October 2, 2017

Docket No. 52-048

U.S. Nuclear Regulatory Commission
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SUBJECT: NuScale Power, LLC Response to NRC Request for Additional Information No. 152 (eRAI No. 9047) on the NuScale Design Certification Application

REFERENCE: U.S. Nuclear Regulatory Commission, "Request for Additional Information No. 152 (eRAI No. 9047)," dated August 05, 2017

The purpose of this letter is to provide the NuScale Power, LLC (NuScale) response to the referenced NRC Request for Additional Information (RAI).

The Enclosure to this letter contains NuScale's response to the following RAI Question from NRC eRAI No. 9047:

- 06.02.05-3

This letter and the enclosed response make no new regulatory commitments and no revisions to any existing regulatory commitments.

If you have any questions on this response, please contact Marty Bryan at 541-452-7172 or at mbryan@nuscalepower.com.

Sincerely,

Zackary W. Rad
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Enclosure 1: NuScale Response to NRC Request for Additional Information eRAI No. 9047

Enclosure 1:

NuScale Response to NRC Request for Additional Information eRAI No. 9047

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Response to Request for Additional Information
Docket No. 52-048

eRAI No.: 9047
Date of RAI Issue: 08/05/2017

NRC Question No.: 06.02.05-3

10 CFR Part 50.44, “Combustible gas control for nuclear power reactors” subpart (c), “Requirements for Future Water-Cooled Reactor Applicants and Licensees,” requires in part that all equipment required to establish safe shutdown and ensure containment function must have the capability to withstand a hydrogen burn and detonation resulting from at least the hydrogen generated following a fuel clad-coolant reaction involving 100 percent of the fuel cladding, unless such detonations can be shown to be unlikely to occur. Following such a hydrogen burn, this equipment must continue to perform its function during design-basis and significant beyond design basis accidents.

For the NuScale design, this includes the containment vessel. TR-0716-50424, “Combustible Gas Control,” provides the demonstration that the NuScale design has the ability to establish and maintain safe shutdown and maintain containment structural integrity during and after exposure to the environmental conditions created by the burning of hydrogen within the CNV.

In TR-0716-50424, it is stated that the TNT equivalence method is used to calculate the pulse period, and the deflagration-to- detonation transition (DDT) pressure is used as the limiting combustion load. In the calculations performed in TR-0716-50424, the DDT pressure appears to be limiting. In the TNT-equivalence calculation performed as part of TR-0716-50424, a yield efficiency factor (alpha) of 0.03 was used, based on an industry reference “Guidelines for Evaluating the Effects of Vapor Cloud Explosions Using a TNT Equivalency Method”, which is available in ADAMS under accession number ML14224A361. In that source, a value of 0.05 (rather than the 0.03 used by NuScale) is recommended for hydrogen, but that this factor is based on a number of factors including layout. Both the source and NUREG-1805 note that level of confinement tends to increase the yield efficiency factor.

Additionally, the scaled distance parameter Z, which is used to determine the effective pulse impacts from the TNT-equivalent detonation, is based on the full containment vessel radius. The justification provided states that the “resulting pulse period is insensitive to this parameter over the majority of distances applicable for the CNV geometry”; while this may be valid for the pulse period, it is not valid for the pressure cited in Table 3-8 of the report. Given that such a distance is not feasible within the containment for most detonation/impact location pairs, this choice appears to be non-conservative. Further, the parameters calculated from the use of Z are based on a TNT explosion in free air at sea level. The impact of the post-accident containment conditions as compared to free air on the calculated parameters is not assessed in the report.

Based on the above discussion, the values used in the TNT-equivalence calculation do not appear representative of the conditions that would exist inside the containment during a severe accident, and the discrepancies between the existing calculation and a more representative one would result in substantial differences in the resultant pressure parameters. NRC staff requests that NuScale justify the use of 0.03 as the yield efficiency factor for the TNT-equivalence calculation and justify the use of the containment radius as the effective distance for all parameters from the TNT-equivalent detonation, given the existing containment and in-containment SSCs configuration and conditions related to hydrogen generation. Another alternative could involve revising the calculation to include more representative parameters for the yield efficiency factor and scaled distance parameter, and re- evaluating the TNT-equivalent pressure and associated parameters, or providing another means to address the potential for a hydrogen detonation in the containment to meet the requirements associated with 50.44(c).

