NuScale Plant Resiliency to an Electromagnetic Pulse

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INTRODUCTION

The phenomenology of an electromagnetic pulse (EMP) has been extensively studied, theoretically and experimentally, since the first EMP experience in 1962 when the 1.4 megaton Starfish Prime detonated 400 km over the Pacific Ocean. Starfish Prime resulted in an EMP, which caused electrical damage nearly 900 miles away in Hawaii. Currently, the Nuclear Regulatory Commission has no regulatory framework to address the EMP risk to nuclear power stations. And, while there are differing opinions as to the direct threat of an EMP to a nuclear power plant, it is generally agreed that the threat should not be ignored.

The Commission to assess the Threat to the United States from Electromagnetic Pulse Attack made a compelling case for the protection of critical infrastructures against the effects of the nuclear EMP and solar geomagnetic disturbances (GMDs) [1]. The Commission placed particular emphasis on the vulnerability and importance of hardening the nation's electric power grid, arguably our most critical infrastructure and, ironically, the most vulnerable to EMP.

Concurrent to the EMP Commission's efforts, the President's National Security Telecommunications Advisory Committee addressed the consequences of scenarios involving the interruption of electricity for months to years over large geographic regions, referred to as 'long term outages' or LTOs [2]. Causes of such outages may include nuclear EMP, solar geomagnetic disturbances, cyber, and coordinated physical attacks. These effects represent arguably the largest-scale common-cause failure events affecting electric power grid operations. To avert LTOs, the U.S. must assure the availability of survivable power sources with long-term, readily accessible and continuous fuel supplies to blackstart the grid, sustain emergency life-support services, and reconstitute local, state, and national infrastructures. Protection of electric power plants will be essential in preventing LTOs and restarting portions of the grid that have failed in the face of wide-area threats.

Current policy requires nuclear plants to shut down during a grid collapse. While this is necessary for operating reactor designs, it is also problematic in that it removes gigawatt sources of electric power with long-duration fuel on-site. Nuclear plants that can operate through or rapidly restart can enable near-continuous power to avert social unrest, prevent long-term cascading failures, and avoid lockup of spinning machinery. However, generation plants are highly likely to fail in an EMP environment in the absence of intentional EMP protection.

The aim of this work is to evaluate NuScale Power's Small Modular Reactor (SMR) system design resiliency to either natural geomagnetic or man-made EMP environments. The collaborative study has two primary objectives: (1) to assess the inherent design features of the NuScale SMR that aid in averting LTO disasters, and (2) to recommend EMP/GMD protection design strategies and techniques to ensure plant resilience against the effects of EMP and GMD.

EMP E1 – E3 THREAT

A schematic, developed by Metatech, of the waveform of the EMP electric field is shown in Figure 1 [3]. This figure shows the physical mechanisms producing the different phases of the waveform and the separation into three phases E1 through E3. As indicated in Figure 1, E1 is the fast component arising from the prompt gammas emanating from the burst and ejecting Compton electrons as they interact with the Earth's atmosphere. These electrons stream downward and spin coherently in the Earth's magnetic field to generate an incredibly fast (nsec) rise time electromagnetic pulse that peaks around 50 kV/m on the Earth's surface. E1 is of highest concern because of its high amplitude and wide bandwidth, allowing it to couple significant energy to conductors as short as 0.3 m.

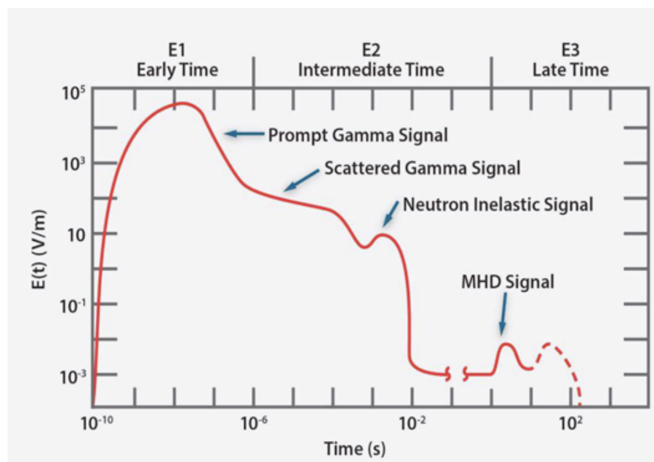

Fig. 1. Intensity of HEMP E1, E2, and E3 phases.[3]

The longer E2 pulse contains both a continuation of the E1 phase by scattered gammas and a later phase that results from inelastic gammas produced by energetic neutrons. Both of these phases are characterized by peak fields on the order of 100 V/m.

