Screening of Other External Hazards in Generation III+ and Generation IV Nuclear Power Plants

Luke Fiely[a], Nicole E. Gaussa[b], Kyle D. Hope[c], Trent Kuhns[d], Richard W. Rolland III[e]
[a] Westinghouse Electric Company LLC, *luke.fiely@westinghouse.com*
[b] Westinghouse Electric Company LLC, *nicole.gaussa@westinghouse.com*
[c] Westinghouse Electric Company LLC, *hopekd@westinghouse.com*
[d] Westinghouse Electric Company LLC, *trent.kuhns@westinghouse.com*
[e] Westinghouse Electric Company LLC, *rollanrw@westinghouse.com*

Abstract: Generation III+ and Generation IV nuclear power plants have a higher degree of reliability and safety features present in their design and operation. As a result, the internal events probabilistic risk assessment (PRA) core damage frequency (CDF) for these plants is lower than legacy nuclear power plants, typically by at least one order of magnitude. Legacy plants (Generation II) typically screened out external hazards with CDF contribution less than 1.0E-06/year in accordance with the Level 1/Large Early Release Frequency American Society of Mechanical Engineers (ASME)/ American Nuclear Society (ANS) PRA Standard. Regulatory Guide 1.200, Revision 2 and Regulatory Guide 1.200, Revision 3 include a requirement related to external hazard screening that modifies the 1.0E-06/year CDF screening threshold for plants with lower risk profiles. The requirement states that the screening value should be adjusted to the baseline risk. An unintended impact of this requirement is that rare external hazards for more reliable plants require much more detailed analyses to support screening out the hazard on the lower CDF basis. In some instances, this can result in the conclusion that the hazard reaches near the limit where it cannot screen out, even though the hazard frequency is identical to legacy plants and mitigation strategies are similar. Examples of such hazards include meteorite / satellite impacts and solar flares. In some instances, the dominant contributor to the hazard frequency is from events that would result in regional or global destruction, so the effort to calculate a high-fidelity estimate of the frequency at this range seems to be of low value. This paper will further examine the challenges and propose suggestions on new approaches to screen these low-frequency hazards for plants with very low baseline internal events PRA CDF values.

Keywords: Probabilistic Risk Assessment, External Hazards, Screening

1. INTRODUCTION

A requirement for both current-generation and next-generation operating nuclear reactors is that they address, in one way or another, the risk from all hazards, operating states, and sources of radioactive material. The process for addressing external hazards for the PRA involves evaluating the risk from those hazards based on a set of qualitative and quantitative screening criteria that are established in Part 6 of the Level 1/Large Early Release Frequency ASME/ANS PRA Standard [4] (endorsed in Regulatory Guide 1.200 [1, 2]) and Section 1 of the ASME/ANS PRA Standard for Advanced Non-Light Water Reactors [3] which is referenced in the "for trial use" Regulatory Guide 1.247 [20]. If one or more of those criteria are met, then the hazard is screened out and does not require further modeling in the PRA. The quantitative screening criteria use the core damage frequency (or hazard frequency and conditional core damage probability (CCDP)) as the metric to evaluate whether screening is appropriate. For legacy plants, the value used for screening out hazards on the basis of CDF[1] is

[1] Alternatively, a hazard can be screened if it has a mean frequency less than 1.0E-05/year and a CCDP less than 1.0E-01 [4].

1.0E-06/year. Given that the "limit" for total risk where it is still acceptable to do voluntary risk-informed applications is CDF of 1.0E-04/year (Regulatory Guide 1.174, Figure 2 [5]), it is clear that the rationale for establishing the screening threshold at 1.0E-06/year is that such hazards represent a small fraction of the total risk (less than 1% of internal events CDF).

