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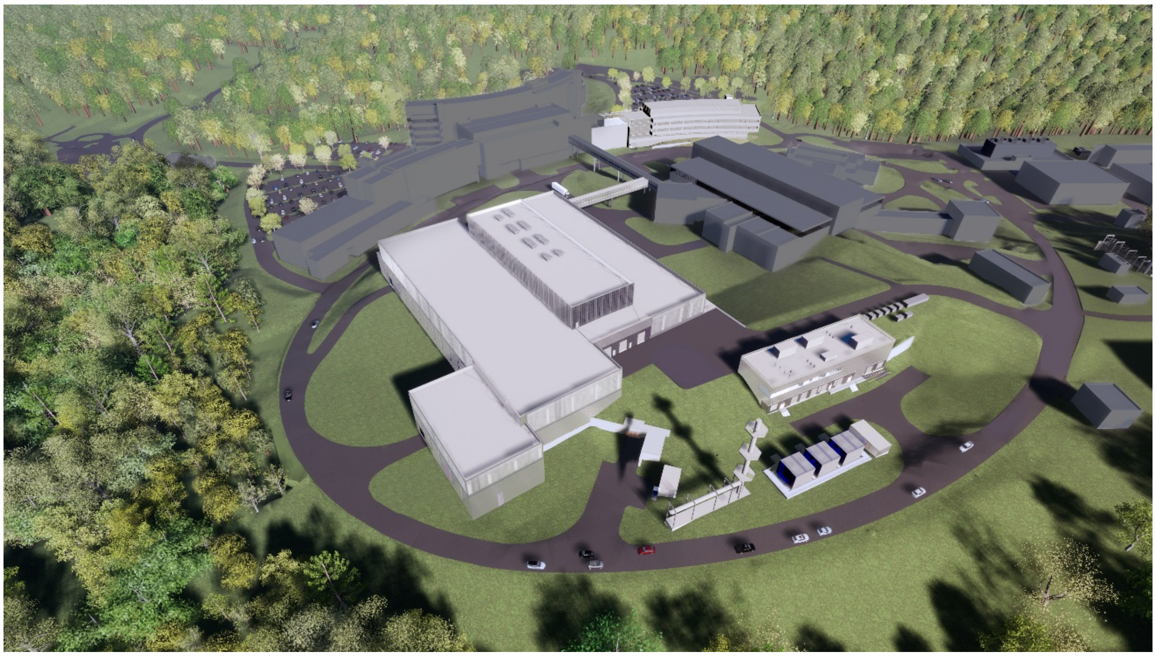
STS BG7-1 Working Group Report on the Evaluation of the Estimated Consequences from the Bounding Seismic Event in the STS PHAR



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April 14, 2022

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SECOND TARGET STATION (STS) PROJECT

STS BG7-1 WORKING GROUP REPORT ON THE EVALUATION OF THE ESTIMATED CONSEQUENCES FROM THE BOUNDING SEISMIC EVENT IN THE STS PHAR

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EXECUTIVE SUMMARY

In conjunction with the Rev. 1 update to the Second Target Station (STS) project Preliminary Hazard Analysis Report (PHAR) (STS-S01030000-ES0002, R01) dated July 26, 2021, an STS project BG7-1 Working Group (WG) was formed to evaluate the seismic events in the PHAR update. The WG was established by Steven M. Trotter, STS ESH&Q Manager and was led by James Eckroth, ORNL Fire Protection Engineering support. Due to the global COVID-19 pandemic, the WG held a series of workshops and meetings remotely from August thru December, 2021 to perform the evaluation and review of the PHAR Rev. 1 seismic events.

The primary purpose of the WG was to review the initial analysis of the current bounding seismic event in the PHAR Rev. 1 to determine if it was sufficiently conservative and whether there were any means to further quantify the unmitigated consequences of this event. In addition to the initial charge, the WG also completed a general review of all seismic events in the PHAR Rev. 1 for completeness, accuracy, and consistency.

The WG concluded that the initial analysis of the bounding seismic event was sufficiently conservative. In addition, the WG does not recommend but does note that options exist to potentially further quantify the unmitigated consequences of this event if necessary and warranted. The WG recommends updating the details in several of the seismic events in the PHAR Rev. 1. These updates would be helpful to the project in understanding and properly mitigating the postulated seismic events.

Based on this comprehensive review, the project should proceed with preliminary design assuming a Seismic Design Category 2 (SDC-2) determination for structures, systems, and components (SSCs) required to perform their safety function in a design basis natural phenomena hazard (NPH) seismic event.