NuScale Response:

This following discussion justifies the NuScale approach documented in TR-0716-50424 for the following topics:

- Use of yield efficiency factor value (0.03)
- Peak pressures in TR-0716-50424, Table 3-8 (Reference 4.1)
- Use of containment radius for determining peak pulse duration
- Other SSC's in CNV

Yield Efficiency Factor

The yield efficiency factor, α, employed in the TNT-equivalence methodology represents a means of addressing the explosive energy content of a combustible gas detonation as compared with an equivalent mass of TNT. In other words, the yield efficiency factor is a fraction of the available combustion energy participating in blast wave generation when compared to a TNT explosion. For gaseous detonations, the recommended yield efficiency factor ranges from 0.01 to 0.15, as described in Chapter 4.3, *"Vapor Cloud Explosion Modeling,"* of CCPS (TR-0716-50424, Reference 5.1.8) and listed in Table 1 below.

Table 1 - Yield Efficiency Factor Ranges

Organization	Yield Efficiency Factor (%)	Notes
Dow Chemical	2-5	2% for Near-field and 5% for Far-Field effects
HSE (UK)	1-3	Recommend 3% for design

FM Global	Class I - 5 Class II - 10 Class III - 15	5 tons or greater 1 ton or greater 1000 lb or greater Used to predict a worst credible case explosion efficiency, based on the class of material.

Note: The FM Global guidance of using the yield efficiency factors based on Material Class of 5%, 10% and 15% are conditional on obtaining the threshold mass of fuel vapor for a worst credible scenario. For hydrogen gas, which is a Class I material, the 5% yield efficiency factor can only be used if the mass of fuel vapor is greater than or equal to 5 tons (10,000 lb). Otherwise, a lower value for yield efficiency should be utilized, as recommended by Dow Chemical and HSE (see Table 1).

As discussed in CCPS textbook (TR-0716-50424, Reference 5.1.8), Lee's Loss Prevention Handbook (TR-0716-50424, Reference 5.1.9), NUREG-1805 TR-0716-50424, Reference 5.1.7) and the FM Global Datasheet 7-42 (TR-0716-50424, Reference 5.1.11), the TNT-equivalence method is by no means a perfect analog to gaseous detonation, as there are several drawbacks. Dense-phase explosives, such as TNT, exhibit detonation C-J pressures of 210 to 220 kbar (~3M psia), while H_2-O_2 exhibits detonation C-J pressures of 19 bar (279 psia) for initial gas pressures at 1 atmosphere. Additionally, dense-phase explosions are treated as point-source detonations, while gaseous detonations encompass the complete containment volume. Lastly, for near-field detonations, TNT-equivalence methodology overpredicts peak pressures as compared with gaseous detonations. Conversely, the CCPS and FM Global references indicate gaseous detonations tend to produce greater overpressures at far-field as compared to TNT-equivalence method. Nonetheless, even when considering the shortcomings, the TNT-equivalence methodology is acceptable and recommended by NUREG-1805, while providing an estimate of gaseous detonations.

Because the scaled distance, Z, is inversely proportional to the cube-root of the TNT mass (see Figure 1), the pulse-period or pulse-duration, t_d, is practically invariant for the range of yield efficiency factors from 0.01 to 0.10, as shown in Figure 2. Thus, using a yield efficiency factor of 0.05, as recommended by FM Global Datasheet 7-42, the resulting pulse-duration is 0.409 ms. Using a yield efficiency factor of 0.03, as employed in the NuScale calculations, the resulting pulse-duration is 0.414 ms (approximate 1% increase). Furthermore, if the yield efficiency factor were increased to 0.10, the pulse-duration would change slightly to 0.42 ms. Again, the overall effect of the cube-root scaling tends to maintain the pulse-duration invariant between yield efficiency factors of 0.01 and 0.10, thus making the choice of yield efficiency factor insignificant.

