Screening of Seismic-Induced Fires

James C. Lin[a]*, Donald J. Wakefield[a], and John Reddington[b]
[a] ABSG Consulting Inc., Irvine, California, United States
[b] First Energy Nuclear Operating Company, Akron, Ohio, United States

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Abstract: Seismic-induced fire has been an issue not addressed quantitatively in both the nuclear plant seismic PRAs and fire PRAs mainly because of the lack of data and a method to estimate the likelihood of a seismic-induced fire. One approach to identify the seismic-induced fire scenarios and evaluate the occurrence frequencies of these scenarios is to perform a screening analysis based on both the likelihood and the impact of such scenarios. Based on frequency of seismically induced fire initiation, there are two aspects to screening fire scenarios: (1) to assess the subset of seismic failure modes that may contribute to fires, the fragility for the structural failure modes including support/anchorage failures conservatively bounds the seismic failure potential; (2) the other factor that can be considered is the conditional probability of potential fire ignition. The seismic screening capacity can be determined by identifying an assumed fragility with which a convolution of the seismic hazard exceedance curves will result in a frequency of SSC failure integrated over the entire seismic hazard acceleration range below an acceptable screening value. For the remaining SSCs that survive the seismic capacity screening, additional screens based on fire consequences can be performed to reduce the number of scenarios to a minimal set for further detailed, quantitative evaluations.

Keywords: Seismic-Induced Fire, Structural Failure Mode, Ignition Probability, Screening, Seismic PRA.

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1. INTRODUCTION

Seismic-induced fire has been an issue not addressed quantitatively in both the nuclear plant seismic probabilistic risk assessments (PRA) and fire PRAs mainly because of the lack of data and a method to estimate the likelihood of a seismic-induced fire. Furthermore, the locations of the seismic-induced fires and the possibility of multiple seismic-induced fires are also difficult to identify. However, given a seismic-induced fire at a specific location, the impact of the seismic-induced fire can be characterized in a relatively straightforward manner using information from the seismic PRA and fire PRA. Nevertheless, identification of seismic-induced fire scenarios is still a challenging task.

One approach to identify the seismic-induced fire scenarios and evaluate the occurrence frequencies of these scenarios is to perform a screening analysis based on both the likelihood and the impact of such scenarios. Before we attempt to identify the seismic-induced fire scenarios, let us examine first how a seismic-induced fire may occur.

2. IGNITION SOURCES AND ENERGY

Based on the past experience, many of the seismic-induced fires that occurred initiated in non-seismically qualified equipment, perhaps due to their higher likelihood of being structurally damaged during a large earthquake. As such, in our search for the potential fire sources, the non-seismically qualified equipment should certainly be considered both as ignition and fuel sources.

To cause a fire, the ignition source with sufficient ignition energy must come in contact with the fuel (i.e., combustibles) or its vapor. During an earthquake, sparks may result from both mechanical and electrical effects. Mechanical friction and impact of a metal object during a seismic event can cause a

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* jlin@absconsulting.com

spark. An electrical spark can be induced by pulling loose an electrical wire connections or contacts between exposed wires/junctions with metal objects. Sparks from a broken/damaged wire during an earthquake are considered more likely than making contacts with exposed wires/junctions. In addition to sparks, ignition energy can also come from hot surfaces.

For sparks generated by mechanical friction or impact with a metal object, the amount of energy contained in the spark is relatively limited because the duration of impact or contact is very short. During a large earthquake with strong vibration and significant displacement, supports for structures, equipment, cabinets, and piping, as well as ceiling/wall materials, etc., may be damaged resulting in falling of their broken pieces and causing impacts with other objects. In addition, vibration and the resultant differential displacements may also cause contacts or friction between two objects that are normally separated spatially. As such, this type of spark may be generated during the time of strong shaking and can occur inside any part of the plant buildings where structural/mechanical failures or differential displacements take place.

The energy contained in the sparks caused by a loose electrical wire or bus bar connection varies depending on the voltage level of the wire or bus bar. Typically, the sparks that may result from a loose electrical wire or connection with the bus bar involving a voltage level below 480V (e.g., 125VDC, 120VAC, or even lower voltage), the energy content is somewhat limited. The arcing that may be generated by a loose electrical wire or connection with a bus bar at voltage 480V and above can contain sufficient energy to ignite most of the combustibles.

