Post-Fukushima Focus on Fire Protection

S. Shanker[1] and M. Rawlingson[2]
[1] AMEC NSS, Toronto, Ontario, Canada, shobhit.shanker@amec.com
[2] AMEC NCL, Toronto, Ontario, Canada, malcolm.rawlingson@amec.com

Abstract

Fire is a known problem in industrial facilities, but also one that is not very well understood. In nuclear facilities, fires pose special concerns because of high temperatures post shut-down and highly radioactive fuels that are contained within them. They are also a major contributor to a reactor's core damage frequency. This paper aims to spark interest amongst young nuclear practitioners by providing an overview of fire protection, revisiting relevant OPEX in the wake of Fukushima, commenting on some challenges based on deep industry insights on dealing with fire issues, and providing some suggestions on meeting these challenges.

1. Introduction

The importance of fire protection at nuclear facilities was underscored by the 1975 Browns Ferry incident. A containment seal test was being performed in the cable spreading room using a candle to detect the slight inflows of air. The candle was inadvertently knocked over and set the polyurethane foam, used as penetration sealing material, on fire. The fire rapidly spread to the polyvinyl chloride (PVC) electrical cable insulation running through the penetrations. The result was a loss of control of reactor cooling, power to some key safety systems, and indication of key plant parameters. Water level in the reactor fell, nearly uncovering some fuel bundles. Although the incident did not seriously damage the reactor core, it served as a wake-up call for the nuclear industry that raised the profile of fire protection and paved the way for more stringent regulations in the United States [1].

Today, fire continues to pose a significant threat to nuclear safety in comparison to other hazards because fire is a common mode event whose frequency exceeds that of earthquakes and weather related events. On average, there will be ten fires per year across over 110 nuclear facilities in North America [2].

In the post-Fukushima nuclear era, the latitude that was once granted by regulators is tightening, and society's tolerance of nuclear risks is diminishing. Operators are challenged to apply modern requirements to older facilities and regulators must ensure adequate safety margins exist during fire events. Finally, public confidence must be restored in the wake of serious events, such as the ones that are revisited in this paper. Therefore, it is important for the nuclear industry to respond more aggressively than it has in the past to fire risks. This paper aims to spark interest amongst young nuclear practitioners to confront fire protection challenges as they rise to leadership.

2. Background

Fires are relatively common in complex industrial facilities because their day-to-day operations entail handling hazardous materials. To illustrate, 80 fires broke out in 59 refineries in the United States between 2009 and 2011 [3]. Although common, many fires do not bear significant consequences [2]. Industrial fire hazards include, but are not limited to: flammable liquids, compressed gas cylinders, lubricant tanks, electrical equipment, welding/cutting processes, aerosol containers, or fueled industrial trucks [4]. While the consequences of many fires are not serious, any fire that does start must be viewed as a failure of basic fire prevention practices. Consequently, due to the unpredictable nature of fire, controlling one is more a matter of luck rather than good judgment.

Fires in nuclear power plants are treated much differently than other industrial fires due to radiological consequences and the enormous amounts of potential energy (> 3,000 MWth) in reactor cores, which require active cooling long after shutdown and also after defueling, when the fuel is stored in spent fuel bays. If fires impair cooling, controlling, and/or safety mechanisms, fuel rods may fail and expose radioactive materials [1]. Radioactive releases from fuel, particularly Iodine 131, may cause deaths or harm thousands [2]. Even after the accident is mitigated, the reactor will likely be damaged beyond economic repair – so too will public confidence in the nuclear industry. Therefore, fire protection programs in nuclear facilities must address threats from fire that could inhibit a reactor's ability to shut down safely (fire safe shutdown analysis).

Protecting nuclear cores from fires requires a balanced approach and a careful selection and application of five key methods of controlling fires in nuclear plants. All of the following methods require thoughtful design of nuclear facilities and supporting programs:

(1) The main fire *prevention* requirement is to eliminate combustibles, hazards, and other ignition sources. Good fire prevention design also reduces the probability of common mode failures, which allow a single type of fault to fail the overall system. This is accomplished by designing diverse and redundant safety systems so that there is a backup if default mechanisms fail [7]. Fires occur when ignition sources come into contact with combustible materials. The ideal fire prevention objective should be to eliminate the chances of fires ever occurring and should therefore serve as the primary fire protection goal of all nuclear power plants.

(2) Early *detection* of fires improves chances of controlling an event when the fires are small. The sooner a fire is discovered, the quicker the response. To achieve this objective, pull stations, conventional detectors and special incipient detectors are tied to central fire alarm systems that notify operators of precise locations of events in the plant.

