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Oak Ridge National Laboratory

EXECUTIVE SUMMARY: SMR CONTAINMENT CABLE AND ELECTRICAL PENETRATION ASSEMBLY SYSTEM

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CRADA Final Report
CRADA No. NFE-21-08839

June 2025

OAK RIDGE National Laboratory

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GAIN NE

SMR CONTAINMENT CABLE AND ELECTRICAL PENETRATION ASSEMBLY SYSTEM

(M3SB-21OR0101082-FINAL REPORT ON VOUCHER 21-26418)

Larry Cunningham, Bob Minadeo, Ed Hurley, Robert Duckworth, Mark Lower

June 2025

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ABBREVIATIONS

DBA	Design Basis Accident
[redacted]	[..REDACTED..]
EPA	Electrical Penetration Assembly
ESG	Engineered Solutions Group, LLC
GAIN	Gateway for Accelerated Innovation in Nuclear
IEEE	Institute of Electrical and Electronics Engineers
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
M&TE	Measurement and Test Equipment
ORNL	Oak Ridge National Laboratory
PWR	Pressurized Water Reactor
RG	Regulatory Guide
SMR	Small Modular Reactor

ABSTRACT

GAIN Project CRADA Number NFE-21-08839, entitled "SMR Containment Cable and EPA System" was initiated by the partnership of Oak Ridge National Laboratory (ORNL) and Engineered Solutions Group (ESG) to test an ESG-designed Electrical Penetration Assembly and Containment Cabling System Qualified for not only SMR technologies, but also Advanced Reactors design. An Electrical Penetration Assembly (EPA) is a component used to allow electrical power and signal conductors as well as optical fiber through the nuclear reactor's containment structure while maintaining a pressure barrier. The EPA ensures the containment's integrity both during the normal operation and also accident conditions by providing a sealed passage for power and signals. This project was undertaken to fill the equipment gap of EPA and Cabling Systems that require much more severe environmental requirements than legacy plant applications present due to their smaller containment volumes that result in high energy densities compared to legacy designs. This high energy density results in severe accident environments and also more severe normal operating conditions.

This document describes cost effective approaches to qualify a unique EPA for Small Modular Reactor (SMR) technologies as legacy LWR EPA technologies will likely have inherent material performance insufficiencies. The DBA profiles for SMRs (and some Advanced Reactor Technologies) are more severe than the legacy qualification requirements making the design of the qualification testing system challenging as the temperatures and pressures can approach the limits permitted by ASME Pressure Vessel Code, as well as accident temperatures exceeding the capability of polymeric gaskets and dielectrics.

Small Modular Reactors are designed to have, as the name suggests, modularity which implies sized for factory fabrication and subsequent assembly at the power plant site. SMR containment is much smaller than a legacy Light Water Reactor containment. The containment walls are likely to be comprised of stainless steel. Qualifying Electrical Penetration Assemblies (EPAs) through these steel vessels are of interest in this work.

Methods are presented here that discuss critical safety and cost effectiveness for these SMR EPA's test systems.

ENGINEERED SOLUTIONS GROUP'S SMR CONTAINMENT CABLE AND ELECTRICAL PENETRATION ASSEMBLY SYSTEM

M3SB-21OR0101082-FINAL REPORT ON VOUCHER 21-26418

1 June 2025

STATEMENT OF OBJECTIVES

GAIN Project CRADA Number NFE-21-08839, entitled "SMR Containment Cable and EPA System" was initiated by the partnership of Oak Ridge National Laboratory (ORNL) and Engineered Solutions Group (ESG) to test an ESG-designed Electrical Penetration Assembly and Containment Cabling System Qualified for not only legacy LWR designs, but also Small Modular Reactors designs currently being designed by several different suppliers. This project was undertaken to fill the equipment gap of EPA and Cabling Systems that require much more severe environmental requirements than legacy plant applications present due to their smaller containment volumes that result in high energy densities compared to legacy designs. This high energy density results in severe accident environments and more severe normal operating conditions as well.

We developed two approaches to qualify Electrical Penetration Assembly (EPA) and Containment Cabling Systems for SMRs and Advanced Reactors. We take into consideration the more severe environmental parameters found with SMR designs. The system will need to meet a qualification test program addressing wear/cyclic aging, potential radiation exposure, thermal aging, vibration aging, thermal cycling, seismic qualification, electrical fault testing (per IEEE 317) and accident simulation.

The equipment must meet the requirements of 10CFR50.49, GDC 50 in 10CFR50 Appendix A, and 10CFR50 Appendix J. NRC Regulatory Guides (RGs) identify an acceptable way of meeting regulatory requirements. RGs frequently endorse a standard for meeting these requirements. Specific to this review, equipment would be qualified in accordance with the following IEEE Standards [7, 8, 9, 11,12].

- IEEE 317-2013 (Electrical Penetration Assemblies), which is endorsed by RG 1.63, Rev. 3
- IEEE 323-2003 and the more current IEC/IEEE 60780-323 (Environmental Qualification of 1E Equipment) which is endorsed by RG 1.89. IEEE 323-2003 is endorsed by RG 1.209.
- IEEE 344-2020 (Seismic Qualification. The 2013 version endorsed by RG 1.100, Rev. 4, with exceptions)
- IEEE 383-2015 (Electrical Cables) (which is endorsed by RG 1.189 Rev. 4 and the -2003 version endorsed by RG 1.211 rev. 0)
- IEEE 572-2019 (Electrical Connectors and Assemblies), which is endorsed by 1.156 Rev 1
- [IEEE 1202 (endorsed by RG 1.189) would normally be applicable but the advanced cable designs are impervious to this cable flame test.]

The primary goal of such a program is to provide an EPA design that can meet the qualification requirements for all legacy light water reactor plants currently operating as well as new plant designs including light water Small Modular Reactors. Thus, these requirements are applicable to plants licensed under 10CFR50 and 10CFR52. Other reactor designs may be evaluated, and this test system and qualification method applied to those applications if the requirements would satisfy the requirements of the intended plant. A secondary benefit of this work is to document some of the history and background in these requirements as there have been recent delays in an SMR licensing process due to NRC Requests for Additional Information in this subject matter area.

