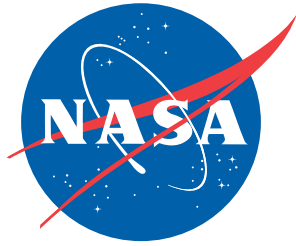


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NESC-RP-06-061



Recommendations for Safe Separation Distances from the Kennedy Space Center (KSC) Vehicle Assembly Building (VAB) Using a Heat-Flux-Based Analytical Approach

Abridged

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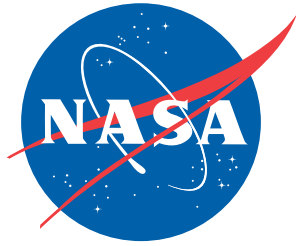
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National Aeronautics and
Space Administration


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March 4, 2011

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1.0	NESC Director	Date
Approved:	<i>Original Signature on File</i>	3/10/11
2.0	NESC Director	Date

Revision	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Mr. Clinton H. Cragg, NESC Principal Engineers Office	07/30/09
2.0	Per 2 nd LaRC Export Control Review: Removed Section 7.2.1, <i>Approach Used for Scoping Calculations</i> , to remove Ares Rocket data information.	Mr. Clinton H. Cragg, NESC Principal Engineers Office	03/04/11



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Technical Assessment Report


1.0 Notification and Authorization

The request for the NASA Engineering and Safety Center (NESC) to provide computational modeling to support the establishment of a safe separation distance surrounding the Kennedy Space Center (KSC) Vehicle Assembly Building (VAB) in support of the Exploration Program was submitted by KSC Safety & Mission Assurance (S&MA) to the NESC Systems Engineering Office (SEO) on October 19, 2006.

NESC Chief Engineer at KSC, Mr. Steve Minute, performed the Initial Evaluation and conveyed the results to the NESC Review Board (NRB) on November 9, 2006.

The authorization to establish an NESC Modeling Team was granted by the NRB on November 9, 2006. NESC Principal Engineer, Mr. Clint Cragg was selected to lead the NESC Modeling Team effort. Mr. Howard “Les” Bowman and later, Mr. John “Eric” Wilson, both of the Naval Air Warfare Center Weapons Division (NAWCWD) were assigned as the co-leads for this effort. The Assessment Plan was presented and approved by the NRB on April 12, 2007. The Final Report was presented and approved by the NRB on July 30, 2009.

The key stakeholder for this study is the KSC Constellation Program (CxP) Office. Other stakeholders include the KSC Launch Vehicle Processing Office and the NASA Headquarters Office of S&MA (OSMA).

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2.0 Signature Page

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Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

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3.0 Team List

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3.1 Acknowledgements

This effort to recommend safe separation distances from the KSC VAB based on analytical modeling of heat flux was part of a larger effort that included testing as one of its factors. The overall effort was led by Eric Smith (KSC). The testing effort was led by Steven Stover (KSC) and supported by Greg McVay and Lester Langford (Stennis Space Center (SSC)). The modeling effort was lead by Clinton Cragg (NESC) and Howard “Les” Bowman (Naval Air Warfare Center Weapons Division (NAWCWD)). John “Eric” Wilson (NAWCWD) took over for Mr. Bowman when Mr. Bowman moved to another position. This report reflects the efforts of the Modeling Team, supplemented with data from the Test Team.

The Modeling Team would like to acknowledge and thank the following people, whose contributions are greatly appreciated:

The support team from ATK at Langley Research Center (LaRC) provided excellent support. The Modeling Team is truly indebted to and appreciative of their excellent care and support:


- Financial/Contracting: Pam Throckmorton and Cody Flowers who worked with Robert Rice (LaRC).
- Project Coordinators: Melinda Meredith, Angela Hinton, Amanda Levy, Debora Briggs, Christina Cooper, and Angela Umfleet. They hosted WebEx, took minutes, kept action logs, and took care of the many administrative details needed to keep the team on track and focused on the tasks at hand.
- Project schedules: Linda Burgess.
- Technical reports: Carolyn Snare and Eric Pope.
- ATK team coordination: Erin Moran and Lisa Behun.

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We also thank the following people from NAWCWD, China Lake:


- Alice Atwood and Kevin Ford for providing ignition data. Ms. Atwood also reviewed many documents on ignition.
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We thank Jennifer Spinti and Phil Smith (University of Utah) for their help and insight and their sharing of data and analyses.

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We also thank the NESC peer reviewers: Dean Kontinos (Ames Research Center (ARC)), and Mark D'Agostino and Chris Morris (Marshall Space Flight Center (MSFC)). Their comments and suggested changes greatly improved the technical aspects of this report.

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4.0 Executive Summary

4.1 Synopsis

The study described in this report had two major objectives:

- Establish a methodology based on thermal flux to determine safe separation distances from the Kennedy Space Center's (KSC's) Vehicle Assembly Building (VAB) with large numbers of solid propellant boosters containing hazard division 1.3 classification propellants, in case of inadvertent ignition.
- Apply this methodology to the consideration of housing eight 5-segment solid propellant boosters in the VAB.


This heat-flux-based approach was used instead of the conventional Department of Defense (DoD) approach. The DoD approach is based on the total weight of propellant in the building and does not consider how many boosters are burning and the associated energy released as a function of time. The criterion used to determine safe separation distance using the heat-flux-based approach is the prevention of 2nd degree burns and associated human fatalities.

Several non-propulsive scenarios were considered; however, only the scenario with eight completely assembled, 5-segment boosters was fully analyzed. The results for the most likely hazard scenario showed that only two boosters inadvertently ignited and burned. The boosters in the adjacent High Bays did not ignite because the failure of the exterior VAB walls allowed exhaust plumes to expand outside the VAB. However, the exhaust plumes expanded so rapidly in this scenario that any personnel within approximately 200 m (656 ft) of the VAB center would perish.

The results of the analyses led to the conclusion that the safe separation distance, determined using the heat-flux-based approach for eight 5-segment boosters in the VAB, is 400 m (1,312 ft) from the VAB High Bay center. This safe separation distance is within the existing VAB hazard arc. However, the western portion of the arc is outside the existing hazard arc. The existing hazard arcs had been determined using the DoD weight-based approach for the Space Shuttle Program (SSP) with four 4-segment boosters in the VAB.

4.2 Background

The VAB was built to process the Saturn Program launch vehicles in the 1960s and later adapted to process SSP launch vehicles. For the past three decades, the VAB has served effectively as the site where SSP Solid Rocket Motors (SRMs) are assembled by stacking and joining the motor segments at their field joints. Once assembled, these SRMs are mated to the External Tank and Orbiter, and then transported to the launch pad as the fully configured Space Shuttle. As the SSP is phased out and new launch vehicles are developed for NASA, the VAB


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will again be adapted to process these new vehicles. The VAB and its immediate environment are depicted in Figure 4.2-1.



Figure 4.2-1. The VAB and its Immediate Environment

The VAB has four High Bays as depicted in Figure 4.2-2.

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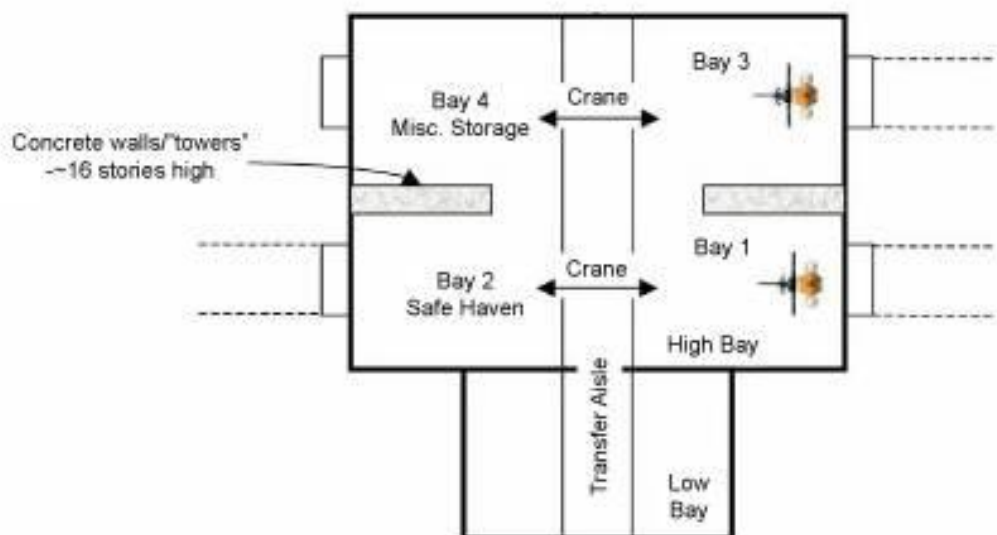



Figure 4.2-2. VAB High Bay and Transfer Aisle Locations. SSP Uses Bays 1 and 3.

Currently, VAB High Bays 3 and 1 are used for assembling the Space Shuttle. In the future, the Constellation Program (CxP) plans to use all four High Bays for assembly and short-term storage of the Orion spacecraft and heavy-lift cargo launch vehicles using the Ares I and Ares V boosters.

The KSC Safety Office determined for the SSP that the Quantity-Distance (QD) arcs for the inhabited building distance (IBD) were formed by circles 400 m (1,312 ft) in radius centered in High Bays 3 and 1 with tangents connecting the two circles. The current VAB safe separation distance, derived using the DoD weight-based approach, allows for processing of four fully assembled, 4-segment SSP SRMs containing approximately 2 million kg (4.44 million lbs) of solid propellant.

The proposed CxP launch schedule could require assembly and storage of as much as 5.3 million kg (11.6 million lbs) of hazard division 1.3 classification propellant within the VAB (up to eight 5-segment Ares V boosters). Application of the DoD weight-based approach for eight Ares V boosters would result in a safe separation distance of 558 m (1,831 ft). This distance extends beyond a number of high-occupancy office buildings in the area surrounding the VAB. The NASA Engineering and Safety Center (NESC) Report, *Review of the Test Plan to Update KSC VAB Propellant Safety Siting Methodology for the Exploration Program* concluded that the DoD weight-based approach may be inappropriate for SRMs with a

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1.3 hazard division classification and recommended that an alternative approach based on calculating the actual threat due to radiative heat flux be evaluated.

The KSC CxP Office is the primary customer, key stakeholder, and co-sponsor for this study. The CxP requirements are driving the number of SRM segments in process at one time, with the results of this study providing valuable information for future facility/process planning. Other stakeholders for this study include the KSC Launch Vehicle Processing Office and the NASA Headquarters Office of Safety and Mission Assurance (OSMA). The KSC Launch Vehicle Processing Office is the primary VAB user and other vehicle processing facilities will be affected by a change in the current QD siting method. Safety and Mission Assurance (S&MA) is responsible for ensuring KSC meets the current QD siting requirements and as such will be asked to approve any proposed changes. Additionally, OSMA is responsible for performing any hazard analyses required to approve the final QD siting. All three of these organizations were included as critical elements of the study team.

The NESC assembled a team of experts to develop an alternative heat-flux-based methodology to determine safe separation distances for the VAB containing eight 5-segment SRM boosters. The NESC team focused on quantifying the thermal threat from burning 5-segment boosters to individuals in near proximity to the VAB and establishing the appropriate safe separation distance.

At the initial Technical Interchange Meeting (TIM) held at KSC on February 27, 2007, several important aspects of a comprehensive VAB hazard study were deemed to be out of scope for this modeling effort. These included:

- Analysis of boosters going propulsive within the VAB or toppled from their original location.
- Structural response of the VAB and ramifications (e.g., building collapse, fragment throw) other than:
 - Destruction of interior cinder block walls (e.g., flow considerations).
 - Failure of exterior VAB wall panels (e.g., venting and increased radiation view factors).
- Hazards from toxic species in the booster exhaust plume.
- Hazards associated with related hardware or facility hypergolic liquid fuels (e.g., explosion and toxic plume).
- Interactions between a hypergolic fire and one or more boosters.
- Increased burn area due to damage of propellant and associated increase in energy release rate.
- Egress of personnel from the VAB or the surrounding area.
- Mitigation studies (e.g., improved nozzle plug, strengthened internal walls between adjacent High Bays, installation of larger sprinkler systems, or changes in VAB venting strategy).

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- Acoustic hazards associated with boosters burning in the VAB.

4.3 Approach

The Modeling Team applied a “pyramid” approach during the analyses. The pyramid approach undertook analyses of increasing complexity, starting with scoping calculations.

The scoping calculations utilizing spreadsheet techniques and a number of conservative, worst-case assumptions were used to bound the problem and establish the direction for more detailed analyses and data collection. The scoping calculations showed:


- In order to determine the energy release rate, the configuration of energetic materials, not just the weight of energetic materials, must be considered.
- The heat-flux-based approach is a viable alternative to the weight-based approach.

The conservative assumptions and parametric variations of some of the input parameters used in these scoping calculations could not justify safe storage of eight fully assembled 5-segment boosters in the VAB and still maintain the existing safe separation distance (400 m (1,312 ft)). A description of the scoping calculations is provided in Sections 7.2.1 and 7.2.2.

To move from preliminary scoping calculations to more detailed analyses, the assembly operations within the VAB were studied and several scenarios were proposed to represent the vehicle configurations that may exist within the VAB. These scenarios were defined as follows:

- Scenario 1. Each of the four VAB High Bays contains two fully assembled 5-segment boosters. Inadvertent ignition of one booster in one High Bay with almost simultaneous ignition of the adjacent booster in the same bay was assumed.
- Scenario 2. Three of the four VAB High Bays contain two fully assembled boosters and the other bay contains one fully assembled booster and one partially assembled booster (a 4-segment stack without the cap segment). Since ignition is more probable for an uncapped stack, it was assumed that ignition would occur in the 4-segment stack and spread to the adjacent booster within the same High Bay.
- Scenario 3. Similar to Scenario 2, but with two 4-segment stacks in one VAB High Bay. Inadvertent ignition of one of the uncapped 4-segment stacks is assumed to occur and spread to the other uncapped stack.

The calculations started with the inadvertent ignition within one High Bay, determined the heat and mass flow from the burning boosters in that one bay to adjacent bays, and predicted time to ignition of the boosters in the other bays. Scenario 1 was initially assumed to be the worst case in determining safe separation distance. Later in the study, Scenarios 1 and 3 were compared with the results described in Section 7.7.


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In performing the analyses of these scenarios, several NESC teams were involved and different analytical codes were used. Section 6.3 describes the methodology that was established, the codes used, the sequence of considerations, and the hand-offs from one NESC team to another. These analyses required the NESC team to consider failure of the booster nozzle plugs, ignition criteria for exposed propellant in the bore, ignition criteria for through-the-case ignition of propellant, failure of internal cinder block walls in the VAB, and failure of VAB exterior wall panels. Results from these detailed calculations are discussed in Sections 7.3–5. Scenario 1 was studied in detail with analysis of four sub-scenarios.

