Combustible Gas Control

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Abstract

This technical report describes the response to combustible gas accumulation in the NuScale Power Plant to demonstrate the design is able to establish and maintain safe shutdown, maintain accident mitigating features, and maintain containment structural integrity during and after hydrogen combustion events. The report describes the analysis of design basis events (DBEs) and beyond design basis events (BDBEs) that may lead to a combustible atmosphere within the NuScale containment vessel (CNV). Combustible gas concentrations within the CNV and potential combustion sequences were analyzed based on regulatory criteria and bounding postulated scenarios, thereby establishing bounding analyses for the NuScale Power Plant design.

This report describes the NuScale CNV structural analysis that demonstrates the CNV and components necessary to establish and maintain safe shutdown can withstand the environmental conditions created by the burning of hydrogen during DBEs and BDBEs. NuScale containment structural integrity is not challenged by bounding combustion events, propagated by combustible gas concentrations generated within the first 72 hours of any DBE or BDBE. The analysis demonstrates that no compensatory measures or mitigating actions are required for any scenario, within the first 72 hours of an event. The report describes the NuScale equipment survivability analysis that demonstrates the NuScale Power Module design ability to establish and maintain safe shutdown and maintain containment structural integrity with systems and components capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen within the CNV. The report describes the NuScale CNV functional capability for ensuring a mixed atmosphere during and after DBEs and BDBEs. This report also describes the NuScale design capability to monitor CNV conditions relative to combustible gas control and accident management. Therefore, this report demonstrates that the NuScale design is able to establish and maintain safe shutdown, maintain accident mitigating features, and maintain containment structural integrity during and after hydrogen combustion events, consistent with the intent of 10 CFR 50.44 requirements.

Executive Summary

This technical report describes the strategy and analysis of combustible gas response in the NuScale Power Plant. The report describes the analysis of events that may lead to a combustible atmosphere within the NuScale containment vessel (CNV). Combustible gas concentrations within the CNV, and potential combustion sequences, were analyzed based on regulatory criteria, applicable guidance, and bounding postulated scenarios, thereby establishing bounding analyses for the NuScale design.

This report provides a detailed overview of the NuScale CNV structural analysis, which demonstrates that the CNV can withstand the environmental conditions created by deflagrations, reflected detonations, and deflagration-to-detonation transitions both for design basis events (DBEs) and beyond design basis events (BDBEs). For the NuScale design, containment structural integrity and the functionality of equipment necessary to establish and maintain safe shutdown are assured, without reliance on an inert atmosphere or equipment to regulate hydrogen concentrations within the first 72 hours of any DBE or BDBE. Hydrogen combustion scenarios occurring within 72 hours following an event initiation have no adverse effect on containment integrity or plant safety functions. The analyses described in this report support four conclusions related to NRC combustible gas control regulatory requirements:

1. Structural analysis (10 CFR 50.44(c)(5)) – NuScale CNV structural integrity is not challenged by combustion events propagated by combustible gas concentrations generated within the first 72 hours of any DBE or BDBE. This report describes the containment response to the structural loads involved in a combustion event. The report addresses an accident that releases hydrogen generated from 100 percent fuel clad-coolant reaction accompanied by hydrogen burning. The report demonstrates that systems necessary to ensure containment integrity perform their function under these conditions.

2. Equipment survivability (10 CFR 50.44(c)(3)) – NuScale containment structures, systems, and components are designed to withstand combustion events propagated by combustible gas concentrations generated within the first 72 hours of any DBE or BDBE. Equipment exposed to CNV combustion conditions that are required to establish and maintain safe shutdown or CNV integrity are designed for loads associated with combustion events and maintain associated functionality. This report demonstrates that the NuScale design is able to establish and maintain safe shutdown and containment structural integrity with structures, systems, and components capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen.

3. Mixed atmosphere (10 CFR 50.44(c)(1)) – The NuScale CNV design passively ensures a mixed atmosphere during DBEs and BDBEs. This report demonstrates that the concentration of combustible gases in any part of the CNV is below a level that supports combustion or detonation that could cause loss of containment integrity.

4. Monitoring (10 CFR 50.44(c)(4) and 10 CFR 50.34(f)(2)(xvii)(C)) – The NuScale design includes monitoring capabilities appropriate for indication of CNV conditions for accident management, including emergency planning. This report identifies instruments and

analyzers that are available to monitor combustible gas concentrations within the containment atmosphere during and following a DBE or BDBE.

1.0 Introduction

1.1 Purpose

The purpose of this report is to describe the strategy and analysis of combustible gas control in the NuScale Power Plant design. This report defines the limiting design basis events (DBEs) and beyond design basis events (BDBEs) considered for combustible gas analysis. The report describes the methodologies used for determining combustible gas concentrations and the structural analysis methodologies for analyzing the effect of combustion events on the containment. The report describes the NuScale combustible gas monitoring capability and available equipment to support potential post 72 hour mitigating actions. Through these descriptions, this report demonstrates that the NuScale design is able to establish and maintain safe shutdown, maintain accident mitigating features, and maintain containment structural integrity during and after bounding combustion events, consistent with the intent of 10 CFR 50.44.

1.2 Scope

The scope of this report is limited to analysis of combustion events in the NuScale containment. The first 72 hours of DBEs or BDBEs are examined. The analysis demonstrates that no compensatory measures or mitigating actions are required for any scenario, within the first 72 hours of an event. Event progression beyond 72 hours is not addressed in this report except to identify applicable monitoring and event mitigation capabilities of the NuScale design. Consistent with NRC rulemaking documents (Reference 5.1.18), accumulation of combustible gases beyond 72 hours can be managed by licensee implementation of severe accident management guidelines (SAMGs) because after 72 hours, sufficient time is available to implement mitigating actions.

This report describes the NuScale containment vessel (CNV) structural analysis that demonstrates the CNV can withstand the environmental conditions created by the burning of hydrogen during DBEs and BDBEs, while maintaining containment structural integrity and safe shutdown capabilities. For reflected detonation loads from DBEs, the results are evaluated against American Society of Mechanical Engineers (ASME) Service Level C limits. For deflagration-to-detonation transition (DDT) loads from DBEs, the results are evaluated against ASME Service Level D limits. For DDT loads from BDBEs, the results are evaluated against strain criteria from Reference 5.1.5.

This report identifies components inside the containment that are required to maintain structural integrity or to establish and maintain safe shutdown, and describes the load specifications with regard to combustion loads that ensure equipment survivability through the ASME design process.

The report scope includes description of the NuScale CNV functional capability for ensuring a mixed atmosphere during design basis and beyond design basis accidents. This report describes the NuScale design capability to monitor CNV conditions relative to combustible gas control and accident management, as well as the NuScale design

capability to mitigate combustible gas concentrations within the CNV for potential post 72 hour accident management compensatory measures.

1.3 Abbreviations, Acronyms and Definitions

Table 1-1 Abbreviations and acronyms

Term	Definition
ASME	American Society of Mechanical Engineers
BDBE	beyond design basis event
C-J	Chapman-Jouguet
CES	containment evacuation system
CFR	Code of Federal Regulations
CIV	containment isolation valve
CNV	containment vessel
CRDM	control rod drive mechanism
DBE	design basis event
DDT	deflagration-to-detonation transition
ECCS	emergency core cooling system
EPA	electrical penetration assembly
LOCA	loss-of-coolant accident
LWR	light water reactor
NPM	NuScale Power Module
NRC	Nuclear Regulatory Commission
PZR	pressurizer
RCS	reactor coolant system
RG	Regulatory Guide
RPV	reactor pressure vessel
RRV	reactor recirculation valve
RVV	reactor vent valve
SAMG	severe accident management guideline
SSC	structures, systems, and components
TNT	Trinitrotoluene

Table 1-2 Definitions

Term	Definition
Chapman-Jouguet ratio	The ratio of the initial pressure to the peak pressure for an ideal detonation. This factor is used to estimate peak pulse pressures for a given combustible gas mixture based on empirical data. Reflection is not considered.
Deflagration	Combustion mode where the propagation rate is dominated by molecular and turbulent transport process.
Deflagration-to-detonation transition	Under certain conditions, a flame may accelerate to high velocities and suddenly transition to a fully developed detonation. The circumstances involve a sufficiently sensitive mixture (very rapid chemical reaction) in a geometric configuration that is favorable to flame acceleration - this usually requires confinement and obstructions or obstacles in the path of the flame. Such mixtures are characterized by a small detonation cell width, high flame speed, and high volume expansion ratio.
Detonation	Combustion mode consisting of a shock wave closely followed by a supersonic exothermic chemical reaction zone front.
Inert atmosphere	A containment atmosphere with less than four percent oxygen by volume.
Mixed atmosphere	The concentration of combustible gases in any part of the containment is below a level that supports combustion that could cause loss of containment integrity.
Minimum ignition energy	The minimum amount of energy required to ignite a combustible vapor, gas or dust cloud, for example by means of an electrostatic discharge.

2.0 Background

The NuScale Power Module (NPM) design is different than light water reactor (LWR) designs currently in operation, including design attributes associated with combustible gas control. The integrated design of the reactor pressure vessel (RPV) and CNV maintains the reactor coolant inventory within the CNV. The CNV is a pressure vessel that houses, supports, and protects the RPV from external hazards and provides a barrier to the release of fission products. The CNV is designed, analyzed, fabricated, inspected, tested, and stamped as an ASME Code Class 1 pressure vessel, which is partially immersed in the reactor pool to facilitate heat removal. The CNV is designed to provide a barrier against the release of fission products while accommodating the calculated pressures and temperatures resulting from postulated mass and energy release inside containment. The CNV is designed to withstand the full spectrum of postulated mass and energy releases (i.e., loss-of-coolant accident (LOCA) and non-LOCA), including combustible gas events.

During normal operations, the CNV is evacuated in order to minimize heat losses from the reactor pressure vessel. Additionally, to provide passive heat removal, the containment is partially immersed in the reactor pool. Due to the small volume and low pressure, the containment provides limited non-condensable gas buffer (namely nitrogen) that would reduce combustible gas concentrations during postulated combustion event scenarios. Further, the passive heat removal function makes it possible to attain low temperatures (and, therefore, low water vapor concentrations) in the containment, even during severe accidents. With little non-condensable or water vapor buffer gas, small contributions of combustible gases from radiolysis (and from fuel clad-coolant reactions in the case of a severe accident) can result in combustible gas concentrations in containment.

Typical combustible gas control measures in existing large LWRs include active control functions and systems that limit containment hydrogen concentrations or inert the containment atmosphere. The NuScale design uses robust passive structures capable of withstanding postulated combustion loads, simplifying design and minimizing the reliance on operator action, to reliably ensure safety. The NuScale containment vessel is an ASME Class MC vessel designed and constructed to Class 1 pressure vessel standards. Containment boundary SSC are also designed and constructed to ASME Class 1 or Class 2 standards, depending on if the SSC also form part of the reactor coolant pressure boundary.

Consistent with the passive design of the NPM, the evaluation contained in this report does not rely on active design features or operator actions for at least 72 hours following an event. The NuScale design does not employ active components to ensure an inert containment atmosphere, or to limit hydrogen concentrations in containment. As there is potential for continued hydrogen and oxygen generation and accumulation for an indefinite period following an event, the analysis presented has focused on the first 72 hours of event scenarios. Accumulation of combustible gases that could develop post 72 hours can be mitigated by the application of SAMGs.

