Insights from the Analyses of Other External Hazards for Nuclear Power Plants

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Abstract: Because the probable maximum events selected in FSAR for nuclear plants may not be the maximum possible events, they could possibly be exceeded by more severe events in the future. As such, there is a need to re-evaluate the other external hazards, especially those associated with the natural phenomena. To ensure that the maximum possible intensities of the natural phenomenon hazards are identified and analyzed, one has to be able to identify the physical limits of the parameters that define the intensities of the hazards. However, in some cases, it is truly difficult to identify the absolute, physical limits of parameters associated with selected natural hazards. One way to address the issue of exceeding the probable maximum event is to evaluate the quantitative risk in terms of core damage and large early release frequencies resulting from the specific hazard of concern. This will require the estimation of the hazard frequency. While it may be possible to assess the occurrence frequencies of selected natural phenomena of limited intensity, the uncertainty in the assessed frequencies of events with magnitude beyond the range of historical occurrences may be uncomfortably high. Furthermore, some of the external hazards may not lend themselves to an easy assessment of their occurrence frequencies. As such, deterministic criteria will still need to be used for the risk evaluation of selected hazard events. This paper groups the entire set of other external hazards into a number of categories and discusses the characteristics, PRA evaluation methods, and other aspects of each of these groups.

Keywords: Other External Hazards, Internal Events PRA, Core Damage Risk, Nuclear Power Plant, SSC

1. INTRODUCTION

Many of the other external hazards, including natural phenomena, have typically been evaluated in the Final Safety Analysis Report (FSAR) as part of the nuclear plant licensing process. In general, the approach used in the FSAR is to specify a probable maximum event (i.e., maximum credible event) substantiated by the historical records, and demonstrate that the plant design can withstand the effects of the probable maximum event selected. Since the Fukushima Daiichi accident, it is thought that, because these probable maximum events selected may not be the maximum possible events, there is still the possibility that these probable maximum events be exceeded by more severe events in the future. As such, the need to re-examine the other external hazards especially those associated with the natural phenomena has been reinvigorated.

To ensure that the maximum possible intensities of the other external hazards are identified and used in the design analysis of nuclear power plants, one has to be able to identify the physical limits of the parameters that define the intensities of the hazards. However, it is, in some cases, truly difficult to identify the absolute, physical limits of parameters associated with selected natural hazards. Yet, we cannot afford to establish an unreasonably high intensity such that the plants cannot be economically designed to withstand these super intensity hazards.

One way to address the issue of exceeding the probable maximum event is to evaluate the quantitative risk in terms of core damage or large early release frequencies resulting from the specific hazard of concern. This will require the estimation of the hazard frequency. While it may be possible to assess the occurrence frequencies of selected natural phenomena of limited intensity, the uncertainty in the

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assessed frequencies of events with magnitude beyond the range of historical occurrences may be uncomfortably high.

Furthermore, some of the external hazards may not be amenable to an easy assessment of their occurrence frequencies. For example, some hazards will only occur at locations with specific geologic or soil conditions. Therefore, the hazard frequency cannot be readily determined because no applicable data is available for the occurrence of the hazard at that specific location. As such, deterministic criteria will still need to be used for the risk evaluation of selected hazard events.

In view of the preceding considerations, this paper groups the entire set of other external hazards into a number of categories and discusses the characteristics, PRA evaluation methods, and other aspects of each of these groups. In addition, this paper will also discuss the analyses of hazards that are not included in Appendix 6-A of the ASME/ANS Probabilistic Risk Assessment (PRA) standard.

2. CATEGORIES OF OTHER EXTERNAL HAZARDS

The major categories of the other external hazards for nuclear power plants may include: weather related events, events resulting from specific soil or geologic conditions, external flooding, high winds, extraterrestrial events, aircraft, marine, and ground (including rail and truck) transportation accidents, onsite chemical storage and nearby facility hazards, other man-made hazards, etc. Addendum B of the ASME/ANS PRA standard grouped the other external hazards into the following categories: biological events, external fires, extraterrestrial events, extreme temperature, ground shifts, heat-sink effects, heavy load drop, high winds, industrial accidents, lightning, site flooding, snow, transportation accidents, turbine-generated missiles, and volcanic activity. From the characteristics of the hazards and the methods that can be used for evaluation, the other external hazards are defined in this paper by the following categories: Aircraft Impacts, Biological Events, External Fires, Extraterrestrial Events, Extreme Temperatures and Selected Atmospheric/Weather Conditions, Geologic Conditions or Soil Related Events, Heavy-Load Drop, Industrial Accidents, Lightning, Marine and Ground Transportation Accidents, Site Flooding, Turbine-Generated Missiles, Ultimate Heat Sink (UHS) Degradation/Loss, Extreme Winds, etc.