The E1 and E2 voltages cause breakdown "flashover" paths within powered-up systems (e.g., electronic boxes, transformers, motors, and generators) that enable grid or internal system power supply energy to surge through the short-circuit current paths created by the electrical arc. In addition to heavy-duty equipment effects, failure of electronic communications, computer, and industrial control components can have catastrophic consequences and are the most sensitive to EMP.

The late time E3, or magnetohydrodynamic (MHD) waveform, is similar in nature to the naturally occurring geomagnetic storm associated with a coronal mass ejection (CME) event.[4] Both nuclear detonations and solar storms induce a geomagnetic disturbance that generates a low frequency, low amplitude series of electromagnetic pulses. The pulse series lasts for minutes (EMP) to hours (solar storm).

The intensity of an E3 waveform appears more benign; however, the quasi-DC currents induced by E3 and GMD can cause direct damage to equipment connected to long lines, and also cause transformers to saturate resulting in harmonic currents. The associated harmonics and impedance mismatches can damage equipment, including uninterruptible power supplies and possibly generators.

Because EMP/E3 and GMD pulses are both quasi-DC with peak amplitudes roughly the same order of magnitude, the same protection devices will be effective against EMP/E3 and GMD. As a result, protection against EMP (including E1, E2, and E3 effects) will also enable systems to survive GMD. The converse is not true, and protection against GMD alone leaves systems vulnerable to E1 and E2 effects. For the purposes of this work, the EMP vulnerability assessment considers the E1, E2 and E3/GMD environments described.

METHODS

The supporting systems and subsystems of the NuScale SMR are identified and prioritized as likely vulnerable or inherently resilient to an EMP. The evaluation involves a qualitative vulnerability assessment of above and below ground subsystems, including communications, controls, switches, transformers and machinery within the SMR with special attention to the nuclear plant's ability to safely shut down and potential to provide continuous power during and after exposure to EMP stresses.

Recommendations are made for an effective EMP protection approach, best practices, and design features to enable the NuScale SMR to operate through exposure to EMP stresses. This work represents the initial investigation into the susceptibility of features of the NuScale design to either solar-caused or high-altitude nuclear burst-caused EMP environments, and describes the protection-engineering approach needed to enable plant survivability.

A notional site layout for a multi-unit NuScale plant is shown in Figure 2 [5]. The major facilities that are addressed in the EMP evaluation include the: Reactor Building, Control Building, Turbine Building, Cooling Towers, and Switchyard. Buildings that are not considered in the evaluation perform non-essential functions for operation such as the Administration and Annex Buildings, the Radioactive Waste Building, Water Treatment Building, and Security and Access Control Buildings.

Systems identified within the RBX as being essential to protect the NuScale core from failure include the Reactor Pressure Vessel (RPV), Containment Vessel (CV), Reactor Coolant System (RCS), Decay Heat Removal System (DHRS), Emergency Core Cooling System (ECCS), Control Rod Drive System (CRDS), Containment Isolation System (CIS) and Ultimate Heat Sink (UHS).

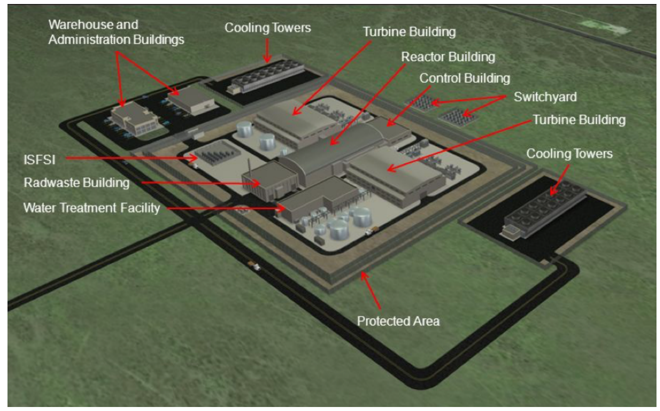

Fig. 2. Notional layout of NuScale multi-unit plant [5].

Based on the NuScale system design, a diagram of plant cable interconnectivity (Figure 3) was constructed to assess the pathways in which the EMP current could flow. Line and cable penetrations between these buildings were considered for impact of the E1 and E3 threat.