A high energy arcing fault has caused explosions in the past. Since the cable trays, conduits, and their support structures are generally built with very strong seismic capacity, they do not fail easily during an earthquake. Most likely, the high energy arcing would only occur in areas where switchgears/buses/motor control centers (MCC) having a voltage level of 480V and above are located. These types of electrical cabinets are typically present in separate rooms (especially for switchgears/buses of 4.16KV or higher) or in areas without substantial combustibles nearby, except for cables. In addition, if the raceways routed into and out of this type of electrical cabinets are sturdily supported or anchored to the wall, the amount of combustibles that could be in contact with any electrical sparks that are generated by overturning of the cabinet would be significantly reduced.

An example electrical arc flash could result from an earthquake-induced severing of the conduits connecting to the top of the electrical cabinets and of the cables routed inside the conduits. Such electrical cabinets as switchgears and MCCs are typically anchored to the concrete pads on the floor. Conduits entering from the top of the cabinets are sometimes braced to the steel frames. Adequate cable flexibility across building joints is thus an important consideration in evaluating the likelihood of a seismic-induced fire due to electrical arcing.

Ignition sources involving equipment with hot surfaces are typically at fixed locations. The energy from hot surfaces can be transferred to the fuel that is in contact with these surfaces. Therefore, to cause fire ignition, the most likely mechanism is for the fluid fuel to spread to the location of the hot surfaces and get in contact with the hot surfaces. These hot surfaces may be the exterior casing of rotating equipment (e.g., pumps, motor-generators, compressors, fans, chillers); motor, generator, or transformer windings; exposed steam pipes (e.g., a small segment of pipes with damaged insulation or with insulation removed for imminent maintenance activities), etc.

3. FUELS/COMBUSTIBLES

There are many different types of combustibles in a nuclear plant. They include cable insulation/jacket materials, plastic casing/materials, hydrocarbon fuels (including such liquid fuels as diesel fuel oil, lubricating oil, and hydraulic oil, as well as gaseous fuels such as hydrogen and propane), etc. In general, solid fuels are more difficult to ignite. Flammable gases and liquid fuels can not only be more easily ignited but also could result in larger fires due to their substantial heat content and the greater potential for fire propagation.

To cause an ignition of the cable insulation/jacket and/or plastic materials, significant ignition energy is needed. It is extremely difficult for mechanical impact/friction sparks or hot surfaces to ignite these types of materials. Therefore, without an external exposure fire, the most likely ignition source for cable insulation/jacket and plastic materials is the high energy arcing generated by a seismically broken/damaged electrical wire or bus bar connection. However, cables and plastic materials can be present in most locations inside the plant buildings.

Hydrocarbon fuels, however, are only present in specific locations inside the plant buildings. In nuclear plants, diesel fuel oil is found in the diesel oil storage tank, diesel oil day tank, and diesel oil piping inside the building that houses the diesel generators or any diesel driven pumps. The largest amount of lubricating oil is the turbine lube oil stored in the Turbine Building. In addition, oil-filled transformers and such rotating equipment as pumps may also contain non-negligible amounts oil (especially larger transformers and pumps). Hydraulic oil is typically contained in the hydraulic equipment in the Turbine Building. These types of hydrocarbon fuel are limited to those locations where the corresponding equipment is located. Due to the relatively low vapor pressure, it is difficult for fuel oil, lubricating oil, and hydraulic oil to be ignited by mechanical sparks because of their limited spark energy available. They can, however, be ignited by hot surfaces and electrical arcing generated from seismically damaged/broken wire (with a voltage of 480V and higher) connections for the oil-filled transformers or motor windings.

For gaseous fuels such as hydrogen and propane, they can be ignited much more easily by any sparks or hot surfaces due to their dispersion characteristics so long as their concentrations in the building atmosphere is within the flammability limits. In general, hydrogen is used in the Turbine Building for generator cooling. It is also used in, for example, the Auxiliary Building for selected Chemical and Volume Control System functions. Typically, hydrogen bottles are stored outside the plant buildings to minimize the impact of its fire and explosion hazards on the plant equipment. Inside the plant buildings, there are primarily small hydrogen tubes (e.g., approximately 1” to 2” diameter lines) which usually are seismically robust. In addition, these tubes are generally well supported (e.g., supported alongside the building walls and not protruding like a cantilever). Unless failure of the building walls occurs, it is unlikely to damage these tubes resulting in a release of the hydrogen gas. Although rarely, it is possible, however, that there may be a very small number of hydrogen bottles inside the Auxiliary or Turbine Building. In nuclear plants, propane is used primarily by the auxiliary boiler in the Turbine Building. Propane tanks are almost always located outside the plant buildings. There may be small propane lines that connect these tanks with the auxiliary boiler inside the Turbine Building. Again, these lines generally have high seismic capacity and are unlikely to fail during an earthquake. However, seismic failure of the structural support/anchorage for the auxiliary boiler could cause a rupture of the connecting propane line.