3. CHARACRTERISTICS AND EVALUATION OF OTHER EXTERNAL HAZARDS

3.1. Aircraft Impacts

Aircraft impacts are considered separately from the rest of the transportation accidents because the evaluation of the frequency and consequences of aircraft crashes are different from the other types of transportation accidents. Aircrafts are generally defined in terms of the following categories: commercial, military, and general aviation. Commercial aviation involves air carriers and air taxi. Military aircrafts include large bomber, cargo, and tanker planes, as well as smaller fighters, attack aircrafts, and trainers. General aviation aircrafts include fixed wing single engine (reciprocating), fixed wing multiengine (reciprocating), fixed wing turboprop, fixed wind turbojet, and helicopters.

The frequency of aircraft crashes is typically calculated by a formula that considers the frequency of airplane flights, crash rate per unit distance traveled or per operation, flight distance nearby the plant within which an aircraft crash can impact the plant area, potential impact area of an aircraft crash, the effective target area, and the likelihood of the location of crashes with respect to the airport or air corridor. In the U.S., the aircraft crash rate is usually derived from the aviation accident data compiled by National Transportation Safety Administration and from data on airport operations and airway flights maintained by Federal Aviation Administration. Aircraft crashes can result from airport operations (including takeoff and landing) and enroute flights on low and high altitude airways. Data on airport operations can be obtained relatively easy. However, the derivation of the frequency of airway flights is more difficult because most of the flights today (including commercial airlines) do not strictly follow the airways. Flight routes are primarily determined by the shortest routes between the origin and destination navigated by the Global Positioning System (GPS). Instead, a rule of 5 miles apart and 1,000 feet vertical separation is used. Aircraft crash rates are dependent on the types of the aircrafts.

Because an airplane can typically glide for some distance following failure or loss of its propulsion, the flight distance nearby the plant within which an aircraft crash can impact the plant area is determined by flight altitude, the shortest distance between the plant and the airway, and the gliding ratio for the type of the aircraft. The potential impact area of an aircraft crash is dependent on the flight altitude and the gliding ratio.

The most important differences between the accidents of aircrafts and other modes of transportation are the consequences of the accidents. For aircraft crashes, only damages to the Systems, Structures, and Components (SSCs) caused by the crash impact are considered. The effective target area includes the critical plant area, the shadow (fly-in) area, and the skidding area. The shadow area is attributed to the height of the plant structures; i.e., impacts resulting from airplanes flying directly into the structures on its descent. It is based on the projection of the vertical face of the structures onto the horizontal surface and is dependent on the aircraft impact angle and the height of the structures. The skidding area is simply the product of the skidding distance and the length of the side of the structures exposed to the aircraft. It is dependent on the flight phase (takeoff, landing, in-flight), dimension of the structures, aircraft's wingspan, impact angle, direction of approach relative to the heading of the structures, and the length of the skid. The aircraft wingspan, impact angle (which is a function of flight altitude), and skid distance are dependent on the type of the airplanes. The average skidding distance is also different between crashes that occurred during takeoff and landing. Finally, the extent of damage that can be produced by the aircraft impact on a building is dependent on the airplane crash speed.

3.2. Biological Events

The types of biological growth or intrusion may include macro-organisms/macro invertebrate (mussels and clams), algae, micro-organisms, and silt, etc. These events are applicable to nuclear plant sites that use once-through water systems drawing water from rivers, lakes, ponds, or the ocean. Collection of silt can occur for plants taking suction of water from rivers. Algae growth often occurs for plants taking suction from lakes or ponds. Agricultural nutrient runoff can contribute to the algae growth. In addition, light penetration provides excellent incubation conditions for algae present in the lake waters entering the raw water systems. The potential impacts of biological events include fouling or plugging of service water or circulating water systems, silt/sediment deposition and buildup, Microbiologically Influenced Corrosion (MIC)/under deposit corrosion (e.g., leading to pitting, pin-hole leaks in raw water system piping and heat exchangers), etc. The specific types of biological events that are applicable to a plant depend on the environment (i.e., ultimate heat sink) that the plant is exposed to.

The typical chemical treatments include the use of dispersant to prevent silt deposition, corrosion inhibitor (e.g., inorganic phosphate by cathodic corrosion and scale inhibition), oxidizing biocide, and non-oxidizing biocide. Examples of oxidizing biocide are chlorine and bleach/bromine (which uses bleach to activate bromine). Due to the environmental pollution concerns, there is only limited-duration application of chlorine at nuclear plants. Oxidizing biocide is typically not compatible with stainless steel material used for tanks, piping, etc. Oxidizing biocide is generally ineffective for clams, but effective for most other biological growth. Chlorination by the use of Sodium Bromide in combination with Sodium Hypochlorite solution can be used for algae control and serves to prevent slime and algae growth in the raw water systems. Nuclear plants have been using Sodium Hypochlorite to replace chlorine for biological growth. However, it is less than effective in controlling microbiological fouling/corrosion. An example of non-oxidizing biocide is quaternary amine (clamicide) which can be used in addition to oxidizing biocide to treat clams and mussels. Non-oxidizing biocide has also been used to control aerobic slime forming bacteria and anaerobic corrosive bacteria.