BENEFITS TO THE GAIN MISSION

This project provided ESG, a small but experienced nuclear energy industry modelling, materials and EQ consulting firm, with access to the technical, regulatory, and financial support necessary to advance their innovation concerning a next generation electrical penetration assembly and feed through design that would accommodate not just SMRs, but likely most advanced reactors. Their design utilizes commercial subcomponents and technologies and test methods that are intended to accelerate qualification, component design and cost-effective commercialization.

ELECTRICAL PENETRATION ASSEMBLY QUALIFICATION BACKGROUND

Containment technologies have been well documented and established (ORNL-NSIC-5, US Reactor Containment Technology, 1965 [29]). Electrical penetration assemblies require environmental and seismic qualifications to the reactor design basis temperature, pressure and seismic profiles for each component, and for the assembly for leakage at accident conditions.

Safety-related electric equipment is defined in 10CFR50.49 [27] as equipment relied upon to remain functional during and following design basis events to ensure:

- reactor coolant pressure boundary integrity;
- the capability to shut down the reactor and maintain a safe shutdown condition; or
- the ability to prevent or mitigate the consequences of accidents whereby there could be a release of radiation to the public.

The IEEE created its own term for safety-related electric equipment which is referred to as "Class 1E." The definition of Class 1E defined in IEEE 308:2020 (and in IEC/IEEE 60780-323:2016) [10, 8] is more specific than the regulator's definition. The Class 1E definition states required nuclear-specific systems and functions. IEEE's 1E safety classification for electric equipment and systems is defined as "safety classification of the electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or are otherwise essential in preventing significant release of radioactive material to the environment." The NRC acknowledges this IEEE definition in 10CFR50.49 and endorses the 2001 version of IEEE 308 in RG 1.32 (Criteria for Power Systems For Nuclear Power Plants, revision 3, March 2004) [23].

Light water reactors' electrical structures, systems, or components (SSC) such as electrical cables, optical fibers, and assemblies would use IEEE 323 (harmonized in 2016 as IEC/IEEE 60780-323) for the parent document in environmental qualification and respective daughter standards. The electrical cables would be qualified in accordance with IEEE 383. Optical Fiber would be qualified in accordance with IEEE 1682. Connector Assemblies used as EPA interfaces would be qualified per IEEE 572. Electrical Penetration Assemblies, which would be comprised of cables as assemblies would be then qualified per IEEE 317 (under 10 CFR 50 Appendix J). IEEE 317 details the primary Containment Penetration Leakage Rate Test requirements found in 10 CFR 50 Appendix A, General Design Criterion 52. US NRC RG 1.63, "Electric Penetration Assemblies in Containment Structures for Nuclear Power Plants,"

documents requirements for electric penetration assemblies in containment structures to withstand a LOCA without loss of mechanical integrity and the external circuit protection for such penetrations. RG 1.63 endorses IEEE 317-1983 (IEEE Standard for Electric Penetration Assemblies in Containment). IEEE 317 includes testing of leakage monitoring via EPA internal pressure changes that might occur due to a leak in the EPA.
US NRC 10 CFR Part 50, Appendix A, General Design Criterion (GDC) 50, describes the requirements for containment electrical penetrations surviving a loss-of-coolant accident (LOCA) without loss of mechanical integrity and the external circuit protection for such penetrations. USNRC 10 CFR 50.53(o) requires that primary reactor containments shall meet the containment leakage test requirements set forth in 10 CFR 50 Appendix J. "Primary reactor containment" is defined in 10 CFR 50, Appendix J as “the structure or vessel that encloses the components of the reactor coolant pressure boundary, as defined in § 50.2, and serves as an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment.”

The SMR EPAs are for primary containment implying that every location where EPAs are placed throughout the SMR containment could see the postulated accident’s profile conditions. The profile used in the Design Input, based on ESG’s Report No. ESG-TP-23096-01 (Figure 1) is a conservative temperature – pressure accident profile combining various SMR technologies. This profile also accommodates the severe accident (beyond design basis) that SMR designs require.
SECY 89-012 facilitates the implementation of the 10 CFR 52 regulation for Accident Management Plans. The three global strategies described in SECY 89-012 are to have

A) procedures for conserving and/or replenishing limited utility resources during the course of an accident;
B) procedures for using plant systems and components for innovative applications during an accident;
C) procedures for defeating interlocks and overriding component protective trips in emergency situations.

These three strategies are to be applied to each of the applicable major safety functions of the plant (including EPA functional and design): reactivity control, coolant inventory control, heat removal and containment performance.
The IEC requirements for EPAs for existing reactor technology are documented in IEC 60772 Ed. 2.0: 2018. Per IEC Project TR 63335 Ed. 1 (Technical Draft Report 45A/1357/DTR) the IEC is assessing SMR EPA concerns that metallic reactor containment instead of concrete reactor buildings require specific penetration designs. Per IEC TR 63335, investigations are needed regarding “reactor electrical penetration assemblies for integrated devices inside reactor vessel like control rod drive mechanism and reactor coolant pump.” The report cites need for investigation in the “use of interconnections between containment and reactor electrical penetration assemblies housed in flexible metal bellows with sealed back-shell connections for submergence in water flooded annulus.” IEC DTR 63335 TR (2020) identifies the need for reports on new instrumentation technologies (smaller size) or use of existing industrial technologies, reduce cabling usage (i.e., multiplexing), use mineral insulated cables and integrate existing

industrial standards (as we have described in this work). [15, 30] Finally, IEC DTR 63335 TR identifies the need for IEC 60772 to be amended to include requirements for Penetration Assemblies for SMRs.

The testing sequence required for EPA qualification will need to follow follows IEEE 317, IEEE 572, and IEEE 383 guidelines, including:

- Baseline functional tests (leakage, resistance, and dielectric tests)
- Thermal cycle aging (100 cycles between 120°F–600°F)
- Radiation & vibration aging tests
- Seismic qualification tests
- Accident simulation (specimens energized under 600VAC & 500VDC, ramping to 640°F/1200 psig over 200 hours)
- Post-test inspections

The ESG design includes metallic and high temperature ceramic materials, as such, the ESG EPA is not subject to typical thermal or radiation aging degradation effects such as those that affect organic materials. Additionally, the ESG EPA can withstand submergence. The ESG EPA considerations eliminate the need for any maintenance other than periodic leak testing as prescribed by 10CFR50 Appendix J requirements.