Based on the preceding considerations, potentially, the most likely seismic-induced fire sources are expected to include:

- High energy arcing of seismically damaged wire or bus bar connections in the areas of switchgears/buses/MCCs (480V and higher) may cause ignition of the nearby combustibles (primarily cables). These are mostly in the switchgear rooms and other plant locations for MCCs. This could lead to damage to the switchgears/buses/MCCs and any other PRA equipment in the area or spread of the fire to additional areas.
- High energy arcing of seismically loosened bus bar connections in the switchgear rooms (480V and higher) may cause explosion. The explosion overpressures could blow open the switchgear room doors and perhaps lead to spreading the ensuing fire to outside the room.
- Seismically damaged piping or containers of hydrogen in the Auxiliary Building may cause a release of hydrogen followed by an ignition of the hydrogen gas by sparks or hot surfaces. The hydrogen fire or explosion could also cause ignition of additional combustibles in the area leading to damage to PRA equipment.

- Seismically damaged piping, seals, blowout panel, or containers of hydrogen or propane in the Turbine Building (e.g., seismically damaged seal to the generator or blowout panel on the covers) may cause a release of hydrogen or propane (e.g., seismic failure of auxiliary boiler) followed by an ignition of the hydrogen or propane gas by sparks or hot surfaces. The hydrogen/propane fire or explosion could also cause ignition of additional combustibles in the area leading to damage to PRA equipment.
- Seismically damaged piping or containers of diesel fuel oil in the Diesel Generator Building may cause a severe leakage of diesel fuel oil followed by an ignition of the diesel fuel oil by hot surfaces or high energy electrical sparks. The resulting oil fire could damage any other PRA equipment in the area.
- Seismically damaged container of turbine lubricating oil in the Turbine Building may cause a major leak followed by an ignition of the lube oil by hot surfaces or high energy electrical arcing. The resulting large oil fire in the Turbine Building could damage PRA equipment in the Turbine Building.
- Seismically induced failure of the pump/compressor (with a significant oil inventory) supports/anchorage in plant buildings may cause a large oil leak followed by an ignition of the oil by hot surfaces or high energy electrical arcing; e.g., from the damaged wire connection for the pump motive power cables.
- Seismically induced failure of the oil-filled transformer supports/anchorage in plant buildings may cause a large oil leak followed by an ignition of the oil by hot surfaces or high energy electrical arcing; e.g., from the damaged wire connection for the transformer winding.
- Seismically induced failure of the supports/anchorage for hydraulic equipment inside plant buildings (e.g., Turbine Building) may cause a large hydraulic oil leak followed by an ignition of the hydraulic oil by hot surfaces or high energy electrical arcing.
- Seismically induced soil failure underneath an oil-filled transformer pad in the yard may cause a structural failure of the transformer and a large oil leak followed by an ignition of the oil by hot surfaces or high energy electrical arcing; e.g., from the damaged wire connection for the transformer winding.

The seismically-induced fire ignition of transient combustibles is expected to be less likely because these solid or liquid fuels must be located nearby a seismically-induced ignition source (e.g., an electrical arc flash, a hot surface) at the time of a large earthquake.

4. FAILURE MODES

To cause an ignition of the hydrocarbon fuel, the containing equipment of the hydrocarbon fuel must first seismically fail causing a release of the hydrocarbon fuel. The released hydrocarbon fuel must then be ignited by an ignition source with sufficient energy. The seismic failure of the containing equipment for the hydrocarbon fuel occurs when the seismic excitation force exceeds its seismic strength capacity. This failure likelihood increases as the seismic acceleration increases. The probability of ignition of the released hydrocarbon fuel is less dependent on the magnitude of the earthquake, although not completely independent because the stronger the seismic excitation, the more structural failures would occur which may result in more impacts and sparks.

For an ignition caused by high energy electrical arcing, sufficient differential displacement must occur causing the electrical wire or bus bar connection to be pulled loose or apart. Only then, arcing may occur due to an electrical discharge across the air gap. Ignition will occur if the spark is in contact with a combustible and the arcing energy is sufficient to cause the combustible to ignite. To pull loose the electrical wire or bus bar connection of a switchgear/bus/MCC, typically, it may involve seismic failure of the cabinet support/anchorage leading to overturning of the electrical cabinet. Therefore, the failure mode is primarily the seismic failure of the switchgear/bus/MCC cabinet anchorage/support. The failure probability is the fragility of the cabinet anchorage/support. Given that there is a seismic-induced differential displacement sufficient to pull the electrical wire or bus bar connection loose, the likelihood of arcing and ignition is dependent on whether the loose connection would be in contact with a combustible and whether sufficient spark energy would be imparted to the combustible. This conditional probability of arcing and ignition is perhaps nearly independent of the magnitude of the earthquake, given that the wire or bus bar connection is already pulled loose.