The nature of this hazard does not really lend itself for easy calculation of the frequency of occurrence. As such, the evaluation of biological events is typically based on whether the chemical treatment performed at the plant can effectively control the biological/microbiological growth or intrusion. The biological event hazard can generally be screened out from detailed evaluation because it occurs slowly and can be monitored, controlled, and mitigated.

3.3. External Fires

The category of external fires includes forest fires, grass fires, and nonsafety building fires. Forest and grass fires that occur outside the plant site boundary. Potential impacts from forest fires include loss or degraded offsite power, plant ventilation impacts (clogging of filters or isolation), degraded conditions (visibility and air quality) for plant personnel, or even failure of plant systems. Most nuclear plants are physically separated from fire hazards in the adjacent areas; i.e., the site is sufficiently cleared in adjacent areas so that forest or brush fires pose no safety hazards. In addition to the mitigating effect of the separation distances of potential fires from the site, the control room is equipped with smoke detectors and manually operated intake dampers to identify and isolate outside smoke, respectively.

The vegetative cover of land surrounding the nuclear plant sites is usually not significant. Also, the plant site itself typically has limited vegetation because it is mostly paved and the area in proximity of plant buildings is cleared to preclude the possibility of external fires damaging equipment or impacting control room operations. From time to time, Security may also require some vegetation removal outside the plant fence line. Therefore, because of the sparse vegetation and because the site is clear, fire cannot propagate to the site. In addition, the plant design and fire-protection provisions are adequate to mitigate the effects.

The main concern of fires in the non-safety buildings include fire damages to accident initiation and mitigation equipment contained in these buildings and propagation of fires from non-safety buildings to safety-related or Category I buildings causing damage to PRA equipment contained in the safety-related buildings. The fire protection program features typically do not differentiate between safety and non-safety buildings. The fire protection design, protection, and considerations are applied equally to both non-safety buildings and safety-related buildings. Reviews of the nuclear plant operating experiences indicate that the detection, response, and suppression for fire incidents in non-safety buildings are generally conducted in the same manner as the safety buildings.

3.4. Extraterrestrial Events

This category includes primarily the meteorite and satellite impact hazards. Both of these hazards have the potential to damage structures and outdoor equipment when they fall to the earth. Almost all meteorites would fragment during entry into the earth's atmosphere because of heating and aerodynamic forces and the fragments quickly decelerate to around 150 miles per hour. The frequency of meteorite impacts can be estimated by evaluating the fraction of meteorite impacting the earth with weights in excess of a specified value sufficient to cause damage to structures or outdoor equipment. Most of the man-made objects in earth orbit that are large enough to cause damage would burn up in the atmosphere before reaching the earth, but some survive reentry and fall to the earth. The frequency of satellite impacts may also be estimated by the frequency of man-made objects in excess of certain weight impacting structures of specific sizes. Both the meteorite and satellite impact hazards can be screened out based on low frequency of occurrence.

3.5. Extreme Temperatures and Selected Atmospheric and Weather Conditions

Fog, frost, hail, high summer temperature, ice cover, low winter temperature, and snow are included in this category. Impacts from fog include poor visibility and humid conditions. Due to the installation of security barriers around the plant facilities, any increased traffic accidents due to heavy fog are not expected to lead to vehicle impact with critical plant structures. Nevertheless, the impacts of fog on traffic accidents are accounted for in the general vehicle accident rates.

Compared to the snow and ice hazards, frost has less occurrence and its impacts on the plant equipment are less severe. For plants located in cold weather regions, cold weather operation is usually assured in that the yard piping is buried below the frost line and outdoor piping serving transformers is of the dry pipe design. Most systems are generally located in heated areas and are not subject to freezing conditions.

The main concern for hail is damage to structures or outdoor equipment from impact. However, most nuclear plant buildings are designed to withstand impacts and loadings greater than those caused by hail. Outside electrical equipment and offsite power could be affected by hail, but given the low frequency of severe hailstorms, their effects are covered under equipment and offsite power failure rates in the Internal Events PRA. In addition to the outdoor transformers and switchyard equipment, there are additional pieces of PRA equipment also exposed to the inclement weather. These include tanks, tank level transmitters, manual valves, check valves, outdoor diesel generator radiator, outdoor diesel generator radiator cooling fans and air flow switches, and expansion joints. In general, the function of the outdoor tanks as a water source would not be affected by hailstone impact because only the top of the tank could be hit by hailstones and any possible damage to the tank top would not lead to the loss of the tank water. For the manual and check valves, no functional damage could result due to the robust design of the valve body. For the tank level transmitters, there are usually enclosures that are sufficiently robust to prevent hail damage. Since most of the outdoor diesel generator radiator cooling fans and air flow switches are located underneath the outdoor diesel generator radiator, they are not directly exposed to the hail impact. With respect to the expansion joints, they are often protected by enclosures which should be sufficient to prevent hail damage.