- Scenario 1a—The cinder block walls between High Bays 1 and 3 and between Bays 2 and 4, and the VAB external walls are assumed to remain intact. This is the scenario that was addressed in previous studies of inadvertent ignition of motors within the VAB. Sub-scale testing of model motors burning in a scaled VAB with interior and exterior walls that do not fail was proposed for consideration.
- Scenario 1b—Same as Scenario 1a, but accounting for failure of the lower halves of internal cinder block walls between High Bays 1 and 3 and between Bays 2 and 4, and the VAB external walls remaining intact.
- Scenario 1c—Same as Scenario 1b, but analyzing for subsequent failure of VAB external wall panels to allow venting of booster plume exhaust. The failure of the external walls occurred within seconds after the ignition of the first boosters and so this scenario was terminated and Scenario 1d was initiated.
- Scenario 1d—This scenario started with the lower half of the interior cinder block and the full external walls of the VAB removed before inadvertent ignition of the first boosters.

The determination of the timing and sequence of booster ignition and combustion within the VAB was a major focus of the NESC Modeling Team, since it is the first step in correctly predicting heat flux to areas surrounding the VAB. The Modeling Team reviewed available historical propellant ignitability data. This review revealed the need to perform experiments to generate data on the ignitability of TP-H1148 propellant at the low heat flux and long exposure times characteristic of accident scenarios. The Modeling Team chose this propellant for study because it is used in the SSP SRMs, and because it or a similar formulation will probably be used in the Ares I and Ares V boosters. Experimental data on TP-H1148 ignitability over much of the heat-flux range of interest to this study was generated by ATK Space Systems in a separately funded effort and by Naval Air Warfare Center Weapons Division (NAWCWD), China Lake.

While the calculations for Scenario 1d were in progress, calculations were also made for Scenario 3d. The results from both scenarios indicated that Scenario 1d was worse than

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Scenario 3d in terms of ignition in the bore of adjacent boosters; there would be more exhaust flow at ground level and therefore a higher probability of ignition of other boosters. Analysis of the potential for ignition through the booster casing in Scenario 3 was not performed. Preliminary analyses for through-the-case ignition was completed for Scenario 1d (see Section 7.5).

An NESC Human Exposure Sub-team was convened and managed by the OSMA. The Human Exposure Sub-team was tasked to determine the acceptable levels of human exposure to radiative heat flux [ref.10]. The Human Exposure Sub-team concluded that prevention of 2nd degree burns (and the potential for fatalities associated with such burns) should be the criterion used for determining safe separation distances between the VAB and inhabited buildings and personnel in the open.

4.4 Results

The results for the various sub-scenarios are summarized below. More detailed discussions are available in subsequent sections.

The pressures calculated from Scenario 1a indicate that the interior walls separating the High Bays would not survive a booster burning for more than a few seconds. From these results, the NESC Modeling Team determined that calculations of Scenario 1b should be initiated. At the request of KSC, the calculations for Scenario 1a (interior walls remaining intact) were run until the ignition of the boosters across the transfer aisle occurred (at 52.5 seconds).

Scenario 1b calculations show that removal of these internal walls significantly changes the exhaust plume flow dynamics and ignition timeline of boosters in the VAB. Once ignited, each booster burns for approximately 2 minutes. By 112 seconds, all eight boosters are burning. In addition, the Scenario 1b calculations showed that a significant number of the VAB external wall panels are also likely to fail. Given these results, the Modeling Team decided to start calculations of Scenario 1c.

Scenario 1c calculations account for external wall panel failure. These calculations show that the exterior wall panels fail within a few seconds after the first two boosters ignite. Because the failure occurred so quickly, this calculation was stopped and the calculations of Scenario 1d were started.

The calculations of Scenario 1d, the most likely portrayal of Scenario 1, show a different situation than the ones addressed in previous analyses performed by other investigators. Because the exhaust plumes of the first two boosters are not confined to within the VAB, the exhaust plume spreads outside the original VAB boundaries. As a result, the boosters in the other High Bays are not predicted to ignite while the originally ignited boosters are burning (130 seconds). The rapid flow of the exhaust plumes produces temperatures higher than 1,000 K (1,340°F) at distances greater than 200 m (656 ft) from the VAB center (as shown in


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Figure 4.4-1). Exposure of humans to these temperatures would cause fatalities. Figure 4.4-1 shows the result of inadvertent booster ignition in High Bay 3. The chances of an inadvertent ignition are equal for each High Bay, so that the results of Figure 4.4-1 would have to be reflected across the symmetry axes to the other three quadrants.

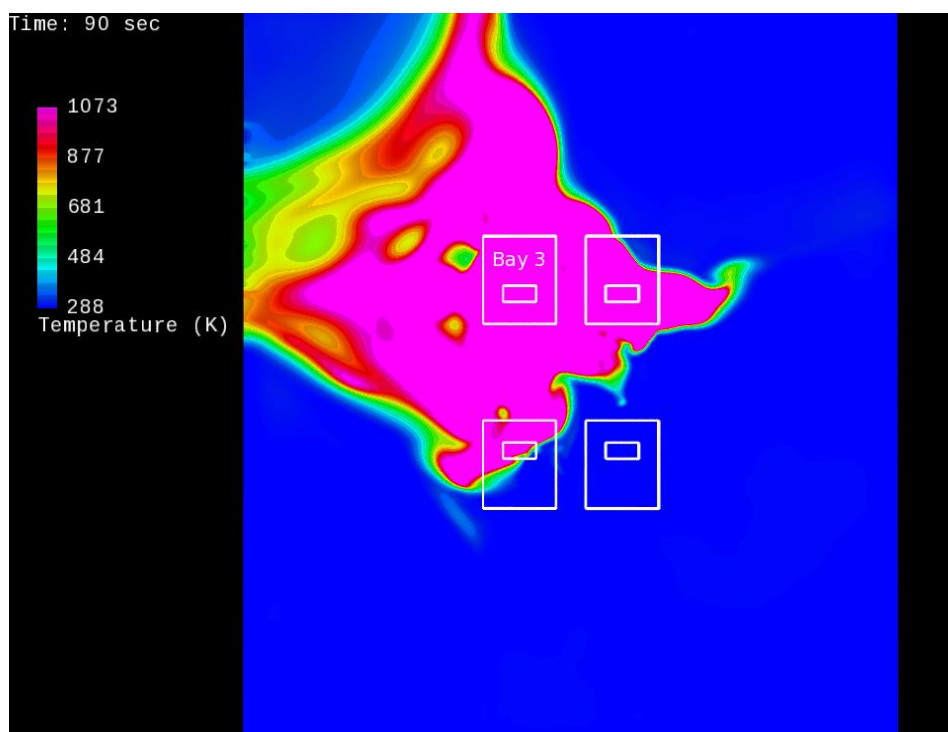



Figure 4.4-1. Temperatures of Exhaust Plumes at 1.68 m (66 in.) Above the VAB Floor 90 seconds After Ignition of Boosters in High Bay 3 for Scenario 1d

Note: The calculation domain (the blue area) was approximately 400 x 400 m (1,312 x 1,312 ft).

The radiation-to-distance from these exhaust products was determined using two approaches:

- The Fire Dynamics Simulator (FDS) code predicted fluxes at various distances from the VAB. Burn injuries were determined as a function of distance from the VAB to determine safe separation distances.
- The Star-CCM+ program was used in conjunction with extrapolated plume locations to determine exposure limit contour and safe separation distances from the VAB.

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The safe separation distances, as determined by the FDS approach, fell within the existing QD arcs, which were set for the SSP using the DoD weight-based approach (see Figure 4.4-2 for Scenario 1d distances). Safe separation distances are defined as the distance to the transition point where 2nd degree burns become more likely than 1st degree burns. In Figure 4.4-2, the transition between 1st and 2nd degree burns is shown by the transition from green to yellow. The existing QD arc is shown by the thin blue circle inside the green area. The dark purple rectangle in the center is the outline of the VAB High Bays.

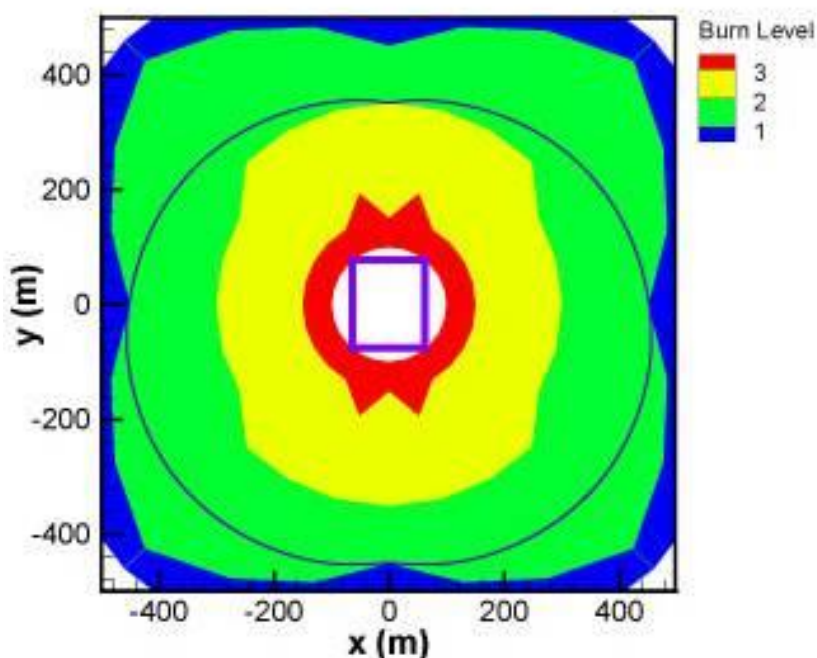



Figure 4.4-2. Scenario 1d Contour Map of Burn Level Due to Radiation as a Function of Position Around the VAB for One Motor Pair (Including Safety Factor and Solar Insolation)

The safe separation distance of 400 m (1,312 ft), as determined by the Star-CCM+ approach, was also located largely within the existing arc determined for the SSP. However, there was one region where the safe separation distances were outside the arc determined for the SSP. This area is shown in Figure 4.4-3. It should be noted that this region, shown in the lower portion of Figure 4.4-3, is in a region where buildings are inside the arc determined for the SSP.

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Because the Star-CCM+ approach produced the longer safe separation distance, the 400-m (1,312-ft) distance was recommended as the safe separation distance. See NESC Recommendation R-1 in Section 8.3.

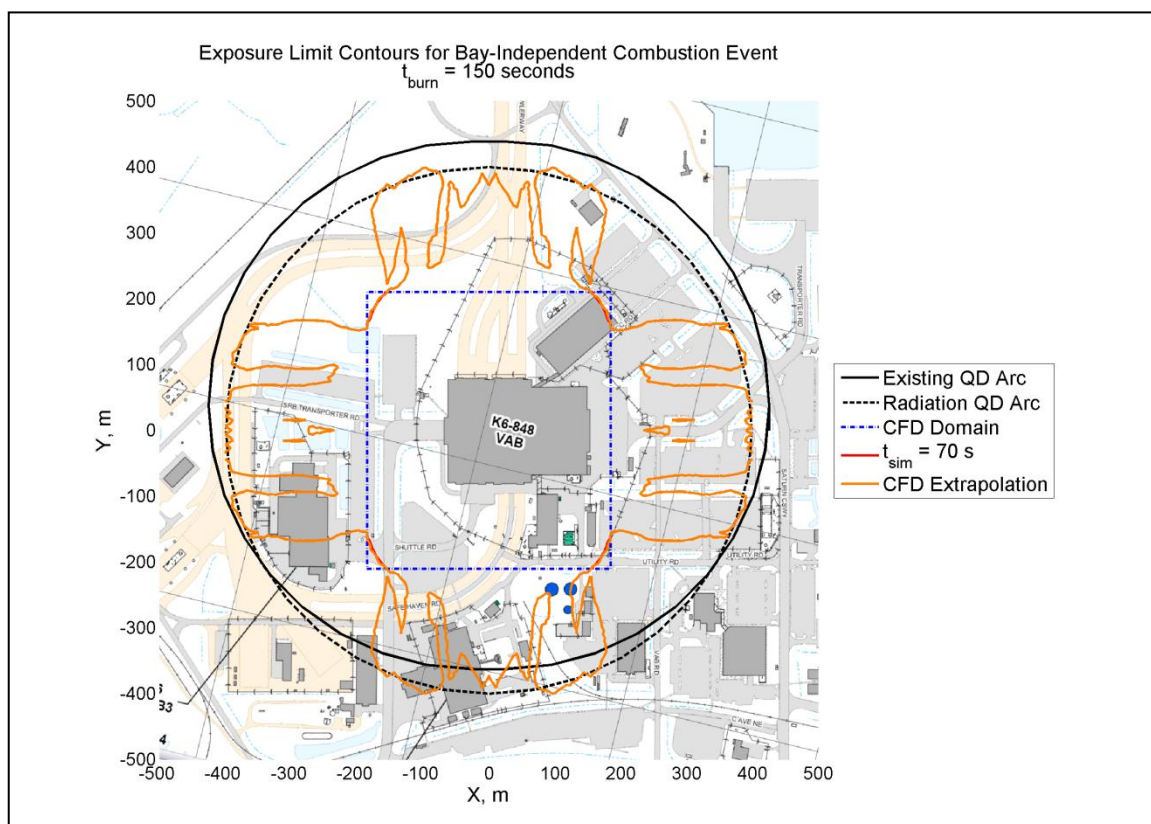



Figure 4.4-3. Contour Map Showing the One Region Where the Safe Separation Distances, Using the Radiation Method, Were Slightly Outside the Arc Determined for the SSP

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4.5 Conclusions from Scenario 1d


The conclusions from the analysis of Scenario 1d—the most likely portrayal of the scenario—showed a different situation than considered in previous studies. These conclusions are listed as follows:

1. Because the external wall panels failed, the exhaust plumes and associated energy expanded outside the VAB confines.
2. This expansion and release of energy was such that the other boosters did not ignite. Only the original two boosters were consumed.
3. Large areas of the exhaust plumes expanded beyond 200 m (656 ft), as measured from the VAB center. Within this region, exposure to the elevated temperatures would result in fatalities. Therefore non-essential personnel need to be prohibited from the region by making the region an exclusionary zone with physical restraint, as recommended in Recommendations R-1 and R-2 (see Section 8.3).
4. Temperatures and heat fluxes within the plumes are sufficient to ignite combustible materials.
5. The safe separation distance, determined as the distance within which personnel are likely to suffer 2nd degree burns with fatalities, is 400 m (1,312 ft). This distance is largely within the existing QD arcs originally established for SSP. See Section 7.5.5 for discussion of a region that exists outside of the current SSP QD arc.
6. Based on the results of this study, the VAB may be used to process and store eight 5-segment boosters for the CxP, as long as the propellant is similar to TP-H1148, the booster segment design is similar to that used in the SSP SRM, and the VAB has a similar configuration.


4.6 Major Considerations in the Findings, Observations, and NESC Recommendations Section

A complete list of the Findings, Observations, and NESC Recommendations is presented in Section 8.0.

- The safe separation distance from the VAB is determined by prevention of 2nd and 3rd degree burns.
- This safe separation distance is a circle of 400 m (1,312 ft) from the VAB High Bay center for eight CxP 5-segment boosters.
- The area within the safe separation circle should be an exclusion zone with fences and controlled access to prevent non-essential or transient personnel uncontrolled access.

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- The interior walls and exterior wall panels fail upon booster ignition and allow rapid expansion of exhaust plumes outside the VAB.
- The rapid expansion and energy release outside the VAB:
 - Prevents ignition of other boosters.
 - Results in fatalities due to exposure to high temperatures ($>1,000\text{ K}$ ($1,340^{\circ}\text{F}$)) for greater than 200 m (656 ft) from the VAB center.
- Any booster design having propellant markedly different than TP-H1148, having more than 5 segments per booster, or a significant change to the VAB configuration should be analyzed using the methods of this study to determine safe separation distances.