However, Section 1.2.5 of Regulatory Guide 1.200 Revision 2 [1], as well as Section C.1.2.6 of Revision 3 [2], include a caveat to this criterion that modifies the 1.0E-06/year CDF screening threshold for plants with lower internal events CDF risk profiles. The requirement states that the screening value should be adjusted to the baseline risk. For next-generation reactors with internal events CDF estimates on the order of 1.0E-06/year[2], establishing that an external hazard is a small contributor to overall risk (i.e., contributes less than 1.0E-08/year CDF or has a mean frequency of less than 1.0E-07/year and a CCDP less than 1.0E-01) can be much more challenging because estimates of the external hazard frequency are often needed at correspondingly lower values to support the screening assessment. The range of frequencies needed to support screening often goes well beyond what can be established from the observational record and therefore is subject to substantial uncertainty.

This paper will first discuss several example hazards and the complexities of screening these in Generation III+ and Generation IV nuclear power plants. After this discussion, proposed approaches will be discussed on potential paths forward to properly assess these hazards to continue to protect the health and safety of the public while providing for realistic risk-informed insights for nuclear power plant operations.

2. EXAMPLE HAZARD SCREENING FOR SOLAR FLARE

Solar flares can generate geomagnetically-induced currents (GICs) in transmission lines. These currents may overload or destabilize the power grid which could lead to a loss of offsite power (LOOP). This may be a long-term LOOP if transformers are permanently damaged. Solar flares may also have negative impacts on instrumentation and control (I&C) and communications systems, especially for digital instrumentation and control (DI&C) systems which are more common-place in next-generation plants [15].

For the example screening assessment presented in this paper, the solar flare hazard is discretized into three bins: low-magnitude, moderate-magnitude, and high-magnitude.

Low magnitude solar flares regularly hit the globe and have negligible, if any, effects. These low magnitude solar flares are typically screened out as a hazard due to the negligible risk to the electrical grid and nuclear power plant when below specified thresholds [17].

Moderate magnitude solar flares may result in a non-recoverable LOOP with no additional damage to PRA-modeled equipment in Generation III+ and Generation IV plants. An estimated frequency of a geomagnetic storm resulting from a solar flare stronger than the March 1989 solar flare event is 1.961E-02/year (Table 1 of Reference [17]). As the March 1989 solar flare event did not cause a LOOP at any nuclear plant, this gives additional confidence that there would be no additional damage beyond a LOOP. Therefore, the CDF contribution from the moderate-magnitude solar flare event is the product of the LOOP CCDP (on the order of 1.0E-06 or smaller) and the frequency for this type of event. The CDF contribution is on the order of 1.0E-08 per year, which is at the threshold limits.

---

[2] A Westinghouse **AP1000**® reactor, a Generation III+ design with passive safety features, has a reported internal events CDF value of approximately 4E-07. AP1000 is a trademark or registered trademark of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.

Large magnitude solar flares are those above the observational maximum. It is assumed that this magnitude of solar flare would be capable of damaging I&C systems in addition to causing a non-recoverable LOOP. The frequency of a solar flare capable of causing this consequence is estimated based on Section 7 of Reference [18]:

> *"Such flares would require that much of the solar surface be covered by strong kilo-gauss fields, exhibiting large sunspots that have not been recorded in four centuries of direct scientific observations and in millennia of sunrises and sunsets viewable by anyone around the world. For example, a flare with an energy of around 1034 ergs suggests a spot coverage of just over 10% of a solar hemisphere, which would be readily visible even to naked-eye observers if it occurred. Sunspot records suggest that no regions were observed in the past four centuries that could power flares larger than those observed in the most recent three decades."*

Therefore, the frequency of a solar flare exceeding the observed maximum energy (and resulting in failure of the non-safety systems) can be estimated based on a gamma distribution constrained noninformative prior distribution represented with no failures previously observed which is represented by a mean value of (observations + 0.5) / time. From the data of 0 observations in 400 years, the occurrence frequency for a solar flare of this magnitude can be calculated as 0.5/400 = 1.25E-03/year. The CDF contribution from solar flares of this magnitude is the product of the solar flare frequency and the CCDP for a LOOP with I&C systems unavailable (with the CCDP being on the order of 1.0E-06 or smaller). This would result in a 1.25E-09/year impact on a conservative end.