As such, the only piece of outdoor PRA equipment that could potentially be damaged by hailstone impact is the outdoor diesel generator radiator cooling coils. However, the top of the outdoor diesel generator radiator cooling coils is typically covered by a metal mesh structure which is judged to be built with sufficient strength to withstand the impact of the largest hailstone expected. The impact with the metal mesh is expected to cause the disintegration of the hailstone thus preventing any subsequent damaging impact with the radiator cooling coils down below. However, even in the event that the falling hailstone penetrates through the openings in the metal mesh structure, the amount of energy and fall speed would decrease substantially after contact with the metal mesh structure. Besides, the size of the hailstone that can actually hit the radiator cooling coils down below would be reduced to no greater than the size of the holes in the metal mesh structure. As such, the hailstones would most likely be either stopped by the metal mesh structure above the radiator cooling coils or reduced to a smaller size with substantially lower speed and impact energy after penetrating through the holes in the metal mesh structure.

High summer temperatures can potentially impact air-conditioning, heating, and ventilation (HVAC) system efficiency, the UHS, offsite power reliability, or the electrical system. Typically, the indoor heat loads resulting from the highest temperature ever reached are still within the design conditions for the HVAC systems. For the consideration of indoor temperature based on the air conditioning loads resulting from the indoor heat gains due to solar radiation and convection through the concrete walls, the site design base temperature may still be conservative, even if the actual outdoor temperature is higher. The calculated hourly indoor heat gains are usually greater for every hour using a constant design outdoor air temperature than they are using the actual outdoor air temperature experienced. Therefore, even though the outdoor temperature may occasionally exceed design temperature for a short time period, the actual heat loads experienced indoors are still below and bounded by the design conditions. The maximum water temperature in the UHS must also be shown to be below the UHS design temperature.

The most important effects of ice cover are ice jam flooding and blockage causing impacts on the cooling water intake. Normally, ice jams form at obstructions and irregularities such as bridge piers, islands, sharp bends, and at the upstream edge of a reach of solid ice. The water level behind the ice jam increases rapidly until the head and/or more ice flow destroys the plug. The characteristics of the

UHS usually contribute to a very low possibility of an ice jam forming. Heavy water traffic and the mitigating effect of warm water discharges from industry upstream can also reduce the possibility of ice jam formation. Blockage of the intake and thus the inability to supply with sufficient water could occur by means of ice floes plugging the front of the structure or by formation of ice on the trash racks or traveling water screens. Typically, intake withdraws water from several feet below the water surface; it is unlikely that ice floes could pile up in such a way as to block a significant portion of the intake opening. In addition, the cleaning mechanism for the trash racks should remove ice just as it removes leaves, branches, and other debris should the broken ice floes pass through the intake opening and block the trash racks. As such, blockage of the intake by accumulation of floating ice on the racks and screens is not expected to occur. Also, due to the size of the ice blocks that may be formed, the physical impact of ice on the intake structure does not typically present a hazard to the safe operation of the plant. Therefore, the formation of an ice jam that would cause a significant rise in the water elevation or that would physically block the intake structure is unlikely to occur.

Low winter temperatures can result in freezing of water in pipes, tanks, or reservoirs. Plant design usually protects against freezing and accounts for the possibility of water in pipes freezing. Typically, outside pipes are either installed underground below frost line or have insulation and heat tracing provided to prevent freezing of the pipes in unheated spaces. For example, freezing in the Refueling Water Storage Tank (RWST) during cold weather periods is prevented by the RWST insulation and by maintaining the RWST temperature above the minimum temperature specified in the Technical Specifications. Heat tracing is provided on all RWST connecting lines exposed to the weather. Cold weather operation for the fire protection system is assured in that yard piping is buried below the frost line and outdoor piping serving transformers is of the dry pipe design. All other portions of the fire protection systems are located in heated areas and are not subject to freezing conditions. Although rarely, the UHS water temperature does occasionally during the extremely cold condition decrease to below the freezing point for a brief period of time. However, because of the turbulent nature of the water flow, the UHS water in the intake structure suction bays will usually not freeze because the duration of below freezing temperatures is short. The most significant impact of the low winter temperatures is freezing of the accident initiation and mitigation equipment/functions. However, because of the short durations of below freezing water temperatures, the freeze protection design of systems and equipment, and the slowly developing impacts of this type of hazard, low winter temperatures can usually be screened out.

Excessive snow can result in additional loading on roofs, impacts on onsite and offsite power, and flooding during melting. Protection from rain, ice, snow, and lightning is typically inherent in both plant building and electrical system design. Buildings are usually designed to withstand impacts and loadings greater than those caused by snow. For containment structure, the roof is designed to support at least 30 lb/ft^2 of snow loading on projected area. For buildings except containment, the roofs are likely designed with a live load (including snow load) of at least 30 to 40 lb/ft^2. The piping which is exposed to atmospheric conditions is also protected from clogging due to ice and snow. Because the design snow load typically exceeds the highest snowfall that can be realistically expected and the roofs over Category I components are constructed such that they can safely hold a minimum depth of rainfall, the snow hazard can usually be screened out.