Note: the pulse-duration is the only parameter obtained from the TNT-equivalence methodology, while peak C-J pressure under gaseous detonation conditions is derived from chemical kinetics and equilibrium of the gas mixture. Additionally, combustible gas calculations performed for the NuScale design conservatively used the total mass of evolved gas during the transient, instead of employing only the fuel mass. That is, the total combined mass of H_2, O_2 and N_2 was assumed as the mass of fuel available for combustion, which overpredicts the actual fuel mass.

A direct consequence of overpredicting the total mass of fuel available, when using the TNT blast curves, is that the pulse-duration is increased slightly (see Table 3).

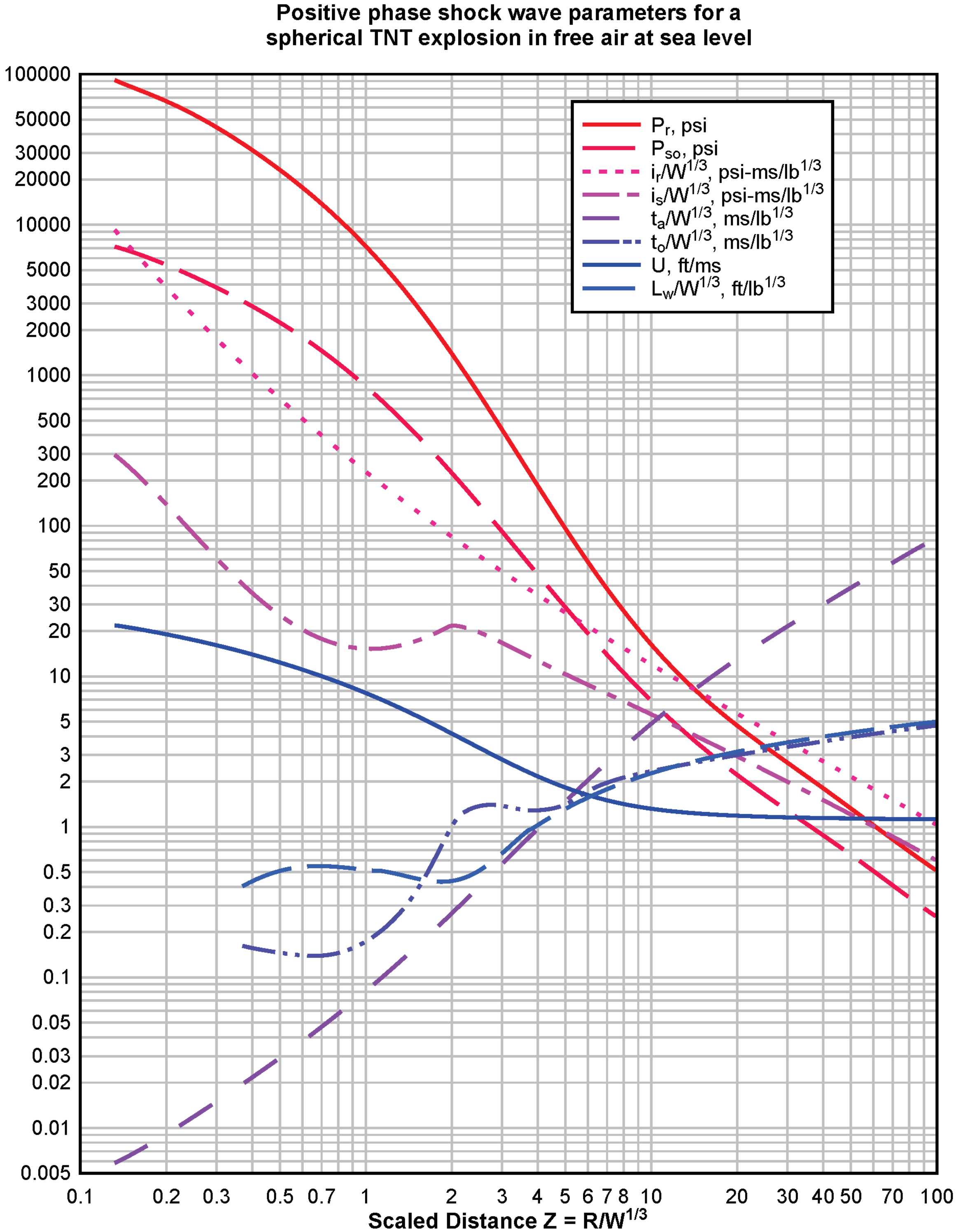

Figure 1 - Blast wave parameters for TNT explosion in air

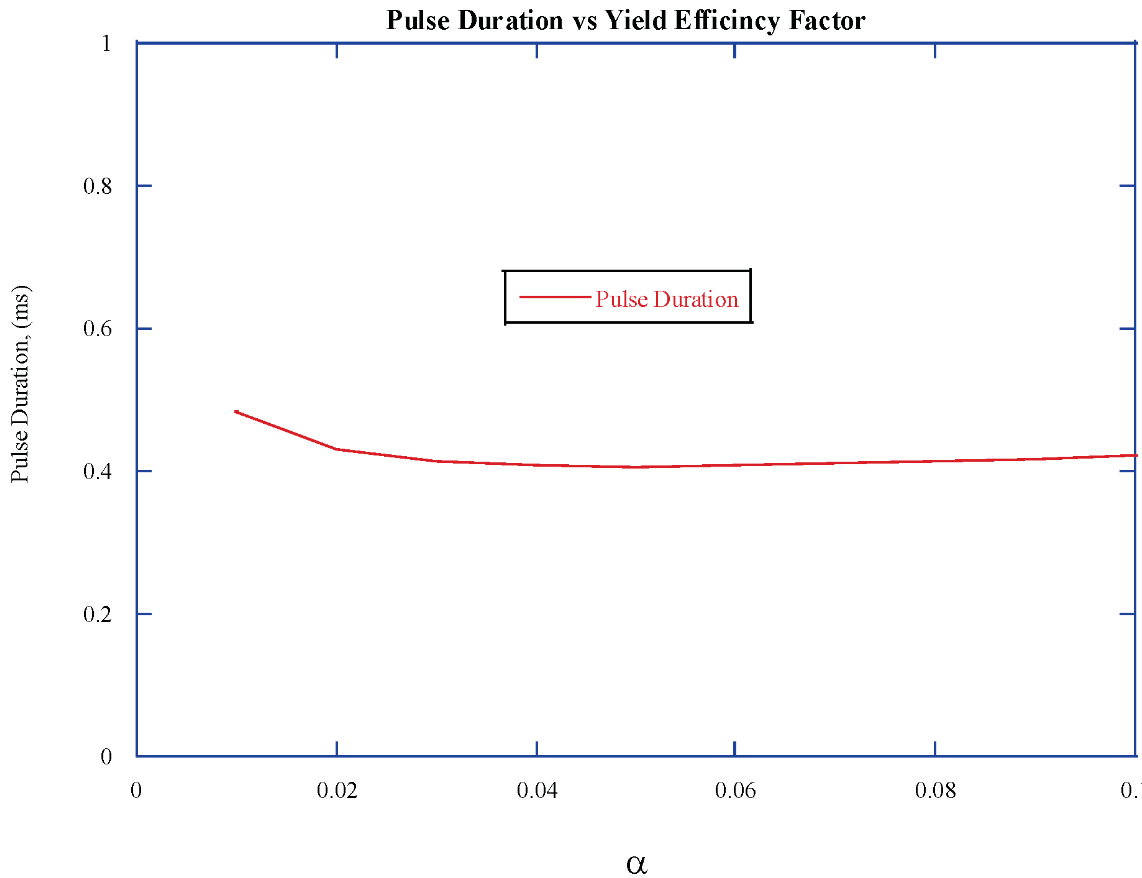

Figure 2 - Pulse duration vs yield efficiency factor.