Combining the medium and high magnitude hazards results in a situation where the results can surpass the 1.0E-08 CDF criterion. Thus, screening out solar flares requires additional detail beyond the simple analysis shown here to screen based on the 1.0E-08/yr CDF criterion. This demonstrates the challenge for hazards with very few events in the observational record because refining this frequency estimate would likely require a more phenomenological (rather than statistical/frequentist) approach.

3. EXAMPLE HAZARD SCREENING FOR METEORITE AND SATELLITE STRIKE

The impact of a meteorite or satellite is screened out of legacy plants' external hazards PRA, but with a lower risk profile, this hazard may not meet the screening criteria. For example, the following equation can be used to estimate the frequency of a meteorite impact based on its size [7]:

$$\boldsymbol{Frequency\ of\ Impact}\ (> \boldsymbol{L}) = \mathbf{1.8368} * \mathbf{10^{-6}} * \boldsymbol{L_{km}^{-2.354}}$$

Where L_{km} is the minimum diameter of the length of the object in kilometers. The impact frequency of meteorites of various sizes can be seen in Table 1 (note that these values can be applied generically anywhere on Earth):

Table 1: Frequency of Impact for Various Size Ranges

Diameter of Object (m)	Frequency of Impact (per year)
Greater than 1500	7.07E-07
1250 to 1500	3.79E-07
1000 to 1250	7.51E-07
900 to 1000	5.17E-07
800 to 900	7.52E-07
700 to 800	1.15E-06
600 to 700	1.86E-06
500 to 600	3.28E-06

Table 1: Frequency of Impact for Various Size Ranges	
Diameter of Object (m)	**Frequency of Impact (per year)**
400 to 500	6.49E-06
300 to 400	1.54E-05
200 to 300	4.99E-05
100 to 200	3.34E-04
75 to 100	4.02E-04
50 to 75	1.30E-03
25 to 50	8.73E-03
10 to 25	8.29E-02
3 to 10	1.50E+00

Table 1 demonstrates that a more detailed approach must be taken to screen meteorites by size since the frequency impacts of meteorites varies greatly depending on the frequency of impact and the relatively high (compared to internal events CDF) impact of the meteorite risk. The approach to screening meteorites discretizes the hazard according to the expected consequences at site so that the various portions of the hazard curve can be associated with different CCDP values.

A direct impact to the site could cause core damage directly, with even the potential of complete destruction of the site and surrounding area. For a simplified conservative analysis, a bounding effect must be determined from potential consequences of a direct impact including seismic effects, thermal effects, ejecta, air blasts, and tsunamis induced by an impact off the coast. For this example, a land impact is assumed. Since the impact frequencies from the equation above represent frequency of impact anywhere on Earth, the frequency of impact at a specific site can be calculated based on the chance of the site being impacted by the calculation of the direct impact radius via the impact simulator [7]. any impacts beyond this radius could have indirect effects to the plant. These indirect consequences include a disturbance of the power grid which could result in a LOOP at the plant.

Air blast is most likely the bounding consequence of a meteorite strike from a direct impact as it encompasses a large area, so it will be used for this example, with a conservative windspeed of 100 mph[3] for damage to occur at a nuclear power plant. Using the impact simulator for assessing windspeed at distances until 100 mph is found [7], a "radius of damage" can be identified which is used to find the area surrounding a plant where a meteorite impact would lead to devastation. The other values needed to assess the impact effects using the simulator are assumed for the purposes of this paper to be:

- Projectile Density: According to Reference 9, the average density of an impactor is 2,700 kg/m^3. The simulator has a "dense rock" setting for 3,000 kg/m^3. This is used as a slightly conservative density for each impact assessment.
- Impact Velocity: According to Reference 10, the average speed of an impactor is 23 km/s. This is used for each impact analysis.
- Impact Angle: The impact angle used is 45 degrees, since this is the most expected impact angle [7].
- Target Density: The meteorite is assumed to impact sedimentary rock. Any other impact assessment would have to be location-specific for any other ground compositions or potential water impacts.

[3] It is recognized this is a conservative value and that Generation III+ and Generation IV plants can likely withstand higher wind speeds. Accurate wind speed thresholds would still result in further refinement requirements based on experience of other external hazard screenings for a Generation III+ plant.