Qualification includes preconditioning the test specimens to simulate their end-of-life condition equivalent to (in this design) 80 years of service and then subjecting them to a series of electrical fault tests, a series of seismic tests (a minimum of five Operating Basis Earthquake tests and one Design Basis Safe Shutdown Earthquake test) followed by a simulated accident test. The seismic and accident test levels were chosen as the worst-case postulated event levels for known light water reactor designs including both legacy and new plant designs including small modular reactors. These levels are extremely conservative and demonstrate the ruggedness of the equipment design.

For these test systems, the EPA is a barrier between containment and space external to containment. SMR containment is assumed to be Stainless Steel. The containment wall, liner flanges holding the feed throughs to outside of containment side of the EPA assembly are all 316 Steel. Therefore, qualification of the inboard side to the most severe environments postulated is acceptable for addressing the qualification of the exterior side. Normal and accident environments affecting the EPA are presented below in Table 1. Qualification Parameters for SMR EPAs can be found in Appendix A.

Parameter	Normal Value	Design Basis Value
Design Life	80 Years	1 Year Post Accident
Temperature	600°F	700°F
Pressure: Inboard	<20 psig	1200 psig
Pressure: Outboard	Ambient	20 psig
Number of Temperature Cycles	100 (70°F to 600°F	N/A
Number of Pressure Cycles	100 (0 to 1000 psig)	N/A
Electric Connector Con/Discon Cycles	100 (pin/socket sets)	N/A
Relative Humidity	10-99%	Saturated
Severe Accident	N/A	700°F,1200 psig plus 5 ATM of H_2+O_2 Ignited following accident

TABLE 1: Conservative Normal and Accident Environments affecting the SMR EPA
The profile below is used as a basis for establishing an IEEE 317 test for various SMRs. The required environment within the accident chamber is 640ºF (337.8ºC) – 64°F (343.3ºC) @ ~1200 psig, with 640ºF target as a target to be reached within 10 seconds of accident initiation to address the postulated thermal shock of the accident.

[REDACTED]

Figure 1: Design Basis Accident Requirements (Report No. ESG-TP-23096-01 23096-01)

SECY 89-012 specifically mentions that "risk significance of seal failure is strongly dependent on the seal design." As NuScale has its design documents on the NRC website, their approach to sealing the penetrations are available to review and are mentioned here for discussion. NuScale and ESG have their own unique EPA seal designs to prevent loss of mechanical integrity during a Loss-of-Coolant Accident. NuScale describes a metallic double O-ring seal in penetrations. NuScale's Metallic O-rings and ESG's ceramic seals are critical to maintaining pressure at the electrical penetration. NuScale's FSAR, Chapter 8, Rev 5, paragraph 8.3.1.2.5, states that both 1E and non-1E penetrations exist through containment. Specifically, their Class 1E EPAs include: CNV 17, 18, 19, and 20. The circuits in the remaining EPAs do not support safety-related functions and are classified as non-Class 1E. According to the FSAR, the EPAs are designed in accordance with IEEE Standard 317-1983. Per NuScale's TR-1116-51962-NP, Paragraph 5.3.2, NuScale EPA sheath modules are installed and tested at their plant. Their EPAs employ glass-to-metal seals that are designed for leakage rates not to exceed 1.0×10^{-3} standard cm^3/s (1.27×10^{-4} SCFH) of dry nitrogen at design pressure and at ambient temperature, including after any design basis event (per IEEE 317).

Glass-to-metal seals usually have low leak rates in the undetectable range, 1.0 x 10^{-7} standard cm^3/s of dry nitrogen at design pressure and at ambient temperature. The glass-to-metal module seal is not vulnerable to thermal or radiation aging and does not require periodic maintenance or testing. The module-to-EPA seal does not require periodic testing, except after completing maintenance activities that affect the seal. The EPA flange seal is the same double O-ring seal design of all Type B penetration seals. The required installation acceptance criterion for leakage rate of each EPA is 1.0 x 10^{-2} cm^3/s (1.27 x 10^{-3} SCFH) per IEEE 317. The leakage margin allotment for Type B testing is preliminarily chosen as 50 times the installation acceptance criterion.

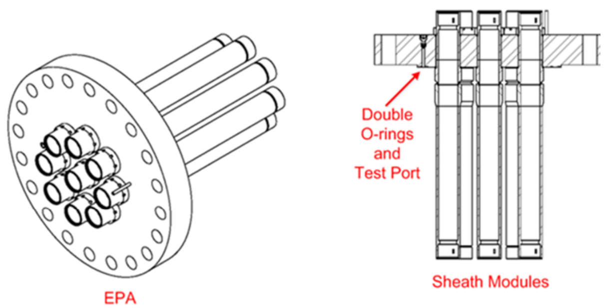

FIGURE 2: Electrical Penetration for NuScale, showing double O-rings and test ports (from NuScale TR-1116-51962-NP)

The ESG EPA (Figure 4) design employs a proprietary [REDACTED]seal rather than double O-rings (Figure 3). The ESG ceramic seal has survived LOCA and 2400 amps on 16 awg wire enduring a 50 msec pulse which is more conservative than the requires 33 msec pulse.

ESG has a proprietary EPA design, referred to as the ([………..REDACTED..]). With the containment liner bolted to the [..REDACTED..], the total cantilever is not a long canister type penetration. The penetration tubes go through the [..redacted....] assembly, are sealed on the inboard and outboard side and have a [REDACTED]that is integrated with the [..REDACTED..]. If mineral insulated, steel sheathed cables or connectors leak, the pressure change would be detected. The ESG EPA complies with requirements including the […..REDACTED……….] and Type B (Appendix J) testing. A concern with most EPA designs is the connector to the EPAs. ESG has solved this issue with a proprietary interconnection.