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1. INTRODUCTION

The STS project will construct a second target station on the Spallation Neutron Source (SNS) site, an initial set of neutron scattering instruments, and the required proton beamline transport to the target. The second target station is proposed to be a rotating solid target. The primary reason for the selection of a rotating solid target is that the decay heat can be passively removed by thermal radiation to the surrounding shielding without reaching temperatures that could cause a significant radiological release. The potential mechanisms for release associated with elevated temperatures are oxidation of the tungsten with a reaction between tungsten and steam that produces a tungstic acid aerosol and hydrogen gas. This reaction starts at approximately 800 degrees C. Preliminary evaluations of the baseline design showed that with no cooling except thermal radiation to the surrounding shielding, the peak tungsten temperature was below 500 degrees C, which is well below the threshold for a tungsten/steam reaction.

In the initial PHAR[1] approximately 225 events were identified in the respective Hazard Evaluation (HE) tables. From these, two types of events were judged to be bounding for unmitigated dose; 1) loss of target cooling with continued beam operation, and 2) a seismic event leading to a hydrogen detonation adjacent to the target (event BG7-1 and similar seismic events). Per DOE guidance[2] dose estimates were calculated for on-site workers at 100 m and for the maximally exposed offsite individual (MEOI) dose based on the conceptual design[3]. This study and the respective results are herein referred to as the "initial analysis".

In the initial analysis, it was postulated that a beyond-design-basis seismic event could result in a hydrogen release from the moderator systems into the core vessel. The seismic event could also cause the core vessel boundary to fail allowing air to enter the vessel so that the potential for either a hydrogen deflagration or detonation exists. Detonation in the free volumes adjacent to the rotating target was assumed to cause a release of a fraction of the target mass. In line with the general practice of conservatively estimating the consequences of a bounding accident and also given the conceptual aspect of the STS design at the time, a number of conservative assumptions (see Appendix A) were made in conjunction with the initial analysis. Although the PHAR was revised in July, 2021, and this revision refined some of the details of the BG7-1 event, the event itself remained the bounding seismic event based on the consequences documented in the initial analysis.

[1] Thomas J. McManamy et al., STS Preliminary Hazard Analysis Report, STS-S01030000-ES0002, R00, April 30, 2019.
[2] DOE-STD-3009-2014, Preparation of Nonreactor Nuclear Facility Documented Safety Analysis, November, 2014.
[3] Thomas J. McManamy and Steven M. Trotter, Second Target Station Bounding Accident Dose Estimates, July, 2019.

On July 22, 2021, this WG was formed[4] to evaluate seismic hazards, and more specifically to evaluate a postulated seismic event which results in structural damage to the STS target building and process equipment, and which is then followed by both an explosion and follow-on fire with subsequent release of hazardous material (PHAR Rev. 1 Event BG7-1). The primary purpose of the WG was to determine if the initial estimate of consequences of the event were sufficiently bounding and also to determine if there are means to further quantify the unmitigated consequences of the event. In carrying out the charge, the memorandum specifically requested that the WG respond to thirteen charge questions related to the initial analysis and estimated consequences. Core WG members and SME support to the WG consisted of STS project ESH&Q, Target Systems, and Cryogenic Moderator System (CMS) staff members and are listed in the subject memorandum.

In addressing the charge questions, the WG determined it would also be beneficial to perform a review of all seismic events in the current PHAR for completeness, accuracy, and consistency. It should be noted that the WG was not charged with evaluating accidents that are initiated by anything other than a seismic event (i.e. evaluating bounding loss of cooling events were not part of the scope of this WG).

The charge questions posed to the WG were primarily based on evaluating various assumptions made during the initial analysis for the bounding seismic event, and also reviewing topics of potential concern identified since the initial analysis. A thorough review of all seismic events and potential responses to the charge questions was conducted from August through December, 2021 through email exchanges, meetings, and a series of workshops.

The remainder of this report provides responses to the specific charge questions and additional context to those responses in the form of findings, comments, and recommendations. The report also provides findings, comments, and recommendations related to the WG general review of all seismic events in the current PHAR[5].

[4] Stephen M. Trotter to James Eckroth, Formation of Working Group to Evaluate Seismic Hazard(s), July 22, 2021, also see Appendix B.
[5] Second Target Station Preliminary Hazard Analysis Report, STS-S01030000-ES0002, R01, July 26, 2021.

2. EVALUATION OF THE ESTIMATED CONSEQUENCES FROM THE BOUNDING SEISMIC EVENT IN THE STS PHAR

2.1 FINDINGS

The initial analysis of the seismic accident bounding consequences estimated the maximally exposed offsite individual (MEOI) dose (also referred to as the public dose) to be 0.62 rem and the on-site 100 meter dose (also referred to as the co-located worker dose or worker group 2 dose) to be 12.63 rem.