At 72 hrs post-accident, the total mass of H_2 available for combustion as compared with oxidizer and diluents is shown in Table 2. At onset of a gaseous detonation event, the initial CNV system pressure is 37.4 psia, which is consistent with the evolution of gas species during radiolytic generation and accumulation within the CNV. The resulting TNT-equivalent mass is conservatively based on 85 lb of total evolved gas, in lieu of 11.6 lb of fuel.

Table 2 - Available Fuel, Oxidizer and Diluents after 72-hrs.

Gas Specie	Partial Pressure (psia)	Moles of Gas	Mass of Gas (lb)
H_2	7.09	2614	11.6
O_2	1.82	669	47.2
N_2	1.15	423	26.1
H_2O	27.33	---	---
Total	**37.4**		**84.9**

However, a strict accounting of conversion to TNT-equivalent mass (see TR-0716-50424, References 5.1.7, 5.1.8, 5.1.9 and 5.1.11) requires the actual fuel mass (i.e., H_2) be employed in obtaining TNT blast wave parameters, according to the following:

$$m_{TNT} = \alpha \frac{\Delta H^{c}_{gas}}{\Delta H^{c}_{TNT}} m_{gas}$$

where m_{gas} = mass of gas, (kg)

ΔH^{c}_{gas} = heat-of-combustion of fuel, (MJ/kg)

ΔH^{c}_{TNT} = heat-of-combustion of TNT, (MJ/kg)

α = yield efficiency factor

Table 3 provides a comparison of TNT-equivalent parameters using the actual fuel mass (11.6 lb) versus the total gas mass (85 lb), while applying a yield efficiency factor of 0.15 for conservatism. As evident from Table 3, the pulse-duration remains around a value 0.4 ms.

Table 3 - Pulse-Width Comparison

Fuel Only			Total Gas		
Gas Mass (lb)	TNT Mass (lb)	Pulse-Duration (ms)	Gas Mass (lb)	TNT Mass (lb)	Pulse-Duration (ms)
11.6	45.4	0.437	85	332.6	0.448

Peak C-J Pressures in Table 3-8

The pressures cited in TR-0716-50424, Table 3-8 are not based on TNT-equivalency explosions in free air at sea level, but rather on theoretical maximum Chapman-Jouguet (C-J) pressure for hydrogen-air (H_2-Air) and hydrogen-oxygen (H_2-O_2) mixtures, which cannot be increased further, based on confinement. Pressures listed in Table 3-8 have been determined based upon post-accident CNV conditions for a DBE or BDBE, thus accounting for gas evolution and accumulation at time of detonation. Table 2 shows that the static internal CNV pressure after 72 hrs has increased from partial vacuum to 37.4 psia.

Because application of the C-J theory to gaseous combustion uses a combination of thermochemical equilibrium and gas dynamics conservation equations across the detonation front, the calculated C-J pressure is by definition, the theoretical maximum incident detonation pressure. The C-J pressure is then amplified by a reflection coefficient consistent with the ratio of specific heats of the burned gas, resulting in the peak reflected gaseous C-J detonation pressure, which is ultimately used in assessing structural behavior.

This, applying the maximum theoretical incident C-J pressure ratio, coupled with the initial CNV system pressure of 37.4 psia at detonation, results in the peak incident C-J pressure;

$P_{cj} / P_i = 8.883$

$P_{cj} = 332\ psia$

Peak C-J pressures are amplified by a reflection coefficient when impacting with a rigid surface, which is described in TR-0716-50424:

$\pi_{ref} = 2.57$

The resulting peak reflected C-J pressure, which is the maximum reflected pressure anywhere in the CNV, is;

$P_{ref} = 854\ psia$

For DDT cases, the peak reflected C-J detonation pressure is further amplified as a means of addressing the higher pressures resulting from pressure piling (or pre-compression) of unburned gases ahead of the detonation front just prior to impact on a rigid surface.