2.1 Regulatory Requirements

10 CFR 50.44, "Combustible gas control for nuclear power reactors," paragraph c states:

> (c) Requirements for future water-cooled reactor applicants and licensees. The requirements in this paragraph apply to all water-cooled reactor construction permits or operating licenses under this part, and to all water-cooled reactor design approvals, design certifications, combined licenses or manufacturing licenses under part 52 of this chapter, any of which are issued after October 16, 2003.
>
>> (1) Mixed atmosphere. All containments must have a capability for ensuring a mixed atmosphere during design-basis and significant beyond design-basis accidents.
>>
>> (2) Combustible gas control. All containments must have an inerted atmosphere, or must limit hydrogen concentrations in containment during and following an accident that releases an equivalent amount of hydrogen as would be generated from a 100 percent fuel clad-coolant reaction, uniformly distributed, to less than 10 percent (by volume) and maintain containment structural integrity and appropriate accident mitigating features.
>>
>> (3) Equipment Survivability. Containments that do not rely upon an inerted atmosphere to control combustible gases must be able to establish and maintain safe shutdown and containment structural integrity with systems and components capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen. Environmental conditions caused by local detonations of hydrogen must also be included, unless such detonations can be shown unlikely to occur. The amount of hydrogen to be considered must be equivalent to that generated from a fuel clad-coolant reaction involving 100 percent of the fuel cladding surrounding the active fuel region.
>>
>> (4) Monitoring. (i) Equipment must be provided for monitoring oxygen in containments that use an inerted atmosphere for combustible gas control. Equipment for monitoring oxygen must be functional, reliable, and capable of continuously measuring the concentration of oxygen in the containment atmosphere following a significant beyond design-basis accident for combustible gas control and accident management, including emergency planning.
>>
>> (ii) Equipment must be provided for monitoring hydrogen in the containment. Equipment for monitoring hydrogen must be functional, reliable, and capable of continuously measuring the concentration of hydrogen in the containment atmosphere following a significant beyond design-basis accident for accident management, including emergency planning.

(5) Structural analysis. An applicant must perform an analysis that demonstrates containment structural integrity. This demonstration must use an analytical technique that is accepted by the NRC and include sufficient supporting justification to show that the technique describes the containment response to the structural loads involved. The analysis must address an accident that releases hydrogen generated from 100 percent fuel clad-coolant reaction accompanied by hydrogen burning. Systems necessary to ensure containment integrity must also be demonstrated to perform their function under these conditions.

This report addresses the requirements of 10 CFR 50.44(c)(1) mixed atmosphere, (3) equipment survivability, (4) monitoring, and (5) structural analysis. The requirements of 10 CFR 50.44(c)(2) combustible gas control, are addressed in an exemption request within the NuScale Design Certification Application.

The combustible gas aspects of 10 CFR 50, Appendix A, Criterion 41, and 10 CFR 50.34(f)(2)(xvii)(C) are also addressed in this report.

10 CFR 50, Appendix A, General Design Criterion 41 states:

Criterion 41 – Containment atmosphere cleanup. Systems to control fission products, hydrogen, oxygen, and other substances that may be released into the reactor containment shall be provided as necessary to reduce, consistent with the functioning of other associated systems, the concentration and quality of fission products released to the environment following postulated accidents, and to control the concentration of hydrogen or oxygen and other substances in the containment atmosphere following postulated accidents to assure that containment integrity is maintained.

Each system shall have suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) its safety function can be accomplished, assuming a single failure.

10 CFR 50.34(f)(2)(xvii) states:

(xvii) Provide instrumentation to measure, record and readout in the control room: (A) containment pressure, (B) containment water level, (C) containment hydrogen concentration, (D) containment radiation intensity (high level), and (E) noble gas effluents at all potential, accident release points. Provide for continuous sampling of radioactive iodines and particulates in gaseous effluents from all potential accident release points, and for onsite capability to analyze and measure these samples. (II.F.1)

The combustible gas requirements of General Design Criterion 41 are addressed in this report, in that containment integrity is maintained for postulated accidents. Containment integrity is described in Section 3.3.

The containment hydrogen concentration instrumentation requirements of 10 CFR 50.34(f)(2)(xvii)(C) are addressed in Section 2.7 of this report.

As there is potential for continued hydrogen and oxygen generation and accumulation for an indefinite period following an event, the analysis presented in this report has focused on the first 72 hours of event scenarios. Consistent with Reference 5.1.18, accumulation of combustible gases beyond 72 hours can be managed by licensee implementation of SAMGs because after 72 hours, sufficient time is available to implement mitigating actions.

2.2 Transient Progressions

This report discusses combustible gas effects independent of a particular event initiation or progression. This independence is possible due to optimization of the event outcomes for maximum pulse pressures in the analysis described in this report. The following sections describe DBE and BDBE progressions related to combustible gas control, and how these events are optimized with regard to combustible gas concentrations and CNV pressures for the purpose of bounding the spectrum of events. The summaries provided in this section are discussed in general terms to facilitate an overview of the NPM response; details are provided in the following report sections and in applicable NuScale Final Safety Analysis Report sections.

2.2.1 Design Basis Events

For the NPM design, combustible gases may accumulate during DBEs or BDBEs. Small amounts of combustible gases are capable of producing a combustible atmosphere in the CNV. The DBEs relevant to combustible gas control include any events that result in emergency core cooling system (ECCS) actuation. Initiating events that result in ECCS operation include LOCAs, spurious valve openings, and a loss of DC power. Regardless of the initiating event, the outcome related to combustible gas control is similar in that the ECCS successfully actuates and maintains RPV liquid level above the top of the core, with no core damage. Due to heat removal capabilities of the NPM design, CNV pressure and temperature decrease rapidly as described in Final Safety Analysis Report Chapter 15 accident analyses. When ECCS actuates the containment will have limited non-condensable gas, the primary source of non-condensable gas being hydrogen used in the reactor coolant system (RCS) for primary water chemistry control. Other sources include potential hydrogen sources that may form in the upper pressurizer (PZR) region of the RPV during normal operation. Initial oxygen concentrations within containment are limited to sources within the initial containment atmosphere. Further discussion of combustible gas sources is provided below in Section 3.3.1.

Continued operation and long-term cooling by the ECCS will result in stabilizing conditions, with CNV temperature gradually approaching the reactor pool temperature. During this time, radiolytically generated gases accumulate in the CNV. Radiolytic

production of gases is capable of creating a flammable atmosphere soon after event initiation at a low CNV pressure {{ }}[2(a),(c),ECI] As radiolytic production continues, a higher pressure flammable atmosphere becomes possible. At 72 hours after event initiation sufficient oxygen could be produced through radiolysis to create a flammable atmosphere up to {{ }}[2(a),(c),ECI] Higher pressures would be inert as discussed in Sections 2.3 and 3.3.1 below.

For each event progression, the temperature is expected to be lower as time passes. Many different event progressions result in a wide range of deterministically possible temperatures and pressures at a given time. For the analyses presented in this report, event conditions were optimized for the purpose of maximizing pulse pressures from combustion. The temperature of the containment at a given time is set to the temperature that yields the maximum combustion pulse pressure by iteration. Higher temperatures induce a water vapor partial pressure that renders the containment inert due to suppressing the concentration of oxygen below the flammability limit. Lower temperatures reduce the CNV pressure while increasing the Chapman-Jouguet (C-J) ratio, with a net effect of reducing the combustion pulse pressure. See Sections 2.3 and 3.3.1 below for additional description of combustible gas concentrations within containment.

Optimization of CNV conditions for the maximum pulse pressure yields a dilute solution with regard to oxygen concentrations. The CNV oxygen concentrations slightly above the lower flammability limit, while not so close to the flammability limit as to drastically reduce the C-J ratio, produce maximum CNV pulse pressure results. Oxygen concentrations this low may be below the flame acceleration limit, which would preclude detonations where no high energy ignition source is available; however, flame acceleration (and thus detonation) is assumed to be possible for all flammable atmospheres due to the difficulty in predicting the impact of turbulence due to local geometry and obstructions on flame acceleration limits.

Combustion pulse pressure from DBEs is bounded by this method of calculation. A typical event would have less oxygen than assumed for this analysis (because oxygen production is bounded) and would either be inert or have a lower combustion pulse pressure than calculated (because it would have too little or too much water vapor in the atmosphere). Therefore, optimum conditions for maximizing combustible gas pulse pressures are possible but unlikely.

2.2.2 Severe Accidents

Severe accidents that are relevant to combustible gas control are BDBEs where the containment is intact. Intact containment scenarios are bounding for this analysis because loss of containment or containment bypass events would reduce the pressure inside containment and lessen the effects of combustion. The BDBE scenarios may be initiated by the same events as discussed above in Section 2.2.1, but with multiple ECCS failures. An unsuccessful ECCS actuation (such as a failure of all reactor vent valves [RVVs], or a failure of all reactor recirculation valves [RRVs]) could result in water being transferred to the CNV until the core becomes uncovered resulting in core damage. The ECCS could be recovered while core damage is occurring, creating a

potential for a specific event to have an extent of clad-coolant reaction anywhere from 0 to 100 percent.

As the event progresses, containment temperature will approach the pool temperature. NuScale has a small containment relative to the size of the core compared to operating reactors. A 100 percent clad-coolant reaction can result in a hydrogen partial pressure in the containment as high as {{
}}[2(a),(c),ECI] A hydrogen pressure this high would ensure an inert environment even after weeks of radiolytic oxygen production. Radiolytic production of oxygen and hydrogen will increase the pressure in the CNV. At the beginning of the event the containment is inert due to a lack of oxygen. Flammability can be attained rapidly for low containment pressures (i.e., small extent of clad-coolant reaction). Flammability cannot be attained within 72 hours for a high containment pressure (i.e., large extent of clad-coolant reaction). See Sections 2.3 and 3.3.2 below for additional description of combustible gas concentrations within containment.

To find the limiting event with regard to maximizing combustion pulse pressure at a given time after event onset, the optimum amount of hydrogen must be determined. Too much hydrogen would render the containment atmosphere inert with the limited amount of oxygen available. Too little hydrogen would decrease the CNV pressure while increasing the C-J ratio, with a net effect of reducing the combustion pulse pressure. Iteration for the highest combustion pulse pressure can identify the limiting event. See Section 3.2.6 for additional information.

A typical severe accident will begin inert, then become flammable through radiolytic production of oxygen (the timing depends on the amount of hydrogen gas produced from the clad-coolant reaction), then continue to increase in oxygen concentration and pressure. The limiting severe accident at a given time (i.e., with a specific quantity of available oxygen) is not the same event for any two times. For a given amount of oxygen, an optimum amount of hydrogen can be found to maximize the calculated combustion pulse pressure. As is the case for DBEs, this optimum is found when oxygen concentrations are a little greater than the lower flammability limit.

Combustion pulse pressure from severe accidents is bounded by this method of calculation. A typical event would have less oxygen than assumed for this analysis (because oxygen production is bounded) and would either be inert or have a lower combustion pulse pressure than calculated (because it would have too little or too much hydrogen in the atmosphere). Therefore, optimum conditions for maximizing combustible gas pulse pressures are possible but unlikely.

2.3 Combustible Gas Generation

The NPM has limited quantities of combustible gas inside containment at the start of an accident. The containment is normally evacuated to a pressure well below 1 psia, and the initial oxygen content is limited to the amount of oxygen, at normal atmospheric concentrations, within the low pressure CNV volume. There are two sources of hydrogen initially present. First, hydrogen is dissolved in the reactor coolant for radiolysis suppression during normal operation. In an accident scenario the dissolved hydrogen

will come out of solution into the gas phase as the NPM cools and depressurizes. Secondly, there may be stagnant hydrogen in the upper region of the pressurizer, including the control rod drive mechanism (CRDM) housings. During normal operation, the RPV high point degasification line is used as needed to remove non-condensable gases as they accumulate in the PZR steam space.

For the purpose of combustible gas analysis with an intact core, the total initial dissolved and gaseous hydrogen quantity is important from the standpoint of calculating the containment pressure at the time of the combustion, since the hydrogen partial pressure contributes to the total system pressure. Note that a specific initial quantity of hydrogen is not needed to achieve a combustible gas concentration in containment. Even small amounts of combustible gas can become flammable in the NuScale containment if water vapor partial pressure drops below about {{ }}[2(a),(c),ECI] Radiolytic production alone can achieve a flammable atmosphere at such low pressures. See Section 3.3 for further details.

During normal operations the CNV is evacuated. Therefore, the initial oxygen content is limited to the amount of oxygen at normal atmospheric concentrations, at small quantities due to the low pressure CNV volume. Oxygen may be added to the containment through radiolysis or air in-leakage. In-leakage is negligible due to containment leakage rate requirements at accident pressures and the relatively small differential pressures (relative to accident pressures) observed when the containment is below atmospheric pressure. In addition, all limiting cases considered in Section 3.3 of this report are above atmospheric pressure, which precludes in-leakage.