The radius of damage and adjusted frequency based on the ratio of the area of damage and the total area of the Earth (5.10E+08 km^2) [19] can be found in Table 2.

Table 2: Adjusted Impact Frequency for Various Size Ranges		
Diameter of Object (m)	**Radius of Damage (km)**	**Adjusted Frequency of Impact (per year)**
Greater than 1500	1350(1)	7.94E-09(2)
1250 to 1500	400	3.74E-10
1000 to 1250	340	5.34E-10
900 to 1000	270	2.32E-10
800 to 900	240	2.67E-10
700 to 800	215	3.27E-10
600 to 700	185	3.92E-10
500 to 600	160	5.17E-10
400 to 500	135	7.28E-10
300 to 400	110	1.15E-09
200 to 300	80	1.97E-09
100 to 200	50	5.14E-09
75 to 100	26	1.67E-09
50 to 75	22	3.89E-09
25 to 50	24	3.10E-08
10 to 25	1(3)	5.11E-10
3 to 10	1(3)	9.25E-09

Note (1): For objects greater than 1500 m, a size of 5000 m was used to identify the radius of damage.

Note (2): Meteorites of this size are associated with planet-wide impacts. Therefore, the "damage area" is the entire Earth, and an "adjusted" frequency which diminishes the impact frequency by the ratio of the "damage area" to the surface area of the Earth may be optimistic for this case.

Note (3): A conservative 1km radius of damage was set since these sizes only cause direct hit damage.

The total frequency of impact from Table 2 is 6.15E-08/year which would be over the screening criteria for a Generation III+ or Generation IV plant under the current guidance thresholds adapted for a low internal events CDF plants and therefore requires additional refinements and analysis to reduce below the other external hazard threshold. Additionally, this assumes that greater than 1.5km meter meteorites would have a reduced impact on the plant based on their impact location even though a global catastrophe is possible. Further detailed analysis that would be undertaken to reduce conservatism in screening out the hazard exponentially increases the complexity. This preliminary analysis demonstrates that quantitative screening of meteorite impact is not trivial, even for sites where meteorite-induced tsunamis are not a consideration and taking into account an assumed reduction impacts on greater than 1.5 km meteorites. Additionally, further complexities are added once evaluation of artificial satellites is taken into account.

Another factor is the impact of broader devastation from larger impacts. A meteorite of at least 1.5 km in diameter impacting anywhere on Earth puts a large fraction of the population at risk of fatal consequences due to the impact [8]. A large enough impact from a meteorite is associated with devastating regional effects including ejecta, seismic effects, and air blasts affecting a radius around the impact site, while also causing globally destructive effects such as climate catastrophe and mass casualties [8]. Option 3 of the proposed approach section below suggests that impacts of this size or larger could be screened from consideration since the resulting widespread effects are much more damaging than a core damage or large early release event from a nuclear power plant. Even if elimination of the frequency associated with 1.5 km diameter meteorites occurs, the total frequency of impact would still be above the threshold and require further refinement.

4. CONSIDERATION OF VOLCANO SUPER-ERUPTION

Other rare events, such as the super-eruption of a volcano, may also require detailed assessments for next generation plants. A volcanic super-eruption is the highest measurable type of eruption, with a Volcanic Explosivity Index (VEI) of 8. Such an event releases 1,000 cubic kilometers of volcanic material (ash) and can result in pyroclastic flows reaching up to tens of thousands of square kilometers [9]. For areas within 60 miles of the volcano, the impacts would be catastrophic, most likely resulting in substantial loss of life [10]. The Yellowstone Caldera in Yellowstone National Park, has a history of having several super-eruptions. It is estimated by the United States Geological Survey (USGS) that the likelihood of a VEI-8 eruption for this volcano is 1 in 730,000 years, or a probability of 1.4E-06/year [6]. Although this probability is questionable given the limited data available, screening based on frequency alone[1,2] is unlikely to be plausible for Generation III+ and Generation IV plants. However, such an event is only applicable to certain areas (within 500 miles of a volcano super-eruption) [10]. For those areas that are located within 60 miles of the volcano, it can be argued that a volcano super-eruption should still be screened from consideration in the PRA, despite being greater than the screening threshold. In such an event, the destruction of affected locations within this distance would be so great that the entire area would be destroyed, and population impacts would be severe (see Option 3 of the proposed approach). For areas that are within 500 miles of a volcano, potential impacts could create a situation where core damage could be plausible with a further basis being required to assess if a new threshold of 1.0E-08/year for CDF would be screen-able.