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5.0 Assessment Plan

The NESC Modeling Team focused on developing a heat-flux-based approach to determining safe separation distances for boosters containing hazard division 1.3 classification propellant in the VAB. Once the methodology was developed, the Modeling Team applied the new approach to determining safe separation distances for the VAB housing numbers of boosters consistent with the CxP vehicle mission throughput requirements.

The Modeling Team was composed of members who are national experts in the testing and analytical approaches needed to address safe separation distances and in the interpretation of such data and application of it to actual operational sites. A TIM was held at KSC on February 27, 2007. This meeting afforded the Modeling Team an opportunity to tour the VAB and gain familiarity with those aspects of the building that impacted the modeling effort. The TIM was used as an opportunity to share ideas on how to proceed with its tasking.

During the TIM, the scope of the Modeling Team efforts was further defined, including determining hazardous scenarios that would be considered out-of-scope. It was decided that the following hazards associated with housing boosters in the VAB would be considered out of scope:

- Analysis of boosters going propulsive within the VAB, or toppled from their original location.

- Structural response of the VAB and ramifications (e.g., building collapse, fragment throw) other than:

- Destruction of interior cinder block walls (e.g., flow considerations).

- Failure of exterior VAB wall panels (e.g., venting and increased radiation view factors).

- Hazards from toxic species in the booster exhaust plume.

- Hazards associated with related hardware or facility hypergolic liquid fuels (e.g., explosion and toxic plume).


- Interactions between a hypergolic fire and one or more boosters.

- Increased burn area due to damage of propellant and associated increase in energy release rate.

- Egress of personnel from the VAB or the surrounding area.

- Mitigation studies (e.g., improved nozzle plug, strengthened internal walls between adjacent High Bays, installation of larger sprinkler systems, or changes in VAB venting strategy).

- Acoustic hazards associated with boosters burning in the VAB.

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In addition, this study did not evaluate considerations of constructing an additional building for assembly of Exploration Launch Vehicles. However, pending revision to the current QD assessment, any new construction would be required to adhere to the identified IBD and the intraline distance.

This study was also intended as a discipline-advancing activity to increase NASA in-house knowledge and skills for the safe separation and siting process.

6.0 Problem Description, Approach, and Risk Assessment

6.1 Prior Studies of VAB Hazards and Explosive Safety

The prior NESC investigation into the VAB propellant safety siting methodology provided details of an in-depth search of documentation relative to past VAB hazards and explosive safety. The documents selected for review by this search were relevant studies dating from the beginning with the SSP's VAB occupation to the time of this study (~1977–2005).


The NESC investigation added to the knowledge of explosive hazards in the VAB with Recommendation 4 stating: “In addition to using the Maximum Credible Event (MCE) approach to modify the weight used in the standard QD relationship, *the heat flux-distance-time associated with the maximum number of motor segments simultaneously burning should be determined. These data should be used in conjunction with the heat flux-health risk tables published by the Society of Fire Protection Engineers (SFPE) to determine safe separation distances. These two approaches, modified weight in the standard QD and the distance-flux-health risk, should both be pursued*” [emphasis added]. The current study supports part of the above recommendation.

Similarly, Reference 6 provides the latest version of the draft NASA Safety Policy. This draft policy incorporates data from the NESC investigation and some of the early findings from the current NESC modeling study.

6.2 Problem Description

The purpose of the NESC Modeling Team effort was to provide modeling and analyses in support of developing a new heat-flux-based method for determining safe separation distance for CxP solid propellant boosters assembled and stored in the VAB. This effort is a follow-on to the NESC investigation. As described in this investigation, the current VAB safe separation distance siting was originally determined for the SSP. Safe separation distance is often referred to as QD when used with the DoD methodology and tables. The distance was based on the weight of the SSP SRM propellant in the VAB (approximately 2 million kg (4.44 million lbs) for two Space Shuttles, each Shuttle having two 4-segment boosters) using the formula:

$$QD = kW^{1/3}$$

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QD = quantity-distance separation distance in feet

k = a constant determined by the hazard division and application (e.g., to IBD)

W = total weight of energetic material (propellant) in pounds


The SSP SRM propellant has a hazard division classification of 1.3 and since the QD arc is determined for distance to inhabited buildings from the VAB, the k factor is 8 in the DoD method. The NESC investigation report has detailed discussions of why the 1.3 hazard division classification is also the proper classification for CxP. This combination of k factor and weight produces a QD arc with a radius of approximately 400 m (1,312 ft) from the centers of High Bays 1 and 3 for the two Space Shuttles. CxP may have 5.4 million kg (12 million lbs) (eight 5-segment boosters) of 1.3 classification propellant in the VAB. Using the current $QD = kW^{1/3}$ approach, the QD arc with an approximate radius of 558 m (1,831 ft) would encompass existing office buildings.

The NESC recommended that NASA develop a new safe separation siting method based on human exposure to heat flux (see Section 6.1). The recommendation was based on the finding that although a weight-based approach may be appropriate for hazard division 1.1 classification materials that detonate or explode (all or almost all of the material is consumed in hundreds of milliseconds), it may not be appropriate for 1.3 materials. The 1.3 materials burn from seconds to minutes. The material is consumed neither quickly nor simultaneously, and in some instances, not completely. In the case of 1.3 materials, the hazard is heat flux from a fire burning over seconds to minutes, not due to blast and fragments from a detonation that occurs in milliseconds.

6.3 Approach

The goal of the heat-flux-based safe separation siting effort was to determine the safe separation arcs resulting from inadvertent ignition and combustion of booster motors in the VAB. The approach used to achieve this goal involved the five steps listed as follows:

- Energy release from boosters.
 - Assume inadvertent ignition of boosters in one VAB High Bay.
 - Determine flow of exhaust plumes from these burning boosters.
 - Determine if and when other boosters within VAB ignite.
 - Determine how many boosters are burning at any time to determine the energy release as a function of time and location.
- Energy to outside of VAB.

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- Determine if and when external wall panels fail.
- Analyze the flow of exhaust plumes outside VAB.
- Determine heat flux as a function of time and distance from the VAB.
- Determine human response to exposure to plumes and radiative flux time history.
- Determine safe separation distances that would effectively prevent 2nd degree burns.

The following portions of this section will examine the processes and considerations for each of the steps in a general overview manner. Following sections will present more detailed discussions and results.

The initial TIM was held at KSC on February 27, 2007. The purpose of this meeting was to define the:

- Current program having the goal of developing a new method to determine safe separation distances based on human response to heat flux and exposure time.
- Application of this new method to determine the safe separation distance required for eight 5-segment boosters burning in the VAB.


The effort was bounded by determining not only what considerations would be in scope, but also what considerations would be out of scope of the effort (see Section 5.0).

The out of scope considerations are important in an MCE analysis, but were not considered in the current study. This current effort considered the hazards associated with the heat flux and the burn injuries resulting from exposure to the heat fluxes associated with inadvertent ignition and combustion of the solid propellant fuelled boosters. The boosters were considered in their original positions and remained at those locations during ignition and combustion.

The NESC Modeling Team started with a conservative spreadsheet analysis, called Apex, to scope the effort (see Section 7.2). The conclusions from the Apex scoping calculations were used to define more rigorous analyses. The more rigorous analyses addressed the issue of determining time and location dependent energy release, essentially how many boosters were burning at any one time in the VAB, and applying the approach described earlier.

Based on the stacking operations within the VAB, three major scenarios were defined:

- Scenario 1 considered two 5-segment boosters in each of the four VAB High Bays.
- Scenario 2 considered seven 5-segment boosters and one 4-segment stack.
- Scenario 3 considered two 4-segment stacks and six 5-segment boosters. Combustion of the 4-segment stacks would produce exhaust plume through the nozzle and from the uncapped fourth segment.

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Because the energy release rate was the highest for the 5-segment boosters, Scenario 1 was chosen as the apparent worst case and analysis started with this scenario.

In Scenario 1a, the same geometries considered in previous investigations and proposed for examination were addressed. Scenario 1a considered inadvertent ignition of one booster in one High Bay that led to the ignition of the adjacent booster within the same bay (for example, High Bay 3). All of the analyses assume that the first reactions start in High Bay 3. The reactions could start in any of the High Bays and the analyses are equally applicable to each bay. The results would simply need to be transferred about the axes of symmetry. The analyses then tracked the exhaust plume from these two burning boosters. Because there is a wall between High Bays 3 and 1, almost all of the exhaust went across the transfer aisle into the opposing bay. Time to ignition of the boosters in the opposing High Bay (in this example, High Bay 4) was determined. Early in the calculations for Scenario 1a, it was determined that the pressures from the plumes of the original burning two boosters would cause the walls between the High Bays (in this scenario, High Bays 3 and 1) to fail and allow the exhaust plume to flow into the adjacent bay.

The scenario with loss of the interior walls adjacent to the initiating High Bay was modeled as Scenario 1b. The results presented in Section 7.4 show that the boosters in High Bay 1 ignite in 43.7 seconds, followed by the boosters in High Bay 4 in 93.8 seconds, and in High Bay 2 in 111.5 seconds. In this scenario all eight boosters are burning for several seconds before the boosters in High Bay 3 burn out. The calculations of Scenario 1b indicated that there was significant pressure against the insides of the external wall panels. The pressures were sufficient to cause the panels to fail.

Scenario 1c was performed determine how quickly wall panels would fail due to boosters burning within the VAB. It was found that the exterior wall panels fail within 3 seconds. Because the exterior wall panels fail so rapidly, Scenario 1d was established and performed. This scenario starts with the lower halves of the interior walls and all the external walls of the VAB removed, since all the walls were found to fail within the first few seconds of the event. With no walls to channel the exhaust flows, the plumes rapidly flow past the original VAB boundaries. The results of the calculations for Scenario 1d are presented in Section 7.5.

While the calculations for Scenario 1d were being run, calculations for Scenario 3d were also performed. In Scenario 3d the same initial geometry (lower half of interior walls and all exterior panels removed) was used, but the geometry of the initially burning motors was different. Instead of two full 5-segment boosters burning, two 4-segment stacks were ignited. There were exhaust plumes coming from the nozzles and the ends of the uncapped stacks. These runs indicated that Scenario 1d was a worse case than Scenario 3d in terms of ignition in the bore. It should be noted that ignition via radiation to the booster casing and possible

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ignition through the casing were not investigated for Scenario 3d. The results for Scenario 3d are presented in Section 7.5.

6.3.1 Scenario 1a

Scenario 1a: Two boosters are initially burning in the VAB. The interior and exterior walls do not fail.

Scenario 1a considers one booster in High Bay 3 inadvertently igniting and causing the other booster in High Bay 3 to ignite. The energy release conditions and mass flow rates at the booster nozzle exits were provided by ATK Space Systems. The flow of the plumes from the two boosters burning was modeled using the OVERFLOW computational fluid dynamics (CFD) code. The geometries of the VAB, boosters, and mobile launch platforms (MLPs) were described using 96 million grid points. In the calculations of Scenario 1a, it was assumed, as in all previous analyses, that the walls remained intact and acted to direct the plume flow. The calculated ignition of motors in High Bay 4 (across the transfer aisle) considered failure of the nozzle plug and ignition of the propellant in the bore caused by gases from the exhaust plumes entering the booster bore.


An alternate ignition mechanism is by radiation from the exhaust plumes incident on the booster case with conduction of heat through the case to the propellant. This condition is slower than ignition due to the flow of exhaust products into the bore. Detailed calculations of ignition through the casing were not performed for Scenario 1a. Initial pressure calculations showed that the internal cinder block would fail, so the conditions of Scenario 1a were deemed unrealistic and Scenario 1b needed to be addressed.

Energy transfer from within- to- outside the VAB, subsequent radiation at a distance, and response of humans to the radiation at a distance were not considered in this scenario because the rigid internal wall assumption was determined to be unrealistic and Scenario 1b was undertaken to better model the expected VAB response.

6.3.2 Scenario 1b

Scenario 1b: Two boosters are initially burning in the VAB. The interior walls between High Bays 3 and 1 and High Bays 4 and 2 were removed. The exterior walls were initially in place.

Scenario 1b is similar to Scenario 1a except that the cinder block walls between High Bays 3 and 1 fail, allowing the gas and particle plume into High Bay 1. The ignition calculations for target boosters were also improved. Nozzle plug failure was calculated as before, but the flow of gases into the bore was now modeled. In Scenario 1b the spread of the exhaust plume from High Bay 3 to the other bays was calculated using the OVERFLOW CFD code. The boosters in High Bay 1 ignited at 43.7 seconds, in High Bay 4 at 93.3 seconds, and in High Bay 2 at 111.5 seconds.

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To determine the transfer of energy from inside the VAB to outside, Hughes Associates, Inc. (HAI) utilized the results from the OVERFLOW calculations with the predicted ignition time lines as input. HAI determined the increased venting area due to bowing/failure of external wall panels using the Fire and Smoke Simulator (FSSIM) code. The FSSIM code was validated using experimental data from the U.S. Navy Hull Vulnerability (HULVUL) program tests [refs. 2, 5, and 11]. The code was used to determine the venting resulting from two 5-segment boosters (i.e., the initiation of Scenario 1) and two 4-segment stacks (i.e., the initiation of Scenario 3).

These results, along with the OVERFLOW calculations and ignition time lines, were input into the FDS code. The FDS code, coupled with a thermal external panel failure criterion of skin temperature in excess of 800°C (1,470°F), determined the external plume and heat flux exiting the VAB.


HAI calculated heat flux as a function of distance from the VAB using the SINDA/FLUINT code to determine a configuration factor map. This map provided configuration factors as a function of distance. These configuration factors were then coupled with the heat flux (emissive power) at the VAB edge calculated by FDS to give the flux-time at any given distance.

The SFPE developed a technical guide for the prediction of burn injuries due to heat flux and exposure times [ref. 10]. The separate NESC Human Exposure Sub-team recommended that safe separation lines be determined to prevent 2nd degree burns to humans, due to the likelihood of fatalities resulting from such burns. The Human Exposure Sub-team also recommended the use of a safety factor of 1.5 effectively applied to decrease the exposure time to reflect uncertainties in the analysis and variability of human responses to thermal exposures. The flux-distance-time data calculated by HAI were combined with the Human Exposure Sub-team recommendation to find the location of the safe separation distance determined using the heat flux approach.

6.3.3 Scenario 1c

Scenario 1c: Two boosters are initially burning in the VAB. The interior walls have been removed. The exterior walls are allowed to fail. The exterior wall failure is monitored.

Scenario 1c starts with the same conditions as Scenario 1b, but tracks the pressures on the VAB exterior walls. Using a blow-out criterion supplied by KSC and matching the calculated wall pressures to that criteria, it was determined that the VAB wall panels were removed within the first 3 seconds after ignition of the first two boosters. This result was the basis for the VAB configuration for Scenario 1d.

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6.3.4 Scenario 1d

Scenario 1d: Two boosters are burning in the VAB. The interior and exterior walls have been removed.

