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INTEGRATED FRAGILITY OF UNDERGROUND CRITICAL INFRASTRUCTURES EXPOSED TO BLAST EVENTS

Gal Shany[1], David Ornai[1], Robert Levy[2] and Igal M. Shohet[1,3]

[1]*Department of Civil and Environmental Engineering, Ben-Gurion University of the Negev, Beer-Sheva, P.O.B. 653, Israel.*
[2]*Department of Civil Engineering, SCE - Shamoon College of Engineering, 56 Bialik st, Beer Sheva 8410802, Israel.*
[3]*Department of Civil and Construction Engineering, ChaoYang University of Technology, 168, Jifeng E. Rd., Wufeng District, Taichung 41349, Taiwan.*

ABSTRACT

Civil society is frequently threatened by terror and war activities. The scenarios caused by these events are highly relevant to the continuous performance and safety of underground Critical Infrastructures (CIs) such as Nuclear Power Plants (NPPs), data centers and hazardous materials storage facilities. The present research is focused on the development of a risk informed decision support methodology, demonstrated on a case study of a tunneled CI in chalk rock, exposed to two war threat scenarios composed by direct hits of Earth Penetrator Weapons (EPWs). The investigated CI is NuScale® Small Modular Reactor (SMR) NPP, built in a tunneled cavern. If this NPP and its nuclear power modules (NPMs) are damaged, it might lead to Core Damage and Large Release of radioactive materials, with significant negative impact on public health and the environment. Integrated risk analysis and assessment methodology was developed while addressing three levels for consideration: (1) Geotechnical level; (2) Structural level; and (3) Systems and Components level. An Integrated Fragility Model (IFM) was developed for blast induced in-structure motions caused by the EPWs, based on seismic fragilities of this SMR and the Nuclear Engineering Institute (NEI) median tolerance values of NPPs systems and components exposed to aircraft crash. The in-structure motions (displacements, velocities and accelerations) were calculated according to analytical-empirical expressions of the blast induced ground shock that fit numerical simulations. The research delivers a novel risk-informed methodology for assessing the resilience of underground Critical Infrastructures (CIs) against Earth-Penetrating Weapons (EPWs) combining Integrated Fragility Modelling for resilience assessment of the NPP and RF modeling for the durability of the Protective cavern.

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Keywords: Blast, Critical Infrastructures, Earth Penetrator Weapons (EPW), Fragility, Nuclear Power Plant (NPP).

1. Introduction

Critical Infrastructures (CIs) are increasingly exposed to evolving threats of terrorism and warfare, including the impact of high-explosive warheads and missiles' strikes. Power supply infrastructure is of particular strategic concern as demonstarted in Russia-Ukraine war. As part of its 2050 energy strategy, Israel is evaluating the demographic and safety implications of establishing SMR at the Shivta Rogem site in the Negev desert. This new type of NPP is recognized for its inherent passive safety features, that are considered more robust, resilient, and safer than older NPPs' types, especially in withstanding against external hazards. Threat scenarios involving high-explosive warheads are particularly relevant

Corresponding author email address: igals@bgu.ac.il

to the operational continuity, resilience, and safety of CIs in war threatend zones. However, key engineering parameters associated with these scenarios are subject to significant uncertainty and are best represented as random variables— an approach suitable for probabilistic and computational analysis [1]. A fundamental principle in engineering is that system capacity must be greater or at least equal to its demand. Although capacity and demand values are traditionally treated as constants, they are increasingly recognized as time-dependent. Modern design methodologies, especially those incorporating structural reliability, account for degradation processes such as wear and tear, plastic deformations, creep, corrosion, and erosion, all of which lowers long-term capacity [2-4]. The capacity valus are divided by safety factors in order to be more conservative. Similarly, demand inherently involves uncertainty and is often expressed as loads multiplied by safety factors. This research was focused on the comparison between hypothetical new built tunneled SMR capacity versus demand. To demonstrate the feasibility of the proposed methodology, a case study was conducted involving an underground tunneled SMR-based NPP. The study applied existing seismic modeling techniques to identify critical structural elements, the reactors' systems and components and their associated failure modes, serving as the foundation for generating fragility curves resulted by the blast induced in-structure shock. A basic layout of the NuScale SMR underground cavern at the Shivta Rogem site was defined based on Sapir and Rosen study [5], incorporating the Adulam chalk formation characteristics outlined by Palchhik and Hatzor [6]. Representative geotechnical properties of the chalk include a Modulus of Elasticity of 9,500 MPa, a Poisson's ratio of 0.2, and a compressive yield strength of 32.9 MPa. Normal penetration depths of EPW-1 and EPW-2 bunker-buster munitions carrying 299 kg and 2,400 kg of TNT equivalents, respectively—were evaluated in relation to the chalk medium. Two separate cavern configurations were analyzed, corresponding to each munition threat scenario. Simulated ground shock and corresponding in-structure shock within the SMR fit analytical-empiracl results [7].