DOE-STD-1020-2016 (Table 2-1) assigns various seismic design categories (SDC) based on the unmitigated failure consequences of a seismic event. For a dose of less than 5 rem to a co-located worker an SDC-1 category is assigned and for a dose of 5 to 100 rem to a co-located worker or a dose of 5 to 25 rem to the public an SDC-2 category is assigned. For a dose greater than 100 rem to a co-located worker or a dose greater than 25 rem to the public either an SDC-3, SDC-4, or SDC-5 category is assigned depending on the magnitude of the dose in excess of 25 rem to the public.

As it relates to the airborne release of solids from the shock effects of a detonation event, calculation methods outlined in DOE-HDBK-3010 were used in the initial analysis to provide for a conservative and bounding airborne release fraction and respirable fraction of solid metals. The initial analysis used the TNT equivalent calculation method outlined in DOE-HDBK-3010 with a mass ratio (MR, i.e., mass of inert material / mass of TNT equivalent) equal to one as the basis for the airborne release of solids. The initial analysis identified the mass of TNT equivalent as 0.125 kg and the mass of the target as 700 kg for an actual MR=5600.

For the estimated release of highly volatile elements and noble gases, the initial analysis used release fraction (RF) values in DOE-STD-1027-2018, Hazard Categorization of Nuclear Facilities, as the basis for selecting RF values for these elements (0.50 and 1.0, respectively).

In the initial analysis, the dose estimate assumed 20 years of operation at 5000 hours per year and further assumed two detonations occurred adjacent to the target as part of the event. A ground level release was assumed with the dispersion factors (X/Q) used for the SNS FSAD. The damage ratio (DR) was taken as 1.0 with an airborne release fraction (ARF) of all non-volatile nuclides equal to the fractional release of $1.79x10^{-4}$ which is derived from the TNT equivalent method in DOE-HDBK-3010 for an MR=1. A dose uncertainty factor of 1.58 was used to account for neutronic calculation uncertainties and uncertainties in measurement and control of the proton beam power, as was done for the SNS FSAD evaluations. A complete list of ssumptions in support of the initial analysis of the seismic accident bounding consequences are provided in Appendix A.

Based on the initial analysis and DOE-STD-1020-2016 requirements, the STS Project Director instructed the STS staff to proceed with conceptual design utilizing an SDC-2 category for the facility.

2.2 COMMENTS

The initial analysis of the seismic accident bounding consequences was very detailed with a well-defined and selected set of assumptions that went into the dose estimates.

The co-located worker dose estimate in the initial analysis (12.63 rem) falls within the SDC-2 threshold of 5 to 100 rem per DOE-STD-1020-2016. The dose estimates in the initial analysis are well below the SDC-3 threshold of >100 rem.

The estimated release of highly volatile nuclides (i.e. radioiodines) in the initial analysis used a release fraction (RF) value of 0.50 (a screening value taken from DOE-STD-1027-2018, Hazard Categorization of Nuclear Facilities) that is very conservative. The total dose estimates in the initial analysis are dominated by the radioiodines contributions to the total dose estimates.

A detailed analysis of a hydrogen-air detonation in a prototypic geometry could be performed and could possibly provide a more quantifiable yet bounding estimate of the damage to the target that a detonation could produce. This detailed analysis may also be able to determine the level of protection the shroud provides to the target from a detonation. Furthermore, the refined damage ratio from the detailed analysis could then possibly be used to better quantify a more accurate and yet still bounding RF for the radioiodine releases as well as potentially further reducing the estimated solid releases.

As such, an option exists to further refine the dose estimates and potentially reduce the current dose estimates should the project determine this path to be advantageous and warranted. However, in addition to fragmentation, the rate of radioiodine releases from the target are temperature driven and for this event the target temperature increases over time due to decay heat. Therefore, any future detailed analysis would also need to quantify and defend the radioiodine releases from temperature increases of the target due to decay heat. Also, the current conservative dose estimates support the potential increase in consequences associated with potential target design changes and/or future facility upgrades while not challenging the threshold for maintaining the current SDC-2 design category.

Updated estimates recommended in this report are intended to capture refinements to the initial analysis based on calculations done by the WG. However, these updated estimates do not encompass a detailed analysis as described above and are not expected to impact the current seismic design category determination of SDC-2.

The remainder of this comment section provides the original charge questions, responses to those specific questions, and additional commentary regarding the responses where warranted.

Question 1:

Given that the CMS total stoichiometric air-hydrogen volume is likely to be 190 m^3 (@STP assuming a 5 kg CMS), is the quantity of stoichiometric air-hydrogen involved in the BG7-1 event initial analysis (0.286 m^3) appropriate?

WG Response to Q1:

The quantity of stoichiometric air-hydrogen involved is appropriate for several reasons, including:

a. There is only a nominal amount of free volume in the vicinity of the target.
b. Calculations show that the release of H_2 into the core vessel is rapid—taking place over only a few minutes. The released H_2 will escape from the core vessel because the volume of H_2 initially at 20º K rapidly expands to many times the core vessel free volume, maintaining a hydrogen rich atmosphere without sufficient oxygen for combustion until most of the hydrogen is released and expansion ceases.
c. Using the recommended MR=24 calculation method (see response to Q11), dose estimates from fragmented solids are very insensitive to the size of the detonation.

