Safety case and external hazards

December 17-18, 2019

NRC Headquarters

Outline for public meeting

- Introduction to Oklo
- Introduction to the Oklo design
- Safety case and external hazard analysis

Introduction to Oklo

Introduction to Oklo

- Founded in 2013
- Awards – MIT 100k, MIT Clean Energy, MassChallenge, YCombinator
- Funded in 2015, additional fundraise in 2018
- Oklo awarded the most GAIN voucher value for use at national labs of any company
- Developing compact fast reactor – advanced fission battery as part of a microgrid clean energy plant

Market need

- Many remote areas currently employ diesel generators for electricity production, which are expensive, unreliable, and dirty
- In Alaska, over 200 microgrids bring power to rural residents
  - Alaskan residential electricity rates average more than 50 cents/kWh
  - 400 million kWh from diesel in Alaska statewide in 2013, costing $200M/yr
- Other isolated areas (e.g. islands) also spend significantly on electricity generation
  - US Virgin Islands spend about $240M/yr
- NRC stated priority for applications for high cost markets (CFR 50.43(b))

Oklo solution – advanced fission battery

- MW-scale to meet the needs of these communities
- Well-understood fuel and materials
- No moving parts in primary heat transport
- Reduced maintenance profile
- No offsite power dependence
- No emissions

Introduction to Aurora

Metal fuel

- Keeps fission products within the metal up to a certain burnup
- Resistant to cracking or chipping - does not pulverize
- Relative ease of manufacture, key properties insensitive to manufacture method
- High thermal conductivity and low specific heat
  - Lower peak fuel temperature and stored energy
  - Easier to dissipate heat from the fuel
- Large negative temperature reactivity coefficient
  - Metal fuel expands due to temperature increases
- Designed to have very low power density
- Utilize data from the IFR program, particularly EBR-II experimental data

Fuel - EBR-II

- EBR-II was a 62.5MWth, 19 MWe sodium-cooled fast reactor with metallic fuel
- EBR-II:
  - operated for 30 years
  - sold power to the grid
  - had higher capacity factor than fleet at the time
- Years of quality assured testing done with the EBR-II reactor

Fuel - EBR-II Shutdown Heat Removal Tests (SHRT)

- Performed on the same day (April 3rd, 1986)
- Two types of unprotected loss-of-cooling accidents
  - Loss of Flow Without Scram
  - Loss of Heat Sink Without Scram
- Performed on the actual, operating reactor at full power
- Started back up after both tests without damage

Fuel - EBR-II safety test takeaways

- “These are sensational results. Two of the most severe accidents that can threaten nuclear power systems have been shown to be of no consequence to safety or even operation of EBR-II. The reactor was inherently protected without requiring emergency power, safety systems, or operator intervention.”
  - -J.I. Sackett
  - “OPERATING AND TEST EXPERIENCE WITH EBR-II, THE IFR PROTOTYPE”, Progress in Nuclear Energy 31, 1-2, pp. 111-129, 1997.

Simple structures, systems, and components (SSCs)

- No pumps, valves, etc. in core or primary heat transport from core
- Passive and very efficient heat transport from core – heat pipes function as thermal superconductors
- About one hundred independent paths for passive heat transport from core
- No chemistry control required
- No pressure control required
- Minimal safety-related SSCs expected

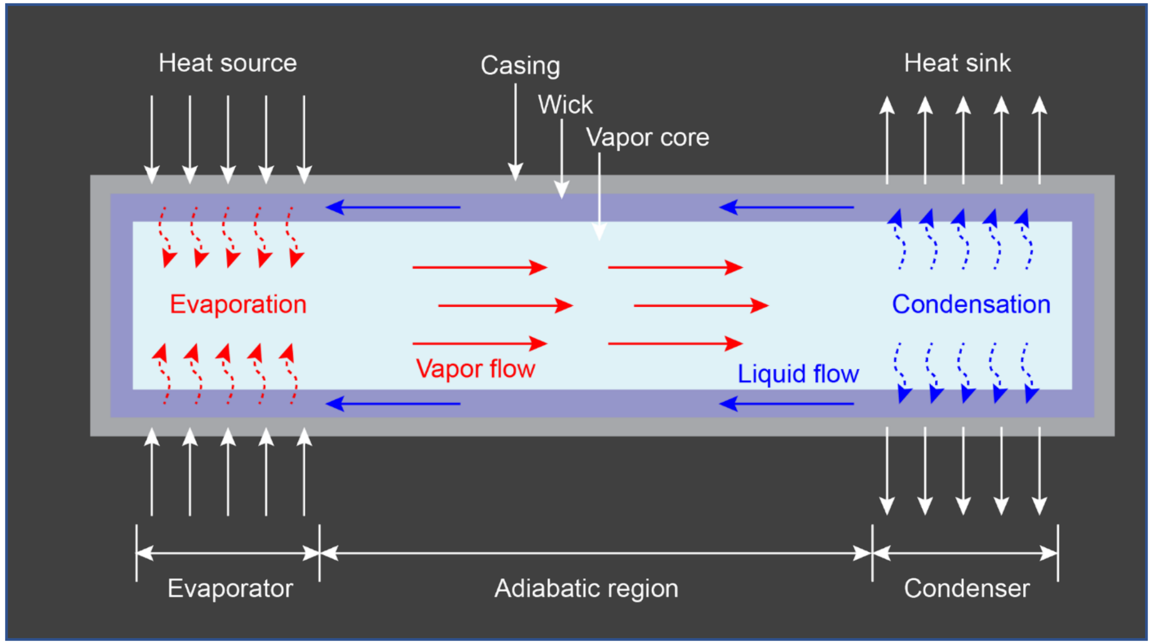
Other Aurora features

- Below-grade emplacement of the entire system offers simplicity, safety, and security benefits, such as mitigation of risk for events like:
  - Seismic
  - Aircraft impact
  - Tornado/high wind
  - Terrorist threat analysis
- Primary heat transport operates at sub-atmospheric pressure
  - No significant driving forces for release
- No periodic refueling intervals
  - Little to no fuel movement
  - Likely no heavy machinery onsite – no way of removing fuel

No offsite power dependence

- Driven by market needs – may be the only source of power
- Thus, designed without reliance on AC power
    - Loss of offsite power (LOOP) and station blackout (SBO) not a concern
- Very little decay heat – no active systems required
    - 1000x less than LWR
    - On the scale of a lawn mower engine within ~12 hours
- Backup sources of power still being evaluated, not needed for safety

Heat pipe operation



- No chemistry control
- No filtering
- No makeup inventory required
- No pressure maintenance required, operates at sub-atmospheric pressure
- No possibility for flow or temperature instabilities as in complex flow loops
- Long life data
- Irradiation data from EBR-II

OKLO

Safety case

Core concept of Aurora safety case

- Small reactor – smaller heat output than the MIT research reactor, decay heat at ~12h after shutdown on order of lawnmower
- Small source term – small, low-enriched fuel inventory + few physically possible ways to mobilize, very low burnup
- Lower power density than the NGNP reactor case

- Safety Goals:
  - Power with minimal risk to public health and safety and the environment
  - Regulatory limits can be met by inherent, physical characteristics as opposed to active or even passive systems

Maximum credible accident

- Used early in regulatory history for new plants
- The worst credible accident(s) caused by any single event or failure
- Reliance on deterministic analysis removes uncertainties introduced through reliance on risk analysis for a FOAK reactor, while Oklo can still show thorough analysis and incorporation of insights from advanced probabilistic risk analysis
- Further precedent for safety case and EPZ/site boundary for reactors of this size regulated by the NRC is shown through existing non-power reactors

Overview of safety case methodology

- Search for all possible initiating events
- Determine relevance to the Aurora design
- Group events into event categories
- Determine bounding events
- Select maximum credible accident
- Develop required safety functions

Safety case conclusion

- Maximum credible accident assumed the single most challenging failure
- Because of the small size of the Aurora reactor, the maximum credible accident is mitigated by the inherent features of the design
  - No safety-related active components
  - Long-term cooling and a safe state achieved solely through inherent means