2. Literature review

The impact of external manmade explosive events on the tunneled SMR can be analyzed while considering SMR response to earthquakes. This comparison highlights both similarities and distinct differences in the nature and effects of these phenomena [8-12]. One key parameter that emerged from caverns blast tests is the Peak Particle Velocity (PPV), with a threshold value for cracking at 1 m/s, commonly identified as the design limit for underground caverns exposed to nearby explosions. Exceeding this threshold may lead to damage beyond cavern's surface cracking, including spalling. Therefore, maintaining PPV below this value is critical for ensuring the structural integrity of an SMR cavern, which directly influences decisions regarding cavern's depth required to protect against the EPWs threats [13]. Tunneling—an essential and rapidly evolving discipline within civil engineering—is particularly vulnerable to various forms of deterioration over time. This research deals only with new built tunneled Reactors Building (RXB). To better understand and mitigate these issues, standard rock classification systems and contemporary tunneling methodologies have been reviewed [14-15]. This research aims to develop a risk-informed, optimization-based decision support framework tailored for enhancing the blast resistance of advanced underground tunneled CIs—specifically SMR-based NPPs—subjected to EPWs attacks. The study focuses on threat scenarios involving munitions detonated above a subterranean cavern housing a NuScale SMR RXB. The central hypothesis is that, if designed and constructed properly, underground infrastructures can provide effective passive protection, maintaining safety performance over a defined operational lifespan. This paper will focus on the analysis of a new built tunneled RXB.

3. Research goals and objectives

This paper addresses an essential and underexplored research gap: the vulnerability of underground tunneled CIs particularly SMR type of NPP, to munitions threats such as earth-penetrating weapons (EPWs). While significant attention has been paid to natural hazards like earthquakes and tsunamis, the risk posed by deliberate war attacks using EPWs remains largely unstudied. Recent statements by [16] and researchers such as [17] reinforce the urgency of expanding the scope of safety analyses to include unpredictable, high-impact threats like terrorism and blast loads. The case study presented in here evaluates the potential impact of EPW-1 and EPW-2 detonations directly above an underground tunneled cavern housing the RXB. Prior work by [18] revealed the original above-ground NuScale SMR design to be highly vulnerable to such attacks. The primary objective is to introduce a risk analysis and assessment framework aimed at preventing Core Damage (CD) and Large Releases (LR) of radioactive materials by ensuring the structural and functional integrity of the underground tunneled RXB and its systems under EPWs' blast induced shocks, that will cause in-structure motions: accelarations, velocities and displacement.

4. Methodology

The methodology is composed by the following phases, while this paper focuses on the penultimate bolded phase:

- Literature review;
- Underground critical energy infrastructures vulnerability and damage assessment, focused on critical SMR RXB structural elements, systems and components exposed to EPW blast induced shock that cause in-structure motions evaluated by Analytical-Empirical formulations;
- **Risk analysis and assessment: Tracing on the SMR geometry and properties; Development of IFM (Integrated Fragility Model) based on the in-structure motions of the NPP components' tolerance under airplane crash, and seismic fragility curves;**
- Structural reliability analysis related to capacity deterioration trend is developed using machine learning (ML) model in order to predict the future geotechnical and structural condition. It comprises data gathering, applying the Random Forest (RF) Algorithm, assessing the results, and specifing data to be collected for future analysis.

The research introduces a novel risk-informed methodology for assessing long term resistance of underground Critical Infrastructures (CIs), specifically Small Modular Reactors (SMRs), against Earth-Penetrating Weapons (EPWs). The core scientific innovation relies on:

- Development of a novel integrated deterministic and probabilistic approach to assess the vulnerability of underground CIs to EPW threats and creation of innovative Integrated Fragility Model (IFM) - blast-specific fragility curves, adapted from seismic fragility models.
- Development of Physical Deterioration Model (PDM) Implementation of deterioration modeling using Machine Learning (RF algorithm) to predict the physical condition of protective caverns for NPP over time.