For a tank containing hydrocarbon fuel to seismically fail causing a release of the hydrocarbon content, the likely failure modes include the support/anchorage failure induced by sufficient vibration energy which leads to buckling failure followed by crack and leakage (for flat bottom tanks), movement of the tank causing failure of the anchor bolts and then failure of the attached piping, support/anchorage failures leading to overturning and ruptures of the tank on impact (less likely than the other two modes), etc. For a pipe to release its hydrocarbon content during a seismic event, the most likely failure modes include seismic failure of the pipe support or excessive differential displacement of the pipe resulting in mechanical impact with an adjacent structure which leads to the rupture of the pipe. This could imply that the evaluation can be focused in areas containing structures, systems, and components (SSC) of different seismic categories, pipe anchorage, and its vicinity.

Similarly, for an oil-filled transformer or a pump to release its oil, there must be sufficient vibration energy to fail its anchorage/support causing the equipment to overturn and rupture its oil casing on impact; i.e., requires structural/anchorage failure to cause a release of the oil contained inside this equipment. For a piece of equipment with a high aspect ratio (e.g., a vertical pump compared to a horizontal pump), there is certainly a higher likelihood to overturn following anchorage/support failures. For an oil-filled transformer with a very low aspect ratio, strong earthquake excitation can cause the anchorage/support to fail and thus move laterally, but it would be more difficult to overturn resulting in a greater impact stress. Note that most of the oil-filled transformers (including Non-Seismic Category I transformers) have similar construction and anchorage. Therefore, most oil-filled transformers have similarly high seismic structural capacity. To also create an arcing, the seismic-induced differential displacements must rip open the electrical wire connections to the transformer or pump/compressor motor. This could also occur when the anchorage fails and the transformer/pump/compressor overturns. Therefore, the most important failure mode is judged to be seismic failure of the anchorage/support causing the transformer/pump/compressor to overturn. Given that both the oil is released and a high energy arcing is generated, the likelihood of ignition is judged to be more of a random event nearly independent of the earthquake magnitude.

5. PROBABILITY OF IGNITION

As discussed in the preceding, the likelihood of a seismic-induced fire given an earthquake is the joint probability of a seismic structural/mechanical failure and ignition. The probability of seismic failure (e.g., seismic failure of the anchorage/supports of an electrical switchgear, pump, transformer, compressor, and tank) can be estimated by the seismic fragility analysis method. The seismic fragility is a function of the seismic acceleration value; e.g., pga. The probability of ignition given a seismic failure leading to a release of hydrocarbon fuel or resulting in the electrical wire or bus bar connections being pull loose/apart is relatively independent of or much less dependent on the earthquake magnitude. Ignition probability is mainly based on the presence and the density/amount of ignition sources in the area, whether the ignition sources can be in contact with the combustibles in the area, how much ignition energy is required and whether there is sufficient energy from the ignition source to ignite the combustibles, etc.

The energy required to ignite the combustible is dependent on the type of the fuel. For gaseous hydrocarbon fuel (e.g., hydrogen and propane), the least amount of energy is required to ignite the vapor cloud of the fuel. Besides, due to the dispersion characteristics of this type of fuel, it can be most easily in contact with ignition sources present in the area. Also, it can be ignited by most ignition sources considered, including the mechanical sparks that may be generated during an earthquake due to falling, collapsing, or movement of objects. As such, the ignition probability of this type of fuel should be the highest. However, the ignition probability may vary depending on the release rate of the hydrocarbon gas. The larger the release rate, the more ignition sources can be encompassed by the flammable gas cloud, prior to dispersion, and thus the greater the chance of ignition. Since the flammable gas cloud released can also be ignited by the mechanical sparks generated during an earthquake event, this portion of the ignition probability contribution may increase as the earthquake magnitude increases. However, it is possible that this portion of the ignition probability may only have a small contribution. Besides, as the extent of seismic failures increases, seismic-induced core damage would be more dominated by seismic failures other than the impacts of seismic-induced fires.

For the liquid hydrocarbon fuel present inside the nuclear plant buildings (e.g., diesel fuel oil, lube oil, hydraulic oil, etc.), the energy required to cause an ignition is significantly higher than that for a flammable gas due to the relatively low vapor pressure. In addition, the ignition sources that can be in contact with this type of fuel are much more limited than those for a flammable gas cloud. The ignition sources must be located where the liquid fuel can spread to. As a result, the probability of ignition given a release of a liquid hydrocarbon fuel should be significantly lower than that for a flammable gas. Furthermore, the probability of ignition for lubricating oil and hydraulic oil should be lower than diesel fuel oil. Nevertheless, the higher the release rate of the liquid fuel, the faster and the farther it can spread and thus the more ignition sources can be encountered; i.e., greater ignition probability.