External hazards

Design siting goal

- Design objective of the Aurora is the ability to be sited in the majority of the U.S.
- Traditionally, external hazards have been evaluated on a site-specific basis
- However, due to the small size of the Aurora and the simple safety case, it is possible to evaluate the design against the most extreme external hazards across the U.S. for most event types

External hazards methodology overview

- Traditional external hazards evaluations utilize probabilistic risk analysis (PRA) to determine which external hazards are likely to occur for a given site
- Deterministic analyses show the resiliency of the facility against extreme external hazards and obviate the need for further analysis, typically done by a PRA
- For most external hazards, the deterministic path is used for the Aurora

External hazards methodology goal

- A robust internal analysis is possible due to the simplicity of the Aurora, which resulted in a single bounding event – the MCA – and simply scoped the safety case
- The complementary piece to the internal analysis is a robust external hazards analysis that demonstrates the robustness of the MCA
- **Goal: To conduct a broad analysis of external hazards to assess if the MCA is still the worst credible accident including external events or there is phenomenology not captured**

Sources for external hazards

- Thorough literature review, including:
  - ASME/ANS RA-S-2008, “Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,”
  - ASME/ANS-RA-S-1.4-2013, “Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants,”
  - NUREG/CR-2300, “PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants,” and
  - NUREG/CR-5042, “Evaluation for External Hazards to Nuclear Power Plants in the United States.”

Identification of all potential external hazards

- 46 potential external hazards:
  - Aircraft impact
  - Avalanche
  - Biological events
  - Coastal erosion
  - Drought
  - External flooding
  - Fog
  - Forest Fire
  - Frost
  - Grass Fire
  - Hail
  - High summer temperature
  - High tide
  - High winds
  - Hurricane
  - Ice cover (causing blockage of river)
  - Industrial or military facility accident
  - Landslide
  - Lightning
  - Low lake or river water level
  - Low winter temperature
  - Non-safety building fire
  - Pipeline accident
  - Precipitation, intense
  - Release of chemicals from onsite storage
  - River diversion
  - Sandstorm
  - Seiche
  - Seismic event
  - Ship impact
  - Sinkholes
  - Snow
  - Soil shrink-swell
  - Storm surge
  - Tornadoes (extreme winds)
  - Toxic gas
  - Transportation accident
  - Tsunami
  - Turbine-generated missiles
  - Vehicle impact
  - Vehicle/ship explosion
  - Volcanic activity
  - Waves

Grouping of external hazards

- All potential hazards evaluated to determine challenge to facility
- Prescreened into event families based on a common challenge
- Most hazards can be screened into a few families due to the simplicity of the Aurora

Bounding deterministic analyses

- Next, a worst-case deterministic analysis was performed to analyze the severity of the external hazard to the Aurora
- These analyses are not site-specific – **intent is to demonstrate the robustness of the Aurora against extreme external events**
- The goal of this portion of the presentation is to give a summary of a few worst-case external hazards analyses
- **Goal: Evaluate the MCA against conservative deterministic external hazard analyses**

External hazards bound by a large explosion

- **Goal: To conduct a large blast analysis to assess if the MCA is bounding.**
- External hazards considered in this deterministic analysis consist of a large blast nearby the Aurora
- Example hazards:
  - Industrial or military facility accident
  - Pipeline accident
  - Transportation accident
  - Vehicle/ship explosion

External hazards bound by a large explosion (cont.)

- Components associated with mitigation of the MCA were analyzed for purposes of nearby external hazards that could result in an explosion
- Analysis shows that these components are extremely robust against blast pressures and other secondary blast effects
- **Conclusion: The MCA is still a bounding and worse event than possible with a large explosion, which are bounded by a large explosion.**

External hazards bound by a large earthquake

- **Goal: To conduct a bounding seismic analysis to assess if the MCA is challenged.**
- External hazards considered in this deterministic analysis can be bounded by analyzing the effects of a large earthquake – that is, building collapse and ground motion
- Example hazards:
    - Hail
    - High winds
    - Sandstorm
    - Seismic event
    - Snow
    - Tornadoes (extreme winds)

External hazards bound by a large earthquake (cont.)

- First, it is necessary to define what an appropriately large earthquake is, such that it would bound a worst-case earthquake in the U.S.
- Oklo conducted analysis to determine the maximum size earthquake that could occur in the entire U.S., based on historic data
- Peak ground acceleration determined that bounds entire U.S.
  - Peak ground acceleration is the maximum ground acceleration that occurs during earthquake, shaking at a specific location
  - Expressed in terms of “fractional gravitational acceleration” – or “g” – otherwise calculated as 32 ft/s^2

External hazards bound by a large earthquake (cont.)

- One example of a large earthquake is the 1994 Northridge earthquake in Los Angeles County
- Richter scale: **6.7**
- Peak ground acceleration (max. recorded in a single direction): **1.8 g**
- 57 deaths
- Highest ever instrumentally recorded in an urban area in North America

External hazards bound by a large earthquake (cont.)

- Next, an analysis was performed on the Aurora, which assumes:
  - A large ground acceleration on the entire reactor building and reactor
  - Potential damage to the reactor building
- Challenges associated with a large earthquake can be analyzed with a structural analysis only for the Aurora, because there are:
  - No reactivity effects associated with sloshing – no substantive liquid inventory
  - No reactivity effects associated with control rod oscillation – no control rods in core during normal operations
- The structural analysis examined:
  - Effects of large ground accelerations
  - Effects of a reactor building damage

External hazards bound by a large earthquake (cont.)

- Conclusion of the bounding U.S. analysis:
  - Reactor unchallenged
  - MCA remains bounding
- Oklo also performed a seismic analysis **beyond any peak ground acceleration ever recorded** to determine the acceleration required for **some** damage to the reactor or housings
  - Resulting earthquake size that would need to occur to damage the reactor is **greater than any earthquake ever recorded and is likely impossible**
- **Conclusion: The MCA is still a bounding and worse event than possible with severe seismic events**

External hazards bound by a large fire

- **Goal: To conduct a bounding fire analysis to assess if the MCA is the maximum credible accident.**
- External hazards considered in this deterministic analysis result in a potential fire in the facility
- Example hazards:
    - Lightning
    - Non-safety building fire
    - Pipeline accident
    - Transportation accident

External hazards bound by a large fire (cont.)

- Aurora incorporates fire protection in design – benefit of designing with many years of operating experience from other plants
- Plant has separate fire areas, which are comprised of fire-rated walls and doors
- Fires cannot spread from fire area to fire area
- **Conclusion: The fire external hazard does not present a significant accident in the Aurora design, and the MCA still represents the maximum credible accident.**

Questions

Break

Outline – day 1

- 1-1:15 PM | Introduction
- 1:15-2:15 PM | Safety case, external hazards (public)
- 2:15-2:30 PM | Break
- 2:30-4:00 PM | Safety case (closed)

Safety Case

Barriers

- Many barriers:
  - Fuel matrix (BISON analysis shows no anticipated fission gas release for Oklo burnup and geometry)(report: December 2017)

  - Heat pipe wall
  - Heat exchanger enclosure
  - Module layers

Barriers

- Many failures need to occur for release, through thick steel materials
- Slow progression accident because of small pressure differences

Fundamental safety functions

- Typically referenced from IAEA Specific Safety Requirements SSR-2/1, “Safety of Nuclear Power Plants: Design”
- Also included in NRC non-LWR Roadmap (ML17312B567)
- Three fundamental safety functions for nuclear power plants to be ensured for all plant states:
  1. Control of reactivity
  2. Removal of heat from the reactor and fuel store
  3. Confinement of radioactive material
- The fundamental safety functions are all ultimately met by inherent characteristics (not active or even passive systems)

Fundamental safety function analysis

Regulatory Safety Case

- There are many ways to analyze the safety case, and many ways to present the safety case in terms of what is credited, but the key is to meet regulatory language, precedent, and intent.
- The key safety features of the Oklo design are clear and based on adequate and qualified data where needed: extremely small source term, very low power density, and strong negative thermal reactivity coefficients.
- The most significant historical precedent is the maximum credible accident, which was present in U.S. nuclear regulatory history since the 1950s.