In 10 CFR 50 Appendix A, General Design Criterion 52, *Capability for containment leakage rate testing*, [20] requires that "the reactor containment and other equipment which may be subjected to containment test conditions shall be designed so that periodic integrated leakage rate testing can be conducted at containment design pressure." Containment is designed so local penetration leak tests can detect and measure leakage across the pressure retaining, boundaries that include flange openings, flanges, I&C penetration assemblies, and electrical penetration assemblies. The leakage limiting boundary is pressurized with air or nitrogen and the pressure decay or the leak flow rate is measured.

NuScale submitted to the US NRC a Final Safety Analysis Report (FSAR), Containment Systems Tier 2, 6.2-55 Revision 5 [17]. In this document it states that preoperational and periodic Type B leakage rate testing is to be performed in accordance with 10 CFR 50, Appendix J, NEI 94-01, and ANSI-56.8, [1, 2, 16, 21] within the defined test intervals. Additionally, the containment penetrations are subject to Type B tests as identified in Table 6.2-4 of the NuScale FSAR. The electrical penetration assemblies are thus subject to preoperational and periodic Type B leakage rate tests. The openings have double seals with a test port to facilitate Type B testing by pressurizing between the seals. Such test ports are of interest in this work especially as the temperatures they could experience may be much higher than existing LWR environments. According to Appendix J, Type B Tests are intended to detect local leaks and to measure leakage across each pressurized or leakage boundary for the following primary reactor containment penetrations:

1. Containment penetrations using resilient seals, gaskets, or sealant compounds, piping penetrations fitted with expansion bellows, as well as electrical penetrations fitted with flexible metal seal assemblies.
2. Air lock door seals which are part of the containment pressure boundary.
3. Doors with resilient seals or gaskets with the exception of seal-welded doors.
4. Components other than those listed above must meet the acceptance criteria in III.B.3.

High temperature electrical penetration assemblies (EPAs) use an established glass-to-metal sealing technology that is not vulnerable to thermal or radiation aging, do not require periodic maintenance, and will achieve a less than minimum detectable leak rate. Such EPAs for example, would be installed in a CNV penetration which includes a flange connection for testing. These installed EPAs are limited to local leak rate test acceptance criteria. The NuScale design has the ability to test the double O-ring seals by pressurizing between the seals. Figure 3 above depicts the double O-ring and test ports.

Type B tests would be performed by local pressurization at containment peak accident pressure, Pa, using either the pressure-decay or flowmeter method of detection. For the pressure-decay method, a test volume is pressurized with air or nitrogen to at least Pa. The decay of pressure rate in the test volume is monitored to calculate a leakage rate using the pressure-decay method. (NuScale Final Safety Analysis Report Containment Systems Tier 2 6.2-56 Revision 5). In accordance with 10 CFR 50, Appendix J, Type B, tests are to be performed during each reactor refueling shutdown, or other convenient intervals in accordance with the Containment Leakage Rate Testing Program (TR-1116-51962) [18].

Electrical penetration assemblies for nuclear reactor containment have electrical safety functions as well as mechanical pressure boundary safety functions to maintain primary containment integrity by precluding leakage out of the containment volume in the event of an accident. Therefore, both electrical integrity and pressure integrity must be demonstrated including qualification of the pressure boundary in the event of an electrical fault as postulated in IEEE 317. The demonstrated containment integrity levels for this test program satisfy many of the Severe Accident levels postulated for the various reactor designs. The EPAs for an SMR need to withstand temperatures whereby polymeric feed throughs' insulation and gaskets for current EPAs such as EPDM, XLPE and polyimide would not survive.

TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

ESG concluded in their review of various SMR temperatures and pressure profiles that a temperature of approximately 340ºC (640ºF in Figure 1) is reasonable and sufficiently conservative to use as the threshold for work in developing a test apparatus for EPA qualifications per IEEE 317 for the SMRs.

ESG has developed feedthroughs that can meet the higher temperature requirements and additionally the EPAs that would be associated with the feedthroughs with a built-in method to perform the required leakage tests. ESG has innovative connectors as well as their feed throughs. These proprietary components are part of the ESG EPA system. Connectors normally have a polymeric insulator for the conductors(s). The EPAs designed by ESG are designed to be solidly fixed through [REDACTED] The use of the flanges with intent to meet IEEE 317 is what ESG refers to as a [..redacted....] Assemble (Figure 3). Additional information regarding ESG's [..redacted....] Penetration Assembly is detailed in Appendix E.

To meet pressure vessel code requirements, the [REDACTED………………………………]. This weight on the side of a steel containment wall might make for a large moment arm during a seismic event. If the number of penetrations is low and the feedthrough diameters are smaller, a smaller, lighter version of the [..REDACTED..] can be used. ORNL has developed a smaller scale version that would accommodate only a few feedthroughs. This might be advantageous in reducing time and cost in the smaller EPA / feedthrough qualification. This ORNL design, the Electrical Penetration Plug, is shown in Figure 4 and is detailed in Appendix F.

[REDACTED]

FIGURE 3: ESG's EPA: [REDACTED …]

[REDACTED]

FIGURE 4: ORNL Electrical Penetration Plug can accommodate the smaller test system integrates the proprietary ESG [REDACTED]

ORNL was to use their test facilities, M&TE, and engineers/technicians to set up and conduct the required testing per selected IEEE standards such that the testing would envelope the above applications for legacy LWR and SMR requirements. ESG was to provide the test specimen designs, prepare the Qualification Test Procedure and Qualification Test Report and support ORNL in conducting the testing. Irradiation (if required) and Seismic testing was to have been outsourced. Despite not performing the test, the design(s) utilizes a simple, cost-effective, unique and original approach that can be applied to the qualification of many of the new equipment designs required to meet SMR conditions which we include in this report.

Initially, it was anticipated that an accident chamber was to have been already built at ORNL and would have been available for meeting design basis temperature and pressure profiles for these EPAs. Unfortunately, that test chamber construction project was cancelled. In response, ESG and ORNL performed initial, and thorough design work with pressure vessel calculations. This “Large Test System” would be capable of testing a 12” diameter [..redacted....] assembly with associated specimen of penetration feed throughs comprised of mineral insulated cables.