In the event of severe accidents, hydrogen is added through radiolysis and fuel clad-coolant reaction. Oxygen is the limiting reactant for combustion in the NuScale design, due to the following: 1) more initial hydrogen than oxygen present in the containment after event initiation, 2) hydrogen generated from fuel clad-coolant reaction, and 3) stoichiometrically proportionate hydrogen generated from radiolysis. Large amounts of hydrogen generated from fuel clad-coolant reaction can result in oxygen concentrations decreasing below the lower flammability limit, and thus an inert atmosphere. Therefore, for severe accident scenarios, the extent of the clad-coolant reaction and the associated hydrogen concentration within the CNV is selected to achieve an optimal combustible atmosphere and a bounding maximum combustion pressure.

Initial hydrogen sources within RCS and the upper pressurizer region, and hydrogen production by radiolysis and fuel clad-coolant reaction, represent bounding sources of hydrogen for this analysis. As discussed above, the combustibility of the containment atmosphere after an initiating event is limited by the availability of oxygen. Hydrogen produced from core-concrete interaction is not applicable as concrete is not used within the CNV. Hydrogen from zinc, galvanized steel or aluminum is small in comparison to the clad-coolant reaction and radiolysis sources which produce enough hydrogen to burn all available oxygen. Additional hydrogen sources would not impact the results of this evaluation.

2.4 Containment Mixing

The NuScale design ensures a mixed atmosphere throughout the CNV during and after DBEs and BDBEs. This mixing minimizes the possibility of locally high concentrations of combustible gas for which combustion could cause loss of containment integrity. Adequate mixing of the containment is ensured by virtue of its partially immersed design with no sub-compartments that could facilitate separation, coupled with the dynamic nature of events that include discharge to the containment (e.g., LOCAs or spurious valve opening).

The containment is initially maintained at a vacuum, making the degree of initial mixing irrelevant to mixing during an accident. The driving forces of the reactor coolant release combined with the initial steam expansion and subsequent condensation in containment create a turbulent condition and mixed environment.

Subsequent to the initial release into containment, the turbulence of steam release and condensation subsides. Containment atmosphere conditions were evaluated throughout the first 72 hours of an event to determine the degree of turbulent mixing present due to convective turbulence alone. Turbulence in the CNV is evaluated by computing the Rayleigh number. The CNV is simplified as a rectangular enclosure with parallel walls, one hot and one cold. This configuration has received extensive study and is representative of the annular CNV geometry. The Rayleigh number is a product of the Grashof number and the Prandtl number for the fluid. The Grashof number (and therefore the Rayleigh number) is a measure of the ratio of the buoyancy forces to the viscous forces acting on the fluid under natural convection (Reference 5.1.21, page 565). The conditions at 72 hours are evaluated to examine if turbulent convective mixing exists in the CNV. The wall temperatures and fluid properties yield a Rayleigh number (based on cell width, as described in Reference 5.1.22) from {{ }}[2(a),(c),ECI] depending on the noncondensable gas concentration, where 5.0E+4 is observed to exhibit bulk turbulent 3D flows (Reference 5.1.22). The boundary layers are not necessarily turbulent in this range of Rayleigh numbers (the boundary layer transition is often suggested to be a Rayleigh number of 1.0E+9), but bulk turbulent 3D flow is demonstrated. Mixing of the atmosphere requires bulk 3D flow rather than boundary layer turbulence, which has received more study due to its importance in heat transfer correlations. The analysis shows that turbulent convective mixing exists in the CNV throughout the first 72 hours of a DBE or BDBE.

The turbulence caused by convective mixing described above will eventually subside as well. As turbulence subsides later in the event, later than 72 hours after an initiating event, continued mixing is ensured through convection and molecular diffusion characteristics of the NPM heat transfer design. Convective mixing is ensured for relevant events because both it and radiolysis are driven by decay heat. There are no partitions or sub-compartments to impede these natural mixing forces. The containment's compact and partially immersed design ensures that the entire volume is adjacent to a heat transfer surface (see Figure 2-1).

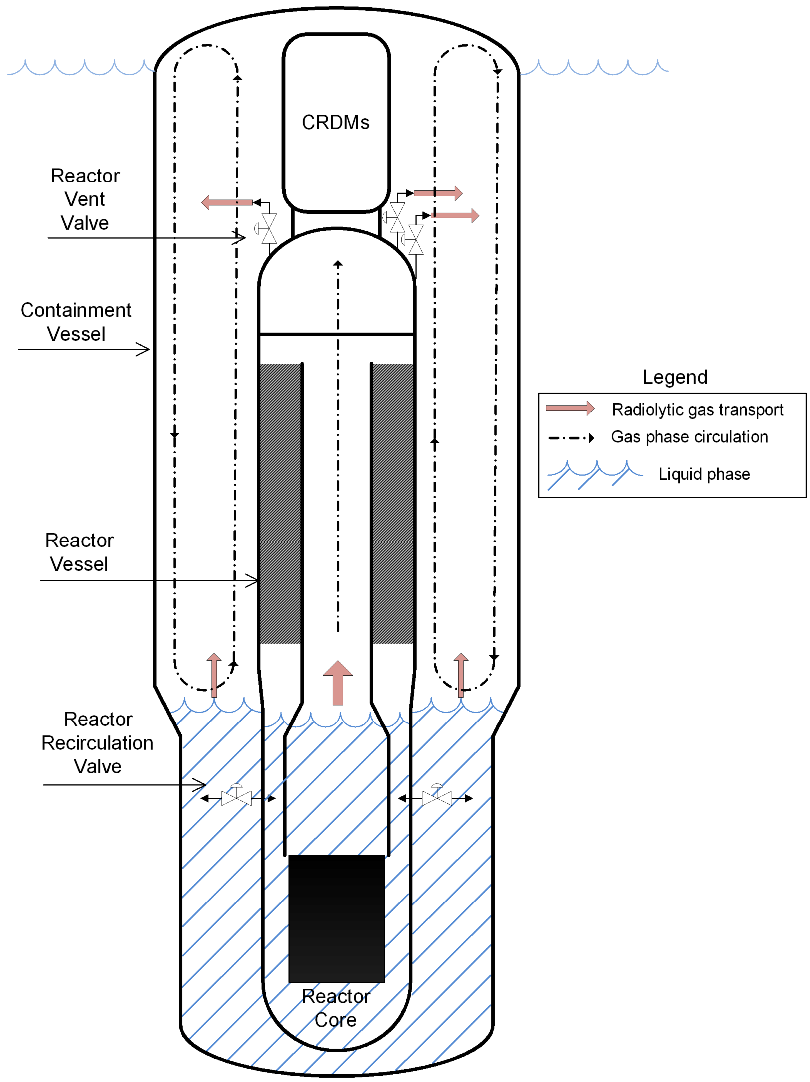

Figure 2-1 Radiolytic transport and containment mixing schematic

2.5 Types of Combustion Considered in the Analysis

Combustible gas production, in combination with the low temperature and initial pressure of the containment, can lead to the formation of a combustible atmosphere within the CNV. Once sufficient oxygen is produced and an ignition source is available, deflagration, detonation or DDT events could occur. The differences between the three combustion event types are summarized below.

A deflagration propagates at subsonic speeds, resulting in a quasi-static pressurization of the CNV and SSC inside containment. This event is best simulated as a suddenly applied force that remains on the structure indefinitely. Pressure reflection is not considered for subsonic events because these do not attain appreciable momentum to cause an amplified reflected pressure pulse.

A detonation results in spherically expanding pressure waves travelling at the C-J speed, leading to incident pressure waves that are twice the peak pressure of a deflagration. Reflected C-J pressure waves are further amplified upon impacting a hard surface and are approximately {{ }}[2(a),(c)] in peak pressure than an incident detonation wave (as discussed in Section 3.2.8).

Deflagration-to-detonation transition is a condition resulting when a gaseous mixture burns leading to flame acceleration that reaches a sonic or supersonic condition where the deflagration transitions to a detonation. If the DDT occurs near a reflecting surface, a significant amplification above the peak reflected C-J pressure is possible due to pre-compression of the unburned gases ahead of the shock front. As discussed in Section 3.3.3, the peak pressure from a DDT is {{ }}[2(a),(c)] the pressure of a reflected detonation wave.

Although electrical components inside containment are not expected to provide an ignition source, due to the low energy required for ignition this ignition source cannot be precluded. Electrical components inside containment include sensors, solenoids, PZR heaters, and CRDMs. The electrical portions of these components are sealed from the containment atmosphere as the containment atmosphere is expected to be periodically wetted to support refueling operations.

Electrostatic charges have also been observed in metal piping systems due to the interaction of the flow and the structure. Although the NPM will be sufficiently grounded to meet instrumentation requirements, it is possible that small electrostatic charges could build and dissipate that would provide an ignition source.

Since means to generate a combustible atmosphere and to provide an ignition source exist, combustion events are accounted for in the design of the NPM components that could be exposed to these loads. Section 3.3.4 of this report defines the ASME stress limits that are applied to the load combinations that address the three types of combustion.

2.6 Containment Structural Analysis

The pressure pulse loading associated with combustion affects all SSC that are in contact with the containment atmosphere. A detailed stress analysis is performed for the CNV to address DBE and BDBE combustion events.

Other SSC in containment can be put into two categories: SSC that the pressure wave travels past, and SSC that form part of the containment pressure boundary and will see a portion of the incident pressure wave.

As discussed in Reference 5.1.18, combustion events are low probability events. NuScale has included loads from deterministically evaluated combustion events in the ASME specifications using Level C (for components required to function for safe shutdown) and Level D (for components required for containment structural integrity) Service Limits. Severe accident loads are evaluated against criteria from Reference 5.1.5.

2.7 Sampling and Monitoring Provisions

While the NPM components are designed to withstand the loads due to these events, the NuScale design provides indication of CNV conditions and combustible gas mitigation options to prevent and mitigate such events, consistent with the specification of mechanical design basis transients for these components.

Hydrogen and oxygen analyzers are provided within the containment sampling system portion of the process sampling system. During normal operation the containment gas discharge from the containment evacuation system (CES) vacuum pumps is continuously routed to the containment sampling system sample panel for online analysis of hydrogen and oxygen concentrations, with continuous indication in the main control room.

The monitors meet the criteria specified in Regulatory Guide (RG) 1.7 for non-safety-related commercial-grade monitors. The hydrogen and oxygen monitoring equipment is designed to be functional, reliable, and operable in DBE and BDBE environmental conditions. The monitors are specified for wide-range monitoring. The hydrogen and oxygen analyzers are also used for containment gas sampling and monitoring during normal operation, therefore, periodic testing and calibration are performed as required by plant surveillance test program to provide ongoing confirmation that the analyzer's monitoring function can be reliably performed post-accident. The monitors meet testing and calibration criteria per Regulatory Position C.2 of RG 1.7. The hydrogen and oxygen monitors provide nonsafety-related display in the main control room. The analyzers also have capability to display information locally at the containment sampling system remote control center.

During DBEs and BDBEs, containment isolation signals isolate CES. The monitors can be brought back online for combustible gas control and accident management, including emergency planning. The monitoring flow path can be established when containment is below 250 psia. Containment pressure is reduced rapidly under accident conditions due to the heat removal capacity of the NuScale design, e.g., containment pressure is reduced to under 250 psia in less than two hours following DBE initiation.

Prior to establishing the monitoring flow path, containment pressure over 250 psia would ensure an inert environment due to a lack of available oxygen. As described in Section 3.3, the total molar quantity of oxygen from initial containment atmosphere and radiolysis production for 72 hours is approximately {{ }}[2(a),(c),ECI] . Using the ideal gas law at the highest temperature from Table 3-1 (using a higher temperature in the ideal gas law results in higher oxygen concentrations), results in an oxygen concentration of less than {{ }}[2(a),(c),ECI] at 250 psia. The containment atmosphere is inert at containment pressures of 250 psia and above. As containment pressure is reduced, containment monitoring can be re-established. The hydrogen and oxygen monitors are available well in advance of potential combustible atmosphere conditions within containment. Indication of hydrogen and oxygen concentrations in the containment atmosphere is available in a sufficiently timely manner to support emergency planning and severe accident management. The considerations discussed in RG 1.7 that are

relevant to design certification applicants for functional requirements of hydrogen monitoring are addressed as follows:

- "The use of the indication of hydrogen concentration by decision-makers for severe accident management and emergency response." As discussed above, the hydrogen and oxygen monitors are available well in advance of potential combustible atmosphere conditions within containment, and typically within 2 hours of event initiation. The containment hydrogen and oxygen monitors are available in a sufficiently timely manner to support emergency planning and severe accident management.