Historical Precedent

“In general terms, they [regulator staff] finally decided that an accident was in the maximum credible category if it was caused by the **one single equipment failure or operational error that would result in the most hazardous release of fission products**. Furthermore, no other postulated credible accident could exceed the consequences of this one.”

“In light-water reactors the regulators postulated the maximum credible accident as the complete rupture of a major or large pipe resulting in complete loss of coolant…”

- *Controlling the Atom: The Beginnings of Nuclear Regulation 1946-1962*, George T. Mazuzan and J. Samuel Walker, University of California Press, 1984, page 228. This book was later published by NRC as NUREG-1610.

Single failure

- **“one single equipment failure or operational error that would result in the most hazardous release of fission products”**
- The Oklo design does not allow for human error (or insider threat) to do anything other than shut down the reactor
- Which means analysis must focus on equipment failure caused by internal or external events

Safety case

Safety case

Overview of regulatory case

Regulatory safety case

- There are many ways to analyze the safety case, and many ways to present the safety case in terms of what is credited, but the key is to meet regulatory language, precedent, and intent
- The key safety features of the Aurora are clear and based on adequate and qualified data where needed: extremely small source term, very low power density, and strong negative thermal reactivity coefficients
- An important regulatory historical precedent is the maximum credible accident, which was present in U.S. nuclear regulatory history since the 1950s

Background on maximum credible accident

- The regulator decided that an accident was in the MCA category if it was caused by the one single equipment failure or operational error that would result in the most hazardous release of fission products; no other postulated credible accident could exceed those consequences
- For an LWR, this is a large break loss of cooling accident (LOCA)
  - Expansion of fuel
  - Flashing to steam
  - Partial meltdown
  - Partial release of fission products to the containment atmosphere

Historical precedent

“In general terms, they [regulator staff] finally decided that an accident was in the maximum credible category if it was caused by the **one single equipment failure or operational error that would result in the most hazardous release of fission products**. Furthermore, no other postulated credible accident could exceed the consequences of this one.”

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Background on maximum credible accident (cont.)

- However, NUREG-0800 states the following:
- Although the loss-of-coolant (LOCA) is typically the maximum credible accident associated with the light-water reactor design, **the applicant should consider other accident sequences of greater radiological consequence for the specific reactor designs selected by the applicants or for reasonably foreseeable future reactor designs**…
- Intent is clear – provide reasonable assurance that the greatest potential consequence of any credible event have been identified
- The regulation does not specify consideration of a core meltdown

Background on maximum credible accident (cont.)

- The Commission's "Policy Statement on the Regulation of Advanced Reactors" also states that:

  > "…the Commission expects that advanced reactors will provide enhanced margins of safety and/or use simplified, inherent, passive, or other innovative means to accomplish their safety and security functions."

- It follows that advanced reactors could have such low probability of accidents yielding significant release of radioactivity that such accidents are not credible or possible

Maximum credible accident

- Reliance on deterministic analysis removes uncertainties introduced through reliance on risk analysis for a FOAK reactor, while Oklo can still show thorough analysis and learnings from advanced probabilistic risk analysis
- Further precedent for safety case and EPZ/site boundary for reactors of this size regulated by the NRC is shown through existing non-power reactors

Safety case

Analysis methodology

Overview of methodology

- Search for all possible initiating events
- Determine relevance to the Aurora design
- Group events into event categories
- Determine bounding events
- Select maximum credible accident
- Develop required safety functions

Key design features

- Low decay heat
- Small power density
- Small inventory

Safety principles

- The safety principles of the Aurora are the following:
  - To provide power with minimal risk to the public health and safety and the environment
  - To restrict the likelihood and consequence of abnormal events by inherent, physical characteristics as opposed to active or even passive systems

Defense-in-depth principles

- Defense-in-depth is considered throughout the Aurora design, including:
    - Small thermal power and low burnup fuel results in limited available source term
    - Inherent reactivity feedback ensures reactor power is controlled
    - Multiple barriers for fission product release
    - Robust passive design ensures adequate heat removal during design basis events
    - Inherent safety characteristics of high-conductivity components and high thermal capacity
    - Slightly sub-atmospheric heat transport limits driving forces for release

Initiating event selection

- Search over operating lifecycle, all sources of radioactivity, and the range of operating modes and conditions for the Aurora
- Review generic events to all nuclear reactors
- Review metal-fueled fast reactor operating experience
- Review compact reactor operating experience and analytical methods
- Review light water reactor events
- Review expert opinion on similar conceptual designs
- Not further discussed in this presentation – part of the PRA

Event categorization

- Iterative process
- Can categorize by type of event or by frequency of occurrence of the event
- Focus in this presentation is categorization by type of event

Event categorization (cont.)

- Event categorization by type is an adaptation of the categorization provided by NUREG-0800, which has successfully binned LWR events through decades of operation
- Although not using NUREG-0800, Oklo discussed the insight of these categories with NRC staff in discussions on application structure in early 2018
- NUREG-0800 groups events into the following seven groups:
  1. Increase in heat removal by the secondary system
  2. Decrease in heat removal by the secondary system
  3. Decrease in RCS flow rate
  4. Reactivity and power distribution anomalies
  5. Increase in reactor coolant inventory
  6. Decrease in reactor coolant inventory
  7. Radioactive release from a subsystem or component
- The seven groups can be paralleled to the Aurora design

Event categorization (cont.)

- Abnormal events in the Aurora reactor generally arise from an imbalance between heat generation and heat removal, which can occur due to:
  - Either an increase or decrease in heat generation or
  - An increase or decrease in heat removal, in each case causing a departure from nominal steady-state operation
- Decrease in heat generation and an increase in heat removal is not challenging
- Because of the small size of the reactor, it is possible to bound these two scenarios with extreme transients:
  - Transient overpower – bounds increase in heat generation
  - Loss of heat sink – bounds decrease in heat removal

Transient overpower description

Transient overpower conditions

- Leads to a reactor trip, does not challenge the safety of the plant

Transient overpower

Transient overpower after trip

Loss of heat sink description

- The power conversion system (PCS) is the only significant credited means that is capable of fully removing the heat generated by the reactor at full power
- Therefore, the complete loss of the PCS is the most challenging event
- Leads to a reactor trip, does not challenge the safety of the plant
- Decay heat generation analysis dominates

Loss of heat sink conditions

- Many conditions or events are possible for a loss of heat sink
- The assumed bounding case is a complete loss of heat sink
- There is no external event that can credibly cause partial loss of heat transport.
- The only condition where a partial loss of heat sink is possible is a heat pipe failure due to failure in manufacturing. Quality control and ITAAC ensures heat pipes function prior to installation and startup.
- Even so, assuming failure of a heat pipe is a negligible event with no cascade and no loss of safety.

Determination of maximum credible accident

- Two events bound the entire internal analysis space for the Aurora:
    - Transient overpower
    - Loss of heat sink
- Transient overpower is a slow-progressing event and is not challenging
    - Results in reactor trip
    - Heat removed by the PCS
- Loss of heat sink is a relatively fast event and disables **all** secondary heat removal capability from the reactor
    - Results in a reactor trip
    - Analysis surrounds removal of decay heat

Safety case

MCA results

Maximum credible accident – loss of heat sink

- Immediate total loss of cooling
- Heat pipes continue operating
- Reactor is shut down when reactor trip setpoints are reached

Model geometry

Additional geometry views

Model conservatisms

Three phases of event progression

- Initial heat redistribution (t ≤ 1500 s):
  - Fuel temperature decreases as heat is conducted away from fuel to other, cooler structures
- Decay-driven heatup (1500 s < t ≤ 25 h):
  - Fuel temperature increases due to short-timescale decay heat addition outpacing residual heat removal
- Residual heat rejection cooldown (t > 25 h):
  - Fuel temperature decreases due to residual heat removal outpacing progressively-decreasing decay heat generation

Phase one: initial heat redistribution

Phase two: decay-driven heatup

Phase three: residual heat rejection cooldown

Assumptions

- Decay heat input taken conservatively at discrete values
- Thermal conductivity of fuel decremented by 20% to account for degradation with burnup
- Heat pipe vapor core modeled as highly conductive solid