WG Commentary to Q1:

Calculations performed in support of this answer will be documented in an *Updated Bounding Source Terms and Radiological Consequences* paper separate from this report.

Question 2:

Are the number of hydrogen detonations in the BG7-1 event initial analysis (two) sufficiently bounding?

WG Response to Q2:

The number of detonations (two) is sufficiently bounding for several reasons:

a. The rapidity of the release of H_2 from a damaged CMS—most released within about a minute with additional smaller amounts being released over a longer period estimated to be on the order of 10 minutes—means that there is no opportunity for stoichiometric mixtures to form and then be detonated again and again. Scenarios postulating the slow release of H_2 into the core vessel over a long period of time are not feasible due to the self-venting characteristic of the cryogenic moderator systems. Slight damage that results in leakage of either H_2 or air into the vacuum insulation layer leads to pressure build up with actuation of the hydrogen boundary rupture discs and passive venting of the H_2 outside the core vessel.

b. Using the recommended MR=24 calculation method (see response to Q11), dose estimates from fragmented solids are very insensitive to the number of detonations.

WG Commentary to Q2:

Calculations in support of this answer will be documented in an *Updated Bounding Source Terms and Radiological Consequences* paper separate from this report.

Question 3:

Not taking into consideration the target shroud, is the use of DOE-HDBK-3010 appropriate for the bounding analysis of the BG7-1 event?

WG Response to Q3:

The use of DOE-HDBK-3010 is appropriate because as it relates to the airborne release of solids from the shock effects of a detonation event, calculation methods outlined in DOE-HDBK-3010 and its referenced sources provide for a conservative and bounding airborne release fraction and respirable fraction of solid metals. While the initial analysis used the TNT equivalent calculation method outlined in DOE-HDBK-3010 that is based on an MR=1, data provided in the reference sources of DOE-HDBK-3010 should be used to perform updated dose estimates using the MR=24 calculation method (see response to Q11).

Question 4:

Do larger quantities of hydrogen remote from the target have the potential for creating an event with consequences worse than those in the BG7-1 event (i.e. CMS5-2 event)?

WG Response to Q4:

The original assumption remains valid. Only detonations that can directly impact the target are able to cause significant amounts of target material to become airborne. As it relates to seismic initiated events, there are no larger quantities of hydrogen remote from the target which have the potential for creating an event with consequences worse than those in the BG7-1 event.

WG Commentary to Q4:

During the evaluation, one accident scenario was hypothesized where large quantities of hydrogen remote from the target (in the target drive area) could have consequences requiring credited controls. However, this accident scenario is not initiated by a seismic event and is not expected to occur in conjunction with a seismic event. A previously identified non-seismic related hazard event is being expanded to include this newly identified hazard scenario.

Question 5:

Does the potential design change to a segmented target substantially impact the initial analysis?

WG Response to Q5:

Negative impacts to the initial analysis are not anticipated from a design change to a segmented target. Recommended revised calculations (see response to Q11) should use updated data for the segmented design.

WG Commentary to Q5:

Parameters in the initial analysis related to the target such as the total mass of tungsten, total mass of tantalum cladding, free void space, etc. that have changed with the segmented target design will be documented in an *Updated Bounding Source Terms and Radiological Consequences* paper separate from this report.

Question 6:

Is the assumption that a large facility fire external to the monolith not contributing to the source term a reasonable assumption?

WG Response to Q6:

This is a reasonable assumption and protected by initial conditions and design features (i.e. massive monolith shielding assembly outside the core vessel with positive retention) as identified in the current PHAR event tables for seismic events that include a large facility fire.

Question 7:

Is there a potential for a small localized and prolonged fire near the target assembly (i.e. within the void space where the hydrogen detonation is postulated to occur) contributing to the source term?

WG Response to Q7:

The rate of release of hydrogen very soon drives a hydrogen rich atmosphere that cannot combust and during which time the great bulk of the hydrogen escapes from the core vessel. The amount of hydrogen that could combust close to the target would not cause significant heating or damage to create an airborne source term.

WG Commentary to Q7:

The respective calculations in support of this response will be documented in an *Updated Bounding Source Terms and Radiological Consequences* paper separate from this report.

Question 8:

Given that the decay heat temperatures are above 300º C, in there a potential for a tantalum cladding source term that has not been included in the initial analysis?

WG Response to Q8:

As a level of conservatism, the potential release of tantalum oxides (resulting from operations and from this accident timeline) should be added to the dose estimates in the recommended MR=24 calculations. These oxides may have a higher airborne release fraction and higher respirable fraction. However, given the limited oxide layer determined to exist before and during the accident, this preferential release has a very nominal effect on the overall dose estimates.