- "Insights from experience or evaluation pertaining to possible scenarios that result in significant generation of hydrogen that would be indicative of core damage or a potential threat to the integrity of the containment building." As discussed above, evaluation pertaining to possible scenarios that result in significant generation of hydrogen has shown that monitoring capabilities are established prior to the generation of potential combustible conditions within containment. Additionally, this report describes structural analyses and ASME design processes that ensure that containment structural integrity and safe shutdown capability are maintained with no operator action for at least 72 hours. The containment hydrogen and oxygen monitors are available in a sufficiently timely manner to support emergency planning and severe accident management.

The monitoring flow path is established using equipment powered by on-site alternating current power sources. The monitoring equipment is isolated by the containment isolation valves (CIVs). The isolation valves may be opened once the containment isolation signal has cleared or via operator action outside the main control room if required. Safety-related power is not required to perform this function.

As described above, the NuScale design includes hydrogen and oxygen monitoring equipment that is functional, reliable, and capable of continuously measuring the concentration of hydrogen and oxygen in the containment atmosphere following a DBE or BDBE for accident management, including emergency planning.

2.8 Design Provisions to Support Potential Mitigative Actions

The NuScale design includes provisions that support potential SAMGs established by a COL applicant referencing the NuScale Power Plant design certification. The NuScale design includes provisions for establishing an inert containment atmosphere and for venting the containment atmosphere during DBEs and BDBEs. The chemical and volume control system includes the capability for nitrogen addition from the nitrogen distribution system into the PZR. Since all relevant events have flow paths between the reactor vessel and CNV through open valves or pipe breaks, nitrogen addition to the RPV is effective in delivering nitrogen to the CNV as well. This capability can be used to inert the containment atmosphere. Additionally, the CES includes provisions for venting the containment during accident conditions, including connections for portable

equipment if necessary for severe conditions. The CES vent flow path is equipped with radiation monitoring capability to monitor iodine, particulate, and noble gas activity of the gaseous effluent. The gas can then be routed to the gaseous radwaste management system or to the plant exhaust stack.

3.0 Analysis

3.1 Approach/Methodology

The NuScale design is capable of withstanding bounding combustion events for an extended duration with no active combustible gas control systems or operator actions. To demonstrate survivability of the CNV, a detailed set of analyses has been performed to determine the following:

- limiting atmospheric composition of the containment for DBE and BDBE cases
- the flammability and detonability of these atmospheres
- the combustion loads for these atmospheres

The combustion loads determined by the analyses were applied to the CNV design. For DBEs, stresses were checked to ensure they are maintained below ASME Service Level C and D stress limits. For BDBEs, strain is shown to be below the guidelines in RG 1.216 (Reference 5.1.5).

Components that are appurtenances to the CNV, or are required to establish and maintain safe shutdown of the NPM, are ensured to withstand the loads described above through the application of the loads in the ASME design specifications for these components. Including this load in the ASME design analyses ensures that detailed assessment of the component will be conducted as part of the ASME design process and the results documented in the ASME design reports.

3.2 Assumptions

The following assumptions are bounding engineering simplifications and methodology approaches used in these analyses that demonstrate the survivability of the CNV and associated SSC required to establish and maintain safe shutdown of the NPM. Consistent with the 10 CFR 50.44(c)(2) exemption request provided with the NuScale DCA, the combustible gas conditions described and analyzed in this report do not credit hydrogen control functions or systems to limit containment hydrogen concentrations or inert the containment atmosphere.

3.2.1 Time of Combustion Event

The analyses assume that combustion occurs at 72 hours.

For DBE and BDBE cases, a sufficient amount of oxygen could be generated in less than 72 hours to result in a combustible atmosphere. However, the longer radiolysis occurs during the event, the higher the system pressure at the time of the combustion. Therefore, the combustion was assumed to occur 72 hours following the event initiation, bounding combustion events within that time frame. This time period is supported by regulatory precedent as well as NRC rulemaking documents related to combustible gas control regulations (Reference 5.1.18) as a reasonable time to implement SAMGs to manage the accumulation of combustible gases.

3.2.2 Initial Containment Temperature and Pressure for Gas Concentration Analysis

To calculate initial gas composition in containment, the analyses assumed containment temperature of 50 degrees F. Initial containment pressure of 1.05 psia was assumed for DBEs. Initial containment pressure of 9.5 psia was assumed for BDBEs.

Containment atmosphere temperature is expected to be greater than 50 degrees F during normal operation. The choice of a low temperature increases the initial oxygen concentration in the containment.

The containment is maintained in a low-pressure state during normal operation such that liquid cannot form. Containment pressure well below 1 psia is normal operating pressure, consistent with initial DBE conditions.

For severe accidents, initial pre-event containment pressures up to the containment pressure analytical limit of 9.5 psia were considered. This assumption isn't typical of a severe accident sequence, but was considered in this analyses as an air in-leakage event could be part of the beginning stages of a severe accident due to the vacuum conditions inside containment.

3.2.3 Initial Containment Atmosphere Concentrations

The initial pre-event containment atmosphere was assumed to be dry air consisting of 21 percent oxygen and 79 percent nitrogen.

Assuming dry air for the initial conditions in the containment is conservative in that it maximizes the amount of oxygen in the atmosphere by eliminating water vapor. Actual dry air is made up of 20.948 percent oxygen, 78.084 percent nitrogen and 0.968 percent other gasses. Rounding oxygen to 21 percent is conservative as it decreases the amount of inert gas initially in containment. Using nitrogen to represent the balance of gasses present in the atmosphere is appropriate due to the limited quantities of other gasses at containment partial vacuum conditions.

3.2.4 Initial Hydrogen Quantity Available in the Reactor Coolant System

The total initial available hydrogen from RCS is approximately {{ }}[2(a),(c),ECI] .

Hydrogen is used for chemistry control within RCS. The molar values of hydrogen in the liquid and gas phases were calculated from the highest allowed concentration of hydrogen in the coolant.

3.2.5 Initial Hydrogen Quantity Available in Pressurizer Region

The total initial available hydrogen from RCS is approximately {{ }}[2(a),(c),ECI].

It is assumed that the upper 3 percent of the PZR gas volume, and the entire CRDM internal volume, is a separated pure hydrogen layer. A separated pure hydrogen layer may form where mixing is low and condensation is high. These conditions exist in the

actively cooled CRDM internal volumes. These conditions may exist in the upper PZR; however, excessive buildup of a hydrogen layer will be detectable by the operators through changes in PZR spray performance.

3.2.6 Extent of Clad-Coolant Reaction for Severe Accidents

The analyses address an accident that releases the amount of hydrogen equivalent to that generated from a fuel clad-coolant reaction involving 100 percent of the fuel cladding surrounding the active fuel region. The extent of the fuel clad-coolant reaction was selected to achieve a detonable atmosphere and to maximize detonation pressure.

For BDBEs that result in core damage, the hydrogen concentration is higher than the upper flammability limit, until sufficient oxygen is generated from radiolysis. To ensure that maximum detonation pressures are calculated at each time step, the amount of zirconium that has oxidized was conservatively chosen to optimize the CNV combustible gas concentrations for maximum detonation pressure.

3.2.7 Containment Temperature at Time of Combustion for Design Basis Events

Similar to the extent of fuel clad-coolant reaction, for DBE cases the containment temperature was chosen to maximize the total system pressure while maintaining sufficient oxygen for combustion.

Depending on the accident scenario, containment temperature at 72 hours could be a wide range of values. At high temperatures, there is sufficient water vapor to preclude combustion. At low temperatures, the total system pressure and the resulting combustion pressures are more benign. As a bounding approach, the containment temperature was chosen to be the limiting temperature to both allow combustion (sufficient oxygen concentration) while also maximizing the total system pressure. This assumption is conservative as it is unlikely that the containment temperature will be at the most limiting condition coincident with a sufficient amount of oxygen generated from radiolysis.

Table 3-1 Containment atmosphere temperature

Time (hours)	Temperature (degree F)
{{	
	}}2(a),(c),ECI

The temperatures in Table 3-1 are not intended as the time history of an individual event, but rather are selected temperatures to ensure that bounding conditions are captured in this analysis. The temperatures were selected to ensure that the mixture is flammable (oxygen is greater than 4 percent) and near the optimum temperatures for maximizing the detonation pulse pressure. This results in oxygen concentrations just above the lower flammability limits. Such temperatures were selected through manual iteration of the methodology.

3.2.8 Detonation Pressure Reflection and Reflection Factor

When detonations occur, if the incident shock wave impacts a rigid surface, amplification occurs due to the pressure reflection from the surface. All detonations loads were assumed to be reflecting loads. The C-J reflection factor is computed to be approximately {{ }}[2(a),(c)] using a bounding specific heat ratio to increase the reflected pressure.

Reflection typically occurs when a detonation shock wave impacts a structure. A specific heat ratio derived from a fuel-rich gas concentration was assumed because the combustible atmosphere in the NuScale design is oxygen limited. Since the reflected detonation pressure was used in calculating the peak DDT pressure, this assumption applies to both detonation and DDT loads.

3.2.9 Radiolytic Generation of Hydrogen Yield Factor

Maximum yield of 0.5 molecules/100eV.

Radiolytic production of hydrogen can be calculated by multiplying the rate of energy deposition into the liquid phase of water by an empirical yield factor. Experiments on radiolytic generation of hydrogen have shown that the maximum yield is around 0.44 molecules/100eV (Reference 5.1.17). Reference 5.1.5, Table 1 recommends the use of 0.5 molecules/100eV for conservatism.

3.2.10 Maximum Energy Deposition due to Radiolysis

To provide bounding radiolysis rates, the density of the water in the NPM was assumed to be 1.0 g/cm^3. The spent fuel isotopic inventory assumed in the analyses was based on a reactor burnup and overpower greater than could be achieved for NuScale fuel assemblies, which results in higher ionizing radiation.

Assuming higher water density increases energy deposition and results in higher radiolysis rates. Assuming that all of the fuel has operated at a higher power and for a longer time than expected also increases radiolysis rates. Higher radiolysis rates decreases the time until a combustible atmosphere is achieved and increases the peak combustion pressures. Energy deposition into the water in the reactor vessel and containment was conservatively calculated using these assumptions, with the Monte Carlo N-Particle transport code (MCNP6) (Reference 5.1.19). MCNP6 was used to calculate energy from decay neutron n-gammas, fission neutron n-gammas, decay gammas, and decay photon energy deposition. Table 3-2 provides the results of the

energy deposition to water in the NPM during an event with an intact core, as discussed further in Section 3.3.2. Each item in the table is the integral between the time listed and the previous time.

Table 3-2 Energy deposition into water

Time (hours)	Energy deposition into water (MeV)
{{	
	}}2(a),(c),ECI

3.2.11 Containment Vessel Material Properties

The CNV material properties assumed in the analyses were selected at {{
}}2(a),(c).

This assumption is reasonable because temperatures close to {{ }}2(a),(c) were used in the gas composition calculations that produce the evaluated loads. This temperature is higher than expected pool water temperature in order to provide bounding results.

3.2.12 Trinitrotoluene Equivalence Method

The Trinitrotoluene (TNT) equivalence method was used to determine the pulse duration for detonation event.

The TNT equivalence method is considered a bounding approach for determining pressure pulses from hydrogen detonations, per Reference 5.1.11.

3.2.13 Yield Strength used for Multilinear Isotropic Hardening Curves

The ASME code-specified minimum yield strengths were used to develop all elastic-plastic strain curves.

This assumption is bounding as materials are typically procured with margin to minimum material strength limits. Lower yield strengths result in higher calculated membrane hoop strains.