Historic data does exist for these weather conditions. However, the actual occurrences of extreme weather conditions to the extent of beyond the plant design basis are still rare. As such, the screening of these hazards is still based primarily on the capability of the plant design to preclude damages that may result from these hazards.

3.6. Geologic Conditions or Soil Related Events

This category of hazards includes avalanche, coastal erosion, landslide, sinkholes, soil shrink-swell, and volcanic activity.

Avalanche is strongly dependent on the plant site and surrounding topography. This hazard can typically be screened out if there are no mountains near the site, or snow and ice do not accumulate around the site because of mild weather. Coastal erosion involves the erosion of the coastal properties caused by such weather phenomena as hurricanes or other severe storms. However, individual storms may not be sufficient to cause damage to plant structures. The extent of impact by this hazard can be monitored by shoreline survey for shoreline movement, field measurements, map measurements, aerial photograph comparisons, etc. This hazard can be screened out if there is a long spatial separation between the shoreline and plant structures, or if the plant is not located near a coast. The landslide hazard can be screened out if the topography of the areas surrounding the site indicates no immediate adjacent hills or mountains that are susceptible to landslide and could impact the plant structures and critical equipment (i.e., the areas that are most susceptible to sliding are sufficiently removed from the main plant areas to present significant risk in the event of a landslide).

Sink hole are generally caused by karst processes. Sinkholes are common where the rock below the land surface is limestone, carbonate rock, salt beds, or rocks that can naturally be dissolved by ground water circulating through them. The mechanisms of formation involve natural processes of erosion or gradual removal of slightly soluble bedrock (such as limestone) by percolating water, the collapse of a cave roof, or a lowering of the water table. Minor sink holes may also be created by leaking underground pipes. In general, however, the types of soils at the plant site and the groundwater level determine if this hazard would occur. During plant excavation and construction, any soils exposed that may cause this hazard would be removed and backfilled with concrete or soils that would not impact the integrity of the foundation of plant structures.

With respect to soil shrink-swell, due to their physical and chemical properties, some clays may swell (expand) when water is absorbed (i.e., wet), and shrink (contract) when the water dries up (i.e., dry). Significant expansion or contraction due to changes in moisture content can damage the foundations of the plant buildings/structures. Typically, during construction, the looser near surface soils and clay soils would be removed and replaced with densely compacted soil (e.g., granular fill), and the safety-related buildings and structures would be founded on bedrock or on compacted granular fill and medium dense to dense in situ granular soils. As such, these buildings/structures are not expected to be affected by any subsurface soil shrink/swell consolidation that may occur.

There are two types of volcanic activities, explosive and quiet flows of lava. Either could impact site structures if they occur nearby. The ash from an explosive eruption could threaten the UHS and also lead to additional roof loading. The only active areas of the contiguous U.S. for volcanic activities are in the Pacific Northwest.

This group of hazards are strongly dependent on the local geologic and soil conditions in the vicinity of the plant. As such, these hazards do not easily lend themselves to frequency assessment. The evaluation of these hazards focuses primarily on the applicability of the conditions that cause these hazards to the plant proximity.

3.7. Heavy-Load Drop

Failures of cranes during movement of heavy loads (e.g., equipment, structures, etc.) could cause impact damage to risk-significant equipment causing loss or degradation of accident mitigation functions. This hazard is typically managed by station procedure for heavy load lifting. Prior to raising any boom or lifting device, usually, the entire work area must be surveyed to ensure adequate clearance exists between systems, structures, components, etc. Generally, a second person must also be used for verification during all boom or lifting activities. The evaluation of this hazard can be performed by examining the procedures intended to preclude the hazard and postulating scenarios that may result from the combinations of failure to observe the procedure and malfunction of the lifting device or other relevant equipment.

3.8. Industrial Accidents

This category of hazard events includes industrial or military facility accident, pipeline accident, release of chemicals from onsite storage, and toxic gas. The main concerns of these events are release of toxic or asphyxiant gas that may cause control room habitability problem, overpressure resulting from flammable gas or chemical explosion damaging critical plant structures and outdoor equipment, explosion-generated missiles impacting critical plant structures and outdoor equipment, and thermal radiation from fires caused by ignition of the flammable materials released.

The key in the evaluation of all of the hazard events in this group is to identify the specific hazardous chemicals that may be released within the hazard impact range from the critical plant area. For pool fires, jet fires, flash fires, and Boiling Liquid Expanding Vapor Explosion (BLEVE) fire balls, the impact range of thermal radiation from these fire hazards is usually shorter than the distance between the critical plant area and the closest offsite facility if the flammable/combustibles are ignited offsite.