Conclusion

- MCA analysis lead to the MCA being set as a complete loss of heat sink as the single most challenging event
  - Additionally with one shutdown rod assumed stuck out of the core
  - Additionally with long delay to shutdown rod drop
  - Once a single rod enters the core, a decay heat analysis problem only
  - Decay heat not challenging and reactor sufficiently cooled through parasitic losses

End of day 1

Outline – day 2

- 10:00 AM -12:00 PM | External Hazards (closed)
- 12:00-1:00 PM | Lunch
- 1:00-3:00 PM | External hazards (closed)

External hazards

External hazards

Overview

Design siting goal

- Design objective of the Aurora is the ability to be sited in the majority of the U.S
- Traditionally, external hazards have been evaluated on a site-specific basis
- However, due to the small size of the Aurora and the simple safety case, it is possible to evaluate the design against the most extreme external hazards across the U.S. for most event types

External hazards methodology overview

- Traditional external hazards evaluations utilize probabilistic risk analysis (PRA) to determine which external hazards are likely to occur for a given site
- Alternatively, it is possible to use deterministic analyses as a method of screening external events from the PRA
- Deterministic analyses show the resiliency of the facility against extreme external hazards and obviate the need for further analysis, typically done by a PRA
- For most external hazards, the deterministic path is used for the Aurora

External hazards methodology goal

- **Goal: To conduct a broad analysis of external hazards to assess if the MCA is challenged.**
- A robust internal analysis is possible due to the simplicity of the system, which resulted in a single bounding event – the MCA
- The complementary piece to the internal analysis is a robust external hazards analysis that demonstrates the robustness of the MCA

Key design features to analyze

- SSCs credited in the MCA analysis, also with insight from Fundamental Safety Functions

External hazards

Methodology for grouping hazards

Steps for external hazards methodology

1. Identify all potential external hazards that may affect the plant considering all plant operating states.
2. Perform a preliminary screening to group the external hazards into event families based on a common challenge condition.
3. Define a set of quantitative screening criteria and perform a bounding deterministic analysis.

Step 1 – identification of all potential external hazards

- Throughout literature review, including:
  - ASME/ANS RA-S-2008, “Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,”
  - ASME/ANS-RA-S-1.4-2013, “Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants,”
  - NUREG/CR-2300, “PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants,” and
  - NUREG/CR-5042, “Evaluation for External Hazards to Nuclear Power Plants in the United States.”

Step 1 – identification of all potential external hazards (cont.)

- 46 potential external hazards:
  - Aircraft impact
  - Avalanche
  - Biological events
  - Coastal erosion
  - Drought
  - External flooding
  - Fog
  - Forest Fire
  - Frost
  - Grass Fire
  - Hail
  - High summer temperature
  - High tide
  - High winds
  - Hurricane
  - Ice cover (causing blockage of river)
  - Industrial or military facility accident
  - Landslide
  - Lightning
  - Low lake or river water level
  - Low winter temperature
  - Non-safety building fire
  - Pipeline accident
  - Precipitation, intense
  - Release of chemicals from onsite storage
  - River diversion
  - Sandstorm
  - Seiche
  - Seismic event
  - Ship impact
  - Sinkholes
  - Snow
  - Soil shrink-swell
  - Storm surge
  - Tornadoes (extreme winds)
  - Toxic gas
  - Transportation accident
  - Tsunami
  - Turbine-generated missiles
  - Vehicle impact
  - Vehicle/ship explosion
  - Volcanic activity
  - Waves

OKLO

Step 2 – Prescreening of external hazards into event families

- All potential hazards evaluated to determine challenge to facility
- Prescreened into event families based on a common challenge

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that do not apply to the Aurora:
  - Biological events
  - Drought
  - Low lake or river water level
  - Release of chemicals from on-site storage
  - River diversion
  - Toxic gas
  - Turbine-generated missiles

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that do not apply to the Aurora:
  - Biological events
  - Drought
  - Low lake or river water level
  - Release of chemicals from on-site storage
  - River diversion
  - Toxic gas
  - Turbine-generated missiles
- Associated with loss of cooling via a water source – do not apply

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that do not apply to the Aurora:
  - Biological events
  - Drought
  - Low lake or river water level
  - Release of chemicals from on-site storage
  - River diversion
  - Toxic gas
  - Turbine-generated missiles
- Associated with large volumes of onsite chemicals – does not apply

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that do not apply to the Aurora:
  - Biological events
  - Drought
  - Low lake or river water level
  - Release of chemicals from on-site storage
  - River diversion
  - Toxic gas
  - Turbine-generated missiles
- Associated with incapacitation of onsite personnel who may have credited actions – does not apply

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that do not apply to the Aurora:
  - Biological events
  - Drought
  - Low lake or river water level
  - Release of chemicals from on-site storage
  - River diversion
  - Toxic gas
  - Turbine-generated missiles
- Associated with dislodging or a large turbine blade – does not apply

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that challenge the heat sink:
  - Frost
  - High summer temperature
  - Low winter temperature
  - Sandstorm
  - Volcanic activity
- Associated with degradation of the heat sink – do not apply because a complete loss of heat sink results in a reactor trip and does not challenge the plant – the MCA

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that can cause a fire:
  - Aircraft impact
  - Fog
  - Lightning
  - Non-safety building fire
  - Pipeline accident
  - Transportation accident

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that can cause a fire:
  - Aircraft impact
  - Fog
  - Lightning
  - Non-safety building fire
  - Pipeline accident
  - Transportation accident
- Accidents that could potentially cause a fire inside the reactor building

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that can cause a fire:
  - Aircraft impact
  - Fog
  - Lightning
  - Non-safety building fire
  - Pipeline accident
  - Transportation accident
- Included because it increases the possibility of aircraft impact or a transportation accident due to reduced visibility

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that can cause a fire:
  - Aircraft impact
  - Fog
  - Lightning
  - Non-safety building fire
  - Pipeline accident
  - Transportation accident
- Could result in a fire inside the building

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that can cause a fire:
  - Aircraft impact
  - Fog
  - Lightning
  - Non-safety building fire
  - Pipeline accident
  - Transportation accident
- Fires within the building are analyzed in a deterministic Fire Hazards Analysis, which assumes a large fire inside the reactor building
- Not analyzed as part of external hazards

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could challenge the reactor building:
  - Aircraft impact
  - Fog
  - Hail
  - High winds
  - Hurricane
  - Sandstorm
  - Seiche
  - Seismic event
  - Tornadoes (extreme winds)
  - Tsunami
  - Vehicle impact

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could challenge the reactor building:
  - Aircraft impact
  - Fog
  - Hail
  - High winds
  - Hurricane
  - Sandstorm
  - Seiche
  - Seismic event
  - Tornadoes (extreme winds)
  - Tsunami
  - Vehicle impact
- Included because of potential damage to the reactor building

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could challenge the reactor building:
  - Aircraft impact
  - Fog
  - Hail
  - High winds
  - Hurricane
  - Sandstorm
  - Seiche
  - Seismic event
  - Tornadoes (extreme winds)
  - Tsunami
  - Vehicle impact
- Included because it increases the possibility of aircraft impact or vehicle impact due to reduced visibility

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could challenge the reactor building:
    - Aircraft impact
    - Fog
    - Hail
    - High winds
    - Hurricane
    - Sandstorm
    - Seiche
    - Seismic event
    - Tornadoes (extreme winds)
    - Tsunami
    - Vehicle impact
- Analyzed further for purposes of the external hazards evaluation

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could challenge the reactor housings:
  - Seismic event
  - Tsunami
- Could have large ground accelerations, further evaluated only for potential structural loading on the reactor module
  - No concerns with sloshing of large volumes of coolant
  - No concerns with reactivity control mechanism oscillations

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could results in an explosion:
  - Fog
  - Industrial or military facility accident
  - Pipeline accident
  - Transportation accident
  - Vehicle/ship explosion

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could results in an explosion:
  - Fog
  - Industrial or military facility accident
  - Pipeline accident
  - Transportation accident
  - Vehicle/ship explosion
- Could result in an explosive force nearby the reactor building

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could results in an explosion:
  - Fog
  - Industrial or military facility accident
  - Pipeline accident
  - Transportation accident
  - Vehicle/ship explosion
- Included because it increases the possibility of a transportation accident due to reduced visibility
- Analyzed further for purposes of the external hazards evaluation

Step 2 – Prescreening of external hazards into event families (cont.)