This example has shown that screening out volcano super-eruption requires additional detail beyond the simple analysis shown here to screen based on the 1.0E-08/yr CDF criterion. This demonstrates the challenge for hazards with very few events in the observational record because refining this frequency estimate would likely require a more phenomenological (rather than statistical/frequentist) approach.

5. PROPOSED APPROACH FOR ADDRESSING VERY LOW-FREQUENCY HAZARDS

As shown in the examples outlined in Section 2, Section 3, and Section 4, the current approach for screening other external hazards in Generation III+ and Generation IV nuclear power plants presents several challenges. With the lower baseline CDF of these plants and adjusting the quantitative screening criteria to 1.0E-08/year CDF (consistent with Regulatory Guide 1.200 [1, 2]), the level of effort required to be able to screen very low-frequency hazards is much higher than the same process when applied to Generation II plants (screening criteria of 1.0E-06/year CDF). The question lies in whether this additional effort provides additional risk insights that can inform design and operation of the plant.

The purpose of performing a PRA is to estimate risk and ultimately use those insights to inform the licensing basis and design, with the ultimate goal being to ensure that safety of the general public is maintained [5, 15]. With those considerations, one must consider whether very low-frequency external hazards (1) have a significant impact on CDF and/or large early release frequency (LERF) and, (2) provide useful risk-insights. For example, a representative Generation III+ plant, the Westinghouse **AP1000®** reactor, has the following CDF values for the different hazards [11]:

- Internal Events: 4E-07

- Flood: 2E-07
- Fire: 7E-07
- Seismic Penalty: 9E-07
- Total: 2.2E-06

As shown in Figure 1, the seismic penalty and fire have the highest percentage contributions (41% and 32%, respectively) to the total CDF.

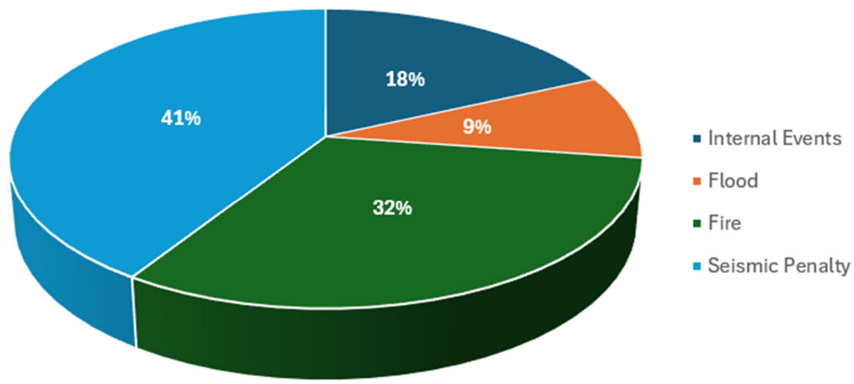

Figure 1 – Percent Contribution of Hazards to Total CDF[4] for Representative Generation III+ Plant

Despite Generation III+ and Generation IV reactors having increased safety compared to Generation II reactors [12], the screening of the same external hazards in a Generation III+ or Generation IV reactor becomes more of a challenge than for a Generation II reactor. This results in a significant amount of technical commitment in external hazard screening that does not measurably provide a benefit to the health and safety of the public. Therefore, it is recommended that the industry examines if improvements can be made to the current screening process while continuing to maintain the health and safety of the public. Some potential approaches are broadly outlined below, although these are not presented in any order of preference.