3.3 Combustible Gas Analysis

Combustible gas concentrations were calculated by determining the quantity of non-condensable gases, then using the ideal gas law to determine the partial pressure of each gas. The volume for the gas phase was established from geometry calculations of the NPM. Water vapor partial pressure was determined through the saturation curve for the assumed iterated temperatures. Concentrations of a gas are the partial pressure of the constituent divided by the total pressure.

Hydrogen quantities were determined by evaluation of initial contents of the NPM, radiolytic production, and clad-coolant reaction. Oxygen quantities were determined by evaluation of initial contents of the NPM and radiolytic production. Nitrogen quantities are determined by evaluation of initial contents of the NPM.

Concentrations were used to determine the C-J ratio for the gas mixture. The pulse pressure was determined by multiplying the C-J ratio by the initial pressure. This peak pulse pressure was multiplied by an amplification factor for reflection upon striking a rigid surface. For DDT evaluation, it was multiplied by an additional amplification factor.

3.3.1 Limiting Combustible Gas Concentrations for Design Basis Events

As described in Section 2.2.1, combustion loads were calculated independent of a particular event sequence in order to produce a bounding result. To determine the peak containment pressure resulting from combustion events, the following quantities of gases were calculated:

- initial amount of oxygen and nitrogen in the containment, based on ideal gas calculation, with NPM free volume of approximately {{ }}2(a),(c),ECI, initial atmosphere assumed to be dry air consisting of 21 percent oxygen and 79 percent nitrogen (Section 3.2.3), and the assumed operating containment temperature and pressure conditions (Section 3.2.2)
- initial amount of available hydrogen in the RCS (Section 3.2.4)
- initial amount of hydrogen accumulated in the upper region of the RPV (Section 3.2.5)
- hydrogen and oxygen generated due to radiolysis (as described below)
- limiting partial pressure of water vapor (as discussed below)

As demonstrated in Section 3.3.3, the pressures for all three types of combustion are a function of the total system pressure at the time of combustion and the C-J ratio. System pressure is maximized by having more air, water vapor, or hydrogen, all of which are diluents and reduce the C-J ratio. To balance these competing effects, the diluent partial pressure was optimized to provide the highest combination of total pressure and C-J ratio at 72 hours while still maintaining a combustible concentration of the limiting reactant, oxygen. This methodology is a bounding approach, as discussed in Section 3.2.7.

{{

}}2(a),(c)ECI Radiolytic production of hydrogen was calculated by multiplying the rate of energy deposition into the liquid phase of water by an empirical yield factor (Section 3.2.9). As discussed in Section 3.2.10, the energy deposition into water in the reactor vessel and containment was conservatively calculated using MCNP6. The integrated results are shown in Figure 3-1.

{{

}}2(a),(c)

Figure 3-1 Integrated energy deposition into water for design basis events

This energy deposition results in a proportional radiolytic production of hydrogen and oxygen. The radiolytic production is shown in Figure 3-2.

{{

}}2(a),(c)

Figure 3-2 Radiolytic production for design basis events

A bounding rate of hydrogen and oxygen generation from radiolysis was determined as described in Section 3.2.10. This rate allows for higher pressures while still maintaining a combustible oxygen concentration (i.e., containment atmosphere with 4 percent oxygen by volume or greater). {{
}}2(a),(c)

At 72 hours, iteration yields a water vapor partial pressure of {{
}}2(a),(c) This results in the highest combustion pulse pressure with the available oxygen.

A second scenario considered in the analysis assumed the NPM is suspended for an extended duration during a refueling evolution (i.e., the NPM is assembled but isolated from supporting systems). The containment gas phase volume assumed in this scenario is reduced because water is added to the CNV prior to disconnecting the NPM for refueling. This scenario was identified for completeness, and is bounded by using the ECCS loads in the structural evaluation.

3.3.2 Severe Accident Combustible Gas Concentrations

The BDBE progressions are generically described in Section 2.2.2. Accidents that consider a damaged reactor core are classified as severe accidents. The fuel clad-coolant reactions for severe accidents result in an increase of hydrogen in containment, which increases the total containment pressure, relative to design basis combustion events. Although this could lead to an inert containment atmosphere due to an oxygen

fraction less than flammable, it is conservative to assume that partial fuel clad-coolant oxidation occurs. The extent of reaction was optimized in the analyses to maintain oxygen concentrations at a flammable level. Due to circulation of fission products throughout the reactor coolant, the rate of radiolysis is also higher. This assumption, combined with the additional hydrogen from the fuel clad-coolant reaction, results in more conservative pressure loading with fuel failure compared to a DBE.

To demonstrate structural integrity, the containment pressures resulting from a postulated DDT event were evaluated to ensure that the ultimate capacity of the containment is maintained 72 hours into the event.

For severe accidents, initial pre-event containment pressures up to the containment pressure analytical limit of 9.5 psia were considered, as discussed in Section 3.2.2. {{

}}2(a),(c),ECI

Radiolytic production was calculated by the COGAP method, as described in Reference 5.1.3, and was based on reactor power of 102 percent. The results are shown in Figure 3-3.

{{

}}2(a),(c)

Figure 3-3 Radiolytic production for severe accidents

{{

}}2(a),(c)

A water vapor partial pressure of {{

}}2(a),(c) This assumption was not important to results because the hydrogen production from the clad-coolant reaction was optimized. Excess hydrogen and water vapor provide an equivalent role in the atmosphere, as described in Section 3.3.3.

{{

}}2(a),(c) This results in the highest combustion pulse pressure with the available oxygen.

3.3.3 Determine Combustible Gas Structural Loads

Structural loads were determined at 72 hours into the event. Although a combustible atmosphere may be achieved before this time, it was assumed that no previous combustion has occurred, since previous combustion would consume oxygen and hydrogen, limiting subsequent combustion loads. Event progression at 72 hours was the longest time considered in the design of SSC, in accordance with the assumption described in Section 3.2.1.

The oxygen concentration was checked to ensure it is above the lower flammability limit. Once combustible conditions are met, the deflagration pressure was obtained based on the total system pressure and the oxygen concentration that was used to determine the C-J pressure.

$$P_{ex} = P_0 R_{CJ} \qquad \text{Equation 3-1}$$

$$P_0 = P_{O_2} + P_{H_2} + P_{H_2O} + P_{N_2} \qquad \text{Equation 3-2}$$

where,

P_{ex}	=	the pressure resulting from deflagration (psi),
P_0	=	initial containment pressure (psi),
P_{O_2}	=	partial pressure of oxygen in containment (psi),
P_{H_2}	=	partial pressure of hydrogen in containment (psi),
P_{H_2O}	=	partial pressure of water vapor in containment (psi),
P_{N_2}	=	partial pressure of nitrogen in containment (psi), and
R_{CJ}	=	the ratio of the C-J pressure over the initial pressure for H_2-O_2 (-).

For NuScale combustion scenarios, the oxygen and air curves presented in Reference 5.1.6 require discussion because the nitrogen to oxygen concentration will

not be similar to air, and because of the presence of a third diluent, water vapor, which is not shown on the curve.

If the x-axis for the curves in Figure 7 of Reference 5.1.6 (i.e., deflagration pressures of hydrogen mixtures) is presented in terms of the limiting reactant, oxygen, the C-J pressure ratio is shown to be insensitive to the quantity and composition of diluent. As shown in Figure 3-4, at low oxygen concentrations, there is minimal difference in the C-J ratio whether the diluent is excess hydrogen or nitrogen. Therefore, it can be concluded that the presence of water vapor in the system should not affect the calculated combustion pressure, for the low oxygen concentrations applicable to the NuScale design.

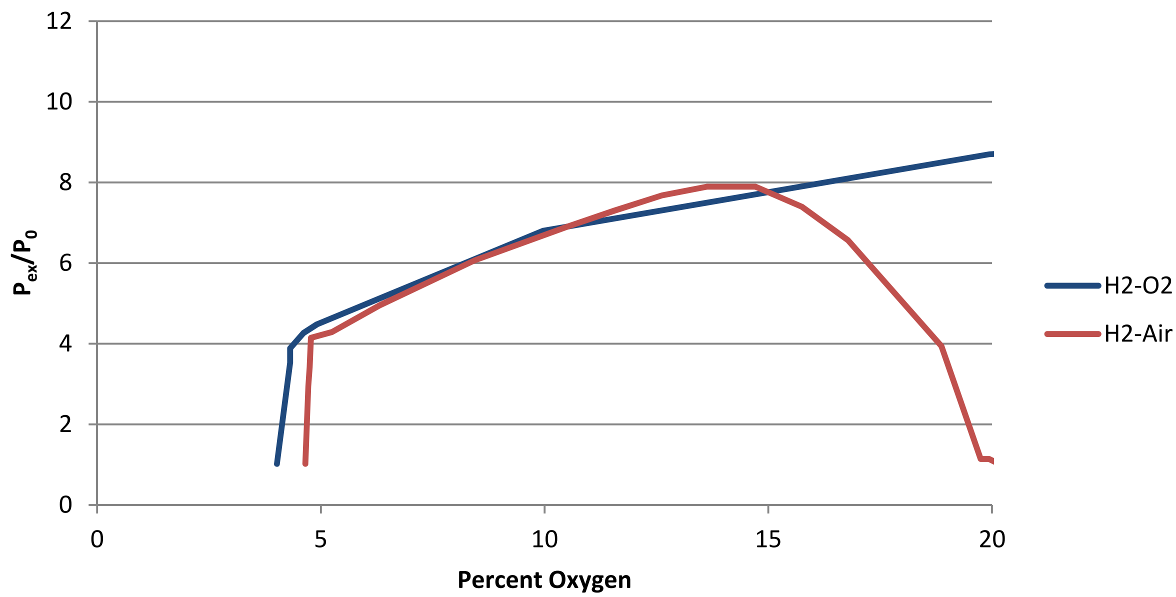

Figure 3-4 Detonation pressures (derived using Figure 7 of Reference 5.1.6)

A detonation pressure pulse is twice the pressure of a deflagration, per Section 1 of Reference 5.1.15 and Figure 2-25 of Reference 5.1.16. Reflected pressures can be computed using a multiplier from Reference 5.1.17. Since the reflected pressure bounds the incident pressure and reflections are observed when a detonation shock wave impacts a rigid surface, all detonation loads considered in the structural analysis were assumed to be the reflected peak pressures, per the assumption described in Section 3.2.8.

Lastly, DDT was considered in the analyses. In experimental analysis, this type of combustion has been shown to produce pressure pulses in the range of three to five times that of a reflected detonation (Section 4 of Reference 5.1.15). A value {{ }}[2(a),(c)] was selected based on engineering judgement. This selection, with the calculated reflection amplification, yields an amplification of around 11 times the C-J pressure. Experimental evidence of

amplifications with reflections indicates that peak pressures of 10 times the C-J pressure are possible.

$$P_{DT} = 2P_{DF}$$ Equation 3-3

$$P_{reflection} = P_{DT}\Pi_{reflection}$$ Equation 3-4

$$\Pi_{reflection} = \frac{5\gamma + 1 + \sqrt{17\gamma^2 + 2\gamma + 1}}{4\gamma}$$ Equation 3-5

$$P_{DDT} = P_{reflection}F_{DDT}$$ Equation 3-6

where,

$P_{reflection}$	=	the maximum peak pressure from reflection of a detonation (psi),
P_{DDT}	=	the maximum peak pressure resulting from DDT (psi),
F_{DDT}	=	DDT amplification factor (-),
P_{ref}	=	reflected pressure (psia),
P_{CJ}	=	C-J pressure (psia), and
γ_{CJ}	=	specific heat ratio at the C-J conditions.

The bounding peak pressure values for combustion events occurring at 72 hours are summarized in Table 3-3.