To ignite the solid combustibles such as cable insulation/jacket and plastic materials, in general, the highest ignition energy may be required. As such, without an external exposure fire, only certain ignition sources (e.g., high energy arcing) can cause the ignition of these materials during an earthquake. Besides, these combustibles are generally fixed in locations. The loose wire or bus bar connections must be close enough to these combustibles for the sparks to cause an ignition which will require a significant differential displacement between the loose wire or bus bar connections and the combustibles. Therefore, it is believed that ignition of solid combustibles during an earthquake should have the lowest frequency of occurrence due to the smallest probability of ignition.

Table A.5 of Reference [1] shows the following ignition probabilities in the process areas inside a petrochemical facility:

Type of Release	Size of Release	Probability of Ignition
Gas	Minor (< 1 kg/s)	0.01
	Major (1 – 50 kg/s)	0.07
	Massive (> 50 kg/s)	0.3
Liquid	Minor (< 1 kg/s)	0.01
	Major (1 – 50 kg/s)	0.03
	Massive (> 50 kg/s)	0.08

The above ignition probabilities can be considered as the probability of immediate ignition; i.e., ignition within a short period from the time of release (e.g., within a few minutes). For flammable gases, a delayed ignition may also occur because the flammable gas can continue to disperse until encountering an ignition source (as long as the concentration of the flammable gas is still within the flammability limits). During an earthquake, immediate ignition appears to be more applicable because mechanical sparks are typically only generated during the period of vibration or during a very short period following the shaking. In addition, due to the compartment design, the ignition sources within the compartment in which the combustibles are located have the most chance of contributing to the seismic-induced fires.

Considering the sizes of the hydrogen/propane lines and the possible break sizes of the oil leakage (from tanks, transformers, pumps, compressors, etc.) in a nuclear plant, it is likely that the release rate resulting from a seismic failure is no greater than 50 kg/s. Even though additional ignition sources may be created during an earthquake (e.g., mechanical sparks due to falling, impact, and friction of objects), it is judged that the probability of ignition should still be less than 0.1 (which is significantly greater than the ignition probability for flammable gases released at less than 50 kg/sec) for all of the ignition source and fuel/combustible combinations considered in this evaluation. Since this is a relatively conservative estimate of the probability of ignition, this conservative value can be considered as bounding for earthquake conditions; i.e., even with the additional ignition sources of mechanical sparks. Because the ignition of combustibles by high energy arcing in the switchgear/bus/MCC area or at the transformers, pumps, or compressors is expected to be significantly less likely than that for the ignition of a flammable gas cloud, these scenarios can also be bounded by this conservative ignition probability of 0.1.

Considering both the seismic structural/mechanical failure and the probability of ignition, the conditional probability of ignition given an earthquake is thus the joint probability of the fragility of the seismic failure mode considered (anchorage/support failure in most cases) and the ignition likelihood; where the seismic fragility is a function of the seismic acceleration and the bounding ignition probability is treated as independent of the seismic acceleration. It is conservatively assumed that the resulting seismic failure mode is an ignitable configuration, with probability 1.0.

6. SCREENING OF SEISMIC-INDUCED FIRE SCENARIOS

Using the preceding considerations, both qualitative and quantitative screening of the seismic-induced fires can be performed. The qualitative screening of the seismic-induced fire scenarios can consider both the likelihood and the impact. The compartment by compartment evaluation may start with a selected set of compartments that contain specific ignition/fuel source combinations that can potentially cause a seismic-induced fire. Additional evaluation criteria that directly influence the likelihood and consequence of a seismic-induced fire may then be used to further screen potential seismic-induced fire scenarios.