4.1. Outline of the research

4.1.1. NuScale SMR RXB geometry and properties

Due to U.S. national security and proprietary concerns, detailed technical specifications of the NuScale SMR are not fully available to the public. Key geometric parameters, including wall lengths, thicknesses, and overall building height, were extracted and assumed from publicly available data. The essential geometrical and material properties used for the case study analyses are summarized in Tables 1 and 2. Table 2 also includes static properties of the RXB's concrete and steel reinforcement, which are fundamental inputs for structural dynamic analyses under explosive loading scenarios. A vertical cross-section of the Reactor Building (RXB) is presented in appendix A.

Table 1: RXB approximated dimensions

Description	Dimension [m]
Total Height	60
Total length	107
Total width	46
Ceiling thickness	1.4
Floor (Basemat) thickness	3
Pool width	19
Pool height	26

Table 2: The RXB materials' properties

Item	English units	SI units
Typical concrete compressive strength (*)	5,000 psi	34.5 MPa
External walls' concrete compressive strength (*)	7,000 psi for	48.3 MPa
Concrete Poisson's ratio	0.17	0.17
Concrete modulus of elasticity	4,031 ksi	27,792.8 MPa
Concrete shear modulus	1,722 ksi	11,872.8 MPa
Steel reinforcement bars yield strength	60 ksi	413.7 MPa
Steel reinforcement bars tensile strength	90 ksi	620.55 Pa

(*) according to American Concrete Institute (ACI).

4.1.2. The threat scenarios

Given their massive penetrations potential and explosions yield, EPW-1 and EPW-2 poses severe threat scenarios for underground tunneled CIs. In this study, their impacts are analyzed in terms of the in-structure motions they generate and their interaction with the RXB's structural and functional limits and its internal systems and components tolerances. Detailed specifications of the EPW-1 and EPW-2, including explosive mass and configuration, are provided in Tables 3 and 4. The modeled threat scenarios are visually represented in Fig. 1.

Table 3: Properties of EPW-1

Total weight	2,132 kg
Explosive's weight (TNT Equivalent)	299 kg
Length	7.6 m
Diameter	0.356 m

Table 4: Properties of EPW-2

Total weight	13,608 kg
Explosive's weight (TNT Equivalent)	2,430 kg
Length	6.2 m
Diameter	0.8 m

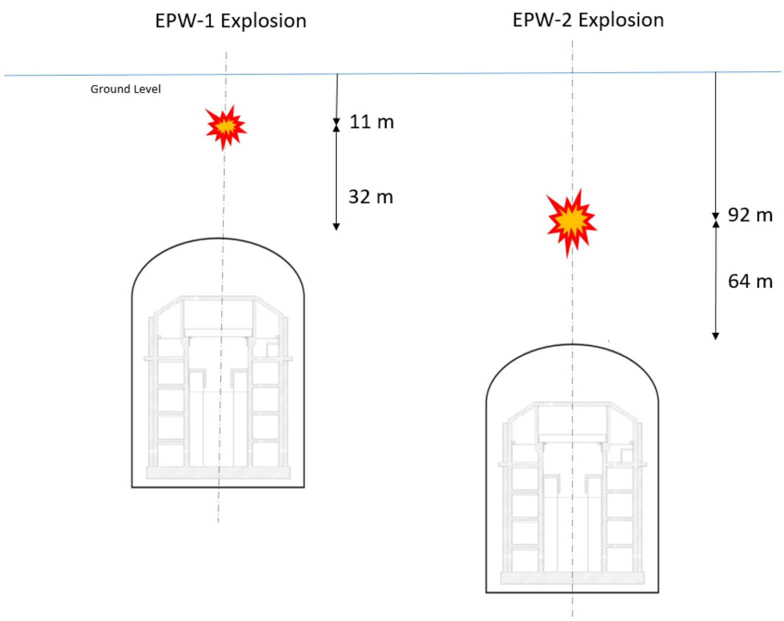


Fig. 1: Vertical cross section of the EPWs penetration depths of 11 m and 92 m, where blast occurs and the distances of 32 m and 64 m to the caverns' tops, while the RXBs are within the caverns. (a) EPW-1 threat scenario is presented on the left; (b) EPW-2 threat scenario is presented on the right.