- External hazards that could results in an explosion:
  - Fog
  - Industrial or military facility accident
  - Pipeline accident
  - Transportation accident
  - Vehicle/ship explosion
- Analyzed further for purposes of the external hazards evaluation

Step 2 – Prescreening of external hazards into event families (cont.)

Hazard	Challenge(s) to facility	External hazards event family	Site-dependent
Aircraft impact	Structural damage to the reactor building	Seismic	
	Fire in the facility	Fire	
Avalanche	--	--	x
Biological events	Not applicable	Not applicable	
Coastal erosion	--	--	x
Drought	Not applicable	Not applicable	
External flooding	Standing water in the facility	--	x
Fog	Structural damage to the reactor building	Seismic	
	Fire in the facility	Fire	
	Explosion causing damage to building	Nearby explosions	
Forest fire	--	--	x
Frost	Degraded heat sink performance	Not applicable	
Grass fire	--	--	x
Hail	Structural damage to the reactor building	Seismic	
High summer temperature	Degraded heat sink performance	Not applicable	
High tide	Standing water in the facility	--	x
High winds	Structural damage to the reactor building	Seismic	
Hurricane	Standing water in the facility	--	x
	Structural damage to the reactor building	Seismic	
Ice cover (causing blockage of river)	Standing water in the facility	--	x
Industrial or military facility accident	Explosion causing damage to building	Nearby explosions	
Landslide	--	--	x
Lightning	Fire in the facility	Fire	
Low lake or river water level	Not applicable	Not applicable	

Step 2 – Prescreening of external hazards into event families (cont.)

Hazard	Challenge(s) to facility	External hazards event family	Site-dependent
Low winter temperature	Degraded heat sink performance	Not applicable	
Non-safety building fire	Fire in the facility	Fire	
Pipeline accident	Fire in the facility	Fire	
	Explosion causing damage to building	Nearby explosions	
Precipitation, intense	Standing water in the facility	--	x
Release of chemicals from onsite storage	Not applicable	Not applicable	
River diversion	Not applicable	Not applicable	
Sandstorm	Degraded heat sink performance	Not applicable	
	Structural damage to the reactor building	Seismic	
Seiche	Standing water in the facility	--	x
Seismic event	Structural damage to the reactor building	Seismic	
	Structural loading to reactor module	Seismic	
Ship impact	--	--	x
Sinkholes	--	--	x
Snow	Structural damage to the reactor building	Seismic	
	Standing water in the facility	--	x
Soil shrink-swell	--	--	x
Storm surge	Standing water in the facility	--	x
Tornadoes (extreme winds)	Structural damage to the reactor building	Seismic	
Toxic gas	Not applicable	Not applicable	
Transportation accident	Fire in the facility	Fire	
	Explosion causing damage to building	Nearby explosions	
Tsunami	Standing water in the facility	--	x
	Structural damage to the reactor building	Seismic	
	Structural loading to reactor module	Seismic	
Turbine-generated missiles	Not applicable	Not applicable	
Vehicle impact	Structural damage to the reactor building	Seismic	
Vehicle/ship explosion	Explosion causing damage to building	Nearby explosions	
Volcanic activity	Degraded heat sink performance	Not applicable	
Waves	Standing water in the facility	--	x

OKLO

Step 2 – Prescreening of external hazards into event families – summary

- All potential external hazards evaluated
- Most prescreened:
  - External hazards that do not apply to the Aurora – not further analyzed
  - External hazards that challenge the heat sink – not further analyzed because bound by the internal safety analysis (the MCA)
  - External hazards that can cause a fire – bound by the internal Fire Hazards Analysis
  - External hazards that could challenge the reactor building – **additional analysis**
  - External hazards that could challenge the reactor module – **additional analysis**
  - External hazards that could results in an explosion – **additional analysis**

Step 2 – External hazards event families

Event family	Common challenge condition(s)	Bounding event	Bound hazards
Fire	Fire in the facility	Large internal fire	Aircraft impact Fog Lightning Non-safety building fire Pipeline accident Transportation accident
Seismic	Structural damage to the reactor building Structural loading to reactor module	Extreme earthquake	Aircraft impact Fog Hail High winds Hurricane Sandstorm Seismic event Snow Tornadoes (extreme winds) Tsunami Vehicle impact
Nearby explosions	Explosion causing damage to the building	Large industrial explosion	Fog Industrial or military facility accident Pipeline accident Transportation accident Vehicle/ship explosion

OKLO

External hazards

Bounding analysis and MCA evaluation

Step 3 – Bounding deterministic analyses

- Quantitative criterion used:
  - Consequences from a release would not cause a whole-body dose more than or equal to one rem or five rem thyroid equivalent dose at the site boundary
  - Basis comes from the Protective Action Guides (PAGs), as defined by the Environmental Protection Agency
  - This criterion is never utilized because no event family results in a dose
- Performed for the 3 event families:
  - Fire
  - Seismic
  - Nearby explosions
- **Goal: Evaluate the MCA against the 3 event families.**

External hazards

Bounding analysis and MCA evaluation – Fire Event Family

Step 3 – Bounding deterministic analyses – Fire Event Family

Event family	Common challenge condition(s)	Bounding event	Bound hazards
Fire	Fire in the facility	Large internal fire	Aircraft impact Fog Lightning Non-safety building fire Pipeline accident Transportation accident

Step 3 – Bounding deterministic analyses – Fire Event Family (cont.)

- **Goal: To conduct a fire analysis to assess if the MCA is challenged.**
- Progression of events:
  - A fire could be the initiating event that disables the PCS and causes the MCA
  - A fire could disable other equipment related to the automatic reactor trip
- Can be confirmed by showing that a fire cannot both cause the MCA and disable the automatic reactor trip
  - A fire that causes the MCA should not disable the automatic reactor trip
  - A fire should not completely disable the automatic reactor trip system
  - A loss of heat sink – the MCA – remains bounding

Step 3 – Bounding deterministic analyses – Fire Event Family (cont.)

- External hazards in the Fire Event Family addressed through a Fire Hazards Analysis (FHA)
- FHA is strictly deterministic
- The FHA contains the following:
  - Evaluation of the potential in-situ and transient fire hazards
  - Determination of the effects of a fire in any location in the plant and the capability to obtain a safe state, i.e. obtain a reactor trip
  - Determination of the appropriate measures for fire prevention, fire detection, fire suppression, and fire containment for each fire area

Step 3 – Bounding deterministic analyses – Fire Event Family (cont.)

Step 3 – Bounding deterministic analyses – Fire Event Family (cont.)

Step 3 – Bounding deterministic analyses – Fire Event Family conclusion

- Analysis for the Fire Event Family needs to show that a fire cannot cause the MCA as well as disable the automatic reactor trip
  - A fire that disables the PCS, and is the cause of the MCA, is confined only to the area where the PCS is located
    - Cannot propagate to another fire area that contains control logic or other circuitry
    - Cannot propagate to another fire area that contains cables that execute the reactor trip
  - A fire in other areas does not disable the automatic reactor trip
    - Cannot propagate to another fire area that contains redundant trip logic
    - Cannot propagate to another fire area that contains cables that execute the reactor trip
    - Cannot propagate to the fire area that houses the PCS
- **Conclusion: The MCA is not challenged by the Fire Event Family.**

External hazards

Bounding analysis and MCA evaluation – Seismic Event Family

Step 3 – Bounding deterministic analyses – Seismic Event Family

Event family	Common challenge condition(s)	Bounding event	Bound hazards
Seismic	Structural damage to the reactor building Structural loading to reactor module	Extreme earthquake	Aircraft impact Fog Hail High winds Hurricane Sandstorm Seismic event Snow Tornadoes (extreme winds) Tsunami Vehicle impact