The discussion of the ignition source and fuel/combustible combinations in the preceding is largely from the likelihood standpoint. We consider flammable gas and liquid fuel because they are more likely to be ignited. Additionally, the emphasis on the fluid fuel is partly attributed to the potential for a larger fire and thus greater impact. Ignition by high energy arcing is also considered because of its higher likelihood of occurrence. Therefore, the following equipment (which can either be a fuel source or an ignition source) is considered based on this perspective:

- Tanks, Bottles, and Piping (including turbine-generator, auxiliary boiler) That Contain Hydrogen, Propane, and Any Other Flammable Gases
- Above-Ground Tanks and Piping That Contain Diesel Fuel Oil
- Tanks, Equipment, and Piping That Contain Lubricating Oil
  - Turbine-Generator
  - Turbine Lube Oil Storage Tank
  - Oil-Filled Transformers
  - Pumps (especially large pumps)
  - Compressors
  - Piping
- Tanks, Equipment, and Piping That Contain Hydraulic Oil
- Equipment with Electrical Wire or Bus Bar Connections at 480V and Above
  - Switchgears/Buses/MCCs
  - Pumps
  - Oil-Filled Transformers
  - Compressors
  - Others (e.g., other applicable NUREG/CR-6850 fire source bins from Fire PRA that are unique and significant for specific plants)

From the impact standpoint, the screening will examine if the seismic-induced fire (which can be derived from the internal fire PRA analysis of the compartments where the ignition sources/fuel are located) will result in additional impacts than those functions already modeled by seismic failures; i.e., the full impacts of the seismic fragility items, including functional effects. In addition, one needs to determine if additional fire propagation pathways may be created by the seismic failures modeled if the compartment does not screen; e.g., collapse of a block wall separating two fire compartments, structural failure of penetration assemblies. Of course, if the conditional impact of seismically induced fires in a compartment is relatively limited or small (e.g., as reflected by a small conditional core damage probability, CCDP, and a small conditional large early release probability, CLERP), seismic-induced fires in that compartment may not need to be considered. If the combined impact of seismic failures and seismic-induced fire is not significantly more severe than that for the seismic failures alone, the postulated seismic-induced fire scenario may also be screened.

For each fire compartment where the credible ignition sources/fuel considered are located (e.g., an oil-filled transformer, a pump, or a compressor containing significant amount of lubricating oil), one will examine if additional PRA equipment is located in the vicinity that can be damaged by the seismic-induced fire source. It must be noted that this is only considering the additional PRA equipment without counting the seismically failed fuel source (which leads to the release of gas or liquid fuel) or ignition source. Although this additional PRA equipment located in the same fire compartment could also be failed by the seismic force (i.e., modeled as a seismic fragility item), the seismic-induced fire is of interest if it increases the likelihood of failure of this additional PRA equipment. Besides, evaluation could also consider the distance between the ignition sources, combustibles, and fire damage susceptible PRA equipment if the likelihood of fire source igniting is high enough to not allow screening out otherwise. If the fire damage susceptible PRA equipment is located at sufficient distance away from the fire source, seismic-induced fire would not lead to additional impacts and can therefore be screened out.

Furthermore, if relevant seismic structural failure is also modeled for this fire compartment, evaluation needs to be performed to determine if this seismic structural failure would alter the potential of fire spread and the overall fire impacts. Also, the seismic-induced fire may impact the post-initiator operator actions by increasing the diagnosis difficulty and stress for the control room operators and by creating a harsh environment for local operator actions that need to travel through or perform specific action in the fire affected area. Therefore, for each such compartment, the operator actions that may potentially be affected should be identified and evaluated if the compartment is not already screened out by other considerations.

For quantitative screening, we propose to use the joint likelihood of seismic structural failure of anchorage/support and ignition probability (i.e., the product of seismic fragility for this failure mode and the ignition probability as a function of seismic acceleration level in pga) in conjunction with the seismic hazard frequencies and the PRA model (which accounts for the combined impact of both seismic failures and seismic-induced fires) to determine the risk significance of seismic-induced fire scenarios. By varying the seismic fragility value, it is possible to identify a seismic capacity curve versus acceleration (for the seismic structural failure of the anchorage/support considered for seismic-induced fire scenarios) beyond which a bounding estimate or a more realistic analysis of the core damage frequency (CDF)/ large early release frequency (LERF) risk contribution is below an acceptable cutoff value; e.g., 1.0E-7/year for CDF. Because the ignition probability is also considered in this evaluation, it is expected that this seismic capacity screening value obtained for the inclusion of seismic-induced fire scenarios would be noticeably lower than the seismic capacity screening value for the inclusion of direct seismic failures in the seismic PRA. Once this seismic capacity screening value for seismic-induced fires is identified, it can be used during walkdown to screen the possible ignition and fuel sources for the inclusion of the seismic-induced fire scenarios in the seismic PRA.

Therefore, based on the frequency of seismically induced fire initiation, there are two aspects to screening fire scenarios:

- To assess the subset of seismic failure modes that may contribute to fires, the fragility for the structural failure modes including support/anchorage failures (but not the functional failure modes which are often lower) conservatively bounds the seismic failure potential.
- The other factor that can be considered is the conditional probability regarding potential fire ignition. Based on data from other industries (e.g. the oil and gas industry where the ignition

probability is a key component of the analysis), this ignition probability is bounded by 0.1 for all SSC types that may lead to fire.