Unfortunately, the Large Test System could not be constructed within the project budget and time limitations. ESG and ORNL then worked to design a smaller accident test system. The “Small Test System” would have identical two source accumulators and one target accumulator, each with a volume of approximately 1.5 ft^3.
EPAs using [REDACTED…………………………………………………………..]. Pressure and Temperature cycling is achieved via saturated water/steam injection into a test chamber, recirculating, recharging and repeating.

Test conditions are achieved through injection of water from a source chamber into the test chamber which holds the device under test. PWR chemical spray constituents added for generic qualification applicability, should be incorporated but concern is raised in corrosion of carbon steel pressure vessels. Since actual pressure is slightly below ambient, the concern over the initial pressure change question is addressed via over pressure margin. Mission time is not compressible due to absence of thermal aging-sensitive materials, so a 200-hour test duration is adequate to represent 1 year test at pressure. Actual test pressure will approximate water saturation pressure at 620°F (~1700 psig). Ramp time may be as short at 2 seconds to reach 600°F+. Submergence will be present over the duration of the test.

The test conditions are achieved by injecting heated water from a source chamber into a target chamber via a fast-acting valve. Attributes of the valve include having a 1" pipe diameter, 3-Piece ball valve, 3600 psi, full port, Stellite™ ball with SS316 and Stellite™ seat, NPT, graphite gasket/stem packing, a spring return actuator and, 700°F service rating. PWR chemical spray constituents would be added for generic qualification applicability but for carbon steel pressure vessels note that the inner vessel wall would be susceptible to internal corrosion.

Assuming that the starting condition for the source vessel is at rated conditions (filled with water heated to 640°F) and that the test chamber is starting with a metal temperature of 150°F, 0 psig and contains 150 pounds of test specimen mass for the larger device under test from ESG), the rapid injection of the water from the pressure tank will create flashing within the test chamber as the saturated liquid flashes violently into a water/steam mixture. In addition, even though the test specimen vessel is equipped with external heaters, the metal temperature will be increased almost solely by the heated water injection. Figure 5 (top) shows a schematic where a source chamber provides heated / pressurized water to a target chamber. The drawing in Figure 3 depicts the IEEE 317 compliant [..REDACTED..] device under test would be arranged in this set up. The feedthroughs penetrate the two flanges comprising the [..REDACTED..]. The [..REDACTED..] then is bolted to the target chamber with temperature and pressure sensors. The [..REDACTED..] would be bolted directly to the SMR containment (CNV).

Band heaters energized to create the required pressure and temperature source, 650°F/1840+ psig.
The Source chamber will then be discharged into the test chamber section and allowed to equilibrate for 60 minutes. After 60 minutes, the test side will then be vented to ambient and allowed to cool to 100°F. This comprises a margin transient for the Accident Simulation Test. It is also a single cycle for the thermal/pressure cycling requirement in the preconditioning phase of testing. The Source chamber will be refilled and heated back to the saturated conditions and then sent back to the test chamber. This sequence would be repeated 100 times and the Source PV section vented and refilled as needed. Additional information regarding the Accident Test Chamber & Steam Supply Chamber Design is found in Appendix B.

Large Test System design (Figure 5) is comprised of commercially available pressure chambers made of US-made spools, pipes and flanges used in the oil and gas industry. More details are available in Appendix C. The larger of the two vessels would be the source and the test chamber would receive high enthalpy steam through a pipe and fast acting valve. The system would be heated with appropriately rated heater bands. It was determined this design could not be viable as there was both poor supply chain availability for the relevant steel materials (during COVID) and the start of a major construction project next to this project's location, making it impossible to continue the large test system. Two test chambers in ORNL storage were considered but were deemed unsuitable for this application.

ESG and ORNL designed the Small Test System that would require only assembly and minimize pressure vessel welding. This system is referred to as the Small Test System in this document. It utilizes US-made [REDACTED …….]and more cost effective. This is described in Appendix D.

[REDACTED]

[REDACTED]

FIGURE 5: Large Test System pressure vessels: Source and Target chamber schematic (Top), [REDACTED] (bottom, right), [REDACTED] (bottom, left). Refer to Appendix C for more details

A smaller and more economical system was designed with a scaling down of ESG's [..redacted....] Assembly ([..REDACTED..]) which contains both feedthroughs and leakage testing method had to be redesigned with limitations to the actual feedthrough tests (size and feedthrough quantity). ESG and ORNL made inquiries with manufacturers of pressure vessels and steam supplies to facilitate the testing. The pressure vessel system approver required a thermal hydraulic dynamic FEA model. We were not able to secure the capability to perform this model. Additionally, the internal fabrication shop eventually decided it could not assemble the small system. An outside fabrication house was asked to perform assembly and pressure testing in parallel with ORNL SME and they responded that by that time, there was insufficient time left in the project to assemble and perform the pressure test. Only long lead time hardware had been procured, namely three accumulators for source and target chambers, and fitted heater bands.

ORNL modelled thermohydraulic response of the Small Test System. We used Flownex™ (Figure for the Small Test System for this purpose. Only one initial trial was performed with one source chamber to one target chamber. The transient discharge from two accumulator source tanks into a single accumulator target tank is more viable. If a third accumulator is needed to meet the temperature profile, the accumulator-based system is scalable to meet that level of additional energy. Input temperatures and water volume would need to be optimized using Flownex ™. Flownex™ could certainly be used for the Large Test System.