The conditions for Scenario 1d start with the lower halves of the internal walls removed as in Scenarios 1b and 1c, but with the exterior panels removed as well because of the results of Scenario 1c. The OVERFLOW calculations were performed with these new boundary conditions. Because there are no walls to restrict or direct the flow, the exhaust plumes from the first two boosters were free to exit the original VAB dimensions. The temperatures of the plume were mapped at a height of about 1.8 m (6 ft) above the original floor plane. This mapping showed that there was a significant hot interior region of temperatures (over 1000 K (1,340°F)) that was quickly formed. This region represents an area of significant risk for human death. In addition, the radiation from these plumes to distance was also determined. The combination of the radiation profiles and the 2nd degree burn criterion discussed earlier determine the safe separation distance for heat radiation.


In addition to the ignition of the booster by gases entering the bore, ignition of boosters through the casing was addressed in Scenario 1d. These calculations used the conditions predicted by the OVERFLOW code as input and then predicted the heat fluxes to the boosters in the adjacent High Bays. The transient heat conduction through the casing to the propellant was analyzed to determine if and when these other boosters would ignite.

6.3.5 Scenario 3d

Scenario 3d: Two 4-segment stacks are burning in the VAB. The interior and exterior walls have been removed.

Scenario 3d was addressed using the same starting conditions as Scenario 1d with the exception that two uncapped 4-segment stacks were the items initially ignited and burning. In these calculations there were plumes from exhaust through the nozzle and jet plumes from the top of the uncapped stack. The mass flow and temperature conditions for these burning 4-segment stacks were provided by ATK Space Systems. OVERFLOW was used to determine the flow fields associated with the burning of the 4-segment stacks. The results were compared with the results from Scenario 1d, and it was determined that Scenario 1d was the worst case with respect to ignition through the bore. The calculations for Scenario 3d were terminated after 25 seconds of burn time and no assessment was made of ignition of additional boosters through the case due to radiation.

The technical approaches, assumptions, and analyses of the Scenarios are presented in more detail in subsequent sections.

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6.4 Risk Assessment

6.4.1 Operational Risk

Operational risk is usually defined in terms of the probability of an event occurring and the consequence or severity if the event occurs.


DoD employs Operational Risk Management (ORM) techniques when dealing with potentially hazardous operations (see OPNAVINST 3500.39A as an example). In the ORM process a matrix is established that examines hazard severity and mishap probability. Four levels of severity are considered:

- Category I: The hazard may cause death, loss of facility/asset, or result in grave damage to national interests.
- Category II: The hazard may cause serious injury; illness; property damage; damage to national, service, or command interests; or degradation to efficient use of assets.
- Category III: The hazard may cause minor injury; illness; property damage; damage to national, service, or command interests; or degradation to efficient use of assets.
- Category IV: The hazard presents minimal threat to personnel safety or health.

Mishap probability also has four levels:

- Level A: Likely to occur immediately or within a short period of time. Expected to occur frequently.
- Level B: Probably will occur in time. Expected to occur several times.
- Level C: May occur in time. Can reasonably be expected to occur sometime.
- Level D: Unlikely to occur.

The ORM matrix has the severity and probability as follows:

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**Risk
Assessment
Code**

1 = Critical
2 = Serious
3 = Moderate
4 = Minor
5 = Negligible

		Probability of Occurrence			
		Likely	Probably	May	Unlikely
		A	B	C	D
S E V E R I T Y	Cat I Catastrophic	1	1	2	3
	Cat II Critical	1	2	3	4
	Cat III Marginal	2	3	4	5
	Cat IV Negligible	3	4	5	5

Risk Levels


Figure 6.4-1. Risk Assessment Code (RAC) for Probability of Occurrence

Inadvertent ignition of a booster or boosters within the VAB would be in the catastrophic category because deaths are likely, and there would be serious loss of facility and assets and grave damage to national interests. However, the event is viewed as unlikely or perhaps may have a low probability of occurrence. This would result in a Risk Assessment Code (RAC) 2 or 3. In many installations RAC 2 or 3 requires controls to be in place that would decrease the exposure of personnel and assets to the hazards. Such controls often include exclusion methods such as fences and guarded entrances.

The consequences of inadvertent ignition of a booster with subsequent spread of combustion to other boosters within the VAB can be severe, with many fatalities likely to occur. The major reasons for this high consequence are:

- The large amount (approximately 5.4 million kg (12 million lbs)) of energetic solid propellant located in one building.
- Even if only two boosters are burning (as in Scenario 1d), there is a significant region of plume products at high temperatures extending outside the original VAB footprint with radiation heat transfer to locations outside the ground plume.
- The non-exclusionary nature of the current QD arcs surrounding the VAB.

The first and second reasons are obvious. There is a tremendous amount of potential chemical energy in a confined space that can be quickly converted to thermal energy. The third reason

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may not be as obvious. The DoD often makes the area within a QD arc an exclusion zone. This means that personnel not part of the operation that defines the hazard zone QD are not allowed within the hazard zone. The exclusion is often enforced using fences at the QD perimeter and sometimes limited access through guarded entrances. In contrast, the current QD arc surrounding the VAB is not restricted and has a parking lot within the defined area. While there is a fence around the VAB, it is within the hazard arc, not at the perimeter.

As noted earlier, this study only addressed the hazards associated with thermal hazards to individuals due to high temperatures and heat flux from the inadvertent ignition of boosters. There are other significant hazards that also need to be addressed in determining safe separation distances from the VAB, but these hazards were deemed to be outside the scope of this study.

While the consequences of inadvertent ignition of boosters are high, the probability of the reactions occurring is considered low. This is largely due to factors as:

- Solid propellant is relatively difficult to ignite. A previous study discussed just how difficult it is to ignite/initiate propellant.
- The probability of inadvertent ignition can be minimized by instituting policies, procedures, and training programs.

6.4.2 Technical Risk


The technical risk surrounding this effort is low to moderate. The reasons are:

- The previous method of determining safe separation distance was a QD method based on the formula


$$QD = kW^{1/3}$$

In this approach the total weight is used and it is assumed that the entire amount of propellant reacts essentially simultaneously, so any analysis that considers time-phased energy release is likely to produce different results.

- The heat flux exposure method described in this report has no direct precedent. There are some related works such as:
 - DoD cook-off of munitions studies and tests [ref. 1].
 - Jet Propulsion Laboratory (JPL)/Sandia National Laboratory program looking at combustion of propellant that might impact other components.
 - U.S. Navy HULVUL program that addressed vulnerability of ships to fire [refs. 2 and 5].
 - SFPE skin-burn prediction guide [refs. 7, 8, and 10].

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- Fire hazard assessment methods associated with natural gas plants [refs. 2, 4, and 9].
- Previous studies of inadvertent booster ignition in the VAB did not address four High Bays with two 5-segment boosters in each bay, failure of walls between bays, failure of external wall panels, or several other key issues.
- The NESC Modeling Team had not worked together in the past resulting in an indirect technical risk. This team had to put together the plan for the modeling effort, understand each group's capabilities, define who would do what efforts, and define where the hand-off points were required.
- Another indirect technical risk occurred because the NESC Modeling Team had an aggressive time schedule. The initial TIM was February 27, 2007. In addition there were several programmatic changes including changes in NASA sponsors, lapses in funding, and changes in personnel working on the program. As noted in the report some of the tasks were not fully completed due to study priorities and time considerations.
- The computational codes suggested for use have limitations in:
 - Scope: What they were designed to address.
 - Applicability: For example, some codes were designed for relatively low Mach number flow. Some codes assume adiabatic conditions.
 - Diversity: For example, some CFD codes can handle high-speed flow, but do not directly calculate radiation.
 - Computing Power: Some codes are relatively simple, while others require massive parallel processing.
 - For example, the OVERFLOW code is a high-Mach-number, adiabatic fluid dynamics code. OVERFLOW gives temperature distributions, not radiation. Use of the temperatures predicted from the OVERFLOW code to determine radiation heat transfer will over-predict the radiative flux. In addition, heat-transfer coefficients were assumed and may not have been validated by experiment. The lack of validated data results in some technical risk.
 - FDS code is a low-Mach-number code that includes radiation. Suitable definition of the mass and energy of the source plume needed to be deduced from ATK Space Systems provided ballistic calculations and from OVERFLOW results.
- Perhaps the biggest technical risk at the beginning of this study was lack of experimental data in several key areas, including:

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- Propellant ignition data at appropriate heat fluxes. Initially the NESC Modeling Team had data at the high flux-short time regimes associated with operational ignition of solid propellants, but not at lower flux-longer time regimes associated with unwanted inadvertent ignition of boosters. In the absence of data at the low fluxes and long times, the Modeling Team had to make extreme extrapolations as a work-around. These extrapolations were over two orders of magnitude in time and a decrease of one order of magnitude in flux. This was recognized as a significant technical risk. Recently ATK Space Systems; and to a lesser extent NAWCWD, China Lake; provided the ignition data at the low heat fluxes. The ATK Space Systems data are shown in Figure 6.4-2.

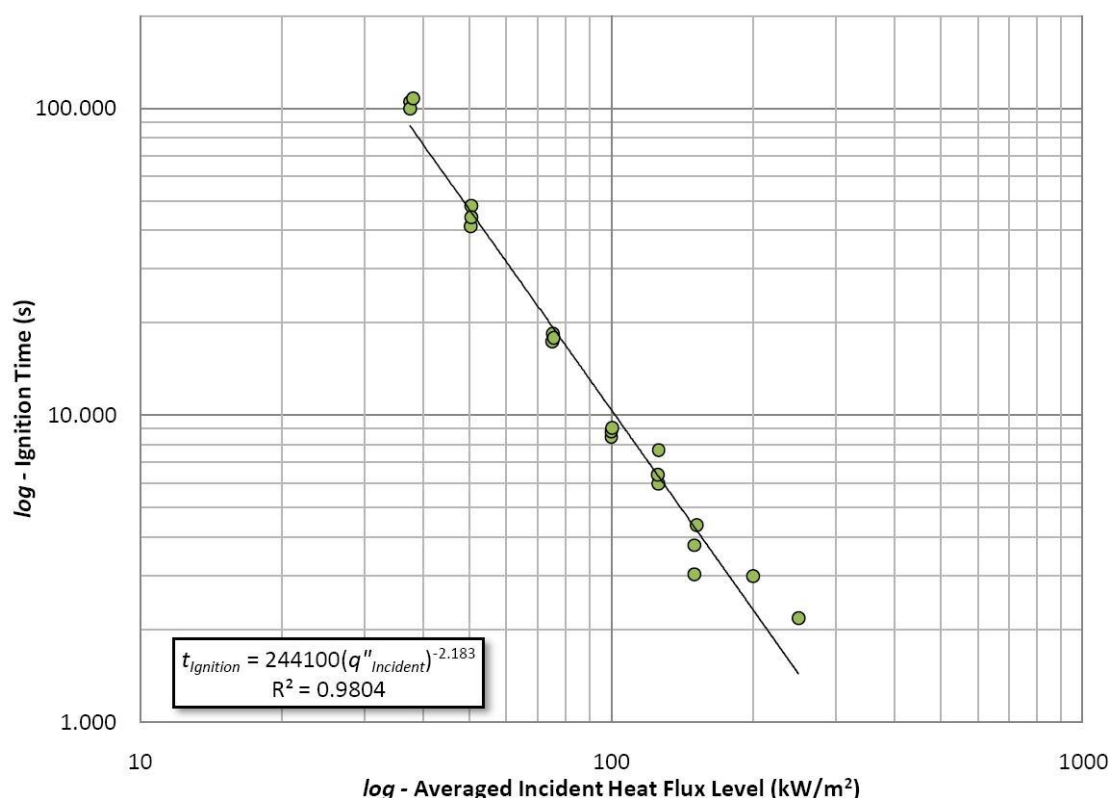



Figure 6.4-2. ATK Space Systems Ignition Data Taken at Low Flux

Note: Graph shows time-to-ignition as a function of incident heat-flux level.

- The NAWCWD, China Lake data are presented and compared with the ATK Space Systems data in Figure 6.4-3.

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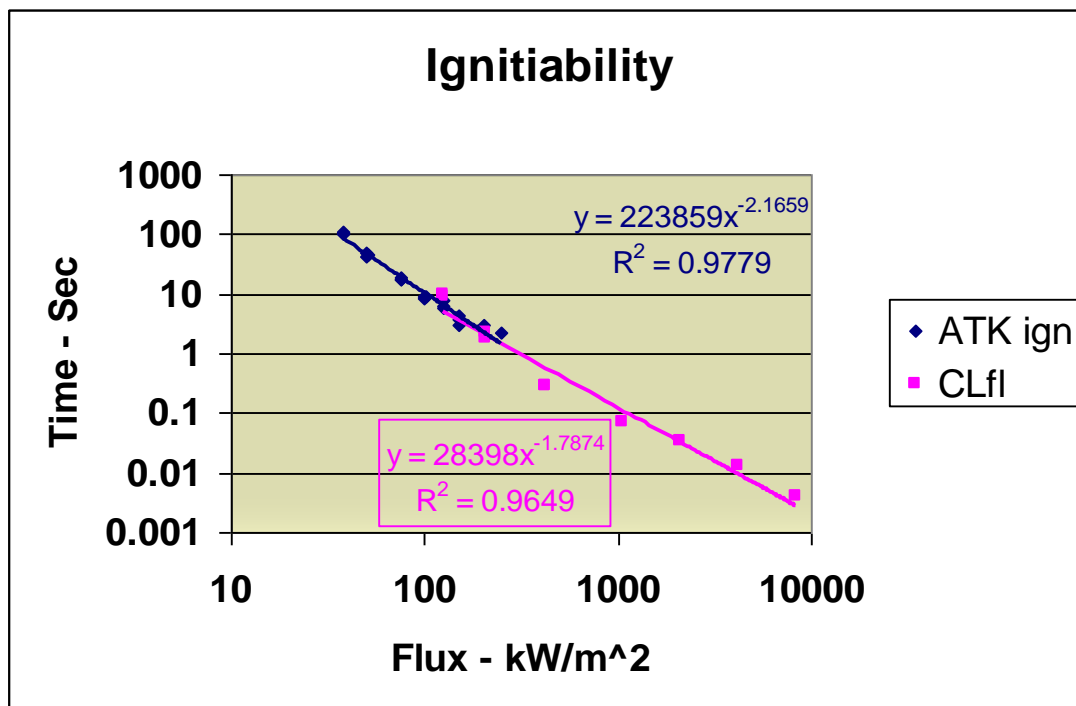



Figure 6.4-3. Comparison of ATK Space Systems and NAWCWD, China Lake Ignition Data at Low Heat Flux

- Fortunately, the experimental data matched well with the extrapolations made earlier (as shown in Figure 6.4-4), reducing this key technical risk. This was critical because the extrapolations were used to determine when individual boosters would ignite, with the resultant ignition timeline (how many boosters burning at any time) determining the heat flux at distance.