(3) Fire *barriers* isolate fires, protect personnel and critical equipment from fires. One example of barriers is wrapping electrical cables that control or power safety equipment. Another example is sealing penetrations in fire walls to prevent the fire from spreading, especially in stairwells that ensure the safety of plant staff during egress.

(4) Sprinkler systems, deluge systems, water mist systems, gaseous discharge systems, fire blankets, and fire extinguishers are examples of *suppression*. While suppression systems are highly effective in most non-nuclear applications, their use in a nuclear plant must be carefully balanced against the risks imposed on safety systems due to inadvertent operation. For example, the control equipment room and the main control room should not have sprinkler systems because of a high likelihood of

damaging critical safety monitors and controls. Therefore, it is vitally important that suppression systems do not damage safety critical components when activated.

(5) Emergency *response* consists of a team of highly trained professionals tasked to respond to nuclear emergencies. It is clear that time is of the essence in a fire and rapid response will often mean the difference between a small fire with little consequence and a large fire that does significant damage to the plant. Nuclear power plant fire brigades in conjunction with their Municipal counterparts need thorough training in plant layout and fire fighting techniques required for successful intervention and mitigation of nuclear plant fires.

3. Fire Protection Operational Experience (OPEX)

Nuclear fires are quite prevalent. As an example, between 1995 and 2008, there were over 125 fires reported in nuclear power plants [2]. Some of those fires damaged critical safety equipment. A short summary of selected incidents and accidents with strong links to fire protection of nuclear power plants is presented here to reinforce its importance in nuclear safety.

(1) On January 1990, the East German Government reported that it had concealed a serious nuclear incident in December 1975 that may have had “Chernobyl like” consequences [5]. The event was initiated by a short circuit in the standby power distribution system, which sparked a fire in the cable that damaged critical safety components that subsequently shut off five of the six cooling pumps [5][6]. Initially, thermosyphoning (natural convection) removed decay heat from the fuel rods in the primary loop. Nearly 8.5 hours later, a single emergency pump was activated on the secondary side for continuous cooling of the core. Human error, poor prevention of common-mode failure in the design, and poor spatial separation were cited as the causes of the event [6]. Some of these issues touch upon the five key aspects of fire protection discussed earlier.

(2) On October 19th, 1989, a serious fire occurred in Spain’s Vandellòs-1, a gas cooled reactor [8]. Turbine blades separated from the rotor, penetrated the turbine casing, and severed a lubricating oil line. The oil line caught fire and burned a neoprene bellow on one of the main cooling water intake pipes to the turbine condenser, which resulted in the basement flooding rapidly. The flooding caused major electrical failures, including a loss of cooling for the reactor core. Although the reactor was ultimately shutdown safely, public demonstrations and high repair costs forced the plant to be decommissioned. Vandellòs-1 was safely laid up, and now serves as a painful relic of the loss of public confidence in nuclear safety.

(3) On March 13th, 1993, Unit 1 of the Narora Atomic Power Station (NAPS-1) in Northern India experienced a major fire due to a rupture of the turbine blades in the last stage of the low pressure turbine. The resulting imbalance in the turbine created vigorous vibrations that ruptured (a) the seals in the hydrogen cooling system, and (b) the lubricating oil tank placed above the turbine. A spark in the rotating turbine blades ignited the hydrogen, which then came into contact with the lubricating oil that subsequently overhead and created a large fire in the turbine hall. The resulting smoke polluted the main control room and compelled operators to vacate the premises. Less than one minute after the initiating event, the fire spread through the generator bus and cables into the control

equipment room. The reactor shutdown systems functioned per design. Cooling and containment were not compromised. There were two root causes associated with this accident: (1) rupture of the turbine blades, and (2) inadequate fire resistance in the cable insulation [9].

(4) On March 28th, 2010, the H. B. Robinson plant in South Carolina experienced a short in a 4,160 Volt cable that caused a fire. A series of other faults, such as a breaker failure and main transformer damage caused power outage in half of the equipment. The situation exacerbated by failures in indicator bulbs and poor training of operators. The event was finally controlled, but subsequent NRC investigations uncovered some deficiencies – a major one being inadequate fire barriers, which likely caused the initial fire to spread along the cable [10].