Also, as it relates to the preferential release of the tantalum metal (not the oxides) versus the tungsten metal, calculations show that this preferential release has a very nominal effect on the overall dose estimates when using the MR=24 calculation method (see response to Q11).

WG Commentary to Q8:

In the initial analysis, the only areas of non-conservatism identified were the following:

- the preferential release of the tantalum metal surface layer of the target rather than the inner tungsten metal during a detonation, and

- the potential for the development of tantalum oxides on the target surface due to decay heat that could be released by a second detonation, and
- the potential for the release of tantalum oxides that may exist on the target over time due to operations that could be released by the first detonation.

These phenomena have the potential to nominally increase the overall dose estimates to the co-located worker by 1.8 rem, 0.5 rem, and 0.07 respectively. The calculations performed in support of this comment will be finalized and documented in an *Updated Bounding Source Terms and Radiological Consequences* paper separate from this report.

Question 9:

Can the quantity of hydrogen involved in the BG7-1 event initial analysis be further refined and still be bounding (i.e. hydrogen quantities in the neutron beam lines within 1 m radius are included in the detonation volume, but a detonation shock wave inside the neutron beam path would directly impact a moderator vessel but not the target, so can these volumes be excluded from the BG7-1 event analysis)?

WG Response to Q9:

Using the recommended MR=24 calculation method (see response to Q11), dose estimates are very insensitive to the size of the detonation as it relates to the solids that are made airborne and respirable. Even when a significantly smaller detonation is assumed, using the TNT equivalent calculation method from the initial analysis (MR=1) results in overly conservative dose estimates compared to those obtained using the MR=24 calculation method. As such, initial calculations should be revised using the MR=24 calculation method to provide further clarity on this parameter rather than focusing on refinement of the size of the detonation and staying with the initial TNT equivalent calculation method that used an MR=1.

WG Commentary to Q9:

A significant amount of time was spent debating the amount of H_2 that could actually be involved in a detonation adjacent to the target (more or less than the initial estimates of 0.2 m^3). However, it was eventually realized that this factor becomes much less important when a less conservative but still very bounding MR value is used in estimating the ARF and RF values associated with an assumed detonation. When using the MR=24 calculation method (see response to Q11), it was estimated that the free volume could be as large as 49.9 m^3 with no material increase in dose contributions from solids that are made airborne and respirable from the detonation of this larger volume.

Question 10:

Given that the physical arrangement of the target includes a stainless steel shroud that is not accounted for in the initial analysis, is there a means to include the shroud in a more detailed analysis such that the consequences could be mitigated by the presence of the shroud.

WG Response to Q10:

While detailed analysis could likely show that the shroud protects the target from an adjacent detonation, when using the MR=24 calculation method the contribution of the solids release from this event is nominal and dominated more by the estimated 50% radioiodine releases. Any future detailed analysis would need to address the topic of radioiodine releases more so than the release of solids. As noted previously, use of the MR=24 calculation method (see response to Q11) results in significantly less releases from solids from the initial TNT equivalent method that used an MR=1 calculation method.

WG Commentary to Q10:

Based on preliminary calculations, a detailed analysis may show that the shroud protects the target from an adjacent detonation. However, it was also noted that there is the possibility of the seismic event damaging the shroud prior to the detonation. The potential for the shroud to be damaged prior to the detonation would add complexity and uncertainty to a more detailed analysis.

Question 11:

From DOE-HDBK-3010, at low mass ratios (mass of inert material/mass of TNT equivalent) the respirable release is comparable to the total material release. As mass ratios increase, the loss ratio becomes significantly less than the total amount of material released, which decreases with increasing mass ratios as well. In the initial analysis of the hydrogen detonation adjacent to the target, the mass ratio is 5600, yet a very conservative release fraction (loss ratio) of 1 has been assumed. Is there a means to quantify and credit the very high mass ratio effect on the release fraction (loss ratio)?

WG Response to Q11:

A revision should be completed to the initial TNT equivalent calculations that used an MR=1 with an updated set of dose estimates using the MR=24 calculation method to provide better clarity to the impacts of this event. While still very conservative, using an MR=24 rather than MR=1 that was used in the initial analysis better quantifies and credits the high mass ratio of the target material to the TNT equivalent mass.

WG Commentary to Q11:

The bases for using an MR=24 and updated source term calculations using an MR=24 will be documented in an *Updated Bounding Source Terms and Radiological Consequences* paper separate from this report.

Question 12:

Given the physical configuration of the void spaces around the target, is a detonation (rather than just a deflagration that does not result in a release) actually achievable?

a. If a detonation is achievable, are the shock effects as calculated using DOE-HDBK-3010 appropriate or can a more quantifiable shock effect be modeled or calculated?
b. Should an external hydrogen explosion and consequences SME be engaged to model the hydrogen release and subsequent deflagration/detonation of hydrogen within the target core vessel?