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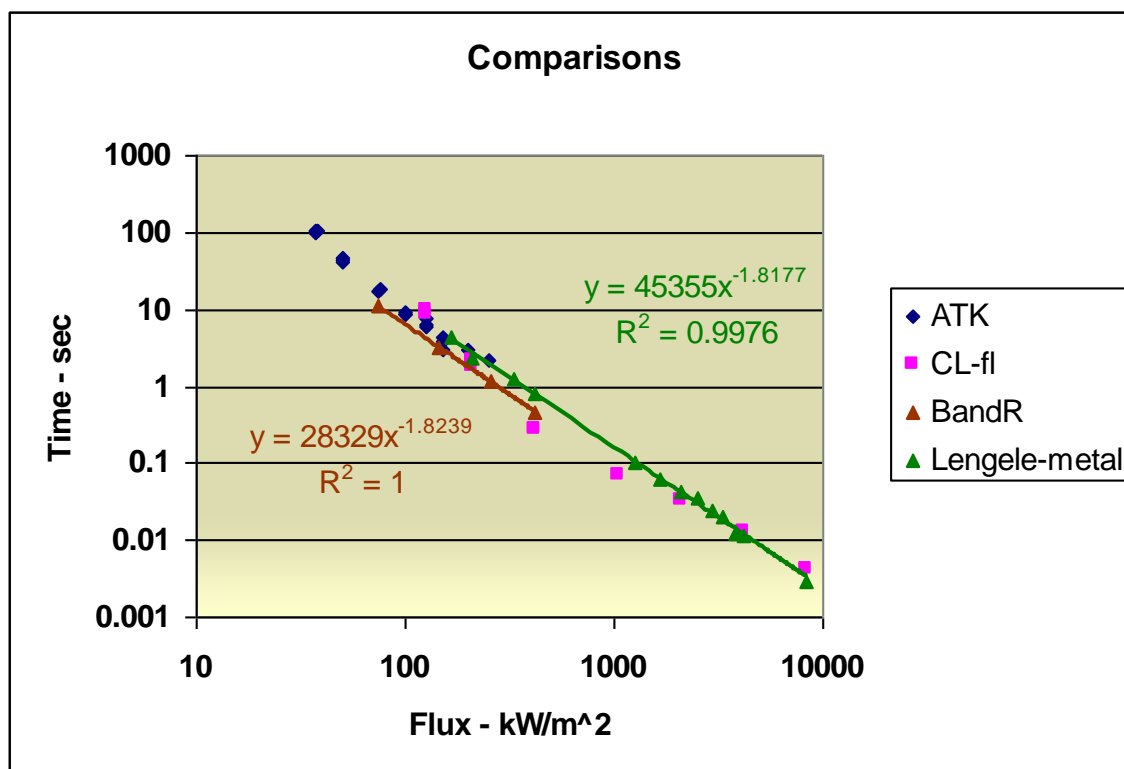



Figure 6.4-4. Comparison of ATK Space Systems and NAWCWD, China Lake Low-Flux Ignition Data with Ignition Data Taken at Higher Flux

- A critical propellant surface temperature was used as the ignition criterion. While a critical surface temperature criterion has limitations at the high fluxes associated with desired ignition of operational boosters, it was used to reduce the complexity already inherent in the ignition analyses. A range of temperatures was considered and the lowest value was chosen as the most conservative estimate.
- Another degree of conservatism was introduced because the OVERFLOW calculations assume adiabatic conditions.
- Analyses were conducted to predict whether the propellant would ignite due to radiation to the booster casing and transient conduction through the case, liner, and insulation to the propellant. Some experimental results were generated in this study using exemplar case and liner materials used with a simulated propellant. The model of these processes compared favorably with the experimental results. Experimental propellant ignition data through the case have recently been obtained.

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- In the instance of ignition of propellant through the case, there are no data on the further development of the accident. For example, the case could fail and the propellant grain could break up, increasing the burning surface area. As noted earlier, these events were not considered in this study.
- Most impingement codes address the response of structures to the impingement of exhaust plumes, not the flow of exhaust plumes after encountering the VAB floor with flow of the exhaust plumes that might ignite other boosters either by direct contact or by radiation from the exhaust plumes. There are data from static booster tests, but those tests involve a free jet, not a plume impinging on the VAB floor and subsequent flow.

7.0 Data Analysis


7.1 Relation of Study to Hazard and MCE Analysis

This study only addresses inadvertent ignition of motors and segments within the VAB and the subsequent thermal hazards. It does not address other hazards that should be identified and evaluated within a comprehensive MCE analysis. Earlier sections in this report presented considerations determined to be outside the scope of the current effort. These out-of-scope hazard areas should be considered in an MCE. In this regard, the current study provides input to an MCE, but it is not the entire MCE.

7.2 Apex Scoping Calculations

Safe separation distance calculations were made using a simplified methodology. These calculations utilized spreadsheet techniques and a number of conservative assumptions to bound the problem and establish the direction for more detailed computations and data collection. This analysis was primarily developed in Spring 2007 with minor additions based upon data obtained during the Summer and early Fall 2007.

The Apex calculations were simple, conservative calculations used for scoping purposes. In these calculations, Steps 1 (energy release) and 2 (energy to outside of VAB) were combined. It was assumed that the energy release was described by thermochemical equilibrium calculations where the propellant completely reacted. The calculations assumed that all units (whether boosters, 4-segment stacks, or individual segments) being considered ignited and burned simultaneously. ATK Space Systems provided mass and energy release data for the various configurations. The energy was considered to be from a point source with no VAB structure (i.e., an open field). The resulting heat flux was considered to be some fraction of the total energy release (radiative fraction) and decreased in distance because the energy was distributed over a hemisphere (reduced by $2\pi r^2$). Radiant fractions of 0.1 to 0.5 were considered.

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Three flux levels were considered in determining the QD. These fluxes, and the associated exposure times for human reaction, were considered based on data from the SFPE *Engineering Guide for Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation* [ref. 10]. While the Apex calculations showed the application of a simple heat flux model for the determination of the QD arc, this analysis did not have the ability to reflect the important effects of the propellant configuration, nor was it able to assess the impact of the burning of a booster pair on ignition of boosters in the adjacent High Bays. More detailed analyses were required.

7.2.1 Approach Used for Scoping Calculations


The simple calculations considered burning fully assembled 5-segment boosters, uncapped 4-segment stacks, and individual segments. A booster is a 5-segment operational SRM. An uncapped 4-segment stack is a booster minus the forward segment. The configurations evaluated were:

- Eight operational 5-segment rocket boosters that burn at full pressure for about 2 minutes.
- Four-segment stacks undergoing assembly operations. If a 4-segment stack inadvertently ignites, it will burn at pressures between approximately 758 kPa (110 psia) at ignition and 159 kPa (23 psia) at burnout. The burn will last about 4.5 minutes.
- Various numbers (up to 40) of individual segments burning. Each segment could burn 9.75 minutes (burning at approximately atmospheric pressure). However, having 40 individual discrete segments burning is not a realistic scenario. Segments are brought into the VAB to be assembled with other segments and the maximum number of un-stacked segments is three (the first segments of two stacks-to-be in a High Bay, plus one segment in the transfer aisle). This individual segment configuration is included in the calculations because at the beginning of this study, calculations and discussions centered on various numbers of individual segments. However, generally no more than three individual discrete segments can be in the VAB at any given time. Any other segments in the VAB will be in partially assembled or complete boosters.

The simple calculations considered total energy release per unit time from the various sources. The total energy release per unit time was taken to be the sensible energy (energy/unit mass), as calculated by thermochemical equilibrium calculations, multiplied by the mass rate of conversion of the solid propellant to product species.

The mass conversion rate is different for individual segments versus stacked segments versus operational boosters burning, reflecting the different pressure regimes during the booster/segment burn.

Not all of the energy released is transmitted by radiative heat transfer to a distance or to a person standing at that distance. Some of the energy will remain with the products or be

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absorbed by nearby structures. For these calculations, the radiant energy transmitted to distance was treated parametrically (i.e., it was assumed to be 50, 40, 30, 20, or 10 percent of the total energy release). The fraction of the total energy rate that is emitted as radiation is often termed the radiative fraction, χ_r . These assumed radiative fraction values were based upon the judgment of the NESC Modeling Team in Spring 2007. The radiant flux at a distance from the point source was determined by a simple hemispherical distribution. The radiant flux was determined by the radiant energy output divided by the hemispherical area at the target radius. Note that these durations were less than the booster burn duration so that these times were used only for process illustration.

The SFPE has provided data tables on human response to radiant heat flux [ref. 10]. These tables discuss radiant flux (amount of energy over a given area) and duration of exposure to the radiant flux. Rather than considering the many different possible combinations of flux-time, three different flux levels were applied in the scoping calculations. Table 7.2-1 presents the three flux levels and the exposure times required to feel pain and for the onset of 2nd degree burns.

Table 7.2-1. Sample Human Consequences of Radiant Heat-Flux Exposure (Source: SFPE)

Incident Flux, \dot{q}_r'' (kW/m ²)	Time to Pain (seconds)	Time to 2 nd Degree Burn (seconds)
4	9	26
10	1.3	7
13	1	5


Note: Time to pain and time to 1st degree burns are essentially the same.

As indicated in Table 7.2-1, these radiant fluxes cause pain in exposed skin in seconds and result in 2nd degree burns in short periods of time. Second degree burns can lead to fatalities. At the higher radiant flux values, individuals will survive only if they can quickly find cover.

The above data can be used to calculate the safe separation distance by applying the following equation:

$$D = \sqrt{\frac{\chi_r \cdot N \cdot m_p \cdot \Delta H_c}{2 \cdot \pi \cdot \dot{q}_r''}}$$

D = safe separation distance

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χ_r = radiative fraction (0.1, 0.2, 0.3, 0.4, or 0.5)

m_p = mass conversion rate per unit for given configurations

ΔH_c = sensible heat

N = number of units that are burning (number of motors, number of stacks, or number of segments)


\dot{q}_r'' = target radiant flux (4, 10, or 13 kW/m²)

This simple heat-flux-based expression can be contrasted with the traditional $QD = kW^{1/3}$ approach. In the flux-based approach, the safe separation distance is dependent upon the square root of the burning rate, rather than the cube root of the total propellant mass. The radiative output expressed as a radiative fraction is explicitly included in the heat-flux-based approach and is not reflected explicitly in the traditional approach. While the simple heat-flux-based method may be insufficiently detailed to resolve the issues in the VAB, the model identifies the possible shortcomings of the traditional approach to siting, as applied to the VAB hazards.

7.2.2 Conclusions from Scoping Calculations

A number of conclusions were drawn from the scoping calculations. These included:


- The current weight-based safe separation methodology, while appropriate for explosions and detonations that consume the energetic material in a matter of microseconds to seconds, may not be suitable for mass fires where the energetic materials may react for several minutes. The traditional weight-based approach does not reflect the temporal and spatial aspects of the problem that are critical to realistic safe siting for mass fire events.
- An alternate approach based on heat flux and the response of humans to these heat-flux levels gives a more realistic, and defensible, safe separation distance for mass fires than does the current weight-based method.
- In some instances (depending on assumptions made), the heat-flux-based approach allows more SRMs to be housed in the VAB than would be allowed using the current weight-based approach.
- Previous discussions had focused on the number of segments in the VAB. The results of this study show that the safe separation distance for fully assembled boosters or motors in various stages of assembly is different than the distance for the same weight of discrete individual segments. Actual configurations (either fully or partially assembled stacked booster configurations) must be considered when calculating safe separation distances.

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The scoping calculations show the viability of the heat-flux-based approach. However, the conservative assumptions and parametric variations of some of the input parameters used in the calculations could not justify safe storage of eight fully assembled 5-segment boosters in the VAB and still maintain the existing safe separation distance of 400 m (1,312 ft).

In order to more accurately define the safe separation distance, the Modeling Team decided that the conservative assumptions and parametric analyses used in the simplified calculations should be replaced by more detailed analyses and experimental data where possible. The elements of a more detailed analysis include:

- Definition of the likely booster stacking configurations in each VAB High Bay at the time of an inadvertent ignition of a single 5-segment booster or a 4-segment stack.
- Prediction of energy release from 5-segment boosters as a function of time and location (i.e., sequencing of booster ignition based on energy transfer from other ignited boosters in the VAB). It was assumed in a more detailed analysis that one booster in a High Bay ignites. The time to ignition and combustion times of other boosters in the adjacent High Bays will be determined by detailed analysis.
- Energy propagation outside the VAB would be determined at the same time considering wall panel failure to allow external heat flow.
- Radiant energy propagation from the VAB to the far-field.
- Human response to the radiant energy at a distance from the VAB.

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7.3 Scenario 1a

Scenario 1a: Two boosters are burning in one VAB High Bay, with interior and exterior walls intact. Scenario 1a is depicted in Figure 7.3-1.

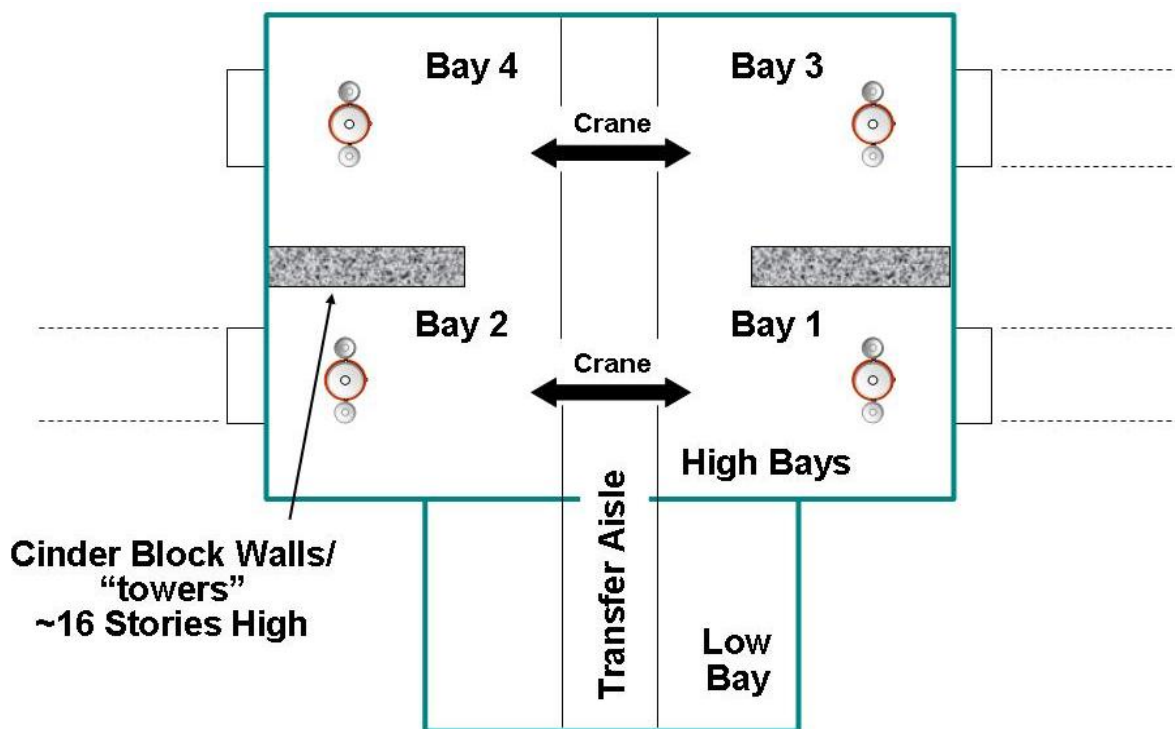



Figure 7.3-1. VAB Plan View

The plan view (Figure 7.3-1) shows two boosters in each High Bay and adjacent bays being separated by 16-story-high cinder block walls (often called towers). The VAB geometry is modeled using data provided by KSC.