Operational Preparedness Levels

The assessment categorized the survivability and resiliency to an EMP into three 'operational preparedness levels' (OPLs) based on recover time objectives (RTOs), i.e. how quickly the nuclear generation plant can be restored to normal operation, as outlined below:

- The OPL 1 option offers the lowest level of protection and enables safe plant shutdown following EMP or GMD exposure with a 150 day recovery time objective.
- The OPL 2 option offers an intermediate level of protection and enables safe plant shutdown and rapid restart following EMP or GMD exposure with a recovery time objective of 12-24 hours.
- The OPL 3 option offers the highest level of protection and enables the plant to 'operate through' an EMP or GMD exposure. The OPL 3 recovery time objective is seconds.

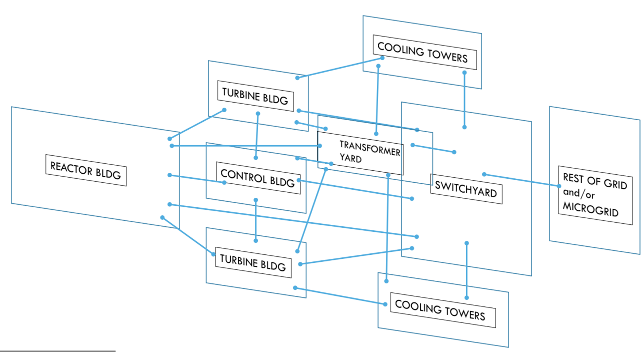

Fig. 3. Plant cable interconnectivity and EMP current pathways.

OBSERVATIONS

Inherent Design Features

The NuScale plant design exhibits many features that reduce EMP vulnerability in comparison with traditional nuclear power plant designs. However, additional design upgrades are needed to assure EMP resilience. The extent of design upgrades depends on the desired "operational preparedness level" or OPL. At the lowest level, the plant can easily be protected to meet OPL 1 as it is inherently designed to safely shutdown without power. Alternatively, the plant could also be designed to meet the OPL 2, safe shutdown and rapid restart, or OPL 3 objective, which would require the most stringent protection engineering to enable the plant to operate through an EMP or GMD event without shutting down.

Several key design features of the current NuScale design that are advantageous for surviving an electromagnetic pulse were identified.

Passive shut-down capability

The NRC has officially stated that it is satisfied that the NuScale design can operate safely without including safety-related backup electrical systems in the system design.[6] There are no safety-related electrical loads, including pumps and electric motor-operated safety valves. Because natural convective core heat removal is used, electrically-operated pumps are not needed to circulate coolant. This means that, if necessary, the reactor can shut down and cool itself for indefinite periods without the need for human intervention, adding water, or external electrical power.

Island Mode operation and steam bypass mode

Island Mode operation is organic to the NuScale plant design and it does not require a connection to the grid to provide electrical power for safety. This also allows for a more responsive recovery to full power following an EMP/GMD event. It is also possible to keep the NPMs safely running should they be deprived of load following the collapse of the rest of grid. This is accomplished using the plant's designed-in steam bypass mode. Thus, the plant is not required to shut down on loss of grid loads but goes into a "stand-by" mode such that it can be rapidly put back into service.

Electrical isolation of safety equipment

The designed-in electrical isolation of safety-related loads from the main plant electrical system ensures that variations in voltage, frequency, and waveform (harmonic distortion) in the onsite power system will have no reasonable likelihood of degrading the performance of safety-related systems.

Inherent shielding

Containment Building shielding - A time domain finite difference model was created to calculate both the electric fields and the short circuit current on conductors behind thick concrete walls with layers of rebar. The effects of both the conductivity and the magnetic permeability of the rebar was examined in one dimension and concluded to adequately dampen an EMP in the Reactor Building. The primary EMP concern in the RBX is limited to penetration treatments - i.e., entryways, pipes, ducts, and cable penetrations to ensure no EMP leakage occurs through the shielding at these points.

Containment Vessel shielding - The multiple layers of an Austenitic stainless-steel liner for the containment vessel contributes to enhanced shielding effectiveness. Additionally, all sensor cables penetrate the reactor containment vessel at a single location (containment vessel top plate), thereby reducing the EMP pathway.

Underground cables and widespread use of fiber optics

Burying conducting lines, even as little as one foot below ground, attenuates E1 induced currents by roughly 20dB. Although plans have not yet been finalized for inter-site cable run locations, it is likely that many of the lines between the Reactor Building and the Control Building will be laid in the underground tunnel between the control building and reactor buildings. NuScale also specifies that communication links between the distributed processors and remote I/O shall use redundant fiber optic cable, which is immune to EMP coupling.