WG Response to Q12:

As a conservative bounding analysis, while the entire geometry of the free void space may not support a detonation, there are partial geometries that could possibly support a detonation or a deflagration to a detonation transition and, as such, a detonation should be assumed to occur for this bounding event.

Shock effects as calculated using DOE-HDBK-3010, as well as using the MR=24 calculation method described in the response to Q11, are both very conservative because the energy deposition of a TNT detonation would occur over a faster time scale and more localized space than would be possible with detonation of a compressible gas mixture. A detailed analysis of a hydrogen-air detonation in prototypic geometry could likely provide a more quantifiable yet bounding estimate of the damage to the target that a detonation could produce. A detailed analysis with a determination of the bounding damage could possibly help to better estimate the rate of radioiodine releases from the target (see response to Q13) as those releases are related to the amount of fragmentation created by the detonations. However, in addition to fragmentation the rate of radioiodine releases from the target are temperature driven and for this event the target temperature increases over time due to decay heat (see response to Q13).

While options exist for a more detailed analysis to better define the consequences of this event, the WG does not recommend pursuing an external hydrogen explosion and consequences SME to model the hydrogen release and subsequent deflagration/detonation of hydrogen within the target core vessel at this time.

WG Commentary to Q12:

A considerable amount of time was spent deliberating whether a detonation (rather than just a deflagration that does not result in a release) was actually achievable as assumed in the initial analysis. In the end, it was qualitatively determined that as a conservative bounding analysis, while the entire geometry of the free void space may not support a detonation, there are partial geometries that could possibly support a detonation or a deflagration to a detonation transition and, as such, a detonation should be assumed to occur for this bounding event.

An external hydrogen explosion and consequences SME could likely model the hydrogen release and subsequent deflagration/detonation of hydrogen within the target core vessel and further refine the consequences. That said, the detailed analysis would need to support the reduction of the current dose estimates by approximately 60% in order to change the current seismic design category of the STS from SDC-2 to SDC-1 while still being conservative, bounding, and defensible. As such, it is not a recommendation of this evaluation that the project pursue further refinement of the estimated consequences of this event at this time.

Question 13:

A conservative assumption in the initial analysis was that each H_2 detonation would cause airborne release of 50% of the target's accumulated radioiodines. This is a conservative assumption because the thermal energy of the detonations is not sufficient to drive release of some of the available radionuclides. For example, due to a significant increase the temperature of the rotor driving a release, a single radionuclide (^{125}I) accounts for more than half of the computed radiation dose.

a. Is there a more quantifiable means to determine the airborne release of the target's accumulated radioiodines?

b. Should a time phased source term be developed to account for target heat up due to decay heat and the initial hydrogen detonations?

WG Response to Q13:

Although the 50% release of the radioiodines in the initial analysis would appear to be very conservative, a defensible means to better quantify the release of the radioiodines and still be bounding has not been determined. Even with the recommended revised calculation method using an MR=24 (see response to Q11), the assumed airborne release fraction is 37%, and this large airborne release fraction is assumed to readily release the associated radioiodines in these small airborne particles. As indicated in the responses to Q10 and Q12, a detailed analysis with a determination of the damage ratio could potentially be beneficial especially as it relates to estimating the rate of radioiodine releases from the target as those releases are related to the amount of fragmentation created by the detonation(s). However, in addition to fragmentation the rate of radioiodine releases from the target are temperature driven and for this event the target temperature increases over time due to decay heat.

If the more mechanistic calculations showed that substantially less than 37% fragmentation of the target would be caused by a detonation, then there may be some prospect for showing that lower and/or slower iodine releases are credible. A multi-hour diffusion of the radioiodines out of a target with only nominal damage, while still accounting for the decay heat up of the target and the associated radioiodines, could potentially be analyzed. If, for example, it could be shown that the highly volatile radioiodines take 8 hours to diffuse out and be released to the environment, the Chi/Q value for atmospheric dispersion would be a factor of ~3 lower and this would reduce the inhalation doses by the same factor[6]. If the project decides to commission a more mechanistic analysis of potential detonation of hydrogen in the core vessel and this analysis shows that the target is not fragmented the question of amount and timing of potential radioiodine releases (i.e. a time phased source term that still accounts for releases associated with target decay heat) could then be revisited at that time.

[6] Andrea Sjoreen and Robert Miller, Atmospheric Dispersion of Mercury Release from Postulated Fire Accidents at the SNS Facility, SNS Document No. 102030102-CA0003-R02, August 2005.

2.3 RECOMMENDATIONS

1. The project should proceed with preliminary design based on a Seismic Design Category 2 (SDC-2) determination for structures, systems, and components (SSCs) required to perform their safety function in a design basis natural phenomena hazard (NPH) seismic event.