7.3.1 Approach Used in Scenario 1a

For Scenario 1a, it is assumed that one of the boosters in High Bay 3 inadvertently ignites and ignites the other booster in High Bay 3. The plumes produced by the boosters pass through the mobile launch platform, impact the VAB floor, and “mushroom” out. The flow of the exhaust plume was modeled with the OVERFLOW CFD code, using 96 million grid points. The code predicted the pressure, temperature, velocity, and plume location at each point for a series of times.

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Relatively early in the Scenario 1a calculations, it became obvious that the cinder block walls in High Bay 3 were exposed to significant pressure and would fail. This was in marked contrast to predictions made in some of the earlier studies of inadvertent ignition of SSP 4-segment boosters within the VAB. These previous studies did not consider the wall failure. As will be shown in Scenario 1b, Section 7.4, consideration of failure of the internal walls is important in accurately predicting booster exhaust plume flow patterns. KSC asked that the NESC Modeling Team continue the Scenario 1a calculations as if the walls did not fail. The calculations showed the flow of exhaust products from High Bay 3 across the transfer aisle into High Bay 4. The analysis then calculated how long it would take for the boosters in High Bay 4 to ignite.

There is little data describing large (greater than 30 in. in diameter) rocket boosters in hot exhaust plumes or fires. One test that was recently performed tested a 8.7 m- (344-in.-) long and 1.3 m- (50-in.-) diameter booster containing a propellant having a 69 percent ammonium perchlorate, 19 percent aluminum, and 12 percent hydroxyl-terminated polybutadiene (HTPB) binder in a large, fast cook-off fuel fire test. The booster was in the fire environment for 3 minutes and 11 seconds, at which time the nozzle plug failed and gases entered the booster bore. After an additional 33 seconds (total time from fuel fire ignition: 3 minutes and 44 seconds), the booster ignited. This showed that failure of the nozzle plug and subsequent flow of gases into the booster bore are major considerations. Because the SSP SRMs have a nozzle plug, it was assumed that the Ares I 5-segment boosters would have a similar nozzle plug, the failure point of the SSP SRM nozzle plug was calculated. The nozzle plug is shown in Figure 7.3-2.

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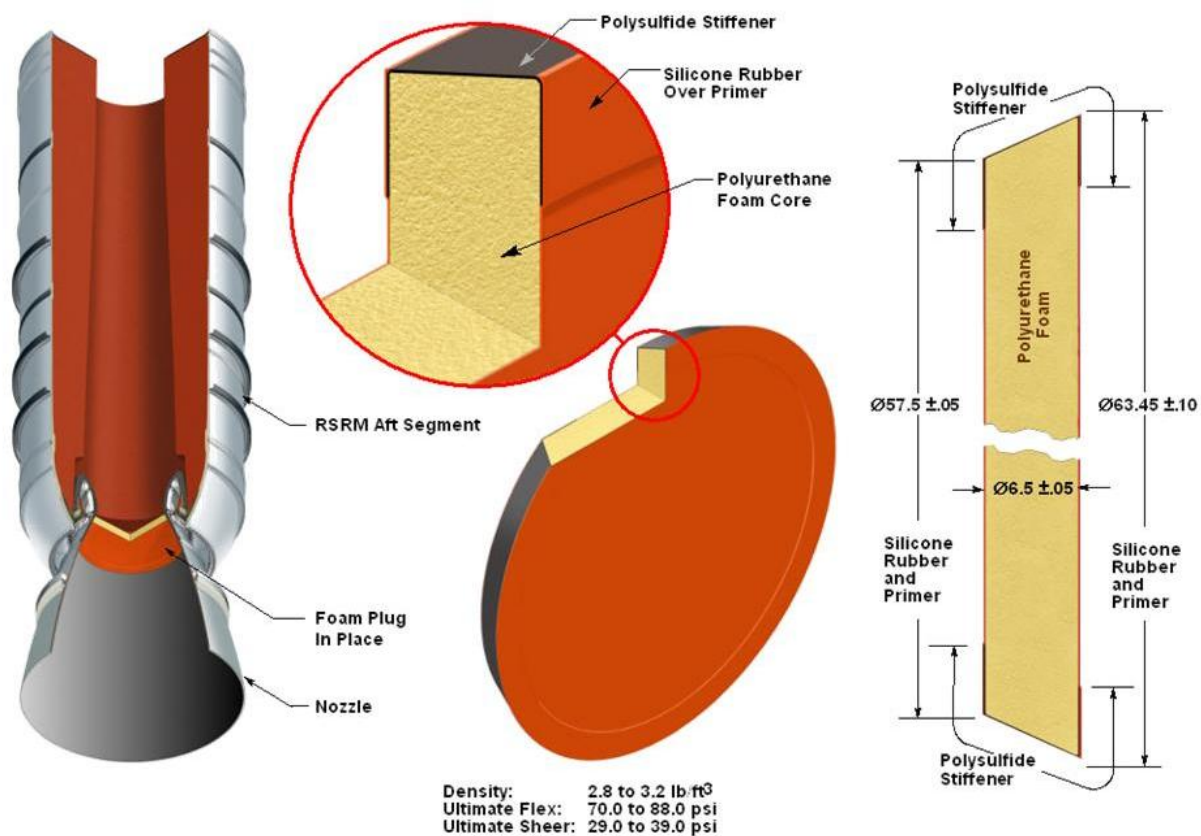



Figure 7.3-2. SSP SRM Nozzle Plug (Source: ATK Space Systems)

The calculations determined that the polyurethane failed at about 150°C (300°F) and the nozzle plug would fail with an overpressure between 13.1 and 30.3 kPa (1.9 and 4.4 psi, respectively). The OVERFLOW calculations were used to determine when pressure on the nozzle plug would lead to its failure. The preliminary ignition criterion used for Scenario 1a was based on gas temperatures in the bore following nozzle plug failure.

7.3.2 Results and Conclusions from Scenario 1a

The calculations for Scenario 1a show that the boosters in High Bay 4 ignite at 52.5 seconds. However, this result is unrealistic because the unreinforced masonry interior walls would fail due to the pressures from the two burning boosters. Failure to account for wall failures incorrectly results in the exhaust gases being channeled across the transfer aisle to the opposing High Bay (in this scenario High Bay 4).

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Analysis shows that the nozzle plugs fail. This allows exhaust gas products to flow into the booster bore. Analysis that accounted for the interior wall failure and development of a better propellant ignition criterion was performed for Scenario 1b.

7.4 Scenario 1b


Scenario 1b: Two boosters are burning within one VAB High Bay. The interior walls have been removed and the exterior walls are initially in place.

Early in the calculations for Scenario 1a, it was determined that the pressures caused by the inadvertent ignition of boosters in High Bay 3 would almost immediately cause the unreinforced masonry walls separating High Bays 3 and 1 to fail (<1 second), allowing the exhaust plumes to flow from High Bays 3 to 1 and into High Bay 4. Scenario 1a was only run until the boosters in High Bay 4 ignited.

Scenario 1b starts out the same as Scenario 1a with two boosters burning in High Bay 3. The exhaust from these burning boosters passes through the MLP, impinges on the VAB floor, and starts to spread. In this scenario the impingement of the plume, with associated pressure, causes the wall between High Bays 3 and 1 to fail, allowing exhaust gases to flow into High Bays 1 and 4. The goal of this scenario analysis was to determine when the boosters in High Bays 1 and 4 ignite, and then how long it takes for the boosters in High Bay 2 to ignite.

The analysis for Scenario 1b also differed in several ways from the analysis performed for Scenario 1a. The differences include:

- Scenario 1a did not include analysis of flow to adjacent High Bays after the boosters in High Bay 4 ignited, nor did the analysis include energy release from the VAB or the determination of safe separation distances.
- A more refined ignition criterion was used to determine when boosters in the adjacent High Bays ignited.
- The analyses for Scenario 1b tracked the flow of exhaust plumes, along with the associated pressures and temperatures, from all burning boosters.
- Using the pressures and temperatures determined from the OVERFLOW analysis, a preliminary scoping calculation of when external wall panels fail allowing plume flow from within the VAB to the outside was performed. This preliminary scoping calculation indicated the need to perform the analyses of Scenarios 1c and 1d.
- Even though the scoping calculations indicated that a more detailed analysis was needed to describe failure of the external wall panels, the radiation from the VAB to distance was determined in Scenario 1b.

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- A preliminary attempt was made to establish safe separation distances based on the prevention of 2nd degree burns due to exposure to this radiation.


7.4.1 Ignition of Boosters in Scenario 1b

As mentioned in the previous section, Scenario 1b differs from Scenario 1a in how the booster ignition is handled after the boosters in High Bay 3 ignite. Scenario 1b models the flow of the plumes from High Bay 3 into High Bays 1 and 4, including the failure of the nozzle plug and subsequent flow of gases and particles into the booster bores.

The temperature, pressure, velocity, and plume location of the gases into the bore were calculated using OVERFLOW CFD. However, a major problem existed when the Scenario 1b calculations were started because no reliable propellant ignition criterion was available. While experimental data and analytical models that describe the ignition of solid propellants have been available for years, unfortunately the data and analyses are for propellant ignited in the operational mode. This mode is characterized by high heat fluxes to the propellant surface that cause the propellant to ignite quickly (tens of milliseconds). The flux regime for the inadvertent ignition of the boosters is much lower. The data from high fluxes were extrapolated to the lower fluxes of interest. While Scenario 1b was being studied, experimental data were gathered under other ATK Space Systems and NAWCWD, China Lake tasking. These data as shown in figures 6.4-3 and 6.4-4, presented earlier, agreed with the extrapolated data.

The ignition criterion that was used considered heat transfer from the gases and particles to the propellant surface. The temperature of the propellant surface at ignition was calculated by HAI using the HEATING 7.3 code. The range of values varied from 260–310°C (500–590°F). The lower value of 260°C (500°F) was selected as the conservative critical propellant surface ignition temperature. ATK Space Systems also calculated the propellant surface temperature at ignition based on their experimental ignition data using the ITRAC code. They calculated surface temperatures ranging from 267–365°C (513–689°F). Their lower value of 267°C (513°F) agreed well with the 260°C (500°F) used in the NESC Modeling Team.

The results for scenario 1b show that the boosters in High Bay 1 ignite at 43.7 seconds. The OVERFLOW calculations show that ignition of the boosters in High Bay 4 does not occur until 93.8 seconds after the boosters in High Bay 3 have ignited. After the boosters in High Bay 4 ignite the interior walls between High Bays 4 and 2 fail. The calculations show that the boosters in High Bay 2 ignite at 111.5 seconds. At this time all eight boosters are burning, but the boosters in High Bay 3 are almost burned out.

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7.4.2 Energy Transfer from the Inside to the Outside of the VAB

The results of the previous section provided the ignition sequence of the boosters burning at any time and the associated energy release. It was then necessary to assess the energy transfer out of the VAB as a function of time.


An approach developed by HAI describes the leakage from the VAB due to roof vents and normal wall leakage and time-dependent leakage that occur when exterior wall panels fail due to initial pressure pulse and skin temperatures that exceed 800°C (1,472°F). This approach first used the FSSIM code to calculate early VAB pressurization to establish initial pressure-induced exterior wall panel failure and establish wall leakage. Then the FDS code was used to determine thermal-induced failures of the VAB siding. The number and location of boosters burning at any given time was obtained from the OVERFLOW calculations for Scenario 1b.

To estimate the heat flux at a distance, the effective VAB emissive power (kW/m² of energy radiated from its surface) was first determined and then that emissive power in combination with a set of configuration factors was used to determine the heat flux as a function of position around the VAB. SINDA/FLUINT was used to compute the configuration factors to vertical cylindrical targets (representing people) located around the VAB out to distances of 1,500 m (4,921 ft) from the VAB center (approximately 3.5 times the current QD distance).

During the calculations of wall-panel failures, it became apparent that there would be significant numbers of wall panels penetrated. Because the degree of wall-panel removal could play a significant role (i.e., removed wall panels would allow the exhaust plume to quickly expand outside the original VAB confines), Scenario 1c was established and calculations made on wall-panel removal rate.

7.4.3 Determination of Criteria for Human Response to Heat Flux-Time Exposure

At the time that the calculations for Scenario 1b were being conducted, a separate sub-team was established to determine a human exposure criterion for safe separation distance from burning boosters in the VAB. The major conclusion was that the criterion should be the prevention of 2nd degree burns, since such burns would likely result in fatalities. Because there are variations in human susceptibility to radiation and uncertainties in the skin-burn data and modeling, a safety factor of 1.5 was applied to the accumulated skin damage.

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7.4.4 Safe Separation Distance/Arcs for Scenario 1b

Because Scenario 1c was established there was no requirement to determine the safe separation distances for Scenario 1b. However it was decided to develop the required methodology using Scenario 1b data.

The analysis showed that an increased safe separation distance would not be required for Scenario 1b, and the transition between 1st and 2nd degree burns for Scenario 1b was inside the current QD arc for four SSP 4-segment boosters.

7.4.5 Results and Conclusions for Scenario 1b

Scenario 1b, when compared to Scenario 1a, shows the differences caused by failure of the masonry walls separating adjacent High Bays. The pressures inside the VAB exerted on the exterior wall panels can cause removal of panels and subsequent flow of exhaust plumes and energy out of the VAB. Consideration of exterior wall panel failure was addressed in Scenarios 1c and 1d.

The NESC Human Exposure Sub-team recommended that a criterion for safe separation distance from the VAB containing burning boosters be the prevention of 2nd degree burns.

When this criterion was coupled with radiation predictions from Scenario 1b, safe separation distance plots were identified. This methodology was subsequently applied to Scenario 1d.

7.5 Scenarios 1c, 1d, and 3d


Scenario 1c: Two 5-segment boosters are burning within one VAB High Bay. The interior walls have been removed. The exterior walls are allowed to fail and are monitored.

Scenario 1d: Two 5-segment boosters are burning within one VAB High Bay. The interior and exterior walls have been removed.

Scenario 3d: Two 4-segment stacks are burning within one VAB High Bay. The interior and exterior walls have been removed.

7.5.1 Approach

As discussed in previous sections, Scenario 1a (Section 7.3) assumes that the VAB interior and exterior walls remain in place. These walls channel the flow of the exhaust plumes from the two boosters burning in one High Bay. The pressure distributions produced in Scenario 1a determined that the interior masonry walls separating adjacent High Bays would fail and allow flow between the bays. In Scenario 1b (Section 7.4), the interior walls separating adjacent High Bays are removed, but the exterior walls are allowed to fail over time, thus containing energy


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within the original VAB confines. This containment allows the boosters in the adjacent High Bay to ignite at approximately 44 seconds, the boosters in the bay across the transfer aisle to ignite at approximately 94 seconds, and the boosters in the other bay to ignite at approximately 112 seconds. At 112 seconds, all of the boosters in Scenario 1b are ignited.

Scenario 1c was essentially a re-run of Scenario 1b, focusing on pressures and temperatures on the exterior wall panels. The pressures and temperatures on the VAB exterior walls are monitored and analyzed in Scenario 1c, compared with improved failure criteria, and wall panels are allowed to fail. This analysis showed that the wall panels were rapidly removed and that the exterior wall panels were removed within 3 seconds from inadvertent ignition of the booster pair. Scenario 1d was performed with the interior and exterior walls removed from the start for computational ease, since the short confinement period would have no discernable effect on the ignition of boosters in the other High Bays.