4.1.3. The three levels of risk analysis and assessment

- **Geotechnical Level (#1) – The Underground Tunneled Cavern**

This level focuses on the combined geological and RXB structural integrity of the underground cavern. At the geotechnical level, the underground tunneled cavern is assumed to provide full blast protection at the time the Critical Infrastructure (CI) becomes operational (called "New Built"). This is a standard and reasonable assumption in engineering practice — that a properly designed and constructed facility will meet its intended safety and performance criteria upon commissioning.

- **Structural Level (#2) – The Reactor Building (RXB) in-structure motions resistance**

At this level, the vulnerability of the RXB's structural elements is evaluated. This includes defining failure scenarios, modeling the RXB geometry and material properties, and reconstructing seismic fragility curves that will represent the expected damage due to blast in-structure motions. Analytical-Empirical assessments of blast-induced ground and in-structure motions are conducted, with results mapped onto shock spectra to calculate failure probabilities. They are compared against U.S. Nuclear Regulatory Commission (NRC) requirements for structural tolerance. The methodology focuses on identifying critical failure modes of the RXB, based on existing seismic response data with modifications tailored to the underground tunneled configuration. The analysis is based on the assumption that the RXB's behavior under blast loading shares key similarities with its response to seismic events, inspite of the differences between their accelerations magnitudes and load or excitation (for blast and earthquakes, respectively) duration times.

- **Systems and Components level (#3)**

The final level addresses the resistance of the systems and components within the RXB to blast induced in-structure motions. An Integrated Fragility Model (IFM) was developed to assess the vulnerability of NuScale SMR components to blast events, combining seismic fragility data with NEI's data of NPP systems and components tolerances to airplane impact [20]. Due to a lack of specific data on external explosion resistance, the model integrates uncertainty parameters aligned with prior research results [21] to create representative fragility curves for blast scenarios.

5. Presentation of the findings

Results from NuScale's Seiemic Margin Assessment (SMA) indicate clear thresholds beyond which structural failure—and consequently, reactor Core Damage (CD)—could occur. The SMA defines performance criteria for a range of structural events that could directly lead to Core Damage (CD) or a Large Release (LR) of radioactive materials. Key structural capacity parameters such as the High Confidence of Low Probability of Failure (HCLPF), median fragility, and randomness-related variability (β_r and β_μ), were derived from NuScale's published fragility analyses [19]. According to this data, structural and component-level failure becomes probable when Peak Ground Acceleration (PGA) exceeds the dynamic capacity of the critical systems. These findings affirm the validity of the proposed methodology and support its application in assessing underground RXB configurations under extreme loading conditions, including those caused by EPW detonations.

5.1. Level 1 results – Geotechnical performance under the threat scenarios

It is assumed that the cavern and the RXB in it are blast resistant due to approriate design and construction. Each of the two caverns' configurations for the two different threat scenarios also obeys the PPV threshold of 1 m/s at each scenario.

5.2. Level 2 Results – structural performance under the threat scenarios

Further on, the analysis is focused on the Reactor Building Crane (RBC), which is the structural element that NuScale has identified as the most sensitive. Its HCLPF is the lowest of all elements, in other words, according to the logic of the Min-Max method, it is the structural element that determines the SMR RXB's capacity to withstand seismic events. Fig. 2 below presents the reconstructed fragility curve based on NuScale's data for a seismic event. The extracted HCLPF of 0.88 g is in line with the HCLPF of NuScale's SMA. It means that under seismic loads, a PGA of 0.88 g is the highest acceptable acceleration according to the definition of HCLPF: 95% confidence of less than 5% failure probability.