Table 3-3 Peak combustion pressures for design basis and severe accident scenarios

	Maximum deflagration pulse pressure (psi)	Maximum reflected detonation pulse pressure (psi)	Maximum reflected DDT pulse pressure (psi)
Design basis	{{		
Severe accident			}}2(a),(c),ECI

3.3.4 Containment Vessel Structural Integrity Analysis

3.3.4.1 Model Overview

The finite element analysis model for the CNV and reactor pool water was used to perform the combustion structural analysis. This model considers the fluid-structure interaction between the CNV and the reactor pool water using acoustic elements with conformal mesh. Only membrane stress, bending stress, and membrane strain are

required from the structural analysis; the CNV model is accurate for this purpose. The model includes the flanges of the top flange cover, pressurizer and steam generator access ports, and the shell manway cover. Piping nozzles, ECCS valve penetrations, and electrical penetrations have significantly lower membrane stresses due to their relatively small diameter and relatively large thickness and were determined to be non-limiting compared to the shell stresses. Therefore, excluding these components from the model does not impact the conclusions of this report. This simplification in the model geometry allows for performing a dynamic analysis of the combustion events.

The dead weight load of the RPV was applied. The impulse peak pressure that was determined for each combustion scenario was applied to the CNV inside surface for the appropriate time duration.

{{

}}2(a),(c),ECI

Figure 3-5 Finite element analysis model for containment vessel and pool water

Various locations in the CNV were selected for stress limit assessment or strain limit assessment. {{

}}2(a),(c),ECI Although a few stress classification lines can be classified as local membrane stress (P_L), all the stress classification lines were treated as general membrane stress (P_m) for simplicity for the purpose of stress limit assessment. Similarly, all the stress classification lines were evaluated for the strain criterion for the severe accident condition.

For DBEs, the CNV model with linear elastic material properties was used to calculate the membrane, bending and triaxial stresses for ASME Service Level C and D stresses.

The material properties used in the elastic model were elastic modulus and Poisson’s ratio at the proper temperature.

For BDBEs, the plastic strains were calculated using the CNV model with elastic-plastic material properties at the proper temperature. Besides the Young’s modulus and Poisson’s ratio, the multilinear isotropic hardening stress-strain curves (i.e., true stress vs. plastic strain in ANSYS input) were used. The ASME Code-specified minimum yield strength and ultimate strength were used to construct the curves using Ramberg-Osgood material constitutive model.

{{

}}2(a),(c),ECI

Figure 3-6 Locations for stress and strain limits

Table 3-4 Path line locations in containment vessel components

Path Line	Symbol in Figure 3-6	{{	Material	Classification
1	A-1/A-2		SA-182 F304/F304L	P_m
2	B-1/B-2		SA-182 F304/F304L	P_L
3	C-1/C-2		SA-508 Grade 3 Class 2	P_m
4	D-1/D-2		SA-508 Grade 3 Class 2	P_m
5	E-1/E-2		SA-508 Grade 3 Class 2	P_m
6	F-1/F-2		SA-508 Grade 3 Class 2	P_m
7	G-1/G-2		SA-508 Grade 3 Class 2	P_m
8	H-1/H-2		SA-965 FXM-19	P_L
9	I-1/I-2		SA-965 FXM-19	P_L
10	J-1/J-2		SA-965 FXM-19	P_m
11	K-1/K-2		SA-965 FXM-19	P_m
12	L-1/L-2		SA-965 FXM-19	P_L
13	M-1/M-2		SA-965 FXM-19	P_L
14	N-1/N-2		SA-240 304/304L	P_m
15	O-1/O-2		SA-182 F304/F304L	P_L
16	P-1/P-2	}}$^{2(a),(c),ECI}$	SA-182 F304/F304L	P_m

Material properties (Young's modulus, Poisson's ratio, percent elongation, yield and ultimate strength, and design stress intensity) were selected at {{ }}$^{2(a),(c),ECI}$, in accordance with the assumption described in Section 3.2.11. Table 3-5, Table 3-6, and Table 3-7 summarize the acceptance criteria used. For each material the stress-strain curves used for the elastic-plastic analysis were developed using the Ramberg-Osgood method. The ASME Code minimum yield strength was used as described in Section 3.2.13.

3.3.4.2 Assigned Loads and Acceptance Criteria

Per RG 1.7 (Reference 5.1.4), structural integrity of the containment structure for a design basis hydrogen deflagration is based upon meeting ASME Level C Service Loadings. Further, based on the assumption described in Section 3.2.8, it is reasonable to evaluate the structure for reflected detonations, as amplification from reflection is typical when a detonation wave encounters a rigid surface. Therefore, reflected detonations were evaluated against ASME Level C stress limits. This bounds weaker combustion events such as incident detonations and deflagrations, and as such no structural evaluation for those loads is presented.

The DDT events are considered to be significantly less probable than detonations. However, the loads from a DDT event were included in the containment design to

provide additional assurance of containment integrity. The DDT loads were evaluated against ASME Service Level D stress limits.

Table 3-5 Stress limit for ASME Level C service loading

Material	P_m	P_L	(P_m+P_b)	Triaxial
Non-ferritic materials SA-182 F304/F304L SA-965 FXM-19 SA-240 304/304L	Max(1.2Sm, 1.0Sy)	1.5Pm	1.5Pm	4.8Sm
Ferritic materials SA-508 Grade 3 Class 2 SA-533 Grade B Class 1	Max(1.1Sm, 0.9Sy)	1.5Pm	1.5Pm	4.8Sm

Table 3-6 Stress limit for ASME Level D service loading

Material	P_m	P_L	(P_m+P_b)
Non-ferritic materials SA-182 F304/F304L SA-965 FXM-19 SA-240 304/304L	Min(2.4Sm, 0.7Su)	1.5Pm	1.5Pm
Ferritic materials SA-508 Grade 3 Class 2 SA-533 Grade B Class 1	0.7Su	1.5Pm	1.5Pm

P_m = General Primary membrane stress intensity, (ksi),

P_L = Local Primary membrane stress intensity, (ksi), and

P_b = Primary bending stress intensity, (ksi).

To quantify the integrity of the containment for a severe accident core melt, the limiting pressure pulse due to reflected DDT was postulated. The acceptance criteria guidance provided in RG 1.216 (Reference 5.1.5) was used, which is based on an elastic-plastic analysis. RG 1.216 allows the maximum membrane hoop plastic strain of 1.5 percent in the cylindrical shell, away from structural discontinuities.

Table 3-7 Strain limit for beyond design basis loading (Regulatory Guide 1.216)

Material	Membrane Hoop Strain
All CNV shell materials	1.5%

3.3.4.3 Impulsive Loading Methodology

All loads were applied as a dynamic load on the CNV inside surface. For reflected detonation loads from DBEs, the results were evaluated against ASME Service Level C limits. For DDT loads from DBEs, the results were evaluated against ASME Service Level D limits. For DDT loads from severe accidents, the results were evaluated against strain criteria from Reference 5.1.5. The pulse pressure was taken from the pressure calculated in the combustion analysis. A pulse width was also specified to define each load.

Detonations propagate in the supersonic regime causing shock waves ahead of the detonation front, resulting in instantaneous pressure rise to a maximum value. Since a detonation event causes an impulsive structural response, the duration of the pressure pulse is as important as the magnitude. In lieu of developing a hydrodynamic analysis model of the gaseous detonation front impinging on the CNV shell to obtain the actual pressure-time history, a simplified TNT-equivalent methodology was used to determine the pulse-period for the event, as described in Figure 3-7. The TNT-equivalency method is conservative for gaseous detonations, per Assumption 3.2.12.

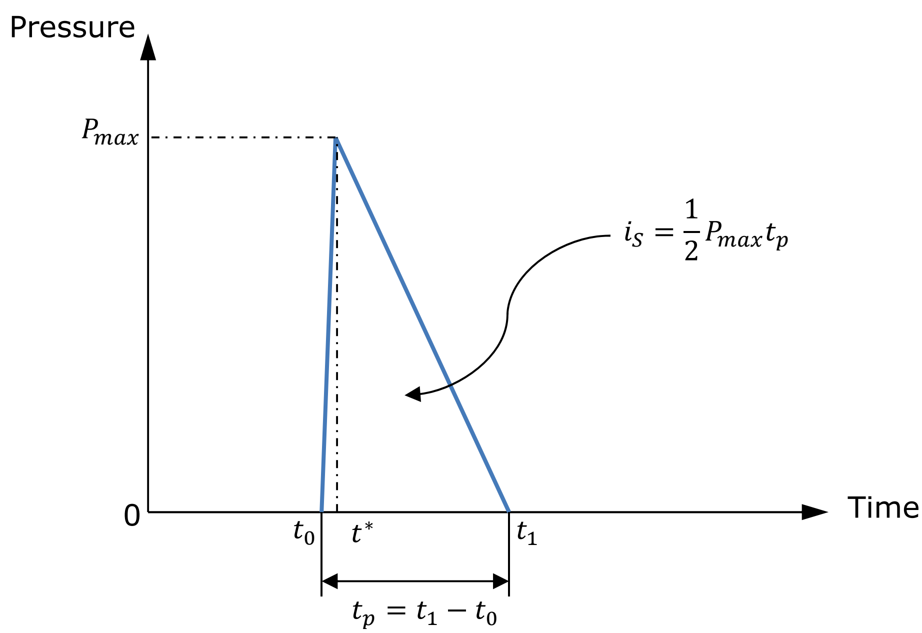

Figure 3-7 Notional pressure pulse for H_2-air or H_2-O_2 detonation

$$i_s = \frac{1}{2} P_{\max} t_p$$ Equation 3-7

where, $i_s =$ reflected impulse, (psi-ms),

$P_{\max} =$ TNT reflected pressure, (psi), and

$t_p =$ pulse period (ms).

This equation is accurate when the initial pressure and the residual pressure are small compared to the peak pressure of the pulse. This is typical of the analyzed conditions in Table 3-3.

To determine the pulse period, the heat-of-combustion of H_2-Air or H_2-O_2 was converted to TNT-equivalent mass of high-explosive, as detailed in several references (References 5.1.7, 5.1.8, 5.1.9, 5.1.10 and 5.1.11). The equivalent mass of TNT is given as the product of the mass of evolved combustible gas mixture and the ratio of heats-of-combustion of gas and TNT, multiplied by an efficiency factor, as shown by Equation 3-8.

$$m_{TNT} = \alpha \frac{\Delta H^c_{gas}}{\Delta H^c_{TNT}} m_{gas}$$ Equation 3-8

where, $\Delta H^c_{gas} =$ heat-of-combustion of gas mixture, (MJ/kg),

$\Delta H^c_{TNT} =$ heat-of-combustion of TNT, (MJ/kg),

$\alpha =$ efficiency factor for gas mixture, and

$m_{gas} =$ total mass of evolved gas, (kg).

The total mass of evolved gas from clad-coolant interaction, radiolysis and including inert gases originally in the system is used herein. This is a substantial conservatism because only a small portion of this gas can undergo combustion due to the limited availability of oxygen. An efficiency factor of 0.03 is used, which is typical for hydrogen explosions in air (Reference 5.1.11). Once the TNT equivalent mass of the gaseous detonation was determined, blast effect curves (References 5.1.12, 5.1.13 and 5.1.14) from high-explosive testing, developed by the US Department of Defense and US Department of Energy, were used to calibrate the pulse-width of the reflected pressure wave, and thus arrive at an overall impulse to the system.

Using this distance and the equivalent TNT mass from Equation 3-8, the scaled mass was determined. The detonation was assumed to occur at the center of the CNV.

Although a range of distances between the explosive source and CNV shell could be assumed, the resulting pulse period is insensitive to this parameter over the majority of distances applicable for the CNV geometry. At distances near the CNV wall, the pulse period increases; however, flame acceleration transition to detonation requires distance to propagate, therefore a detonation source close to the wall is not plausible. Flame acceleration is required to initiate a detonation because no high energy ignition sources are available in the containment.

$$Z = \frac{R_o}{W^{1/3}}$$ Equation 3-9

where,

Z = scaled distance, (ft/lb$^{1/3}$),

R_o = distance from the center of the explosive source to target (ft), and

W = equivalent mass of TNT, (lb).