The seismic screening capacity can be determined by identifying an assumed fragility (e.g., in terms of the high confidence low probability of failure [HCLPF] capacity in pga) with which a convolution of the seismic hazard exceedance curves will result in a frequency of SSC failure integrated over the entire seismic hazard acceleration range below an acceptable screening value. If 5.0E-7 per year is taken to be the single SSC screening fire initiation frequency, the frequency of a single structural failure would be 5.0E-7 divided by the bounding conditional probability of ignition of 0.1; i.e., 5.0E-6 per year. Note that seismically initiated fires do not necessarily, by themselves, cause core damage. Other failures that must also occur could drive the fire-induced core damage frequency lower.

In addition, at high accelerations, there is overlap between the seismic-induced fire impacts and other contributors to seismic core damage. So, the added contribution to core damage frequency from the seismic-induced fire scenarios is not the full 5.0E-07/year due to this overlap. Therefore, because of the additional failures reflected by the CCDP associated with the seismic-induced fire scenario that must occur to lead to core damage and the overlap of seismic-induced fire damages with other seismic failures at high accelerations, an added contribution of lower than 1.0E-7 is thus expected if the SSC has a single SSC seismic failure frequency of 5.0E-7 per year. Further, considering the bounding ignition probability, the frequency of the structural failure mode considered can be taken to be 5.0E-6 per year.

If the seismic screening capacity thus determined is bounded by an acceleration of, for example, 0.35g, it means that SSCs with structural failures modes with a HCLPF greater than 0.35g could be screened by just considering the 0.1 conditional probability of ignition. Such a screen would eliminate many potential fire sources from further investigation. Furthermore, if we exclude the seismic-induced fire contribution from accelerations greater than the level above which the conditional seismic core damage probability is 1.0 (e.g., only consider seismic-induced fires at seismic levels less than 0.5g), the screening seismic capacity for seismic-induced fire scenarios could be as low as 0.25g.

For the remaining SSCs that survive the seismic capacity screening, additional screens based on fire consequences can be performed to reduce the number of scenarios to a minimal set for further detailed, quantitative evaluations.

The procedure that can be used for the identification and screening of seismic-induced fires is to perform the evaluation compartment by compartment. This is mainly because many of the seismic-induced fires may be initiated from the non-seismically qualified equipment which may not be included in the seismic equipment list (SEL) or in the seismic PRA (SPRA) model. However, during the seismic PRA walkdown of the SSCs included in the SEL, the potential effects of Seismic Category II SSCs over Seismic Category I are examined by the fragility analysts. Nevertheless, this walkdown evaluation is performed from the standpoint of seismic failure interactions; i.e., not from the perspective of seismic-induced fires. As such, the SEL developed may not be complete for the analysis of seismic-induced fires. However, a special table can also be compiled for the likely fire ignition sources that are not included in the SEL; e.g., hydrogen lines, fuel oil lines. If no credit is taken for equipment inside a specific building, SSCs in that building can be excluded from this table because the seismic-induced fire impacts resulting from these SSCs cannot add to the core damage frequency. As such, SSCs in fire compartments that are located in buildings that are not credited for seismic events can be screened.

7. CONTAINMENT INTEGRITY

The impact of seismic-induced fires on the containment integrity is primarily the possible effects of fire on the failure of containment isolation or spurious opening of valves leading to interfacing systems loss of coolant accident (LOCA) (ISLOCA). These could result from the fire impacts on the electrical cabinets/MCCs containing the circuitries for the control of the containment isolation function/valves, and for the control of the isolation valves involved in ISLOCA. Therefore, the plant areas containing these electrical cabinets should also be examined for the potential of a seismic-induced fire. For the isolation functions associated with the containment isolation valves, most of the relevant electrical cabinets would be at low voltage level (i.e., 480V and below). Since containment isolation has a significant impact on LERF, fires caused by seismic-induced arcing related to these electrical cabinets may also need to be considered.

However, almost all of the air-operated and perhaps, at some plants, selected motor-operated containment isolation valves are designed to fail in the close position on loss of power or air. Fire damage to their control circuits could result in a hot short preventing the air-operated (or selected motor-operated valves) to fail in the close position. But, based on the results of the fire tests conducted in recent years [2], essentially all of the hot shorts would eventually turn into the open-circuit failure mode. The longest duration of hot short in the previous fire tests was not longer than 12 minutes. For an air-operated (or selected motor-operated) valve with a fail-safe design, the open circuit failure mode will cause the valve to close. Therefore, for containment isolation valves or ISLOCA related isolation valves, only cabinets associated with motor-operated valves need to be examined. At some U.S. nuclear plants, the power supplies to the motor-operated valves at high-low pressure interfaces are removed (e.g., de-energized with the breaker racked out) to prevent inadvertent opening (e.g., fire-induced) of these motor-operated valves, regardless of the cause of the fire.