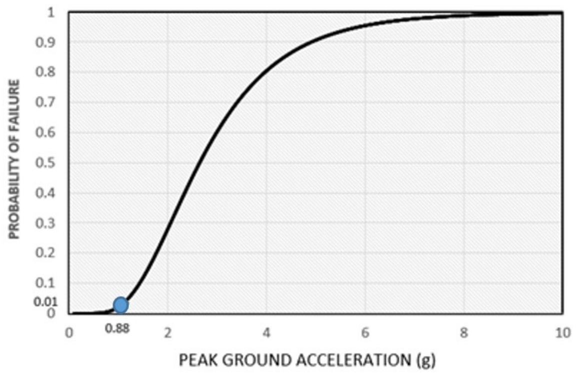
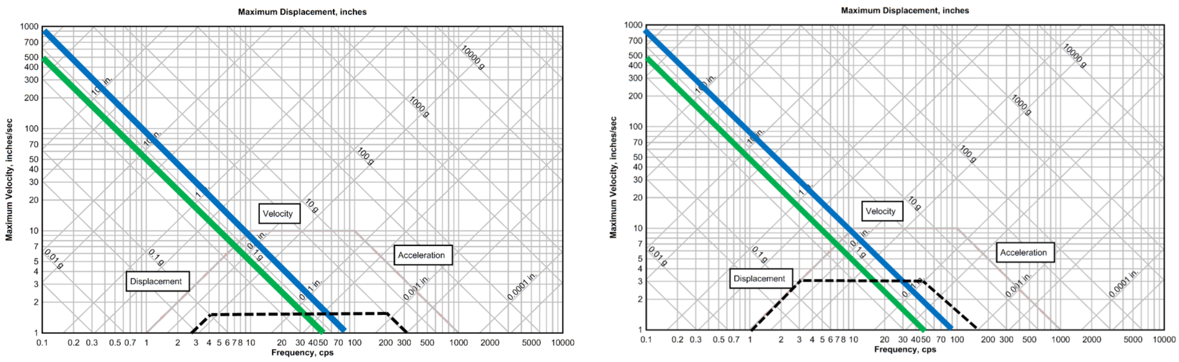


Fig. 2: Reconstruction of the RBC seismic fragility curve

(Schematic notation of the HCLPF)

The average in-structure spectral accelerations resulting from the EPW-1 and EPW-2 threats' scenarios were found to be 5.2 g and 3.45 g, respectively. These values which are much greater than 0.88 g indicate complete structural failure under both conditions, significantly exceeding the 1% probability of failure. These findings are consistent with NuScale's own structural performance characterizations, which recognize a high sensitivity of the RXB's structural elements to dynamic loads such as those produced by earthquakes. Importantly, the NuScale SMR was not originally designed to withstand external blast events, and the aforementioned results clearly reflect it. Since the accelerations exceed the HCLPF, the design does not meet U.S. NRC safety goals, which require: A Core Damage Frequency (CDF) of less than 1×10^{-4}/year, and a Large Release Frequency (LRF) of less than 1×10^{-6}/year. Fig. 3 shows two trapezes in black scattered lines presenting the average spectral in-structure motions for the RBC under the two threat scenarios, compared to the RBC tolerances of two accelerations with their probabilities of failure, received from the fragility curves. It clearly emphasizes that the in-structure motions resulted by the two EPWs, especially the accelerations are much greater than allowable 0.88 g, and a risk greater than 50% is expected.



Probability of Failure	Acceleration	Description
1%	0.88 (g)	green line
50%	2.64 (g)	blue line

Probability of Failure	Acceleration	Description
1%	0.88 (g)	green line
50%	2.64 (g)	blue line

Fig. 3: RBC average spectral in-structure motions (black scattered line) resulted from (1) EPW-1 explosion. A =5.2 (g), V= 0.045 (m/s) =1.77 (inch/s), D=0.002 (m)=0.0787 (inch)-left figure; (2) EPW-2 explosion A =3.45 (g), V= 0.078 (m/s)=3.07 (inch/ s), D=0.007 (m) = 0.276 (inch)-right figure.

5.3. Level 3 Results-systems and components performance under the threat scenarios

Systems and components within the RXB may be damaged due to blast-induced in-structure motions. Currently, there is a knowledge gap regarding the resistance of NPP components—specifically NuScale SMR systems and components—to external explosions. To address this issue, a novel Integrated Fragility Model (IFM) creates representative fragility curves for blast events, utilizing seismic fragility data and the Nuclear Energy Institute (NEI) probability of failure (POF) data for airplane impacts on NPPs systems and components [19]. These curves were combined with NuScale's uncertainty parameters to refine the fragility analysis for blast scenarios. The uncertainty parameters— $\beta_r = 0.28$ and $\beta_\mu = 0.39$—were consistent with values from [21], who first published fragility data for NPPs under earthquake and blast conditions. Given the uncertainty parameters and a median fragility of 27 g (the lowest value mentioned in [20]) in the two threats' scenarios, the calculated spectral accelerations (5.2 g and 3.45 g) means that the probabilities of failure for the systems and components are less than 1%. This suggests that the systems and components are likely to withstand the blast-induced in-structure motions. Fig 4. demonstrates the integrated fragility curve.