For the release of flammable gases which are lighter than air (e.g., natural gas), in general, they will quickly dissipates in the air to concentrations below the lower flammability limit. As such, the risk from the release of lighter-than-air flammable gas is usually not significant unless it is close to the critical plant area. For heavier-than-air flammable gases (e.g., propane), however, it takes much longer distance to disperse to concentrations below the lower flammability limit. They tend to remain close to the ground and drift with the wind until it is encountered by an ignition source or dispersed to concentrations below the lower flammability limit. Ignition of a flammable gas can result in a flash fire (which could flash all the way back to the release source) or vapor cloud explosion (VCE) which could cause overpressure damage or explosion-generated missile impact to the critical SSCs in the plant. The criterion used for the consideration of damage to SSCs due to explosion overpressure is typically 1 psi. In terms of explosion-generated missiles, SSCs could be considered damaged if the explosion fragments can fly sufficient distance to reach the SSCs considered. Of course, a more detailed analysis can also consider if the missile that reach the plant has sufficient energy to penetrate the building exterior walls.

Flammable gases may be stored at nearby industrial or military facilities, transported in nearby pipelines, or kept in onsite storage locations. The distance from the release point at which the flammable gas has dispersed to concentrations below the lower flammability limit can be calculated using dispersion analysis software program. For the kind of flammable gases that may be present onsite, transported in the nearby pipeline, or stored in nearby industrial or military facilities, VCE in the form of deflagration can only occur in confined or congested spaces. For such explosive charge as dynamite, detonation could occur and would produce blast pressure and impact range significantly greater than that generated by deflagration. The other type of explosion that may also occur is BLEVE resulting from excessive external heating of the storage vessels containing selected flammable liquids (e.g., propane) due to a pool fire or a jet fire.

For the evaluation of toxic gas, the analysis determines if, after dispersion from the release point to the control room ventilation intake, the concentration of the toxic gas is above the toxicity limit at the control room ventilation intake or inside the control room. Although not toxic, some gases stored onsite or offsite (e.g., propane, nitrogen, CO_2) may still be hazardous to the control room operator because they can cause asphyxiation by displacing sufficient oxygen in the air. The dispersion and concentrations of toxic gas or asphyxiant as a function of distance from the release point can also be calculated using a dispersion analysis software program which would use such input atmospheric data as wind direction, wind speed, and atmospheric stability. Typically, releases of toxic or asphyxiant gases from offsite locations would not result in control room habitability issue due to the sufficient dispersion distance.

The screening of chemicals that may potentially be hazardous may use criteria such as solid chemicals; chemicals with all hazard ratings less than 3; chemicals with vapor pressure at ambient conditions less than 10 torr; chemicals with flash point in excess of 100^{o}F (or flammability rating < 3), but no asphyxiation and toxicity concern; chemicals of small quantities (e.g., with storage weights less than 100 lbs, individual storage container no greater than 5 gallons), etc.

3.9. Lightning

Lightning strikes can damage onsite electrical equipment and can impact the availability of offsite power. Protection from lightning is generally inherent in both plant building and electrical system design. Lightning grounds have typically been provided where necessary to prevent lightning from adversely affecting the plant. Lightning arrestors are usually provided for station service transformers, main transformers, and various buses, which are located in the switchyard.

Partial or complete loss of offsite power due to lightning or other causes have been examined as part of the Internal Events PRA, and other effects of lightning on nuclear power plants are generally insignificant. The approach used with respect to the evaluation of lightning is to review all the lightning events that have occurred at the plant site and determine the impact of the lightning events on the plant. If the impact of lightning is no more severe than the loss of offsite power with respect to plant safety, then no further analysis is necessary because they have already been accounted for in the Internal Events PRA. Otherwise, a probabilistic analysis to determine the lightning strike frequency and the lightning-induced core damage frequency would be needed.

3.10. Marine and Ground Transportation Accidents

The group of marine and ground transportation accidents includes such hazards as ship impact, vehicle impact, and vehicle or ship explosion. Generally speaking, toxic gas (which was already discussed previously under the group of industrial accidents) can also result from these transportation accidents. Ground transportation includes both trucks and railways. Due to the terrorist protection measures, the risk of vehicle impact at nuclear plants has reduced substantially. All U.S. plants have very strict vehicle control programs. In addition, vehicle barrier systems and other physical barriers are installed in every part of the critical plant areas. Also, due to the separation distance between the critical plant areas and the adjacent main roads or highways, truck accidents offsite causing physical impact to the onsite SSCs are extremely unlikely. For waterway traffic, the only credible ship impact is with the intake structure. For many nuclear plants, some kind of structures (e.g., breakwater, reef) may be present that can keep strayed or floating marine vessels from colliding with the intake structure. Nevertheless, the evaluation of ship impact can be based on the determination whether the intake structure can withstand the impact of the largest marine vessels allowed in the nearby waterways. The effects of vehicle or ship explosion are similar to those discussed for the industrial accidents. The evaluation needs to determine the kinds of chemicals in addition to gasoline that may be carried by trucks, railroad cars, and marine vessels that may use the nearby waterways.