(5) On June 8th, 2010 at the Surry plant in Virginia, a maintenance worker accidentally dropped a tool that shorted an electrical circuit controlling the feedwater system in Unit 1. Ninety minutes after shutdown, a resistor-capacitor (RC) filter in the main control room overheated, causing a fire that blew fuses to instruments monitoring important safety parameters. A similar RC filter in Unit 2 had caught fire only seven months earlier [10]. Although power was restored and the overall situation was controlled, there were two important lessons learned: (i) although the event was not initiated by fire, it could have escalated because of one; and (ii) known fire related deficiencies continue to threaten nuclear safety.

(6) There have been cases where materials or services were supplied to utilities bearing false promises. One example is the usage of Thermo-Lag 330 in the 1980s and 1990s to protect safety system cables in nuclear facilities from fire. In 1992, it was found that the required protection level was not met by this material because it degraded cable insulation, which could potentially cause fires and compromise the integrity of safety systems. The NRC recommended that all utilities using Thermo-Lag 330 implement compensatory fire watch and replace the poor product with approved fire barriers [11]. This experience stressed the importance of utilities and suppliers honestly pulling together to ensure that advertised safety ratings are in fact met.

(7) On March 11th, 2011, a 9.0 magnitude earthquake rattled Japan, causing a 14 meter Tsunami to douse the entire Fukushima nuclear facility [12]. This wrecked the backup diesel generator, thereby debilitating all active cooling capabilities, and unleashing an unforgettable sequence of events that placed this disaster amongst the top of the list of all significant nuclear disasters. There were specific events within the larger calamity that were linked to fire protection and can therefore offer some lessons learned. These are summarized here:

- On March 12th, 14th, and 15th, Units 1, 3, and 4 experienced massive explosions, respectively, that injured 15 people and caused significant damage to the reactor building. Each of these explosions were caused by hydrogen, which is explosive when concentrations are high enough and it is exposed to either oxygen or a spark. It accumulates when the Zirconium fuel sheath absorbs oxygen from steam as its temperature rises above 1,200°C [13]. The Narora event described above also suffered from an inadvertent hydrogen explosion in the turbine. Both Fukushima and Narora serve as reminders of the potentially disastrous effects of ignition sources nearing hydrogen sources. Therefore, a key fire protection design objective is to keep ignition sources away from hydrogen sources. Isolating hydrogen from oxygen is not directly a fire protection objective, but one that also warrants attention since explosions create a flurry of unexpected fires in unpredictable areas of the plant.

- On March 15th, a fire ignited in Unit 4, which also contained the spent fuel. Spent fuel was stored in tanks and required cooling that was disabled due to a loss of primary and backup power [13]. The fire, coupled with a loss of cooling capability for the highly radioactive spent fuel, may have posed severe radiological consequences. The emergency response crews were tasked with the dangerous responsibility of not only manually cooling the reactor core, but also the spent fuel pool [13].
- On March 15th, high radiation levels (approximately 400 mSv in some areas) prompted the evacuation of all personnel who were not directly required to mitigate the accident. Only the emergency response crew of 50 people, dubbed popularly by the media as "Fukushima 50", was retained at the plant to control the event [13].
- On March 17th through 20th, there were several smaller explosions and hydrogen fires that were fought by the emergency response crews [13].

The Fukushima experience has taught two very important lessons with respect to fire protection: (i) hydrogen explosions are highly unpredictable, extremely powerful, and may occur during accident scenarios due to sparks/fires, or may create unexpected fires post-explosion that may then spread to highly vulnerable areas of the plant; and (ii) due to the unpredictable nature of fires during accidents, emergency response is the last line of defense and therefore should not be underestimated.

The nuclear industry understands these points and is working towards establishing benchmarks through post-Fukushima assessments conducted by the World Association of Nuclear Operators (WANO) – Significant Operating Experience Report (SOER), Each WANO member is undertaking its own audits. The Canadian Nuclear Safety Commission (CNSC) Fukushima Task Force has offered recommendations for hydrogen accumulation and also for emergency response for its CANDU licensees [14]. The Korean inspectors have also offered a few key fire protection recommendations, which include [15]:

- Simplifying fire protection plans.
- Higher level of cooperation between internal an external fire stations.
- Adopting performance-based fire protection philosophy, which is briefly summarized in the next section.

There is compelling evidence supporting the notion that nuclear safety and fire protection at nuclear facilities are inextricably linked. The seven events revisited here are to serve as reminders for nuclear professionals to not minimize the threats posed by fire on nuclear facilities. Each of the events discussed here expose slightly different vulnerabilities and characteristics of nuclear power plants. From Browns Ferry in 1975 to Fukushima in 2011, the unifying thread amongst each of these events over the past 37 years is that whether or not a fire initiated the event, it certainly played a major contributing role in cascading it.