<u>Option 1</u>

For Generation III+ and Generation IV plants, it may be more beneficial to examine the impact of an external hazard on total CDF as opposed to just internal events CDF. In other words, a solution could be to develop an additional screening criterion that is based on all-hazards risk. Based on the representative Generation III+ plant described above, the all-hazards screening criterion would be less than or equal to 2E-08/year (approximately equivalent to 1% of the all-hazards risk). Ideally, this option would include a way to establish a screening criterion based on an all-hazards risk value that is not subject to frequent changes (i.e., some type of exemption from PRA configuration control).

As fire and penalties (e.g. seismic and high winds, depending on plant location) typically dominate results, the likelihood of another external hazard greatly impacting overall CDF is low. Additionally, the consideration of other external hazards is not likely to drastically impact what systems and components are considered risk important. Several risk-informed applications examine importance measures of components, and these importance measures are essentially weighted against each of the

[4] Figure 1 was generated using the data from [11].

hazards modeled in a PRA model when applications examine multiple PRA models. This is referred to as an integrated importance measure assessment (an example is shown in Section 5.6 of [14]). These hazards are not likely to provide additional risk insights into improvements of plant safety or for insights into implementation of risk-informed programs given the plant response for low frequency other external hazard initiating events likely doesn't differ from already modeled hazards and that their overall contribution to CDF would be relatively low compared to other hazards if modeled in detail in the PRA.

Option 2

Another concept to remember is that risk-informing the design can only be realistically completed against a devastating event that can be reasonably mitigated against. If a major devastation event occurs where the CCDP is equal to 1.0, regardless of the robustness of the design, the ability to risk-inform the design or provide risk-insights from this evaluation are minimal. The surrounding area is likely to be completely devastated as well from the event that caused the devastation of the nuclear power plant. Therefore, further refinements of the frequency of these types of hazards do not provide for additional risk insights in the plant.

The Nuclear Regulatory Commission (NRC) has developed Quantitative Health Objectives (QHOs) in order to risk-inform 10 Code of Federal Regulations (CFR) Part 50 and "assess the effectiveness of the regulation," which are as follows [13]:

- *"The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1%) of the sum of prompt fatality risks resulting from other accident to which members of the U.S. population are generally exposed."*
- *"The risk to the population in the area of nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes."*

These considerations of low frequency other external hazards do not provide beneficial risk-insights especially given that these hazards to the public near the nuclear power plant would be exposed to the external hazard as well, with the hazards themselves likely causing more of an impact than the fatality risk from a nuclear accident in the vicinity of the said event. Therefore, the current external hazard screening process is potentially exceeding the goals of the established QHOs. Furthermore, without providing useful risk insights, there is no benefit to analyzing these low frequency other external hazards for next-generation plants, particularly when these low-frequency external hazards can be easily screened out from detailed evaluation for Generation II plants.

Option 3

In scenarios where an event provides for such devastation to the continent or the Earth-wide population, there is likely not any significant risk insights that can be gained during the effort to screen these hazards. These near world-ending events are unfortunately at a high enough frequency that they require detailed consideration to support quantitative screening using the next-generation screening criteria. It is proposed that this range of the hazard (i.e., those magnitudes for which the CCDP is most certainly 1.0 and in addition are associated with even more devastating consequences for an area much larger than the plant) be screened from the assessment. For example, as discussed earlier, meteorites over 1.5 km are considered globally devastating since they put a significant fraction of the global population at risk of fatal consequences [8]. Any consequences of the plant are nearly meaningless with regards to health and safety of the public as the world population is essentially devastated from the event itself. Although this is potentially allowable under current guidelines based on past peer reviews, it is recommended that further guidance acknowledge this to avoid confusion in future analyses.

6. CONCLUSION

The solution to the problem presented in this paper is not immediately evident and will require input from many organizations throughout the industry including the NRC and Joint Committee on Nuclear Risk Management (JCNRM). However, it is evident that with the continued development of Generation III+ and Generation IV nuclear power plants, the existing screening criteria presents a unique challenge where the continued increasing safety of nuclear power plants requires further evaluation of these rare other external hazards. The overall intent of the screening criteria and developing PRAs may need to be re-visited as CDF and LERF (or, indeed other new risk metrics) of Generation III+ and Generation IV nuclear power plants continue to decrease. The industry should continue to focus on a risk-informed design where the focus is on analysis of impacts that can be used to further risk-inform the design, rather than spend significant engineering resources on evaluations on rare external hazards.