2. The initial estimates of seismic accident bounding consequences should be updated and documented for the STS. The update should incorporate the calculations performed by the WG in support of responses to several of the charge questions (see responses to Q1, Q2, Q7, Q8, and Q9). In addition, several key parameters related to the proposed segmented target should be updated when performing the revisions to the source terms and radiological consequences for the STS (see response to Q5). Furthermore, the updated calculations should utilize an MR equal to 24 rather than an MR equal to one that was used in the initial estimates of the source terms. While still very conservative, the recommended MR=24 calculation method better quantifies and credits the high mass ratio of the target material to the TNT equivalent mass (see response to Q11).

3. GENERAL REVIEW OF ALL SEISMIC EVENTS IN THE STS PHAR

3.1 FINDINGS

PHAR Rev. 0 included ten seismic events as the cause of the event, primarily related to the cryogenic moderator system (CMS) and the building general (BG).

In addition to the initial ten seismic events in the PHAR Rev. 0, the PHAR Rev. 1 added one seismic event for an accelerator interface component (AIC) and deleted one redundant seismic event for the building general.

3.2 COMMENTS

PHAR Rev. 1 has a diverse and well-rounded set of seismic related events impacting various important SSCs in the target building. Assumptions and initial conditions for these seismic events as well as the mitigating features and attributes for these events were much further defined and refined in the latest PHAR versus the earlier version. One incorrect reference to SDC-3 was found in event CMS7-3 (see Recommendation No. 1) and a few inconsistencies in identified initial conditions and mitigating features and attributes were identified in several of the seismic events (see Recommendation No. 2).

It should be noted that continuing evolution of the PHAR from Rev. 1 resulted in a re-designation of some hazard events. One notable and significant outcome of this evolution was that the BG7-1 bounding seismic event (the origins of the name of this WG) that results in structural damage to target building and subsequent release of hazardous material followed by an explosion and follow-on fire was moved to CMS7-3 so that similar events were within the same appendix of the PHAR. Therefore, forthcoming revisions to the PHAR will note that the BG7-1 event should be deleted and now captured in event CMS7-3.

3.3 RECOMMENDATIONS

1. In the planned PHAR Rev. 2, remove the reference to an SDC-3 design for monolith retention found in hazard event CMS7-3 in the PHAR Rev. 1.

2. Review all seismic events in the PHAR Rev. 1 to ensure there is harmony and symmetry to the initial conditions and mitigating features and attributes identified, especially as it relates to identifying the best fit set of credited controls.

APPENDIX A

LIST OF ASSUMPTIONS IN THE STS BOUNDING ACCIDENT DOSE ESTIMATES (JULY 2019) (INITIAL ANALYSIS)

The following set of assumptions were used for the evaluation:

1. Proton beam trips off due to seismically induced motion of LINAC components
2. Moderator boundary and core vessel boundary failure with hydrogen and air release into core vessel
3. Hydrogen released into vessel warms on contact with 50^{o} C shielding to STP conditions (20^{o} C)
4. Hydrogen/air mixture at 1 bar in a volume of 0.2 m^3 near the target exists
5. Void volumetric shape does not prevent hydrogen detonation
6. Hydrogen Detonation occurs next to solid target
7. Target mass release estimate does not consider protection by stainless steel target shroud
8. Target mass release is equal to TNT mass equivalent of hydrogen (per DOE-HDBK-3010-94 for detonation next to solid materials) with an RF=1
9. Monolith shielding does not reduce release fraction (no material deposits inside core vessel)
10. Detonation in larger free volume (2.5 m3) does not release target material or significantly reconfigure shielding
11. Detonation opens moderators and releases remaining trapped hydrogen from the system into vessel
12. Second stoichiometric detonation occurs after most hydrogen vents through core vessel boundary failures
13. Some monolith shielding motion possible from seismic event but is retained by concrete outer wall
14. Ground level release is assumed because of loss of core vessel boundary integrity
15. Target is unlikely to be exposed or heated by an external fire
16. Decay heat would still be removed by conduction and thermal radiation to adjacent shielding, even if some collapse occurs

APPENDIX B

CHARGE MEMO

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Date: July 22, 2021

To: James Eckroth

c: Peter Rosenblad

From: Steven M. Trotter

Subject: **Formation of Working Group to Evaluate Seismic Hazard(s)**

I request that you organize and lead a Working Group (WG) charged to evaluate a postulated seismic event which results in structural damage to the STS target building and process equipment, and which is then followed by both an explosion and follow-on fire with subsequent release of hazardous material (Event BG7-1). The purpose of the working group is to determine if the initial analysis of the event is sufficiently bounding and if there are means to further quantify the unmitigated consequences of the event.