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- **Goal: To conduct a seismic analysis to assess if the MCA is challenged.**
- Progression of events of a large earthquake:
  - Assumes a large ground acceleration on the reactor building and reactor module
  - Reactor building could be significantly damaged
    - Full collapse is bounding
    - A complete loss of PCS is bounding – the MCA
  - Reactor module could experience large structural loading
- Confirmed by showing that a large earthquake cannot:
  - Challenge the integrity of the reactor module
  - Challenge the insertion of the shutdown rods

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Challenges associated with a large earthquake can be analyzed with a structural analysis only
  - No reactivity effects associated with sloshing – no substantive liquid inventory
  - No reactivity effects associated with control rod oscillation – shutdown rods remain outside of the active core
- The structural analysis should examine:
  - Effects of large ground accelerations
  - Effects of a reactor building collapse
- Goal of the large ground acceleration analysis:
  - Demonstrate the the reactor module integrity is maintained
  - Demonstrate that the shutdown rods can insert
- Goal of the reactor building collapse analysis:
  - Demonstrate that the integrity of the module is maintained to enable the shutdown rods to insert

OKLO

External hazards

Bounding analysis and MCA evaluation – Seismic Event Family

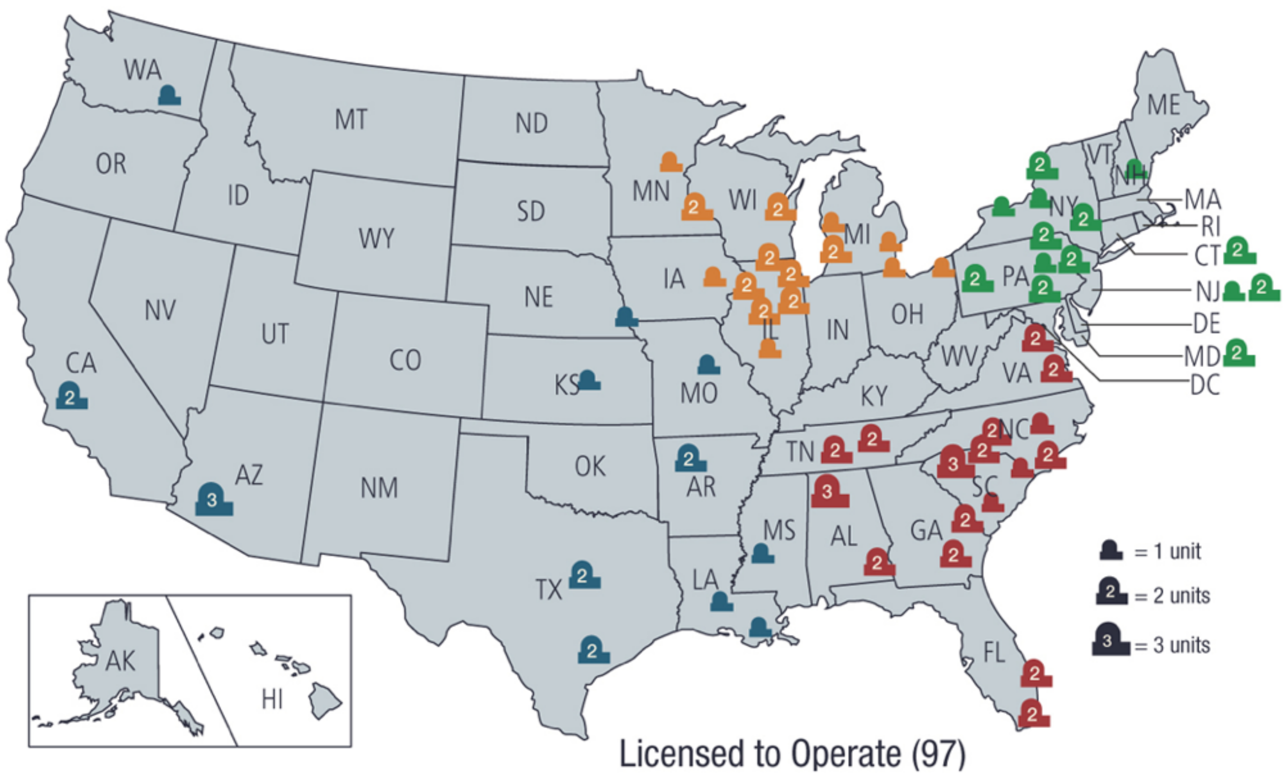
Large ground acceleration analysis

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- First step in the large ground acceleration analysis is to develop robust value that is representative of the entire U.S.
  - Contiguous U.S. well characterized by the operating nuclear fleet
  - Alaska and other U.S. sites can be examined through appropriate civil engineering codes (ASCE 7)
- Parameters are conservatively biased

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

U.S. Operating Commercial Nuclear Power Reactors



Licensed to Operate (97)

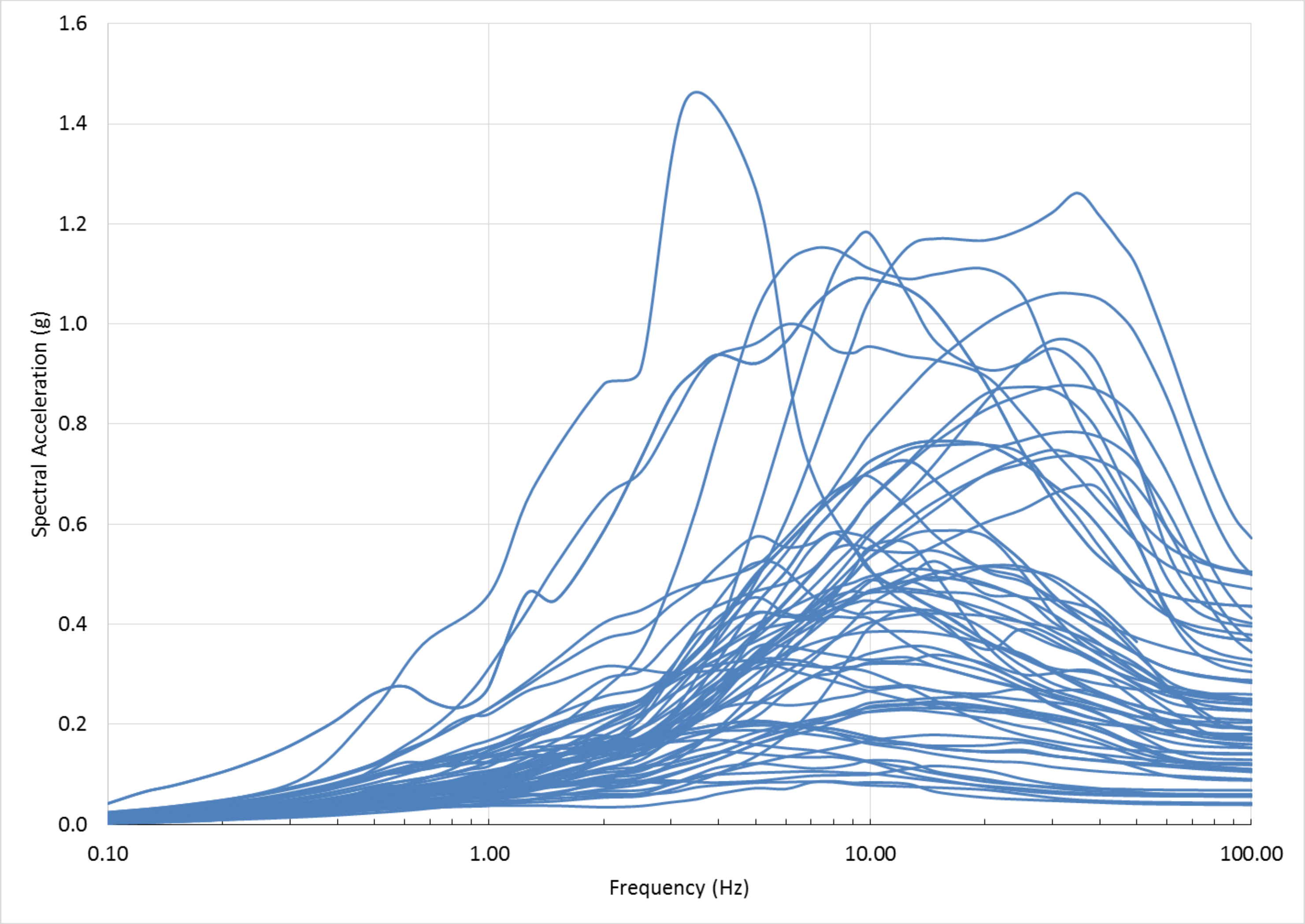
- Map of nuclear power plants in the U.S.