7. UPDATES

Section 3.0 had additional clarity added for meteorites of 1500m or larger.

A previous version of this paper identified in Section 5.0, Option 1 the value of 2E-10/year; it has been updated to 2E-08/year.

In Section 5.0, Option 1, a sentence in the final paragraph was reworded for clarity.

8. REFERENCES

[1] "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities," Regulatory Guide 1.200, Revision 2, U.S. Nuclear Regulatory Commission, 2009.

[2] "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities," Regulatory Guide 1.200, Revision 3, U.S. Nuclear Regulatory Commission, 2020.

[3] "Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants," ASME/ANS RA-S-1.4-2021, *ASME*/ANS, 2021.

[4] "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-Sa-2009, ASME/ANS, 2009.

[5] "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," Regulatory Guide 1.174, Revision 3, U.S. Nuclear Regulatory Commission, 2018.

[6] "Yellowstone Volcano," VolcanoDB, Website: https://volcanodb.com/yellowstone-volcano.

[7] "Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth" by Gareth S. Collins, H. Jay Melosh, and Robert A. Marcus, Meteoritics & Planetary Science 40, Nr 6, 817–840 (2005). Website: https://impact.ese.ic.ac.uk/ImpactEarth/ImpactEffects/.

[8] "Study to Determine the Feasibility of Extending the Search for Near Earth Objects to Smaller Limiting Diameters," NASA Technical Report, 2003.

[9] "Earth's Active Supervolcanoes: The VEI-8 Eruptions and Their Restless Calderas," OZ Geology, 2025, Website: https://ozgeology.com/en-us/blogs/news/earth-s-active-supervolcanoes-the-vei-8-eruptions-and-their-restless-calderas.

[10] "Yellowstone Eruption Warning: 'Normal Life Wining 500 Miles Impossible," Express, 2022, Website: https://www.express.co.uk/news/science/1548304/yellowstone-warning-supervolcano-eruption-us-volcano-news-spt.

[11] ML26029A439, "Southern Nuclear Operating Company Vogtle Electric Generating Plant Units 3 and 4 License Amendment Request to Revise Technical Specifications to Include Risk Informed Completion Times," NRC, 2026.

[12] "Advanced Nuclear Power Reactors," World Nuclear Associations, 2025, Website: https://world-nuclear.org/information-library/nuclear-power-reactors/other/advanced-nuclear-power-reactors.

[13] ML022120663, "Appendix C, Quantitative Guidelines from the Framework for Risk-Informing 10 CFR Part 50," NRC, 2002, Website: https://www.nrc.gov/docs/ML0221/ML022120663.pdf.

[14] ML052910035, NEI 00-04, Revision 0, "10 CFR 50.69 SSC Categorization Guideline," NEI, 2005.

[15] EPRI 3002005287, "Identification of External Hazards for Analysis in Probabilistic Risk Assessment," EPRI, 2015.

[16] NRC Information Notice 90-42, "Failure of Electrical Power Equipment Due to Solar Magnetic Disturbances," June 1990.

[17] Love, Jeffrey J., "Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms," Geophysical Research Letters, Vol. 39, 2012, Website: Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms - Love - 2012 - Geophysical Research Letters - Wiley Online Library.

[18] Schrijver, C.J. et al, "Estimating the frequency of extremely energetic solar events, based on solar, stellar, lunar and terrestrial records," Journal of Geophysical Research, Vol. 117, 2012.

[19] "Planet Earth's Playlist," United States Group of Earth Observations, Website: https://usgeo.gov/jazz-observatory/2023/stories/scienceonasphere.html?category=Blue_Planet.

[20] ML21288A018, "Regulatory Guide 1.247, 'Acceptability of Probabilistic Risk Assessment Results for Advanced Non-Light Water Reactor Risk-Informed Activities,'" NRC, 2021.