7.5.2 Results of OVERFLOW CFD Code Analysis

The results from the Scenario 1d calculations showed that the flow of the exhaust plumes from the boosters burning within one High Bay rapidly spread beyond the original VAB confines. Figures 7.5-1 through 7.5-8 show temperature contour data for a cut plane drawn through High Bays 3 and 1. Note that the temperatures depicted within the 1073-K (1,472°F) contour are that temperature and higher. Boosters in any of the High Bays could have inadvertently ignited and High Bay 3 was analyzed as an exemplar of all the bays.

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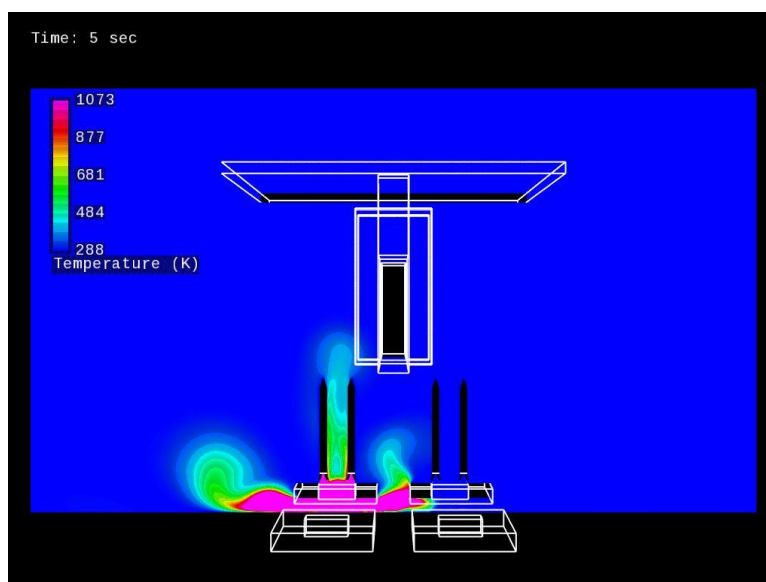


Figure 7.5-1. Temperatures Associated with Exhaust Plume Flow at 5 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

Note: Boosters in High Bays 4 and 2 removed for clarity.

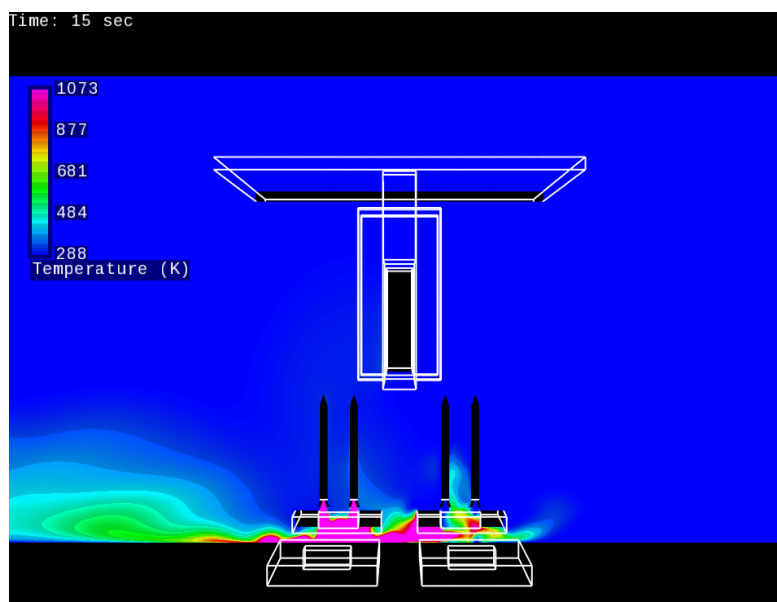



Figure 7.5-2. Temperatures Associated with Exhaust Plume Flow at 15 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

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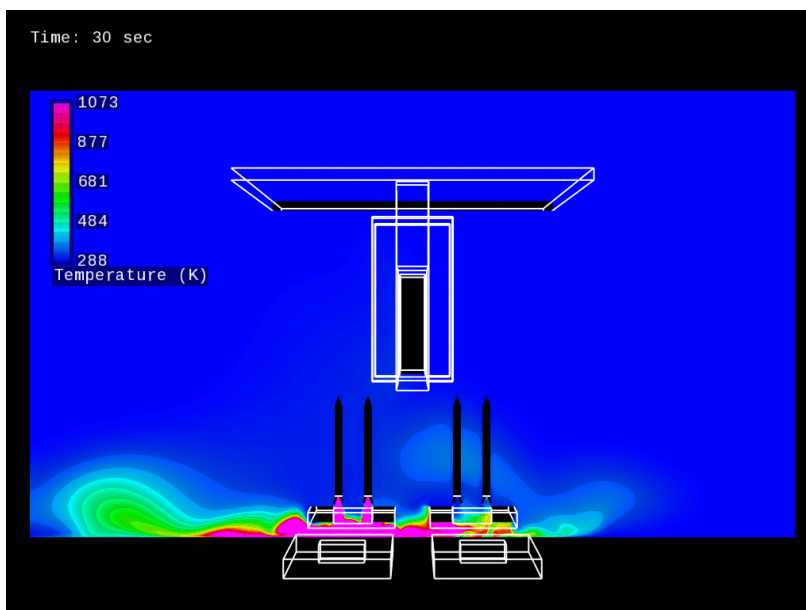


Figure 7.5-3. Temperatures Associated with Exhaust Plumes 30 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

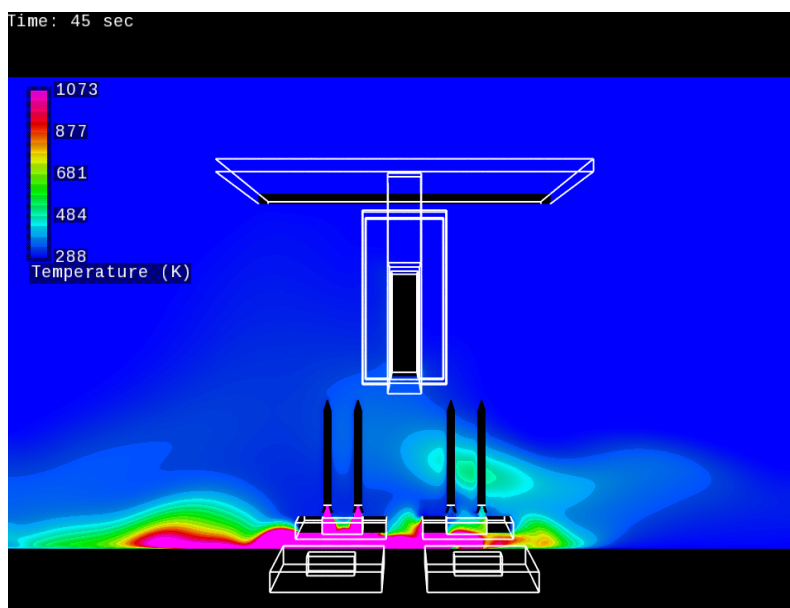



Figure 7.5-4. Temperatures Associated with Exhaust Plumes 45 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

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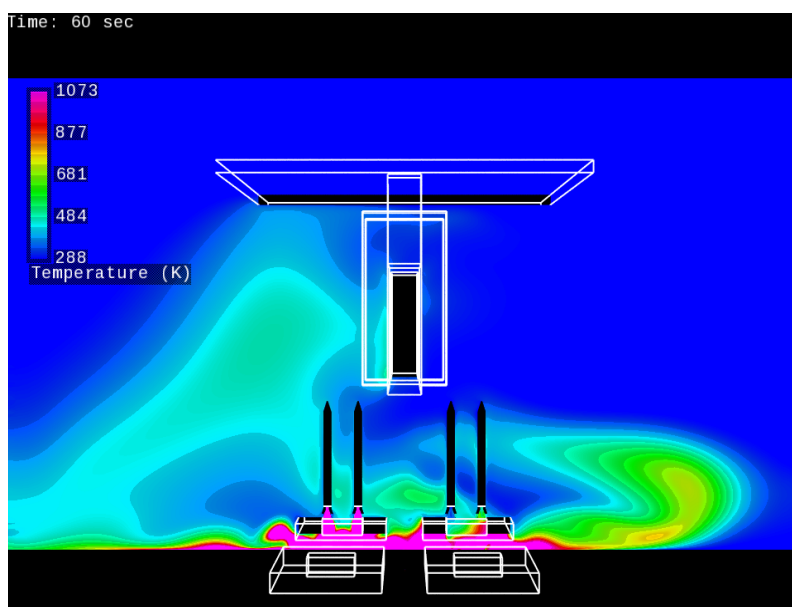


Figure 7.5-5. Temperatures of Exhaust Plumes 60 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

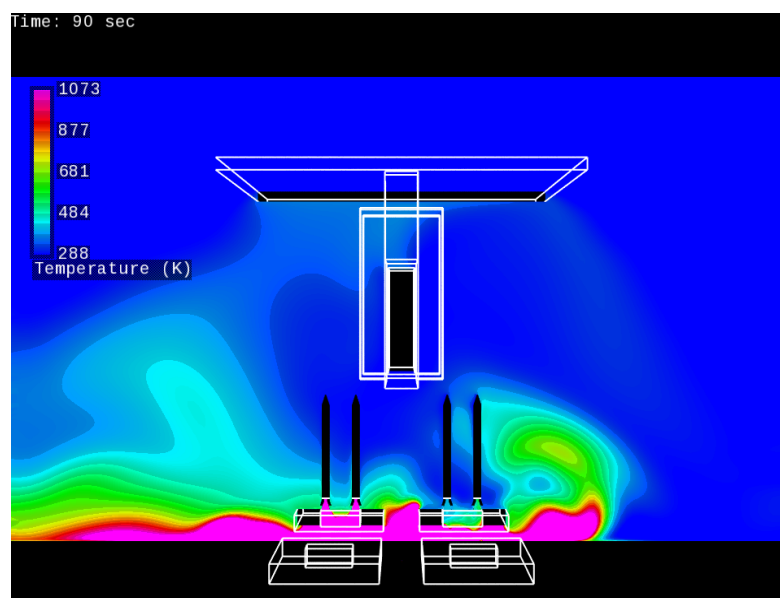



Figure 7.5-6. Temperatures of Exhaust Plumes 90 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

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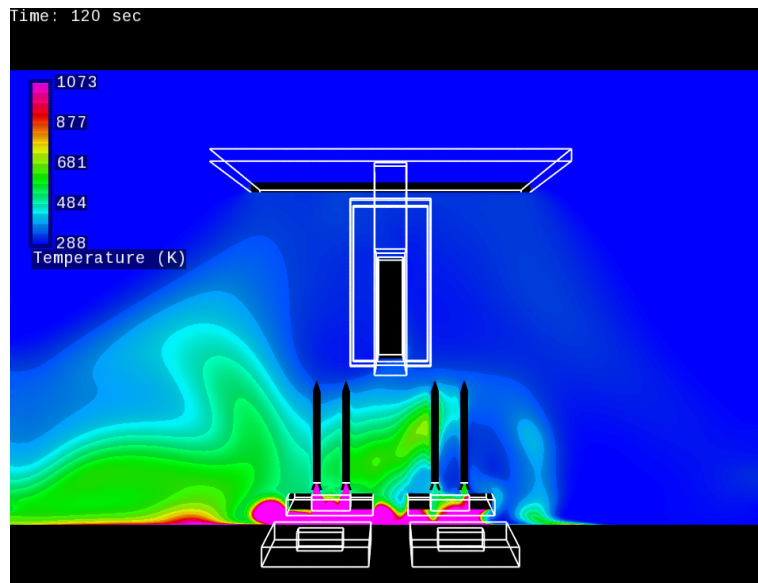


Figure 7.5-7. Temperatures of Exhaust Plumes 120 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

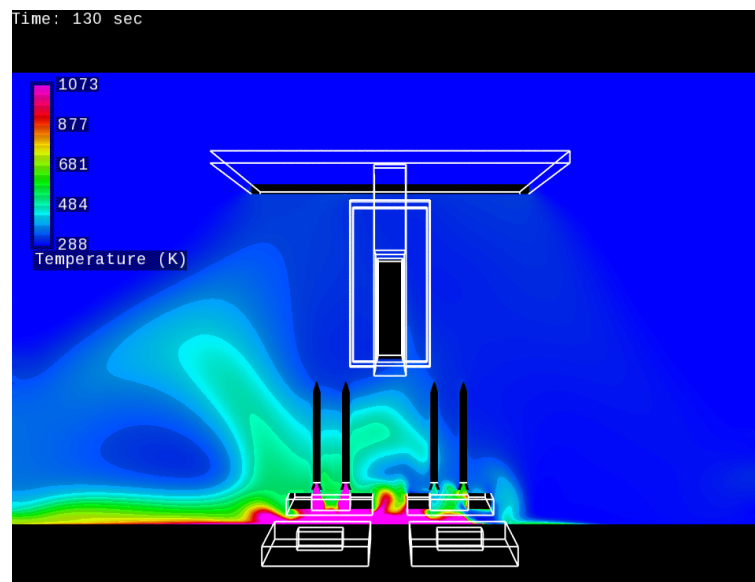



Figure 7.5-8. Temperatures of Exhaust Plumes 130 seconds After Ignition of Boosters in High Bay 3 with Flow Toward High Bay 1 During Scenario 1d

Note: These boosters have essentially burned out at this time.


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Analyses of thermal conditions within the bore or through the case indicated that boosters in High Bay 1 would not ignite.

Figures 7.5-9 through 7.5-15 show the boosters in High Bay 3 burning with the flow of exhaust products in the cut plane between High Bays 3 and 4. As noted earlier, the analyses indicated that boosters in High Bay 4 would not ignite.