Finally, it should be emphasized that although TNT-equivalent method is utilized herein to determine the pulse-duration of a blast wave, only the maximum C-J pressure associated with a gaseous detonation is employed. Pressures generated by a TNT explosive are overpredicted for near-field conditions, while far-field pressures are well underpredicted.

Containment Radius

The TNT-equivalent calculation uses the containment radius to obtain the peak reflected pulse duration on the shell wall, thereby conservatively using the smallest geometric dimension from a TNT point-source to any point on the CNV shell. Longer distances could be obtained; for example, assuming a detonation starting at mid-height, running axially and impacting at the CNV head.

However, the overall distance travelled would be about 38 ft, resulting in a scaled distance, Z, of approximately 9.4 ft/lb$^{1/3}$, and peak reflected pressures of 20 psia (see Figure 1), which are not credible for gaseous detonations. As stated earlier, far-field effects are underpredicted when using the TNT-equivalent methodology and should be avoided. Therefore, the conservative approach in evaluating the CNV structural response is based on using the CNV radius to determine the pulse-duration, coupled with the peak reflected pressure based on C-J conditions of the gas mixture, not the peak reflected TNT-equivalent pressure. For smaller distances, e.g., below the CNV radius, a reduced pulse-duration is evident as shown in Figure 3. However, as mentioned earlier, two shortcomings with TNT-equivalent methodology are the near-field and far-field effects.

Near-field Effects

Extremely high pressures are generated from the TNT charge at very short distances, as evidenced by inspection of Figure 1. These extremely high pressures are not valid for gaseous detonations . For near-field detonations, TNT-equivalence methodology overpredicts peak pressures as compared with gaseous detonations. Gas phase detonations require a period of flame acceleration, wherein a deflagration from a low energy ignition source develops into a detonation front. Spatially, this is referred to as a run-up distance. TNT point source methodologies predict loads to increase with a cube function as the ignition source is approached. Due to this inconsistency between the core phenomena of short range TNT detonations vs short range gas phase combustion, estimation of loads using a TNT methodology at very short distances is not appropriate. Additionally, for close-in distances, DDT will not occur because a deflagration requires a significant run-up distance to create flame acceleration and transition to detonation, which cannot be accommodated at short distances.

Far-field Effects

Very low pressures result in TNT explosions at far distances, as evidenced by inspection of Figure 1. Far-field pressures from TNT blast curves cannot be relied upon for equating gaseous detonations because they decay at $1/R^2$ and expand the pulse-duration accordingly, resulting in unrealistic pressure and impulse.