The WG Core Members are the following personnel:

Jim Eckroth – Lead WG Member
Aaron Jacques – Target Systems SME Support to WG
Jim Janney – Cryogenic Moderator System SME Support to WG
Mike Harrington- Core WG Member
Robert Lowrie – Core WG Member
Tom McManamy – Core WG Member
TBD - External Hydrogen Explosion and Consequences SME Support to WG

PHAR EVENT BG7-1 WORKING GROUP CHARGE

Event BG7-1 Description

A seismic event results in structural damage to target building and STS process equipment followed by both an explosion and follow-on fire with subsequent release of hazardous material.

Purpose of Working Group

Event BG7-1 is one of two events (the other is loss of cooling) for the STS that has been qualitatively and conservatively analyzed to potentially result in a public radiological exposure consequence. The purpose of this working group is to determine if the initial analysis is sufficiently bounding and also determine if there are means to further quantify the unmitigated consequences of this event.

In carrying out this charge, the WG should respond to the following charge questions:

Charge Questions Related to Initial Analysis Being Sufficiently Bounding

1. Given that the CMS total stoichiometric air-hydrogen volume is likely to be 190 m^3 (@STP assuming a 5 kg CMS), is the quantity of stoichiometric air-hydrogen involved in the BG7-1 event initial analysis (0.286 m^3) appropriate?

2. Are the number of hydrogen detonations in the BG7-1 event initial analysis (two) sufficiently bounding?

3. Not taking into consideration the target shroud, is the use of DOE-HDBK-3010 appropriate for the bounding analysis of the BG7-1 event?

4. Do larger quantities of hydrogen remote from the target have the potential for creating an event with consequences worse than those in the BG7-1 event (i.e. CMS5-2 event)?

5. Does the potential design change to a segmented target substantially impact the initial analysis?

6. Is the assumption that a large facility fire external to the monolith not contributing to the source term a reasonable assumption?

7. Is there a potential for a small localized and prolonged fire near the target assembly (i.e., within the void space where the hydrogen detonation is postulated to occur) contributing to the source term?

8. Given that the decay heat temperatures are above 300 degrees C, in there a potential for a tantalum cladding source term that has not been included in the initial analysis?

Charge Questions Related to Potential Means to Further Quantify the Consequences of this Event

9. Can the quantity of hydrogen involved in the BG7-1 event initial analysis be further refined and still be bounding (i.e., hydrogen quantities in the neutron beam lines within 1 m radius are included in the detonation volume, but a detonation shock wave inside the neutron beam path would directly impact a moderator vessel but not the target, so can these volumes be excluded from the BG7-1 event analysis)?

10. Given that the physical arrangement of the target includes a stainless steel shroud that is not accounted for in the initial analysis, is there a means to include the shroud in a more detailed analysis such that the consequences could be mitigated by the presence of the shroud?

Note: Any detailed analysis of the shroud impacting the consequences of this event needs to consider that the shroud is initially ductile but that radiation damage may also have embrittled the shroud.

11. From DOE-HDBK-3010, at low mass ratios (mass of inert material/mass of TNT equivalent) the respirable release is comparable to the total material release. As mass ratios increases, the loss ratio becomes significantly less than the total amount of material released, which decreases with increasing mass ration as well. In the initial analysis of the hydrogen detonation adjacent to the target, the mass ratio is 5600, yet a very conservative release fraction (loss ratio) of 1 has been assumed. Is there a means to quantify and credit the very high mass ratio effect on the release fraction (loss ratio)?

12. Given the physical configuration of the void spaces around the target, is a detonation (rather than just a deflagration that does not result in a release) actually achievable?

> a. If a detonation is achievable, are the shock effects as calculated using DOE-HDBK-3010 appropriate or can a more quantifiable shock effect be modeled or calculated?
>
> b. Should an external hydrogen explosion and consequences SME be engaged to model the hydrogen release and subsequent deflagration/detonation of hydrogen within the target core vessel?
>
> Note: If engaging a hydrogen SME is considered a prudent approach, the core team WG members should research hydrogen SME options and provide STS management with the name(s) of recommended SME and a draft Statement of Work (SOW) of the proposed analysis?

13. A conservative assumption in the initial analysis was that each H2 detonation would cause airborne release of 50% of the target's accumulated radioiodines. This is a conservative assumption because the thermal energy of the detonations is not sufficient drive release of some of the available radionuclides. For example, due to a significant increase the temperature of the rotor driving a release, I-125 accounts for more than half of the computed radiation dose.

> a. Is there a more quantifiable means to determine the airborne release of the target's accumulated radioiodines?
>
> b. Should a time phased source term be developed to account for target heat up due to decay heat and the initial hydrogen detonations?

In closing, should you require additional information or support at any time, please contact me at 865-241-9420 or trottersm@ornl.gov at your earliest convenience.