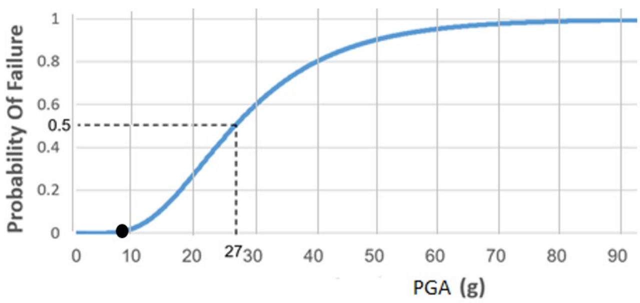
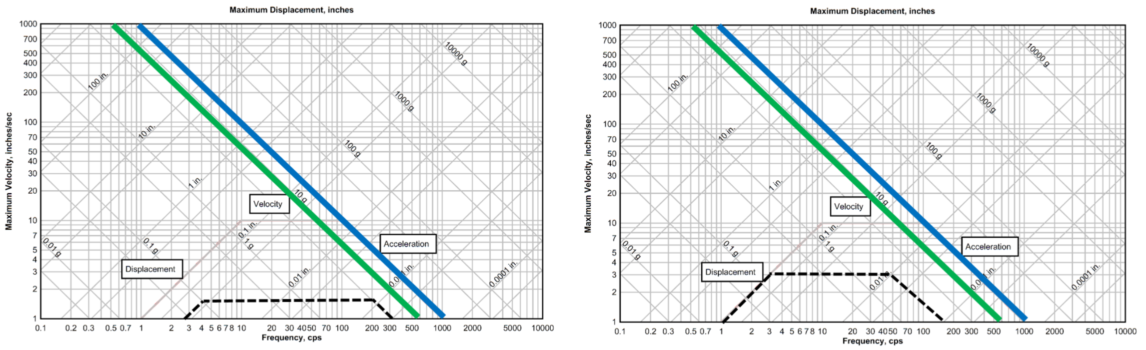


Fig. 4: NuScale SMR Systems and Components integrated fragility curve

(The black dot is a schematic notation of 1% probability pf failure at a PGA of 8.9 g)

Fig. 5 shows two trapezes in black scattered lines of the average spectral in-structure motions, caused by the EPWs threats, for the SMR systems and components compared to tolerances received from the integrated fragility curve, presenting various accelerations with their probabilities of failure.



Probability of Failure	Acceleration	Description
1%	8.9 (g)	
50%	27 (g)	

Probability of Failure	Acceleration	Description
1%	8.9 (g)	
50%	27 (g)	

Fig. 5: Average spectral in-structure motions (black scattered line) resulted from (1) EPW-1 explosion. A =5.2 (g), V= 0.045 (m/s) =1.77 (inch/s), D=0.002 (m)=0.0787 (inch)-left figure; (2) EPW-2 explosion A =3.45 (g), V= 0.078 (m/s)=3.07 (inch/ s), D=0.007 (m) = 0.276 (inch)-right figure.

5.4. Combined Results

Although Level 3 results show that the systems and components meet the required criteria, Level 2 reveals failure in the structural elements under the given threats' scenarios. The failure of the structural elements indicates that, while systems and components are compliant with the U.S. NRC safety goals, the NuScale SMR Reactors Building (RXB) overall structural integrity would fail under the current configuration at the tested site.

6. Recommendations

In order to meet US NRC requirements, four risk mitigation alternatives based on modifying the RXB configuration are proposed:

- Separate the RXB from the tunnelled cavern side walls in order to reduce the shock wave direct transfer through the RXB's facades: This adjustment results in lower vertical accelerations: A = 0.16 g for a EPW-1 impact at 109 m, and A = 0.4 g for a EPW-2 impact at 141 m, both of which are below the HCLPF limit of 0.88 g, thus ensuring compliance with NRC failure probability standards. However, horizontal accelerations in both the latitudinal and longitudinal directions should also be taken into account.