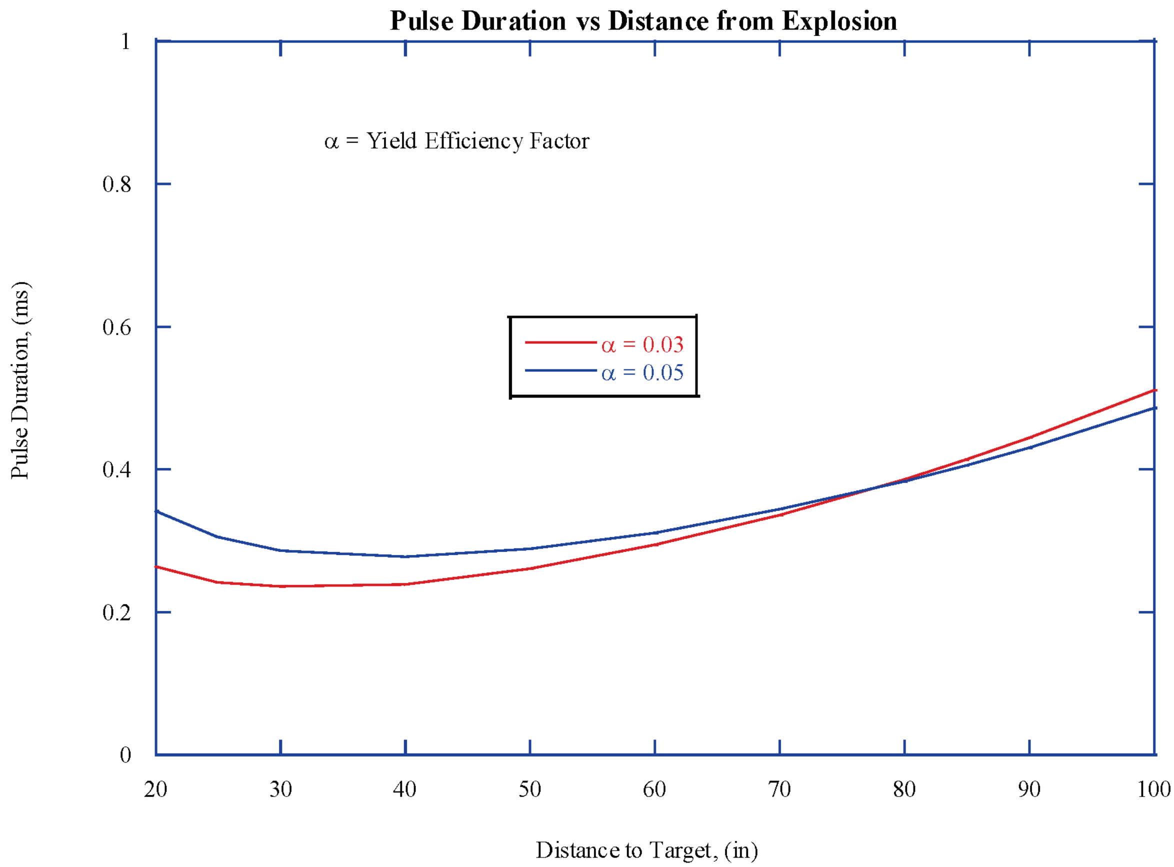

Figure 3 - Pulse duration vs distance for different yield efficiency factors.

As stated in Reference 1, without the benefit of a computational hydrodynamics code to resolve the blast characteristics of a gaseous detonation, The TNT-equivalent methodology provides an acceptable estimate in obtaining a measure of the pulse-duration only, while employing the C-J conditions for the gas detonation pressure.

Other SSC's Internal to CNV

For evaluating the response of nearby SSC's, the same reflected detonation and DDT loads are considered. Short distances for components are not appropriate for the same reason as for the shell sections of the CNV: detonation requires a run-up distance for flame acceleration and TNT-equivalency methodologies over predict blast wave impulses at very short distances due to the point source methodology. Load transients for SSC's are included in ASME Specifications. For components that are required for containment integrity or safe shutdown, these loads include combustion loads consistent with TR-0716-50424. Respective engineering evaluations will be included in ASME calculations for the specific components.

Conclusion

NuScale Power, LLC has provided a discussion of the yield efficiency factor used in TNT-equivalent calculations to determine representative pulse duration for a gaseous detonation event. Sensitivities to parameters of interest show that pulse duration becomes invariant for the range of yield efficiency factors from 0.01 to 0.10. Therefore, use of 0.05 as recommended by FM Global Datasheet 7-42 will not appreciably change the final resulting pulse duration. Chapman-Jouguet detonation pressures are theoretical maximums that cannot be further increased by confinement. Short distances used for estimating pulse durations are not appropriate because the non-linear effects inherent in TNT-equivalency methodologies at short distances are not consistent with the behavior of gaseous detonation fronts. Gaseous detonations require critical run up distances to obtain detonation pulse pressures that exceed the distances where extreme nonlinear results are found in TNT-equivalency methodologies.

Impact on DCA:

There are no impacts to the DCA as a result of this response.