8. MULTIPLE, CONCURRENT SEISMIC-INDUCED FIRES

Due to the correlation in both the seismic excitation and SSC strengths, seismic PRAs typically model like equipment located in the same building at the same elevation as dependent; i.e., they would be treated as failing concurrently. For seismic-induced fires, this implies that multiple fires may occur concurrently in the plant. However, while the structural failure aspects may be correlated, the conditional probability of ignition at different locations (i.e., in different compartments) is largely independent. Therefore, overall, the occurrence of multiple, concurrent fires are still, to a large extent, a random phenomenon. For the initial screening of seismic-induced fire scenarios, the evaluation can be performed individually for each compartment since seismic-induced fires in different compartment are treated as independent. Once all of the seismic-induced fire scenarios and their corresponding locations have been identified, one can re-evaluate if it is possible that any of these seismic-induced fire scenarios identified are correlated.

9. WALKDOWN IDENTIFICATION AND SCREENING

During seismic-induced fire walkdown, inspections of the ignition and fuel sources discussed previously should be performed to determine:

- Could the seismic structural (e.g., anchorage/support) failure occur with significant likelihood by determining if the seismic capacity for the failure mode considered is above the screening value?
  - Is the anchorage/support sufficiently strong? Well supported/anchored? Co-located SSCs of different seismic categories?
  - Is it possible for the equipment considered to overturn causing a severe impact stress?
  - Is it possible for seismic-induced differential displacement or impact stress due to overturn to cause rupture of the pressure boundary for the fuel source?
  - Is it possible for seismic-induced differential displacement or impact stress due to overturn to pull loose/apart electrical wire or bus bar connections? Adequate cable flexibility across building joints?
- Are there ignition or fuel sources nearby to permit ignition?
  - Given a release of fluid fuel, are there ignition sources nearby with sufficient ignition energy to cause ignition? Are these ignition sources properly secured (i.e., can be free of seismic damage)? Can these ignition sources be in contact with the fuel?

  - Are there combustibles nearby? Are these combustibles properly secured (i.e., can be free of seismic damage)? Can these combustibles be in contact with the ignition sources?
  - Are the possible ignition or fuel sources adequately secured to greatly reduce the likelihood of ignition?
  - Can the ignition lead to a significant fire?
  - Are there additional combustibles available to permit fire spread?
- Can the seismic failures create additional fire propagation pathways in the area?
- In addition to the SSCs that fail seismically, is there additional PRA equipment in the area that can be impacted by the seismic-induced fire?
  - Is there additional PRA equipment in the compartment that can be damaged by a seismically induced fire?
  - Are the fire-induced CCDP and CLERP for the fire compartment below the screening values (if the seismic failures do not introduce additional fire propagation pathways and enlarge the fire impacts evaluated in Fire PRA)?
  - Is the fire damage susceptible PRA equipment located with sufficient distance away from the seismic-induced fire sources (i.e., beyond the zone of influence for fire impacts)?
- Are there any post-earthquake operator actions performed in the area or that must pass through the area?
  - Would these post-earthquake operator actions be further affected by the seismic-induced fire effects?

The above considerations and evaluations will help to identify the seismic-induced fire scenarios that can realistically occur based on the actual plant configurations if the potential fire compartments do not all screen.

10. CONCLUSION

Seismic-induced fire scenarios can be evaluated by first performing identification and screening of the potential scenarios. Both qualitative and quantitative screening can be conducted. Qualitative screening can be based on the potential for the types and locations of equipment that may cause a seismic-induced fire as well as the potential impacts that may result. Quantitative screening can be performed using the frequency of seismic-induced fire initiation to determine screening seismic capacity value for a single SSC which should be noticeably lower than the screening seismic capacity for direct seismic failure contributors to CDF/LERF because a conditional ignition probability can also be considered. Quantitative screening can also use the fire consequence reflected by the fire compartment CCDP and CLERP as additional criteria.

References

[1] WS Atkins Consultants Ltd. "*Development of a Method for the Determination of On-Site Ignition Probabilities*", Health and Safety Executive, RSU 4014/R04.081, (2004).

[2] Electric Power Research Institute, "*Characterization of Fire-Induced Circuit Faults, Results of Cable Fire Testing*", EPRI Final Report 1003326, December 2002.