized as a part of the IPEEE review process, and not considered to be well founded. This case does confirm behaviors that have been noted experimentally. In particular, fires propagate much more readily in vertical cable trays than in horizontal trays.

The fire damage to adjacent switchgear cubicles is also interesting to note. Only two adjacent cubicles were damaged severely. Four other cubicles, next to the first two, experienced minor surface damage. It is suspected by investigators that the radiative heat reflecting off of the wall that runs parallel to the switchgear caused the damage to these four cubicles. This demonstrates that despite a severe fire in one cubicle, the fire may not propagate internally in the horizontal direction. In a fire PRA, practices in this regard vary widely. Some PRA's would credit a solid steel barrier with preventing fire propagation. In other analyses, if the cubicles are separated by a single metal sheet, the likelihood of propagation across cubicles is considered to be high. Testing (References [A24-2,3]) illustrates that fire propagation given a solid single wall panel is unlikely unless there is direct contact between the wall panel and a secondary fuel source. It is not clear what the exact configurations involved in this case were. Radiative heat reflecting off of other objects is modeled in some of the existing fire propagation models. Re-radiation and reflection is considered in such models as COMPBRN IIIe (Reference [A24-4]). Another observation of some interest is that the heat shield (partial wall) separating the two trains functioned properly and protected the Train B switchgear from the fire.

This incident also demonstrates that given an energetic failure of a switchgear and ensuing fire, large quantities of smoke may be generated and the smoke will likely not be confined to the compartment of origin. In a fire PRA, the impact of smoke outside the compartment of origin is seldom modeled explicitly. In this particular case, smoke did escape from the room of fire origin, but no direct effects of the smoke propagation were noted.

A final point of interest is that in fire PRAs, if the fire does not impact safety related equipment, it is commonly assumed that the operators would take the proper actions to provide core cooling and reactor shutdown, and such scenarios are screened. This incident demonstrates that the plant may experience a large number of inter-related deviations from the expected chain of events. Such deviations may impact operators' judgement regarding the best course of actions and proper shutdown of the plant. In this incident, the fire was limited to non-vital switchgear but the overall incident did cause considerable operational upset. Nonetheless, the operators took the proper actions for the plant conditions that existed and ultimately there was only a minor challenge to nuclear safety (a plant trip with redundant plant safety systems available).

A24.4 References

A24-1 Inspection Report 50-382/95-15, by U.S. Nuclear Regulatory Commission, of Waterford Steam Electric Station, Unit 3, June 13-16, 1995.

A24-2 J. Chavez, *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets, Part I - Cabinet Effects Tests*, SAND86-0336V1, NUREG/CR-4527/V1, SNL/USNRC, April 1987.

A24-3 J. Chavez and S. P. Nowlen, *An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Cabinets, Part II - Room Effects Tests*, SAND86-0336V2, NUREG/CR-4527/V2, SNL/USNRC, October 1988.

A24-4 V. Ho, et al., "COMPRN IIIe: An Interactive Computer Code for Fire Risk Analysis," University of California at Los Angeles, EPRI NP-7282, May 1991.

Appendix 25 - Analysis of Palo Verde, Unit 2 Fire on April 4, 1996

A25.1 Plant Description

Palo Verde Nuclear Generating Station is located outside Phoenix, Arizona. The site has 3 pressurized water reactor (PWR) units rated at 1,270 MWE each. The units each started commercial operation between 1986 and 1988.

A25.2 Chain of Events Summary

On April 4, 1996, Unit 2 was in a refueling outage. At 17:00 a fire watch detected smoke in the back panel area of the control room. Smoke was emanating from the Train B emergency lighting un-interruptible power supply panel. At about the same time, an auxiliary operator discovered smoke and fire in the Train B DC equipment room at the 100 foot elevation of the Auxiliary Building. This second fire was found on the 480/120 volt essential lighting isolation transformer. Multiple trouble alarms on the fire detectors had masked the actual fire alarm coming from this equipment room such that the valid fire alarm signal that had come in was not noticed by the operators.