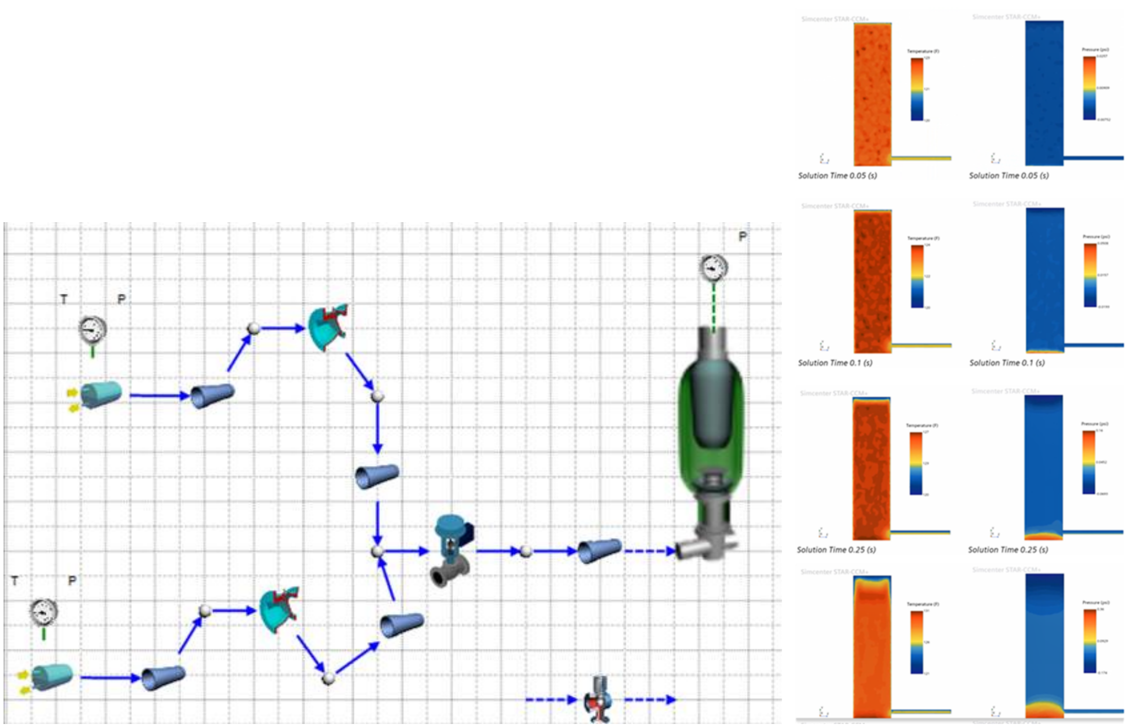

Figure 6: Flownex model of the small pressure vessels test arrangement (Left). Initial response of transient temperature and pressure of 640°F water rapidly injected into 11 gallon accumulator (TOP responses from 0.5 seconds to 10.0 seconds).

In the optimized case, source tanks are heated from 120°F, ambient pressure to 640°F, 1200 psig. Conditions are held for 1 h. Valves are opened between source tank(s) and target tank, and a history of hydraulic stress on the emulated pressurizer plate (for electrical penetrations) and mechanical stress on piping and target tanks are to be recorded.

SUBJECT INVENTIONS

ESG has developed a novel and unique EPA for SMRs, high temperature reactors and similar applications with steel containment.
[……redacted………………………….… ……………………………………]

ESG has also developed an in-containment cabling system for use in conjunction with the EPA. This invention is ESG's background intellectual property.
[……redacted………………………….… ……………………………………]

ESG, in an effort to resolve the challenge of not having the LOCA chamber at ORNL as expected, developed their own design in a manner to use commercially available material
[……redacted]. This is the Large Test Chamber which is described in this document. This is project-related Generated Intellectual Property.

ORNL and ESG together have developed a novel and unique miniaturized EPA as a derivative of the
[……redacted] It is referred to in this document as the Plug. The Plug, like the ESG [redacted], includes designs for high temperature feedthroughs and connectors in a manner that maintains pressure boundary required by 10CFR50 Appendix J. The ORNL Plug design can constantly monitor pressure changes within the penetrations as it was developed with ESG during this project. The ORNL Plug was originally intended to be a test EPA to replace the ESG [REDACTED] [..REDACTED..]design in response to not having the Large Test System as expected. The ORNL Plug incorporates ESG intellectual property. The Plug has some advantages and disadvantages. Since it is smaller than the [..REDACTED..], it holds fewer feed throughs, and their diameters will need to be smaller. The Plug has an advantage in that as it is lighter (5 – 50 pounds as opposed to a ~2,000-pound [..REDACTED..], there is less of a moment arm which would be

safer in a seismic event. Additionally, the Plug is scalable and can be added in rows and columns through a steel containment wall. This is project-related Generated Intellectual Property.

ORNL and ESG, in an effort to resolve the challenge of not being able to produce the Large Test System as expected at ORNL, developed a design in a manner to use commercially available material (pressure rated Department of Transportation pressure code certified accumulators and piping that is US-made and commercially available). This is project-related Generated Intellectual Property. The intent was to minimize welding modifications when fabricating the system. This is the Small Test System which is described in this document (Appendix D).

COMMERCIALIZATION POSSIBILITIES

There is a need for high temperature EPAs and feedthroughs. Each applicant can benefit from a qualified solution that will meet their environmental qualification requirements. The requirements intended for both the [..REDACTED..] and Plug envelope the most severe parameters. Commercialization would be feasible for the ESG [..REDACTED..] as well as the ORNL Plug. There is ESG Intellectual Property intermingled with the Plug which will need to be worked through. ESG would be receptive to discussing an agreement.

Should the Small and Large Test Chambers be fabricated at ORNL, it might be an opportunity to perform advanced reactor environmental tests. ORNL would not intend on competing with qualification test labs but to our knowledge there are no LOCA chambers in the nuclear supply chain yet that can meet the advanced reactor profiles.

PLANS FOR FUTURE COLLABORATION

There is an opportunity for collaboration between ESG and ORNL in design of advanced reactor compatible feedthrough connectors that can be quickly released and reconnected between refuelings. We have heard that the currently planned method of opening a penetration at a NuScale SMR is for a person to go inside containment (EPA would be unbolted and suspended) and quickly unscrew connectors. ESG and ORNL have discussed concepts that would be superior to this method.

There is an opportunity for collaboration in testing using Small and/or Large Test Chambers to advance high temperature reactor component development.

The NRC expects to receive 25 SMR license applications within the next five years. Once lab testing proficiency is established, collaboration with SMR licensees would hasten the SMR company's approval progress.

There were delays with NuScale's license application. Some of the delays were directly caused by NRC questions of the NuScale EPA design. ESG/ORNL/Applicant collaboration is a possibility in terms of not only the Plug or the [..REDACTED..] but the License counsel and performing EPA Design and Testing. There would be a value in having one scalable EPA solution which would be compatible with the *modular* attribute of the SMR.