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment
As of August 2019

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- After March 2011 Fukushima Earthquake event, the NRC issued a request for information (50.54(f)) from all U.S. operating plants to re-evaluate their respective plants using the latest seismic hazard and regulatory guidance
- As part of their responses, all plants provided site-specific seismic ground motion response spectra (GMRS) to the NRC for screening purposes
- Based on a review of peak seismic parameters, the maximum spectral acceleration and ground acceleration are **1.45 g** and **0.57 g**
- The GMRS encompass a wide range of site locations, including hard rock and soil sites.

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)



- U.S. Plant Seismicity (Ground Motion Response Spectra)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- The American Society of Civil Engineer Standard, ASCE 7, provides minimum load requirements for the design of buildings and other structures that are subject to building code requirements
- ASCE 7 provides seismic maps, which are used to design and evaluate structures to resist earthquake demands
- The seismic maps are performance-based with a target risk of structural collapse 1% in 50 years based upon a generic structural fragility
- The Aurora reactor module was assumed to be Risk Category IV in ASCE 7
  - This is the most stringent category

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

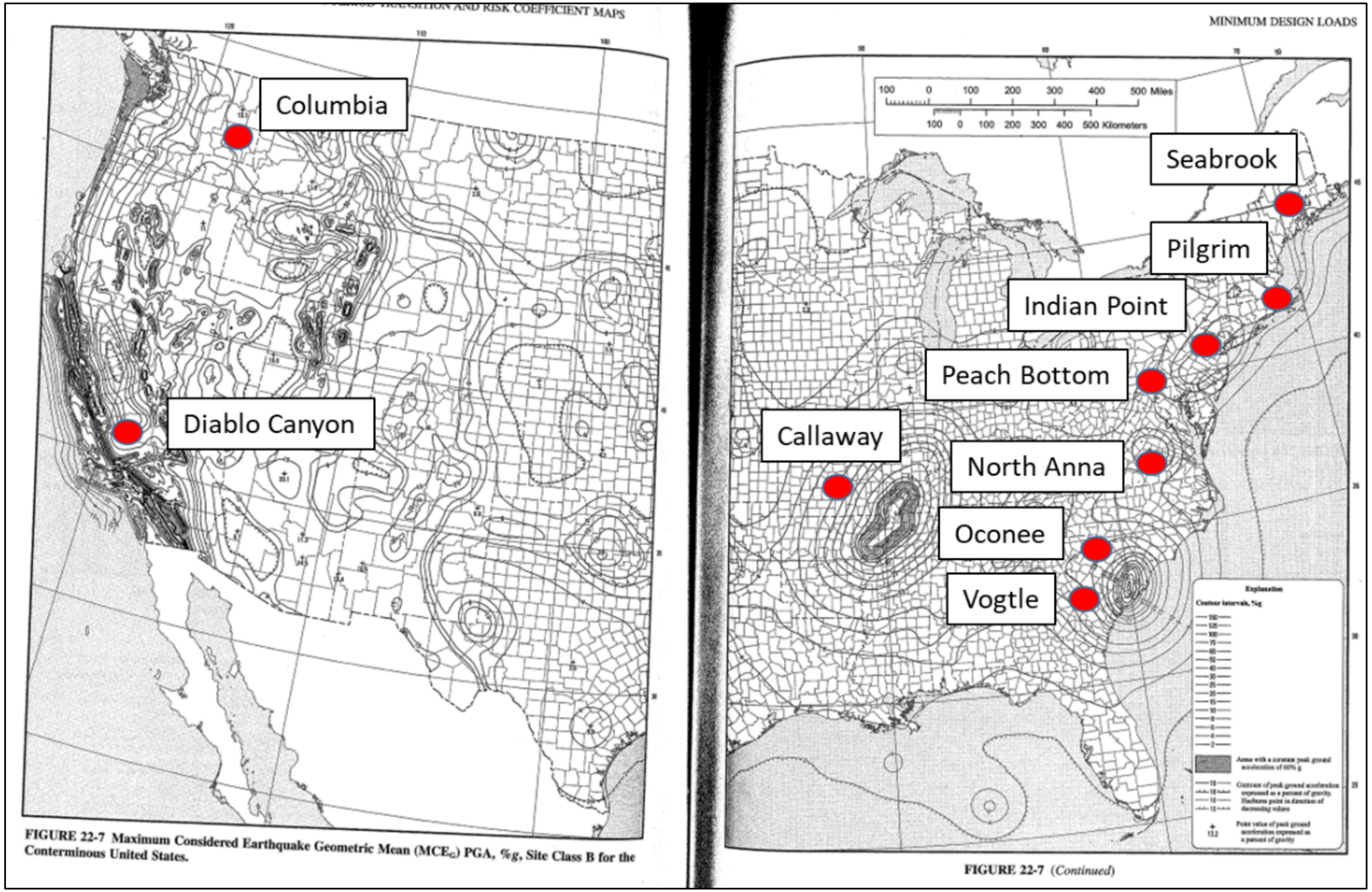


FIGURE 22-7 Maximum Considered Earthquake Geometric Mean (MCE_G) PGA, %g, Site Class B for the Conterminous United States.

FIGURE 22-7 *(Continued)*

- U.S. Seismic Design (ASCE 7; Continental)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