4. Key Challenges and Suggestions

The nuclear industry faces enormous threats from factors that are highly complex and extremely difficult to control, such as the inflated public perceptions of the short term promises of alternative energy sources, negative public perceptions of the costs and benefits of nuclear power [16], and most importantly, the threats each utility poses on the other if it experiences a calamity like

Fukushima. The last item is particularly relevant in the context of fire protection because one severe fire in a nuclear facility, such as those discussed in the previous section, have a potential of causing severe core damage and listing the event in the ranks of Chernobyl, Three Mile Island, and Fukushima. Nuclear history has demonstrated that a disaster in one utility will have ramifications on the rest of the industry and thereby jeopardize its growth. It follows that such disasters will also jeopardize access to affordable energy that humanity depends so heavily upon. Since this causality will not change in the future, it is crucial for the industry to respond to the challenges that lay ahead if it wishes to survive. Some of the challenges the nuclear industry faces with respect to fire protection are summarized here, and suggestions based on industry experience are provided for moving forward.

(1) Fire protection is complex, and the exodus of senior fire protection specialists in the coming years will leave a wide knowledge gap. Fire protection programs may be weakened without careful succession planning, thereby exposing nuclear facilities to additional risks. It is important for young leaders in the nuclear industry to rise to this challenge. Though complex, fire protection is a rewarding field that lies at the intersection of human response and technology – where creative solutions are sought for unique problems. Opportunities range widely from laying plans, modeling fires, mitigating hazards, interfacing with regulators, to designing fire prevention, detection, and suppression systems. Accordingly, there are substantial growth opportunities in both technical and non technical areas of a field that is critical to nuclear safety, not very well understood, and is currently under high scrutiny by regulators. There are six innovative ways recommended here for aspiring fire protection professionals to bridge the knowledge gap:

- Finding mentors who can help chart a path to the various roles a professional in the field of fire protection may assume is likely the most efficient way of understanding both the requirements and the outcomes.
- Requesting work assignments in the field of fire protection by supporting experts in preparing fire safety assessments, such as code compliance reviews, fire hazard assessments, and fire safe shutdown analyses is a low risk hands-on way of learning the nuances of the profession. These reports are typically prepared every three to five years depending upon the licensing requirement, so opportunities for getting involved arise periodically – at least in theory. Depending upon the requirement of the jurisdiction, the gaps arising from these reviews must be resolved by either performing the action (i.e. eliminating the hazard), or providing a performance based alternative solution. There are ample learning opportunities in either direction.
- Reading industry journals and OPEX is an effective way of receiving key industry insights and reinforcing lessons learned from other facilities. The Fire Protection Magazine is published by the Society of Fire Protection Engineers (SFPE), and serves as a great inlet to the broader industry. There are also local chapters of SFPE that offer various forums to network with industry professionals and to learn.
- Enrolling in colleges and universities for additional certification in fire protection on a part-time basis will help develop a strong theoretical base without forgoing the industry experience. This will inevitably help fire protection professionals craft creative solutions to a wide array of problems they may see. Most professionals with a technical degree already have the prerequisites for these courses.
- For professionals who are already working in the area of fire protection but wish to specialize can do so by taking additional training on specialist topics such as fire modeling and sprinkler design (NFPA-13).

- Joining technical codes and standards committees, which develop the rules for authorities having jurisdiction (AHJs) to enforce with respect to fire protection, is a great way to learn the technical, legal and regulatory nuances of the profession. Currently, these committees consist of seasoned experts who are in a position to mentor aspiring committee members. Over time, as experts disengage from committees, it will be much more difficult for aspiring fire protection professionals to harness their knowledge.

(2) The Browns Ferry accident sprang an era of deterministic fire protection requirements, which were prescriptive rule-based requirements imposed on all utilities to ensure the latest fire protection codes and standards were implemented. The introduction of the rule-based requirements was appropriate for the time because it forced the industry to focus on fire protection at nuclear power plants, but over time, there were three issues that emerged with this approach [17]:

- Prescriptive requirements came into play long before risk-informed and performance-based analytical techniques were developed. Therefore, they do not adapt well to the state of the art understanding of fire protection.
- Prescriptive requirements did not take advantage of probabilistic risk assessment (PRA), which accurately facilitates a comparison of relative risks between multiple fire hazards.
- Risk-based assessments have the potential for generating significant insights regarding fire risks, whereas prescriptive methods are much more static in nature. Thus, prescriptive methods are not able to take advantage of the operational experience gained from utilizing risk-based assessments over time.