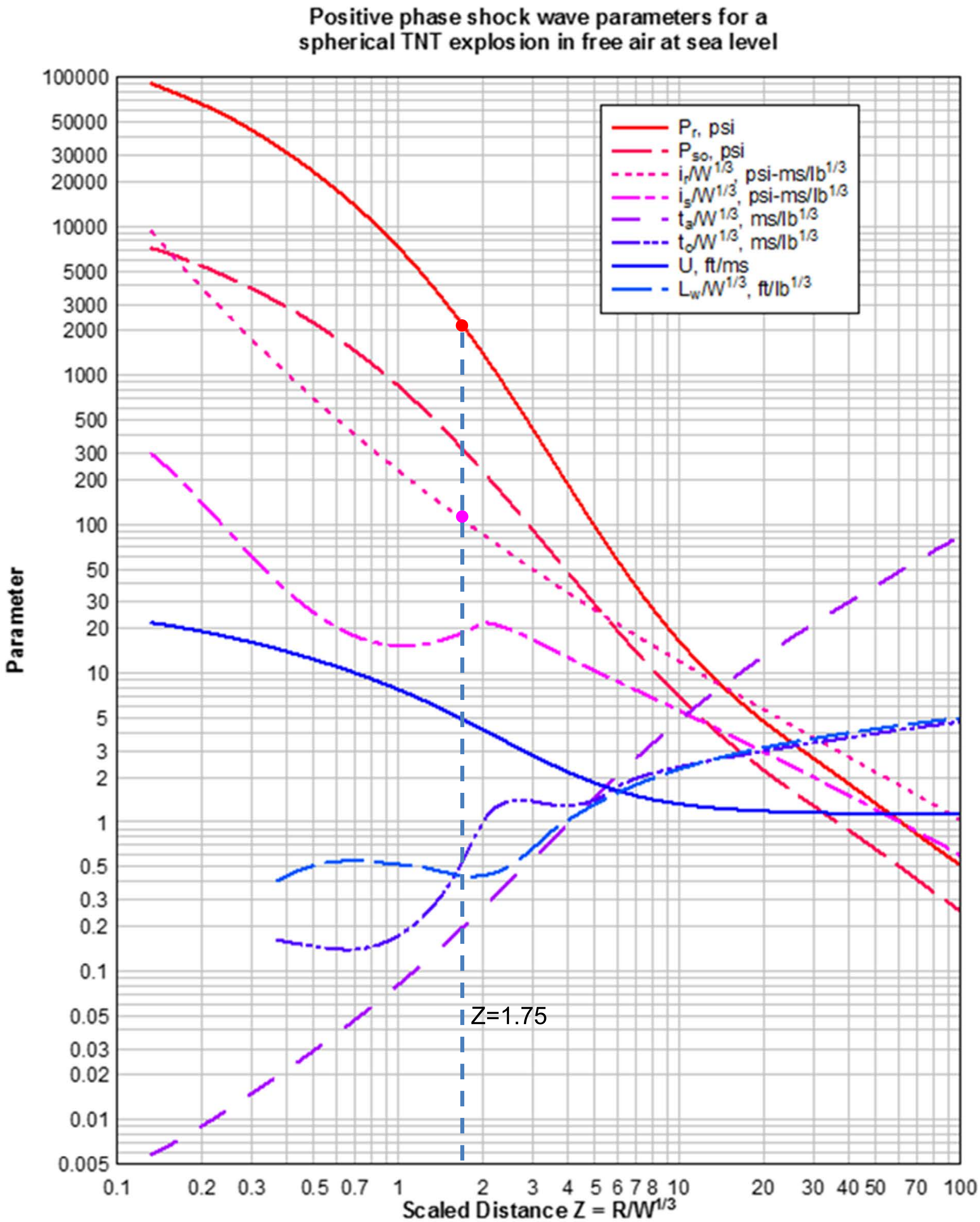

Figure 3-8 Scaled blast parameters for Trinitrotoluene equivalent load (Reference 5.1.14)

Based on the scaled mass, Z, the reflected impulse and TNT pressure expected pulse period were determined using Figure 3-8. Lastly, the pulse period was found using Equation 3-7.

The pulse periods for design basis and severe accident pressure pulse cases are provided in Table 3-9. These pulses were applied to the structure with the associated detonation and DDT pressures identified in Table 3-8.

Table 3-8 Detonation pulse period

Case	Reflected Detonation Pressure (psia)	DDT Pressure (psia)	TNT Equivalent Pressure (psia)	DDT Specific Impulse (psi-sec)	Pulse Period (s)
Design basis 72 hr	{{				
Severe accident 72 hr					}}2(a),(c),ECI

Table 3-9 Combustion load condition summary

Case	Pressure Applied (psi)	Pulse Period (s)	Stress Limit Evaluated
Design basis 72 hr – Reflected detonation	{{		Level C
Design basis 72 hr – DDT			Level D
Severe accident 72 hr – DDT		}}2(a),(c),ECI	Hoop strain < 1.5%

3.3.4.4 Containment Vessel Analysis Results

Results for the design basis reflected detonation event are presented in Table 3-10 for the selected CNV locations. The last column on the right provides the ratio of maximum calculated stress to allowable stress for a reflected detonation occurring after 72 hours of gas accumulation.

Results show the CNV is able to withstand the reflected detonation event and maintain stresses below ASME Service Level C limits for 72 hours gas accumulation. {{

}}2(a),(c),ECI

Table 3-10 Containment vessel shell stresses from reflected detonation load (Level C loading)

Path No.	Calculated P_m (or P_L), psi	Limit P_m (or P_L), psi	Calculated P_L+P_b, psi	Limit P_L+P_b, psi	Calculated Triaxial Stress, psi	Limit Triaxial Stress, psi	Max Stress Ratio
1	{{						
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							}}2(a),(c),ECI

Results for the design basis DDT event are presented in Table 3-11 for the selected CNV locations. The last column on the right provides the ratio of maximum calculated stress to allowable stress for a DDT combustion event that occurs after 72 hours of combustible gas accumulation. Results show the CNV is able to withstand the DDT event and maintain stresses below ASME Service Level D limits for 72 hours gas accumulation.

Table 3-11 Containment vessel shell stresses from deflagration-to-detonation transition load (Level D loading)

Path No.	Calculated P_m (or P_L), psi	Limit P_m (or P_L), psi	Calculated P_L+P_b, psi	Limit P_L+P_b, psi	Max Stress Ratio
1	{{				
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					}}2(a),(c),ECI

Lastly, results for the severe accident DDT event are presented in Table 3-12 for the selected CNV locations. The results column provides the membrane hoop strain. Results show the CNV is able to withstand the loads due to a DDT event and maintains significant margin to the 1.5 percent strain limit for 72 hours combustible gas accumulation.

Table 3-12 Containment vessel shell membrane hoop strain from deflagration-to-detonation load (severe accident)

Path No.	Membrane Hoop Strain, %	Limit, %	Strain Ratio
1	{{		
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			}}2(a),(c),ECI

3.3.4.5 Containment Bolt Stress Analysis

An evaluation of the flange cover bolting was completed to ensure the integrity of the flanged joints. The CRDM access flange, the shell side manway, the steam generator inspection ports, and the PZR access cover were evaluated. The forces across each bolted surface were calculated using the same model described in Section 3.3.4.1. The force on each stud was computed considering the stiffness of the joint. This force was combined with the thermal expansion and bolt preload and assessed against the ASME Service Level C and D limits for the corresponding combustion event. Severe accident loads were also evaluated against Service Level D limits for the bolts.

Table 3-13 identifies the containment flange bolting materials considered. Table 3-14 shows the summary of stress ratios for each joint and condition considered. Table 3-15 lists the detailed results for the limiting joint, which is the CRDM Access. These results

show that the bolted joints are adequately designed to ensure containment integrity through combustion events.

Table 3-13 Containment flange bolting materials

CNV Main Closure	CRDM Access (CNV25)	Shell Manway (CNV26)	SG Inspection (CNV27-30)	PZR Access (CNV31-32)
SB-637, Alloy 718	SA-564, GR 630	SB-637, Alloy 718	SB-637, Alloy 718	SB-637, Alloy 718

Table 3-14 Containment vessel major flange bolting assessment results

Service Level	Allowable Methodology	Stress Ratio, Calculated/Allowable				
		Main CNV Closure	CRDM Access (CNV25)	Shell Manway (CNV26)	SG Inspection (CNV27-30)	PZR Access (CNV31-32)
Design Basis Event, no DDT	NB-3232.1	{{				
	NB-3232.2					
Design Basis Event with DDT	F-1335.1					
	F-1335.2					
	F-1335.3					
Beyond Design Basis Event	F-1335.1					
	F-1335.2					
	F-1335.3					}}2(a),(c),ECI

Table 3-15 Detailed results for CRDM Access Flange (CNV25)

Service Level	**Stress**	**Allowable Methodology**	**CRDM Access (CNV25)**
Design Basis Event, no DDT	Tensile Calculated (psi)	NB-3232.1	{{
	Allowable (psi)		
	Ratio		
	Maximum Calculated (psi)	NB-3232.2	
	Allowable (psi)		
	Ratio		
Design Basis Event with DDT	Tensile Calculated (psi)	F-1335.1	
	Allowable (psi)		
	Ratio		
	Shear Calculated (psi)	F-1335.2	
	Allowable (psi)		
	Ratio		
	Combined Stress Ratio	F-1335.3	
Beyond Design Basis Event	Tensile Calculated (psi)	F-1335.1	
	Allowable (psi)		
	Ratio		
	Shear Calculated (psi)	F-1335.2	
	Allowable (psi)		
	Ratio		
	Combined Stress Ratio	F-1335.3	}}2(a),(c),ECI

3.3.5 Evaluation of Containment Structures, Systems, and Components

All containment SSC that make up a portion of the containment pressure boundary must maintain structural integrity in response to combustion loads to ensure containment integrity. The SSC that support emergency core cooling and containment heat removal functions must maintain their function to ensure core cooling. The CNV structural integrity analysis within this report ensures continued containment heat removal functionality.

Of the SSC within the CNV that are potentially exposed to combustion conditions, only ECCS valves and CIVs are required to be functional after a combustion event in order to ensure containment integrity and core cooling. The ECCS valves must retain their flow capabilities to maintain core cooling. The CIVs must maintain a leak tight barrier to ensure containment integrity. Structural integrity and core cooling capability of these components is ensured through the specification of appropriate loads in the ASME design specifications.

In addition, cables and wiring in the CNV must remain intact such that they do not generate debris. These components are not required for maintaining safe shutdown directly, but generation of debris within the CNV could reduce the capability to maintain core cooling. Only particles with a diameter smaller than 22 microns are expected to be transported in the low flows found in the CNV liquid during ECCS operation, so generation of debris from combustion events is not expected to contribute relevant debris loads. The containment does not house any materials that are expected to generate such debris under any load (i.e., the containment does not house insulation, coatings, or materials that could form chemical precipitates).

A summary of the performance requirements for SSC is provided in Table 3-16.

Table 3-16 Containment structures, systems, and components and performance requirements

<table>
<tr><th>Component</th><th>Performance Requirement</th><th>Reflected Detonation Treatment</th><th>DDT Load Treatment</th></tr>
<tr><td>CIVs</td><td>Remain closed</td><td rowspan="4">ASME Service Level C</td><td rowspan="4">ASME Service Level D</td></tr>
<tr><td>ECCS main valves</td><td>Remain open</td></tr>
<tr><td>ECCS trip and reset valve</td><td rowspan="2">Preserve containment structural integrity</td></tr>
<tr><td>Electrical penetration assemblies</td></tr>
<tr><td>Cables and wiring</td><td>Do not generate debris</td><td colspan="2">Environmental Qualification</td></tr>
</table>

For the purpose of evaluating the effect of a combustion pressure pulse on containment SSC, the SSC are categorized into two categories.

The first category is components that form part of the pressure boundary and could be exposed to the entire pressure pulse. For the containment, these consist of the CNV itself (structural integrity analysis results are presented in Section 3.3.4) and any other

SSC that form part of the containment pressure boundary, which include CIVs, ECCS trip and reset valves, and electrical penetration assemblies.

The second category is components that are situated to allow the pressure pulse to travel around the structure. Unlike other pressure loads that affect containment SSC, the shock wave associated with a combustion event has a short pulse duration, and thus a high frequency. The ECCS main valves fall into this category, and they are discussed in Section 3.3.5.1 below. Control rod drives also fall into this category. Control rods are inserted prior to combustible gas accumulation and potential combustion sequences. Control rods are required to remain inserted to maintain safe shutdown capability at the time of combustion, no plausible consequence of combustion could reduce shutdown capability of control rods.