PROJECT SUMMARY

SMR containments are designed differently compared to legacy light water reactor containment. SMR containment will be comprised of stainless steel. The temperature and pressure requirements for an SMR will exceed many LWRs requirements. A review of SMR requirements was performed by ESG and is summarized in the report as design inputs that envelope the reviewed SMR EPA qualification requirements. The collaboration between ESG and ORNL was established to test ESG's EPA design. The testing was not completed. However, the project has led to two EPA design testing programs and an additional miniature ORNL EPA design concept.

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APPENDIX A. QUALIFICATION PARAMETERS FOR EPA

The Qualification Parameters for EPA define worst-case containment conditions based on commercial light-water reactor designs, including both legacy and new constructions. The EPA serves as a barrier between containment and external environments, with the inboard and outboard sides sharing identical material characteristics and failure modes. Thus, qualifying the inboard side for extreme conditions sufficiently addresses the qualification of the exterior side.

The EPA must withstand normal and accident conditions, as outlined in the Environmental & Operational Parameters table below:

Parameter	**Normal Value**	**Design Basis Value**
Design Life	80 Years	1 Year Post-Accident
Temperature	600°F	700°F
Pressure (Inboard)	<20 psig	1200 psig
Pressure (Outboard)	Ambient	20 psig
Temperature Cycles	100 (70°F to 600°F)	N/A
Pressure Cycles	100 (0 to 1000 psig)	N/A
Electric Connector Cycles	100 (pin/socket sets)	N/A
Radiation (Gamma)	5E7 rads	2E8 rads
Radiation (Beta)	<1E7 rads	1.5E9 rads
Submergence	No	120 ft depth
Spray Exposure	No	24 hours (water, NaOH, H_3BO_3, TSP)
Relative Humidity	10-99%	Saturated
Non-Seismic Vibration	Per IEEE 382	No
Seismic Events	5 OBE (IEEE 344)	1 SSE (IEEE 344)
Seismic Vibration	7g (1-100 Hz)	10g (1-100 Hz)
Severe Accident Conditions	N/A	700°F, 1200 psig + 5 ATM H_2/O_2 Ignition

Functional & Electrical Requirements:

- Functional: Insulation resistance ≥ 1E9 ohms, circuit resistance <100 milliohms, dielectric withstand of 2200VAC for 60 sec., leakage ≤ 1E-3 SCCM.
- Electrical Fault Tests: Includes overload tests (IEEE 317 Sec 4.2.3), short-circuit current test (IEEE 317 Sec 4.2.4), and thermal capacity evaluation (I^2t per IEEE 317 Sec 4.2.5).

Pressure/Temperature Cycling Test:
Testing involves saturated water/steam application:
[REDACTED][REDACTED ………]**Design Considerations:**
[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

[REDACTED]
[REDACTED]
[REDACTED][
REDACTED]

Test Sequence:
Testing follows IEEE 317, IEEE 572, and IEEE 383 guidelines, including:

- [REDACTED]
- [REDACTED]
- [REDACTED]
- [REDACTED]
- [REDACTED]
- Post-test inspections

APPENDIX B. ACCIDENT TEST CHAMBER & STEAM SUPPLY CHAMBER DESIGN

Temperature Profile

- The LOCA curves are more extreme, with two peaks, the highest reaching [REDACTED]°F.
- IEEE 323 requires adding 15°F to the peak, yielding a [REDACTED]°F accident temperature.
- The green curve represents a bounding temperature profile incorporating this margin, which must be achieved in the accident (small) chamber.
- This data is preliminary, based on multiple SMR vendors, and final designs could require an even higher peak accident temperature.
- The actual accident test temperature may exceed [REDACTED]°F due to rapid steam injection, making [REDACTED]°F a minimum target.
- Ideally, some margin should be included in the accident chamber design.

Pressure Profile

- The LOCA pressure curve is more extreme than HELB.
- IEEE 323 mandates a 10% margin on the pressure profile; the green curve represents this bounding pressure envelope for the accident chamber.
- As with temperature, this data is preliminary, and final SMR designs may require a higher peak accident pressure.
- Additionally, steam injection could overshoot both peak temperature and peak pressure in the accident chamber.

The test must meet temperature and pressure requirements, achieving at least saturated 650°F in the accident chamber for SMR qualification. The source supply chamber must exceed 650°F to compensate for temperature drops during injection. To redistribute thermal energy, an initial 700°F starting temperature in the large chamber is appropriate. The test's temperature requirement applies to the space surrounding specimens, not chamber walls.

This section outlines the design specifications for pressure vessels, prepared in accordance with ASME Section VIII, Division 2 (2021 Edition), Paragraph 2.2.2.

Site & Environmental Conditions.

The vessels would be located at Oak Ridge National Laboratory (ORNL), Tennessee, under the Department of Energy's jurisdiction. As they are situated indoors, environmental factors such as wind, seismic, and snow loads are not applicable. The lowest one-day mean temperature is 50°F.

Vessel Identification & Configuration

The ESG SMR Accident Simulator System utilizes saturated steam as its service fluid. The vessel is oriented horizontally with openings, connections, and closures including safety relief valves, drain/vent valves, and a 12” flange. The two shell dimensions are 18.0” nominal ID, 116” long and 12.0” nominal ID, 32” long, respectively, each with 2:1 elliptical heads and seamless construction. The support method consists of unattached saddles.

Design & Operating Conditions

- Design Pressure: MAWP 2500 psi, capable of full vacuum externally due to cooling.
- Design Temperature: [REDACTED]2500 psi, with external pressure of 15 psi at 70°F.
- Minimum Metal Temperature: 50°F at 1400 psi.
- Operating Pressure: [REDACTED]psi with an operating temperature of [REDACTED]°F.
- Thermal or flow transients are accounted for.

Fatigue & Service Life Considerations

- Cyclic operating conditions: Pressure cycles during startup and shutdown.
- Design life: 5 years max, with 100 cycles per year to simulate 80 years plus 20 SCRAMS. Minimum design life of 1000 cycles preferred.
- Fatigue screening: Conducted per ASME Method B.