The fires led to the loss of power to Train B control room emergency lighting circuits, to some of general plant essential lighting, and to plant fire detection and alarm system panels. The circuit breaker supplying power to the un-interruptible power supply panel tripped open when cables in the conduit supplying the power supply panel overheated causing various conductors to short circuit. The circuit breaker trip also de-energized power to the fire detection and alarm panels in the auxiliary building. The fire alarm annunciator monitor (a computer screen) indicated a large number of fire detector trouble alarms and these multiple alarms were scrolling on the monitor. This was attributed to the de-energized fire detection and alarm panels.

The fire in the equipment room was reported to the control room and the onsite fire brigade was activated. They attacked the fire immediately and put it out in a short time. It is not entirely clear if the fire brigade also reported to the main control room or not. The fire in the main control room was apparently handled by the operators. In either case, the control room fire was also quickly extinguished. The direct damage caused by these two fires was limited to the components of origin. That is, neither fire propagated beyond the point of ignition.

A25.3 Incident Analysis

In this incident, the fires were neither severe from a classical fire protection standpoint nor from a nuclear safety standpoint. The most interesting aspect of this incident is the occurrence of multiple simultaneous fires, one of which occurred in the plant's main control room. Incidents involving multiple initial fires have been observed in several other plants (as discussed elsewhere in this report). In some cases, particularly incidents at non-U.S. reactors, the fires have led to extensive damage. PRAs currently do not treat concurrent fires. Rather, only a single fire is postulated in a single location at a given time. This is discussed in detail in the body of this report.

The cause of simultaneous fires at Palo Verde was traced to a fault in the isolation transformer located in Train B DC equipment room. This failure caused a short circuit fault to the station ground through the transformer's panel ground. The neutral leg of the transformer was not connected to ground. Also, an inverter that served as the alternate essential lighting uninterruptible power supply was grounded improperly. The ground connection of the inverter served as the return path for the isolation transformer's ground fault that passed through the essential lighting power supply panel. The conductors that carried the fault current were not designed to handle the high currents caused by the fault. As a result they overheated and ignited the combustible materials around them. Clearly, the common factor leading to the multiple ignitions was a common overloaded electrical conductor.

It is also interesting to note that the fires in this case were, in effect, self-ignited cable fires. An electrical fault led to an ampacity overload on a particular cable, and the cable was ignited in two locations as a result. The units at Palo Verde are relatively new (construction began on Unit 2 in 1976 and the current U.S. cable flammability standard, IEEE 383, was adopted in 1975); hence, it can be assumed that the cables installed in the plant are of a low-flame-spread type. This incident is one of the very few incidents, if not the only incident, where a self-ignited cable fire in low-flame-spread cables has not self-extinguished. In typical fire PRAs, the potential for a sustained self-ignited cable fires is typically considered vanishingly small provided the cables are certified as low-flame-spread. This incident appears to illustrate that the possibility of such fires does exist at some level, though the actual frequency of such fires remains uncertain. If this is, indeed, the only such event in the experience base, then the assumption of low frequency would still be justified.

A25.4 References

A25-1 NRC Information Notice - IN 97-01, "Improper Electrical Grounding Results in Simultaneous Fires in the Control Room and the Safe-Shutdown Equipment Room", U.S. Nuclear Regulatory Commission, January 8, 1997.

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11. ABSTRACT *(200 words or less)*

This report presents the findings of an effort to gain new fire probabilistic risk assessment (PRA) methodology insights from fire incidents in nuclear power plants. The study is based on the review of a specific set of 25 fire incidents including fires at both U.S. and foreign reactors. The sequence of actions and events observed in each fire incident is reconstructed based on the available information. This chain of events is then examined and compared to typical assumptions and practices of fire PRA. The review focuses on two types of actions and events. First are events that illustrate interesting insights regarding factors that fall within the scope of current fire PRA methods. Second are events observed in actual fire incidents that fall outside the scope of current fire PRA methods. Fire PRA insights are then drawn based on these observations. The review concludes that the overall structure of a typical fire PRA can appropriately capture the dominant factors involved in a fire incident. However, several areas of potential methodological improvement are identified. A few factors are also identified that fall outside the scope of current fire PRAs including the occurrence of multiple initial fires or secondary fires, multiple simultaneous initiating events, and some aspects of the smoke control and human response assessment.

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