- Add base isolators, springs, and/or dampers that can reduce blast-induced in-structure accelerations: Base isolators would separate the RXB from the cavern's bottom surface, while reducing horizontal and vertical motions. Springs and dampers placed between the RXB and cavern vertical surfaces can absorb in-structure motions and dissipate the excessive energy, ensuring that the resulting in-structure accelerations remain below 0.88 g.
- Deepen the cavern: Increasing the cavern's depth and the distance from the EPWs' blasts will reduce the blast induced in-structure motions. However, challenges related to groundwater and maintenance may arise, particularly if the RXB is moved below the water table. These concerns can be mitigated in the design of underground tunneled structures.
- Select alternative locations for the the tunneled SMR with favorable rock properties:
    a. A site with stronger rock will decrease the EPWs penetration depths and the resulted RXB in-structure accelerations may be lower.
    b. A site with various rock layers, especially such that dissipates shock waves e.g. porose rock, may attenuate shock waves and the RXB in-structure accelerations.

These options aim to enhance the SMR's protection from EPWs and ensure compliance with nuclear safety standards.

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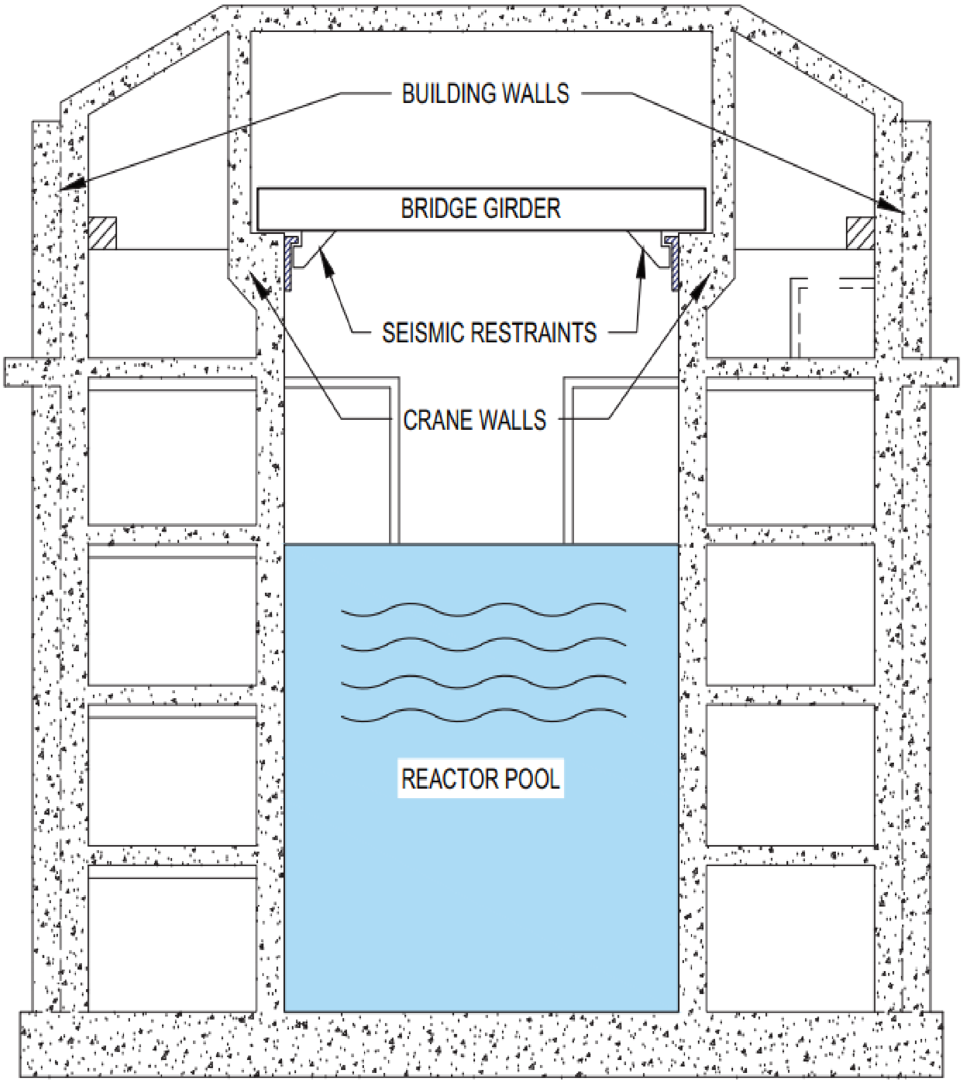
Appendix A. NuScale RXB vertical cross-section [22]



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