3.11. Site Flooding

The category of site flooding includes such hazards as external flooding, high tide, intense precipitation, seiche, storm surge, tsunami, and waves. External flooding can result from a number of different sources of water; e.g., intense precipitation, snow melt, river flooding, dam failures, hurricane in conjunction with storm surge and waves, high tide in combination with waves, intense precipitation in combination with snowmelt, intense precipitation in conjunction with dam failure, intense precipitation in conjunction with snow melt and river flooding, etc. The primary analysis for external flooding is to evaluate the water surface elevations and determine if the maximum water surface elevation would exceed the grade level causing intrusion of the flood water into the critical plant buildings. The estimation of the site water surface elevations involves the analysis of the rate of water addition (e.g., the hydrological analysis) and the hydraulic analysis to determine onsite water flow and runoff depth.

Seiche may be generated by meteorological effects, wind, seismic activity, or tsunamis. It is only applicable to plants located near a large body of water where surge or seiche flooding could be a credible source of flooding. By itself, high tide is usually protected by the plant design. As such, for site flooding evaluation, high tide is considered in combination with other meteorological and/or hydrologic conditions that may occur in the plant area. As listed previously, intense precipitation may also occur in combination with snow melt, dam failure, high tide, storm surge, and waves to result in the maximum water surface elevations possible at the plant site.

Both the low pressure weather system (e.g., during a hurricane or typhoon) and wind can cause surges in the water level. With sufficient speed and duration, the wind could move the surface waters from one position to another, causing an increase in the water level. The magnitude of the wind induced surges and waves depend primarily on the wind speed, the distance over the water the wind blows, and the depth of the water. As such, a low pressure system associated with a hurricane/typhoon in combination with the wind generated by a hurricane/typhoon can induce a significant storm surge and waves. In addition, the precipitation that accompanies a hurricane/typhoon will further increase the water level. The evaluation of the increase in water level due to these natural phenomena is to some extent determined by the physical parameters used to model these natural phenomena. The maximum possible values of these parameters are, sometimes, difficult to determine because they may be affected, in some cases, by many other factors.

Tsunami can result from underwater earthquake, landslide, and volcanic eruption. The most severe tsunami is caused by underwater seismic activity occurring in the subduction zones off the coast where the tectonic plates join. Flooding induced by tsunami caused by landslide is more limited to its local area; i.e., has smaller impact area. Most nuclear plants are sited in locations far away from the subduction zone, landslide, and volcanic areas.

In general, the evaluation of the site flooding hazards is still deterministic in nature. Assessment of the frequency of occurrence of most of the natural phenomena in this group involves very large uncertainties because the data for beyond-design-basis extreme events can only be extrapolated from the historical records.

3.12. Turbine-Generated Missiles

The wheel capable of producing the largest missile is the last stage wheel of the low pressure turbine. Compared to low pressure turbine with shrunk-on disks, it is much less likely to generate turbine missiles for rotors consisting of the shaft with the turbine wheels as one forging. For some of the one-piece design, the speed capability of the rotors is higher than the maximum attainable speed of the turbine and the probability of missiles being generated from this rotor is not present. Turbine-generated missiles are thus not credible for the design. The turbine manufacturers will typically perform an analysis of the turbine reliability, which considers known and likely failure mechanisms (i.e., use data for crack initiation and growth) and expresses such failure probability in terms of the intervals between inservice inspection and test. The results of this analysis can be used for the evaluation of this hazard.

3.13. Ultimate Heat Sink Degradation/Loss

The ultimate heat sink provides the cooling water supply to the plant. The hazards that can affect the functionality of the ultimate heat sink include drought, low lake/river water level, and river channel diversion. When evaporation greatly exceeds precipitation for prolonged periods during a drought, a condition of low water level in the UHS may occur. In addition, severe wind could also cause tilted water level and possibly a low water level at the location of the plant cooling water intake. However, nuclear plants are typically designed with a large volume of water impounded to meet the cooling water requirements for an extended period of time even in the worst low UHS water level condition.

Another possible cause of low lake water level is the loss of lake water into a salt mine due to oil and gas drilling. In the 1980 salt mine drilling accident on Lake Peigneur, the Texaco's oil rig drilled directly into the Crystal Diamond salt mine instead of under the lake (caused by a miscalculation) which resulted in draining of the lake water and along with it 11 barges plus a tug boat.

Upstream river diversion cannot occur if the river valley is deeply entrenched in bedrock of sandstones and shales.

3.14. Extreme Winds

The wind hazards include extreme straight winds and tornadoes, hurricanes/typhoons, and sandstorms. Since the safety-related buildings at nuclear plants are designed as a minimum to withstand tornado wind pressure, these structures are generally more than capable to withstand the wind loading from the extreme straight winds. Compared to the wind loading for a hurricane/typhoon, the wind loading from a design basis tornado is usually more limiting.