Structural integrity and safe shutdown are ensured through the application of combustion loads to these components that is specified in the ASME Design Specification for each component.

3.3.5.1 Emergency Core Cooling System RVV and RRV Valves

During a combustion event, the RVVs and nozzles would be exposed to a combustion load. These valves are required to remain open to provide continued core cooling. The ECCS function and containment integrity are the only requirements for safe shutdown capability. The RRVs are also required to maintain core cooling. For all bounding combustion scenarios the RRVs would be submerged in the CNV liquid and, therefore, not exposed to a combustion pressure pulse.

The RVVs are located on the RPV head where the combustion front is expected to rapidly pass over the valve. As described in Reference 5.1.20, open structures have lower total force applied because the combustion wave travels to the back side of the object rapidly enough to counteract the impulse on the front face of the object. The net force on the object is then only that due to drag pressure plus an initial spike of short duration due to the reflection effect on the front surface.

The RVV valves and nozzle must continue to perform their safety function following the event. Because the RVVs are already open at the time of a CNV combustion event, the valves must remain open after the impact, but need not change position again. Inadvertent closure of an already open valve under load is unlikely due to the passive spring for maintaining the open position. Reflected detonation loads associated with design-basis combustion events are provided as ASME Service Level C for these components to ensure that they will support continued core cooling. DDT loads are specified as ASME Service Level D. In the rare event of a DDT, the valve must remain open but is not required to open and close on demand after the event. The ECCS valves support this functionality with the allowed deformation associated with ASME Service Level D limits.

3.3.5.2 Containment Isolation Valves

For each containment pressure boundary that is open directly to the containment or RCS volumes, two in-series CIVs are provided. Containment isolation valves are included for the RCS injection, discharge, high point vent, and PZR spray lines, which connect to the RCS; and the containment evacuation and containment flood and drain lines, which connect to the containment volume. Double valve isolation is also provided for the control rod drive cooling lines, although those valves are not expected to experience a combustion load since the control rod drive cooling line is not open to the containment or RCS atmosphere. Single valve isolation is provided for the steam generating system feedwater and steam lines, although those valves will also not experience combustion since the secondary side is not open to the containment or RCS. For the lines connected to the RCS, as well as the containment flood and drain lines, the effect of the pressure pulse on the isolation valves is expected to be minimal, as the pressure wave will be partially attenuated as it travel through the small diameter piping. However, the containment evacuation line does not have piping, so no damping or attenuation of the pressure pulse is expected.

The CIVs are a wedged, quarter turn ball type, hemispherical cartridge valve with a hydraulic actuator to open and a nitrogen accumulator to close. The ball is exposed to the containment pressure and the seat is located outboard of the CNV. Therefore, when the containment experiences a high pressure condition, the ball is pushed against the valve seat, increasing the seating force of the valve. While the pressure pulse due to combustion is not expected to damage the ball or the seating surface, if minor damage did occur, the second isolation valve is available to provide containment integrity. Consistent with the CNV design, the same passive design approach that provides for safe and reliable operation following a loss of coolant accident or pipe break (i.e. high containment pressure provides for increased seating force of the CIVs) provides for acceptable component performance in the event of a combustion scenario.

Reflected detonations are specified as ASME Service Level C, while DDT events are specified as ASME Service Level D.

3.3.5.3 Emergency Core Cooling System Trip and Reset Valve Assemblies

Three RVV and two RRV emergency core cooling system valve trip/reset pilot assemblies are welded to the external side of the CNV safe end penetrations. These assemblies represent an extension of the containment pressure boundary. The valves operate using the RCS as hydraulic fluid and, therefore, the pressure boundary is designed to RCS pressure of 2100 psia. There are three openings to the valve assembly: the reset supply flow, and pilot flow and the trip outflow. The pilot and supply lines are connected to small diameter RCS piping and, therefore, these regions are not subject to a combustion load. The trip outflow is open to containment, and it is possible that a pressure pulse could be transmitted in to the valve body from this opening. Due to the small opening of the trip outflow, the force generated from a pressure pulse will not challenge the pressure boundary since the area is small. {{

}}$^{2(a),(c),ECI}$

{{

}}2(a),(c),ECI

Reflected detonations are specified as ASME Service Level C, while DDT events are specified as ASME Service Level D.

3.3.5.4 Electrical Penetration Assemblies

There are 11 electrical penetration assemblies (EPAs) located on the CNV head. The EPAs are designed to route electrical conductors through containment and to provide a leak tight barrier for the containment atmosphere. The EPA is an assembly of a flange, insulated electrical conductors, conductor seals, module seals, connectors and aperture seals that provide for the passage of electrical conductors through a single aperture of the CNV. The EPAs are an appurtenance to the containment vessel and are designed to ASME Code Section III Subsection NB. The pressure boundary surfaces of the EPAs are shielded from a postulated combustion load due to the electrical conduit and conduit routing tubes. In addition to shielding the load from impinging on the flange surface, these components add stiffness to the overall assembly, compared to the flanges and manway covers assessed in Section 3.3.4. The effect of a combustion load on this appurtenance is bounded by the stress analysis performed for the CNV.

Reflected detonations are specified as ASME Service Level C, while DDT events are specified as ASME Service Level D.

3.3.5.5 Cables and Wiring in the Containment Vessel

These components are not required for structural integrity or safe shutdown of the reactor, however, safe shutdown capability of the ECCS is dependent on a containment that does not have sources of debris, as discussed above. The cables in the CNV are mineral insulated cables with a steel sheath or protected in a metal conduit. These arrangements are not susceptible to degradation that would generate debris under loads due to the high strength of the mineral insulated cables and the density of the material (too dense to be transported as debris for expected particle sizes). In addition, cables or conduit are small components in free space where the combustion wave is expected to rapidly pass over the cable or conduit. As described in Reference 5.1.20, open structures have lower total force applied because the combustion wave travels to the back side of the object rapidly enough to counteract the impulse on the front face of the object. The net force on the object is then only that due to drag pressure plus an initial spike of short duration due to the reflection effect on the front surface. The wiring and cabling are required to remain intact under combustion loads.

3.3.5.6 Temperature Effects of Combustion

The heat of combustion has been analyzed to determine potential impacts to CNV components. Containment components are not expected to experience a significant temperature increase and therefore the heat of combustion is not expected to impact CNV components. Considering the amount of combustible gas within the containment atmosphere, and the large mass of highly thermal conductive materials available within

the NPM, the heat of combustion is expected to dissipate rapidly without significant temperature increases to CNV components.

As described in Section 3.3, the amount of oxygen available within the first 72 hours of any DBE or BDBE will not exceed {{ }}[2(a),(c)]. This can react with {{ }}[2(a),(c)] hydrogen. The heat of combustion of hydrogen is 6.1E+4 BTU/lbm (Reference 5.1.10). Therefore, the total energy produced from a potential combustion event will not exceed {{ }}[2(a),(c)]. Applied to the mass of the NPM materials potentially exposed to this energy, this equates to an insignificant temperature increase (i.e., less than three degrees F as discussed further below).

The NuScale NPM consists of a large mass of high thermal conductivity materials providing massive heat sink capabilities. Steel is the dominant material in the CNV and NPM components exposed to potential combustion energies. To assess the potential instantaneous temperature increases from combustion events, the entire heat of combustion calculated above was applied to one percent of the mass of steel materials potentially exposed to this energy. This is conservatively bounding considering the distribution of potential combustion event energy within the CNV atmosphere, the heat transfer properties of the materials exposed to this energy, and discounting the heat dissipation properties of other materials within the CNV exposed to this energy (e.g., water, steam, and other CNV atmospheric components). Steel has a specific heat of approximately 0.11 BTU/lbm-F (Reference 5.1.21). When applied to just one percent of the potential mass exposed to the combustion atmosphere (i.e., approximately 1.1E+4 lbm of steel), the total combustion energy produces a temperature increase of less than {{ }}[2(a),(c)]. This temperature increase is within design parameters for the CNV and NPM components exposed to potential combustion energies when applied at the highest temperature conditions expected (e.g., as discussed in Section 3.2.7, the starting temperature of CNV steel is not more than 250 degrees F).

Instantaneous temperature rises of all components exposed to the containment atmosphere during a combustion event are therefore expected to be much smaller than {{ }}[2(a),(c)] and well within design parameters due to the large available heat sink available within the NPM design. The heat of combustion is expected to dissipate rapidly without significant temperature increases to CNV components. Containment components are not expected to experience a significant temperature increase and therefore the heat of combustion is not expected to impact CNV components.

4.0 Summary and Conclusions

This report discusses the differences between the combustible gas analyses for typical operating large LWRs and the NuScale small modular design, and provides a description of combustible gas control in the NuScale Power Plant. The NuScale design uses passive safety systems, simplifying design and operation, to ensure reliability and safety. The majority of SSC inside containment, and the CNV itself, are fabricated to ASME Section III pressure vessel standards; all are designed to withstand postulated combustible gas events without adverse effect on the structural integrity or safety functions.

This report provides the bounding scenarios and assumptions that define design-basis and beyond design basis combustion events for the NuScale design. In keeping with the passive safety approach, the containment is designed to withstand bounding loads from deflagration, incident detonation, reflected detonation, and DDT events for 72 hours. The combustion design loads were evaluated against ASME Service Level C and D loads for all components that could be exposed to a combustion event.

Based on the limiting combustion pressures, this report provides a structural evaluation to demonstrate the ability of the containment vessel to withstand the design loads with no compromise of structural integrity or capability to establish and maintain safe shutdown. The limiting locations of the CNV show approximately 60 percent margin to the design stress limits for the reflected detonation load, and approximately 15 percent margin to the design stress limits for the DDT load. To quantify the integrity of the containment for a severe accident core melt event, an elastic-plastic analysis was performed. The highest membrane hoop strain provides approximately 85 percent margin to the recommended strain limit of 1.5 percent. Combustion loads on other containment SSC are shown to be bounded by the CNV analysis or are provided in the ASME design specifications to ensure components are designed to establish and maintain safe shutdown when subjected to combustion loads.

Structural analysis demonstrates that the containment is capable of withstanding the combustion loads with significant margin to stress and strain limits as required by 10 CFR 50.44. This report demonstrates that the containment is designed to withstand the adverse effects of combustion in order to establish and maintain safe shutdown and maintain containment structural integrity for protection of public health and safety.

The analyses described in this report support four conclusions related to NRC combustible gas control regulatory requirements:

1. Structural analysis (10 CFR 50.44(c)(5)) – NuScale CNV structural integrity is not challenged by bounding combustion events, propagated by combustible gas concentrations generated within the first 72 hours of any design basis or beyond design basis event. This report describes the containment response to the structural loads involved. The report addresses an accident that releases hydrogen generated from 100 percent fuel clad-coolant reaction accompanied by hydrogen burning. The report demonstrates that systems necessary to ensure containment integrity perform their function under these conditions.

2. Equipment survivability (10 CFR 50.44(c)(3)) – NuScale CNV structures, systems, and components are not challenged by bounding combustion events, propagated by combustible gas concentrations generated within the first 72 hours of any design basis or beyond design basis event. This report demonstrates that the NuScale design is able to establish and maintain safe shutdown and containment structural integrity with systems and components capable of performing their functions during and after exposure to the environmental conditions created by the burning of hydrogen.

3. Mixed atmosphere (10 CFR 50.44(c)(1)) – The NuScale CNV design ensures a mixed atmosphere during design basis and beyond design basis events. This report demonstrates that the concentration of combustible gases in any part of the CNV is below a level that supports combustion or detonation that could cause loss of containment integrity.

4. Monitoring (10 CFR 50.44(c)(4)) – The NuScale design includes monitoring capabilities appropriate for indication of CNV conditions that may require post 72 hour mitigating actions in extreme cases. The report demonstrates that the equipment for monitoring hydrogen and oxygen is reliable, and capable of continuously measuring the concentration of hydrogen and oxygen in the containment atmosphere following a design basis or beyond design-basis accident, for combustible gas control and accident management, including emergency planning.

5.0 References

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