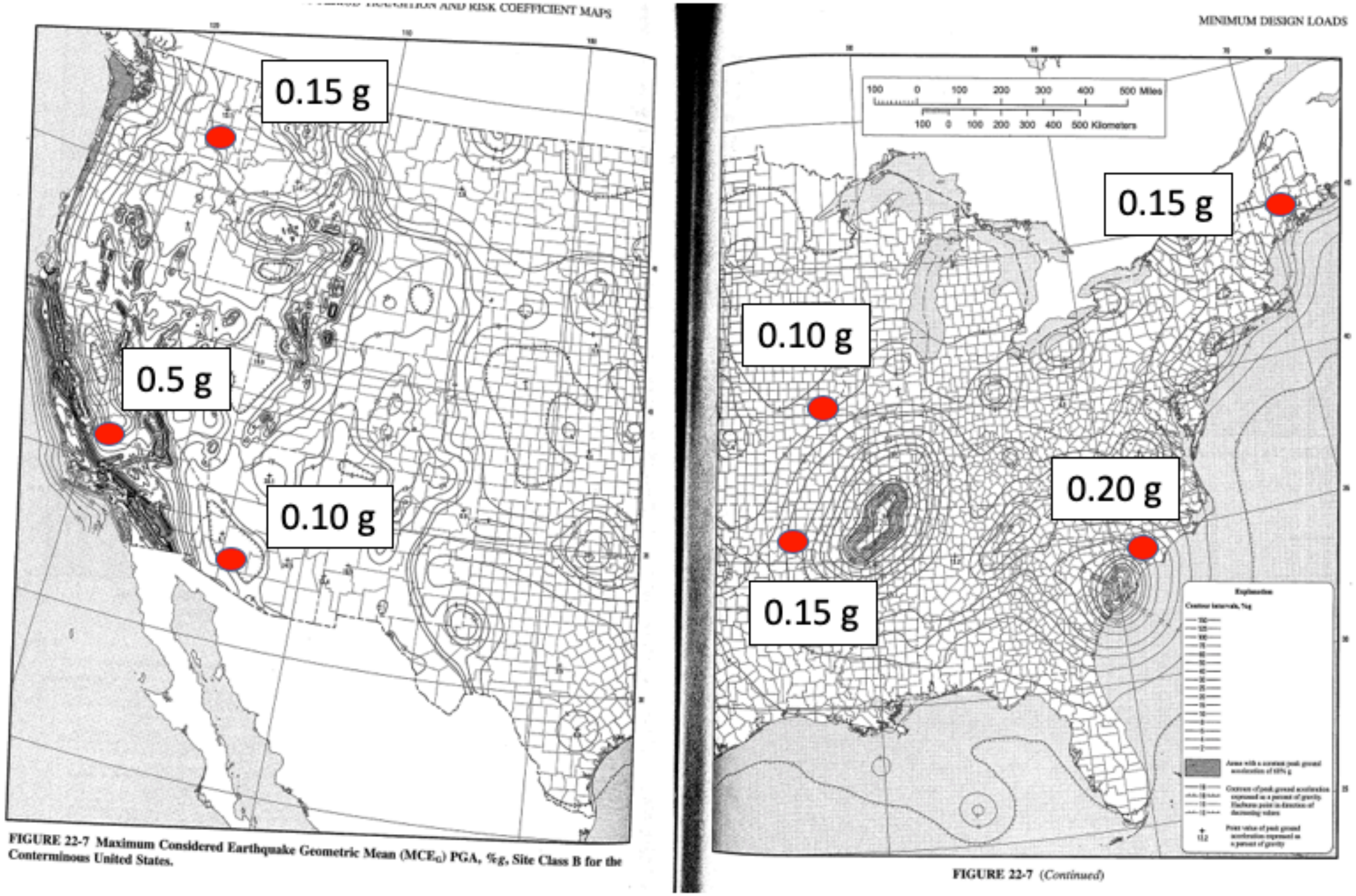


FIGURE 22-7 Maximum Considered Earthquake Geometric Mean (MCE$_G$) PGA, %g, Site Class B for the Conterminous United States.

FIGURE 22-7 *(Continued)*

- U.S. Seismic Design (ASCE 7; Continental)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Nine U.S. sites were selected based on a wide range of potential micro-reactor sites (Alaska, Puerto Rico, St. Thomas, and Hawaii)
- The ASCE 7 PGA for these sites ranged from **0.27g** to **0.5g**

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Representative Alaska sites

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Representative Puerto Rico sites

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Representative St. Thomas sites

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Representative Hawaii sites

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Key design features of the reactor module:

- Very rigid and rugged structure
- Reactor module is small

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- **No structural challenges to the reactor module**
- **No challenges to shutdown rod insertion**

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Conclusion of the bounding U.S. analysis:
  - Reactor module unchallenged structurally
  - Shutdown rod insertion unchallenged due to displacement
- Oklo also performed a "pushover analysis"
  - Goal was to determine the level of seismic acceleration that corresponds to failure initiation of the reactor module

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Conclusion of the bounding U.S. analysis:
  - **Reactor module unchallenged structurally**
  - **Shutdown rod insertion unchallenged due to displacement**
- Conclusion of the "pushover analysis":
  - **The reactor module is robust beyond any ground acceleration that is credible**

External hazards

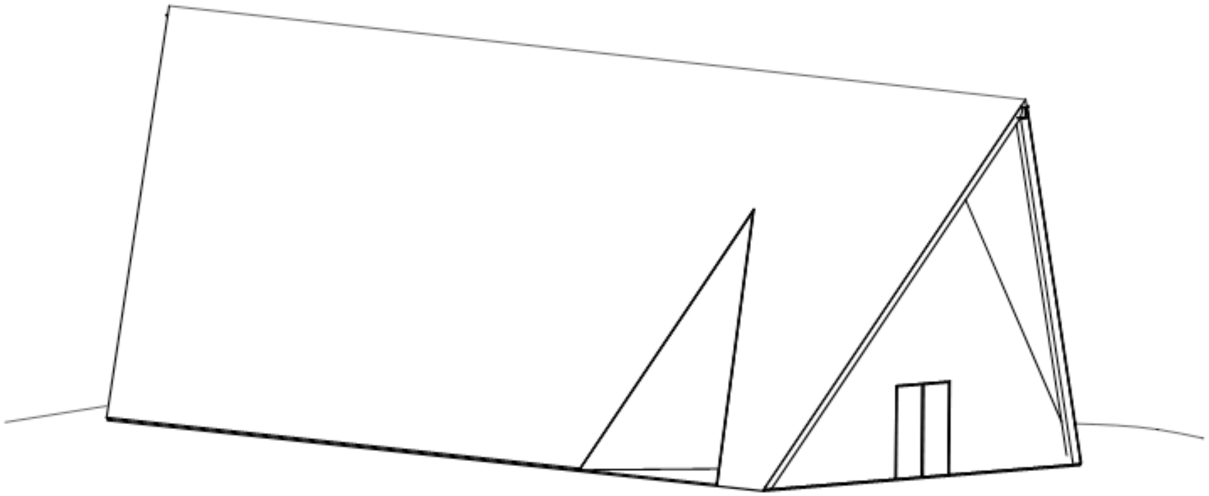
Bounding analysis and MCA evaluation – Seismic Event Family

Reactor building collapse analysis

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Reactor building is an A-frame



Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- The most conservative assumptions were used

- Full force of impact from falling from maximum height hitting with minimum effective diameter
- Penetrations occur with no force lost to deformation
- Full penetration occurs, no spalling or scabbing

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Floor assumptions:

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Roof beam assumptions:

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Crane assumptions:

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Penetration equation used:

$$T = \frac{(0.5MV^2)^{2/3}}{672K_S D}$$

T = thickness of steel for missile to just perforate (in.)

M = missile mass (lb-sec^2/ft)

V = missile impact velocity (ft/sec)

K_S = steel constant ~1

D = missile diameter (in.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

Step 3 – Bounding deterministic analyses – Seismic Event Family (cont.)

- Conclusion of the reactor building collapse (i.e., 2:1) analysis:

External hazards

Bounding analysis and MCA evaluation – Seismic Event Family

Conclusion

Step 3 – Bounding deterministic analyses – Seismic Event Family conclusion

- Evaluated large earthquake against the Aurora:
  - Effects of large ground accelerations
    - Demonstrated the the reactor module integrity is maintained
    - Demonstrated that the shutdown rods can insert
  - Effects of reactor building collapse
    - Demonstrated that the integrity of the module equipment housing is maintained to enable the shutdown rods to insert
- A large ground acceleration did not pose a structural challenge to the reactor module
- A large ground acceleration did not challenge the design tolerance associated with the shutdown rod insertion
- A reactor building collapse did not challenge the integrity

- **Conclusion: The MCA is not challenged by the Seismic Event Family.**

External hazards

Bounding analysis and MCA evaluation – Explosions Event Family

Step 3 – Bounding deterministic analyses – Explosions Event Family

Event family	Common challenge condition(s)	Bounding event	Bound hazards
Nearby explosions	Explosion causing damage to the building	Large industrial explosion	Fog Industrial or military facility accident Pipeline accident Transportation accident Vehicle/ship explosion

Step 3 – Bounding deterministic analyses – Explosions Event Family (cont.)

- **Goal: To conduct a blast analysis to assess if the MCA is challenged.**

Step 3 – Bounding deterministic analyses – Explosions Event Family (cont.)

- Initial calculations showed overpressure limits as high as over 40 psi
- Result of static overpressure analysis showed strong resistance against a large blast, even with the most conservative parameters applied
    - If blasts are present nearby the site, they will be evaluated to see if this overpressure limit could be exceeded, although it is unlikely

Step 3 – Bounding deterministic analyses – Explosions Event Family conclusion

- **Conclusion: The MCA is not challenged by the Explosions Event Family.**

External hazards

Remaining hazards and site commitments

Site-dependent external hazards

- Derived from list of all potential external hazards
  - Not all hazards able to be prescreened into event families
  - These are mitigated by appropriate site selection or further analyses
- Following slide shows the external hazards not prescreened

Site-dependent external hazards (cont.)

- Mitigated by appropriate site selection:
    - Avalanche
    - Coastal erosion
    - Forest fire
    - Grass fire
    - Landslide
    - Ship impact
    - Sinkholes
    - Soil shrink-swell
    - Extreme explosive hazard
    - Flooding challenges

Conclusion, Discussion