The risk-sinficant impacts of tornadoes include the tornado wind loading and tornado-missile impact. Because Category I buildings are designed for earthquakes which represent significantly greater loading than tornado wind, they can withstand the strongest tornado that can be expected. As such, only the non-Category I buildings (e.g., turbine building) are likely to be damaged by tornado wind loading. In addition, outdoor equipment (e.g., switchyard, yard transformers, outdoor diesel generator radiator, etc.) may also be damaged. Therefore, the main impacts of tornadoes include the potential failures of the PRA equipment located outdoors and inside the non-Category I buildings (e.g., by building debris) as well as the potential failures of the operator actions that must pass through or are performed in the non-Category I buildings or on the yard. Nevertheless, the frame and concrete floors of the turbine building are expected to be largely undamaged in the event of a tornado. However, equipment in the turbine building at or above ground level could fail due to the effects of wind and debris.

To protect against tornado missiles, the exterior structure elements of safety related buildings are typically designed with missile barriers (e.g., greater thickness to prevent missile penetration). To evaluate the likelihood of SSC damage by tornado missiles, Monte Carlo simulation techniques may be used.

The concerns of sand and dust storms involve blockage of HVAC systems, impacts on the UHS, and effects on onsite and offsite electrical equipment. This is only applicable to plants situated at a location susceptible to this hazard (e.g., at or nearby a desert).

4. PLANT UNIQUE EXTERNAL HAZARDS

For each nuclear plant, there may also be a few unique or additional external hazards that are not listed in the ASME/ANS PRA standard. This may include such hazards as cottonwood debris, frazil ice, industrial sabotage, mayfly activity, military action, and solar flares. Industrial sabotage and military action are generally not evaluated in the PRA analysis.

For plants with raw water intake, frazil ice may, in general, form on the equipment/structure surfaces at the intake structure or pumphouse/forebay. Generically, for plants with intake structure located offshore at the bottom of the water, the most likely location of frazil ice formation is the intake surfaces at the offshore intake structure. For these plants, although frazil ice may also form on the trash rack and traveling screens at the pumphouse/forebay, it is usually less likely due to the various design protection (e.g., natural earth heating of the intake water in the underground intake tunnel, recirculation of the warm discharge water for suction during winter, and backwash of the traveling screen). For plants with intake structure serving both the intake and the pumphouse functions, the metal trash racks and traveling screens at the intake structure may, in general, get plugged with frazil ice, resulting in significant reduction of the available head, the blockage of the ultimate heat sink, and the freezing open of gates. However, the frazil ice phenomenon is a relatively slow developing event. The timing of the event is multiple hours before the phenomenon is obvious with a significant number of additional hours before sufficient flow blockage could occur and the unit would need to shut down. Also, the frazil ice conditions are short lived and usually pass after 12 hours.

Infestation of mayflies could affect offsite power and the associated outdoor electrical equipment. Mayfly activity may also cause blockage of roof drains. In addition, mayflies can potentially cause clogging of safety-related and non-safety related ventilation intakes and outside heat exchanger fans. An important plant measures to minimize the impact of mayflies involves inspections of areas where mayflies may collect. Reduction in station lightning prior to dusk keeps the mayflies from entering the plant. Frequent mayfly infestation checks during operator rounds and clearing of the ventilation intakes and mayfly fouling in the outdoors main transformer coolers and other heat exchangers help maintain the ventilation systems and electrical component cooling equipment functional. Checking and clearing mayflies from plant structures and roofs as well as flushing drain spouts to ensure no blockage have also been effective.

In addition to mayflies, cottonwood debris can also potentially cause similar impact on the HVAC equipment (e.g., clogging of ventilation intakes). To eliminate this problem, seasonal plant checklist needs to include clear instructions on the actions for protecting plant equipment from cottonwood debris. As part of the operator round checks which inspect equipment for mayfly fouling, operators should also examine clogging/blockage that may be caused by cottonwood debris.

A massive solar flare could potentially disable large portions of the U.S. electrical grid for an extended period of time (i.e., long-term, widespread power outages). As such, the primary impact of solar flares on the risk of nuclear plants is the potential to cause the loss of offsite power.

5. CONCLUSION

Since some of the other external hazards do not lend themselves to quantitative frequency analysis, the evaluation of other external hazards must be performed using a combination of deterministic and probabilistic methods. Quantitative frequency analysis of selected other external hazards may involve substantial uncertainties because the historic data may need to be extrapolated to derive the frequency of extreme events; e.g., selected natural phenomena.

Combinations of natural phenomena can realistically occur to produce the most severe impacts challenging the safe operations of the nuclear plants. Therefore, evaluations of the combination events are also essential part of the evaluation of other external hazards.

References

[1] The American Society of Mechanical Engineers and American Nuclear Society, "*Addenda to ASME/ANS RA-S-2008 – Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications*", ASME/ANS RA-Sb-2013, The American Society of Mechanical Engineers and American Nuclear Society, 2013, New York.