Built in redundancy

In complex systems, redundancy is the preferred method of achieving system operational resiliency. The NuScale plants feature multiple reactors, multiple turbine generators, an Auxiliary AC Power Source (AAPS), two 2MW backup diesel generators for blackstarting the plant, multiple main power transformers (MPTs) and unit auxiliary transformers (UATs), and redundant backup battery banks.

Numerous other design features contributing to a resilient plant design that can accommodate features to meet OPL 2 and 3 include the use of: good grounding practices, lightning protection systems, surge arrestors for connections to the switchyard, delta-wye transformers, and circumferentially bonded stainless-steel piping.

RECOMMENDATIONS

The associated EMP/GMD protection issues, and their impacts on plant operation were considered for each mission-critical building or external system element on the NuScale plant site. For each building or system, recommendations are also provided for addressing identified issues, including both protection engineering and procedural solutions. Protection engineering solutions are preferred, especially if the plant is to operate through EMP and GMD events. Operational procedures are admissible if the operational performance objective is to allow the plant to shut down during an EMP/GMD contingency and be rapidly restarted, but are not recommended if the objective is to enable the plant to "operate through" an EMP contingency. Operational procedures require receipt of EMP attack warning far enough in advance to execute protection procedures. For EMP, advance warning may not occur.

Low Risk Protection

It is considered better practice to protect the complete system rather than subsets or components. Electromagnetic protection is based on building a barrier to prevent electromagnetic fields and currents from reaching mission critical equipment, verifying that the barrier is effective, and maintaining the barrier's integrity over the life cycle of the system. The barrier includes shielding and shield penetration protection. A properly designed barrier will make equipment behind it safe from wide variations in threatening external electromagnetic fields. A major benefit of a low-risk barrier is that systems placed inside the barrier require no EMP protection. Thus, commercial-off-the-shelf (COTS) equipment can be purchased and used allowing appreciable procurement and life-cycle maintenance savings. [7]

Most high voltage electric grid assets, such as transformers and HV breakers, must be, by necessity, located at exposed positions outside the EMP barrier. These high voltage systems often have critical low voltage electronic sensing and control equipment bolted on their frame or installed nearby. These electronic systems can be protected using box-level shielding and penetration filters. Overvoltage protection on high-voltage equipment is needed for E1/E2 protection and capacitor blocking devices are needed for E3/GMD. Switchyard communication/control/data buildings and shelters can be protected using the same shielding approaches used successfully by DoD for their Command, Control, Communications, Computers and Intelligence (C4I) systems. Using metal construction materials facilitates the shielding of interior equipment. New prefabricated metal building designs are available and effective if metal wall penetrations are treated properly.[8]

Elements of low-risk protection engineering involve:

1. A facility shield that is a continuous conductive enclosure that meets or exceeds specified shielding effectiveness requirements;

2. Protection of all shield penetrations or EMP field and induced current points of entry (POEs) including wire penetrations, conduit and pipe penetrations, doors, and apertures;

3. Quality assurance and acceptance testing for the electromagnetic barriers, and verification testing of the completed, operational facility; and

4. Comprehensive hardness maintenance and surveillance (HM/HS) to sustain system hardness in face of wear and tear, equipment or configuration changes and facility additions.

CONCLUSIONS

A thorough evaluation of the NuScale plant design was considered at a systems level. Inherent design features were considered that allow protections from EMP, and recommendations were made to ensure OPL 1 as well as further harden the NuScale design to meet OPL 2 (rapid restart) and OPL 3 (operate through) objectives. The extent of required protection will depend on the selected operational preparedness level option. In summary, the study concluded:

- OPL 1 is achievable with minimum design changes due to the passive shutdown system design of a NuScale NPM, thereby allowing the protection of the Reactor Building to be sufficient to ensure safe shutdown.

- OPL 2 requires design upgrades including EMP protection of the Reactor Building (OPL 1) plus the Control Building, Steam Turbine Generators, Cooling Towers, and Switchyard. Where switchover to backup systems and replacement or repaired of debilitated subsystems is possible, operational "work around" procedures are admissible as part of the protection process.

- OPL 3 is achievable with substantive design upgrades to the same facilities and systems as OPL 2 (Reactor and Control Buildings, Steam Turbine Generators, Cooling Towers, and Switchyard). However, for OPL 3, protection engineering must be comprehensive such that all systems will continue to operate trans-event without the need for repair or replacement of any subsystems.

ACKNOWLEDGMENTS

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