Materials of Construction

The vessel consists of carbon steel components:

- Shell & Heads: SA-516 Gr. 70.
- Nozzles: SA-106C Seamless Pipe.
- Flanges: SA-516 Gr. 70 LWN.
- Bolting: SA-193 B7 CL2 threaded studs and SA-194 7 CL2 nuts.
- No corrosion/erosion allowances are necessary.

Loads & Overpressure Protection

- Internal & External Pressure Loads are accounted for.
- Seismic loading is not considered.
- Hydrogen burn test incorporated by adjusting operating pressure.
- Pressure relief valve protects against overpressure, set to ≤2500 psi, ASME-certified, spring-operated, direct-acting, reclosing.

Testing & Additional Requirements

- Welding Joints: Visual, surface, and radiography/ultrasonic testing based on joint type.
- Hydrostatic Testing: Clean potable water at 50°F–120°F, vessel positioned horizontally.
- Inspection: Initial check by Commissioned Inspector per ORNL SBMS guidelines.

Design Considerations

- The material strength basis for 1[REDACTED]
- Instrument interfaces include multiple thermocouple entry points, pressure taps, a sparkplug port, and a sight glass feature for liquid level determination.
- Vessel ports must be welded or threaded and sealed to ensure leak-free specimen testing.
- Valves must be leak-free, with the control valve being air-to-close for rapid operation.
- Gaskets must withstand [REDACTED]°F with zero leakage—polymer gaskets are unsuitable.
- A recirculation pump will maintain fresh heated inventory in the small chamber, and CAL-SIL insulation (2” minimum) will help control heat loss.

- [REDACTED] Each chamber's heating system should be independently controlled.

APPENDIX C. LARGE TEST SYSTEM

The Large test SYSTEM in Figure X, would have a volume of approximately 4,000 cu inches. The source chamber at the right of Figure X would have a volume of approximately 30,500 cu inches. COMPRESS Pressure Vessel Design Calculations in accordance with ASME Section VIII Division 2, 2021 Edition Class 2 are available upon request[1].

[1]COMPRESS Pressure Vessel Design Calculations Item: ESG Reactor - 12" Vessel Designer: Mark Lower March 8, 2022.
[1]COMPRESS Pressure Vessel Design Calculations Item: ESG Reactor - 18" Vessel Designer: Mark Lower March 9, 2022

[REDACTED]

[REDACTED]

[REDACTED]

APPENDIX D. SMALL TEST SYSTEM

A pressure vessel is to be used to contain heated, pressurized water, sufficient to rapidly be discharged via a fast-acting valve into a smaller pressure vessel (likely 1.5 cu ft). The purpose is to test Electrical Penetration Assemblies (EPA) that are designed to penetrate steel SMR containment walls. The environmental qualification profile is much more severe than existing LWRs.
The EPA feedthroughs will be made of stainless tubing covering Magnesium Oxide and nickel-plated copper wire of various cross sections.
A Source chamber is to be filled mostly with water to maximize enthalpy / energy transfer to test chamber.

The Small Test System is described below. The [..redacted....] Assembly has to be modified and less penetrations can be tested due to smaller size. The Small Test Chamber & Source Chamber Specifications are summarized below. The smaller test chamber (left in Figure Y) has a volume of ~4,000 cu in.

- The source chamber (right in Figure X) has a volume of ~30,500 cu in.
- [REDACTED], Cr-Mo Steel, SA- 372, Grade F Class 70, Section VIII MAWP
- Welding procedure: ORNL-approved for SA 372 Gr F Cl 70, following ASME P1 metals welding guidelines.

Thermal Profile & Valve Operation:

- Source chambers heated to [REDACTED]°F max (ASME alloy limit).
- Spring-loaded valve rapidly opens to target chamber.

Target Cylinder Configuration:
[REDACTED] ([REDACTED]with MAWP of 6200 PSI)

- with top section port removed and flange welded in place.
- Flange bolt holes match the device under test.
- Device under test base:
    - Flange with identical pressure rating as the welded flange.
    - One-inch steel plate welded with half-inch annular space between flange and plate.
    - Stainless steel tubes with MgO-insulated electrical conductors, secured with Swageloks.
    - ¼-inch holes drilled in each steel tube, aligning MgO insulation with the gap between plate and flange.
    - Pressure change in gap due to leakage is measured during design basis event testing.

Instrumentation & Testing Requirements:

- Test chamber:
    - Three fast-acting thermocouples (T/Cs).
    - Pressure sensor.
    - Insulation resistance (IR) measured in cables.
- Source chambers:
    - Thermocouples (T/Cs).
    - Safety relief valve (SRV) rated to 2500 psi.
    - Insulated [REDACTED]for [REDACTED]°F accumulator heating.
    - Piping to one fast-acting valve.
- Water recirculation required for repeated testing (hundreds of tests planned).

[REDACTED]

APPENDIX E ESG [..REDACTED....] ASSEMBLY DETAIL

[REDACTED]

The penetration feedthrough tubes will each be [REDACTED…..]. They will be centered around the midline where the leakage capture volume is.. [*redacted*]. If cables or connectors leak the pressure change [*redacted*] would be detected.

Flanges are welded circumferentially but a ring shape gap between them is preserved for pressure changes during test. The outboard extension is ¼" NPT Pressure Port through outboard flange to measure pressure changes in the gap between [..redacted....]s. The Inboard: has 4 temp sensors and one Pressure sensor for chamber. IEEE 317. A Blue tap into cylinder flange top and bottom (avoid bolt holes) and connect a pressure rated Sight Glass for visual confirmation - [..REDACTED..] and the Cylinder's Flange - [REDACTED ……….].

Penetrations - [..redacted....] Assembly with Blind flange on inboard and outboard sides; 4 Penetration Test Samples, [REDACTED]

APPENDIX F. ORNL PLUG ASSEMBLY DETAIL

A Smaller [..redacted....] Assembly, or Plug, developed by ORNL as a derivative of the ESG [..REDACTED..], can nominally hold two feedthroughs, and can maintain their pressure. A Schematic of Smaller Pressure Vessel Plug Assembly is provided that accommodates the ESG feedthroughs.

[REDACTED]