Prescriptive requirements also do not adapt well to all plants, particularly those that are aging. This reality compels utilities to repeatedly request for concessions from regulators [1]. This lengthy process not only diverts focus away from higher risk items, but also erodes the trilateral trust between the regulator, general public, and utility when there are many open actions on public record that utilities are simply unable to complete [19]. In 1996, the Nuclear Regulatory Commission (NRC) of the United States stated that “a revised fire protection rule that would allow flexibility and facilitate the use of alternate approaches to meet the fire safety objectives may reduce the need for exemptions” [17]. Thereafter, the NRC, NFPA, and the nuclear industry converged around the view that risk-informed, performance-based processes should be introduced as an option for licensees while also maintaining the rule-based requirements of the past during the transition phases. In February 2001, NFPA 805 “Performance-based standard for fire protection for light water reactor electric generating plants” was issued in the United States to offer licensees an option to adopt this method [17].

An industry shift from deterministic methods to performance based risk informed (PB/RI) methods holds promise. It is expected that with this shift, utilities will be able to focus attention on areas that pose the greatest risk to nuclear safety, providing an appropriately customized solution for each plant. Tools such as NFPA 805 are already in place to aid light water reactor operators in shifting to PB/RI methods [18]. There are other utilities around the world using other types of reactors who also intend to follow suit [15].

In Canada, fire protection for nuclear power plants is governed by the CSA N293 Standard, which offers licensees the latitude to choose performance based approaches provided that the AHJ concurs with the approach [20]. As such, a prescriptive requirement may be satisfied by an alternative solution provided that a third party and the AHJ review it. This way, innovative solutions to complex fire protection problems can be found by trilateral dialogues between utilities, industry experts, and regulators. Such conversations promote transparency and build trust between the utility and the regulator, which would be difficult to build if the standards were highly prescriptive without providing an option to propose performance based solutions.

(3) The 2011 Fukushima disaster raised concerns regarding the adequacy of emergency response, which is a vital component of fire protection. Fire behavior is difficult to predict in accident scenarios despite robust analyses and strict adherence to fire codes, leaving emergency response as the last line of defense. Thus, utilities must fortify emergency response programs and partner with municipalities [14].

5. Conclusion

The aftermath of Fukushima is drawing attention from regulators, placing high financial and resourcing pressures on utilities to evolve their safety standards. This evolution is achievable in the area of fire protection, but because of its multidisciplinary nature, it requires relentless cooperation between fire protection program owners and all other departments. Fire protection program managers must offer guidance and support to other departments to help them understand their role in supporting the five aspects of fire protection: prevention, detection, suppression, barriers, and emergency response.

The OPEX presented in this paper underscores the importance of fire protection at nuclear facilities. Irrespective of the precise root cause of the events presented, fires broke out in all of them and exacerbated the situation. Each event highlighted different vulnerabilities and characteristics of nuclear power plants, but together, they told a single story that fire protection and nuclear safety are inextricably linked.

On the regulatory front, utilities must strive to make only the commitments that they can, and more importantly, should meet. By relying on modern risk-informed, performance-based tools and striving for a trusting and transparent relationship with the AHJ, utilities have the opportunity to propose solutions that may meet or exceed the minimum requirements stipulated in the governing codes/standards. As more facilities opt for performance based approaches to solving fire protection problems, more risks will get characterized. With a strong understanding of the relative risks between different fire hazards, utilities will be able to ensure that focus is not diverted away from the most important upgrades.

The departure of senior fire protection specialists will require careful succession planning, and young leaders are well poised to respond to the challenges ahead. Aspiring fire protection professionals must work with management to bridge the knowledge gap and qualify themselves by:

- Finding mentors to help chart a path towards achieving fire protection expertise.
- Supporting fire protection experts in preparing fire safety assessments and also by closing the gaps that emerged from the assessments.

- Getting involved with the fire protection industry by reading journals, magazines, relevant fire protection OPEX, joining associations (SFPE), and attending conferences.
- Enrolling in certificate and diploma programs for fire protection to lay a theoretical foundation.
- Enrolling in specialized professional training courses.
- Joining technical committees for codes and standards that are applicable to fire protection.

Nuclear utilities currently play a major role in securing energy in both developed and developing countries. Furthermore, nuclear power holds tremendous promise for securing the world's energy requirements in the future while simultaneously reducing harmful environmental effects. However, in order for the nuclear industry to succeed, the public must be convinced that all contributing risks to nuclear safety are minimized – including those stemming from fires.

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