Figure 7.5-9. Temperature of Exhaust Plumes 5 seconds After Ignition of Boosters in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

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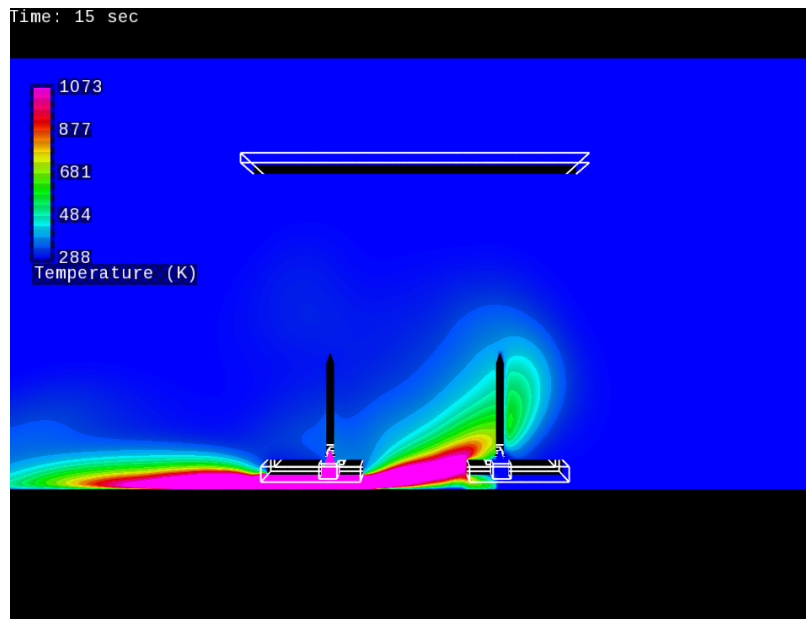


Figure 7.5-10. Temperatures of Exhaust Plumes at 15 seconds After Ignition of Boosters Burning in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

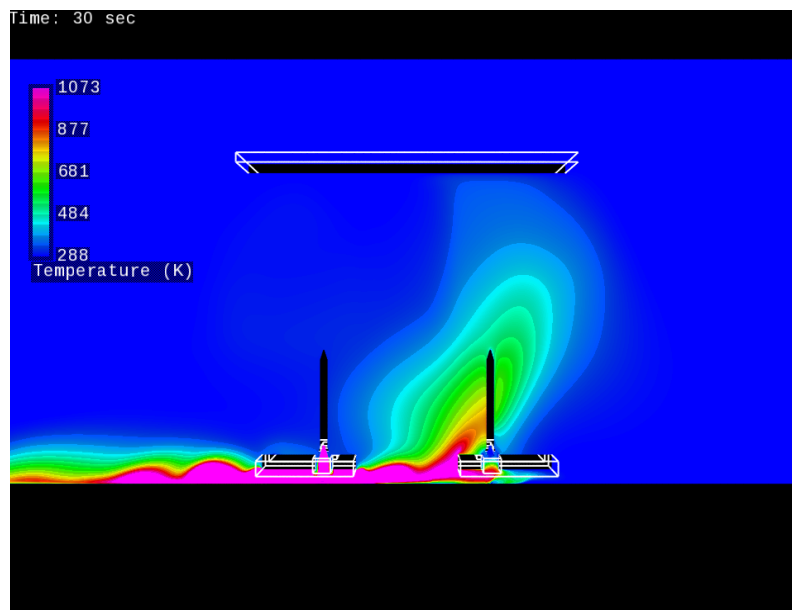



Figure 7.5-11. Temperatures of Exhaust Plumes at 30 seconds After Ignition of Boosters in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

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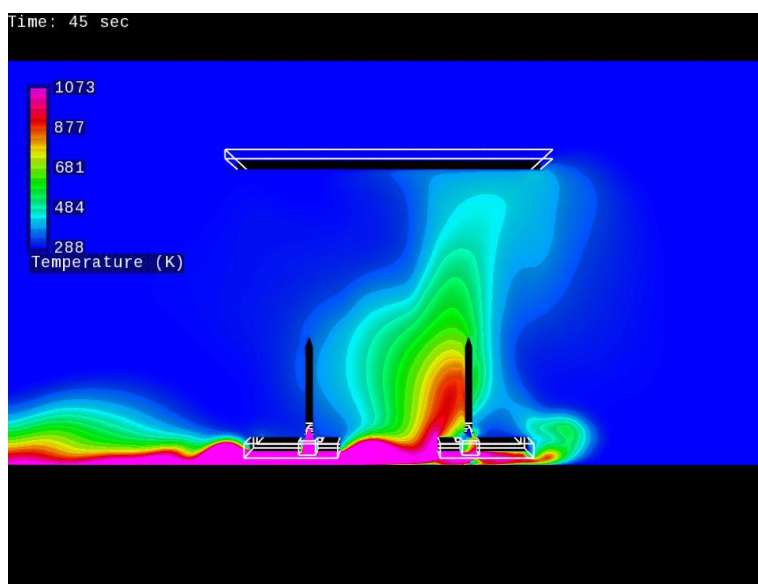


Figure 7.5-12. Temperatures of Exhaust Plumes at 45 seconds After Ignition of Boosters in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

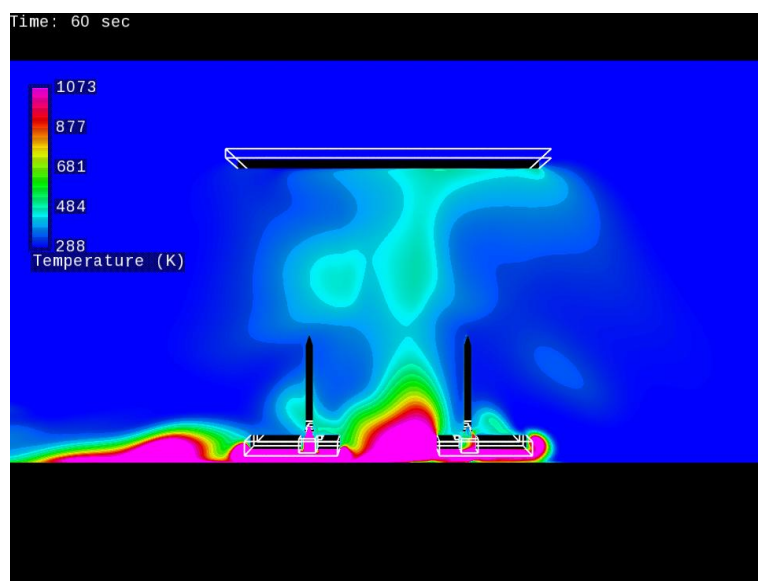



Figure 7.5-13. Temperatures of Exhaust Plumes 60 seconds After Ignition of Boosters in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

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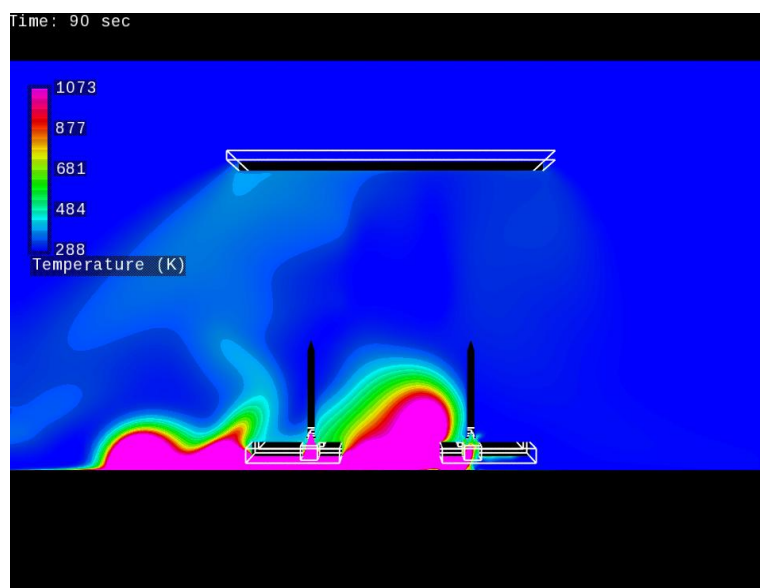


Figure 7.5-14. Temperatures of Exhaust Plumes at 90 seconds After Ignition of Boosters in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

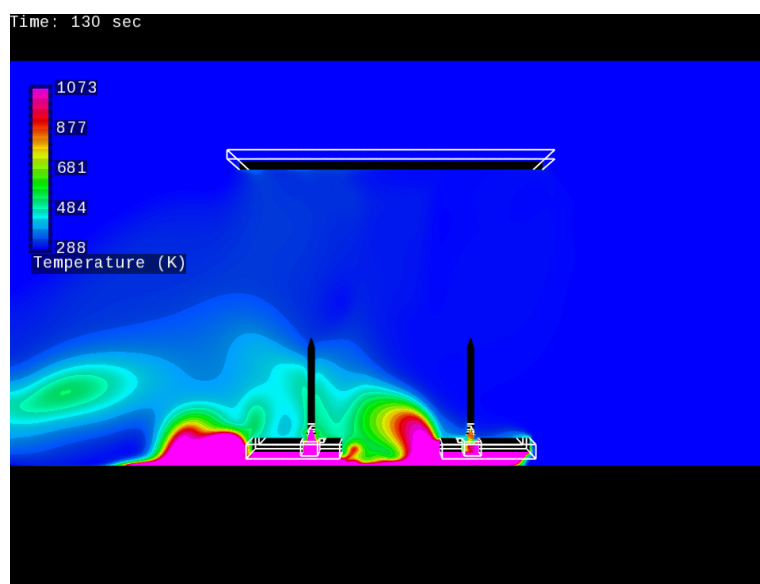



Figure 7.5-15. Temperatures of Exhaust Plumes at 130 seconds After Ignition of Boosters in High Bay 3 in the Cut Plane Between High Bays 3 and 4 During Scenario 1d

Note: At this time the High Bay 3 boosters are essentially at burn out.

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Analysis of the thermal conditions at the nozzle and through the case indicates that while temperatures were relatively high in the transfer aisle and in High Bay 4, the boosters in High Bay 4 did not ignite using the ignition criterion established for Scenarios 1b–1d. The results show that the only boosters burning were the two boosters that were assumed to inadvertently ignite (i.e., the reaction did not spread to other boosters within the VAB). This is in contrast to the results of Scenario 1b where all eight boosters were burning at one time. The failure of the light-weight, relatively weak VAB wall panels effectively mitigated the hazard of igniting boosters within the adjacent High Bays.

While only two boosters burned, there was a serious spread of exhaust plumes outside the original VAB footprint bounds. This is shown in Figures 7.5-16 through 7.5-21. In these figures the temperatures at a cut plane 1.7 m (66 in.) above the VAB floor are mapped. This height was chosen to represent the height of human beings. The calculation domain shown is approximately 400 x 400 m (1,312 x 1,312 ft).

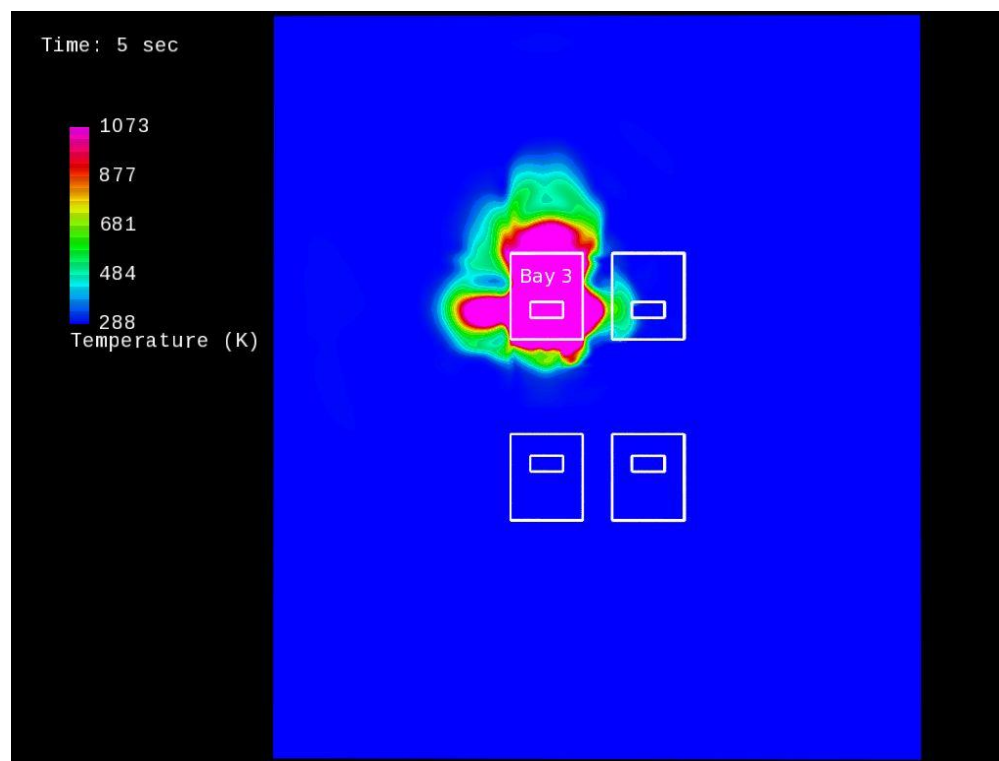



Figure 7.5-16. Exhaust Plume Temperatures at 1.7 m (66 in.) Above the Floor of VAB at 5 seconds After Ignition of Boosters in High Bay 3 During Scenario 1d

Note: The calculation domain (blue area) is approximately 400 x 400 m (1,312 x 1,312 ft).

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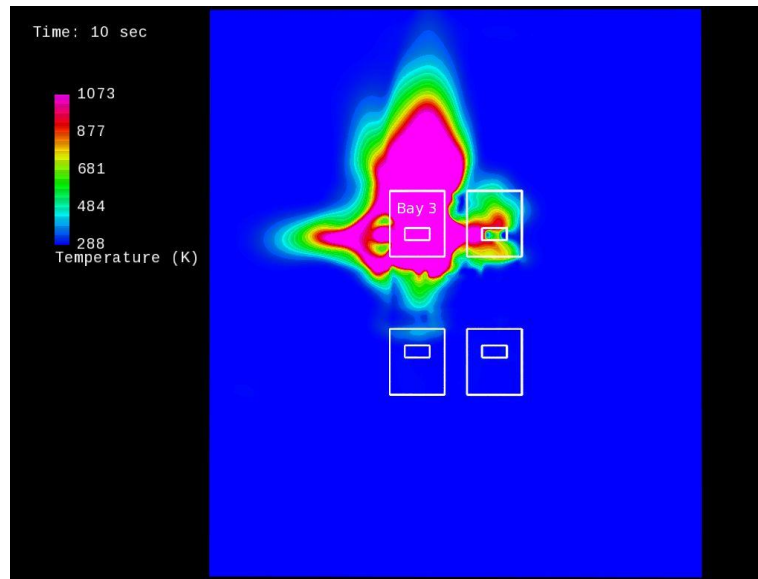


Figure 7.5-17. Exhaust Plume Temperatures at 1.7 m (66 in.) Above the Floor of VAB at 10 seconds After Ignition of Boosters in High Bay 3 During Scenario 1d

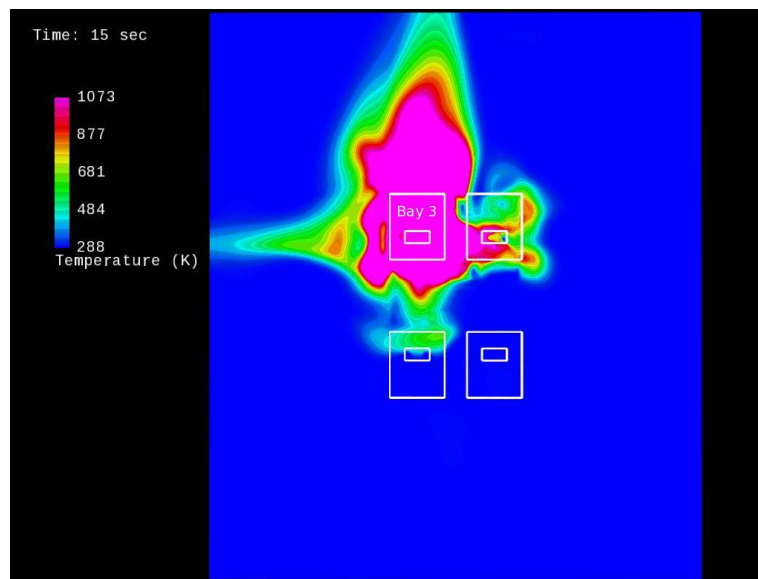



Figure 7.5-18. Exhaust Plume Temperatures at 1.7 m (66 in.) Above the VAB Floor at 15 seconds After Ignition of Boosters in High Bay 3 During Scenario 1d

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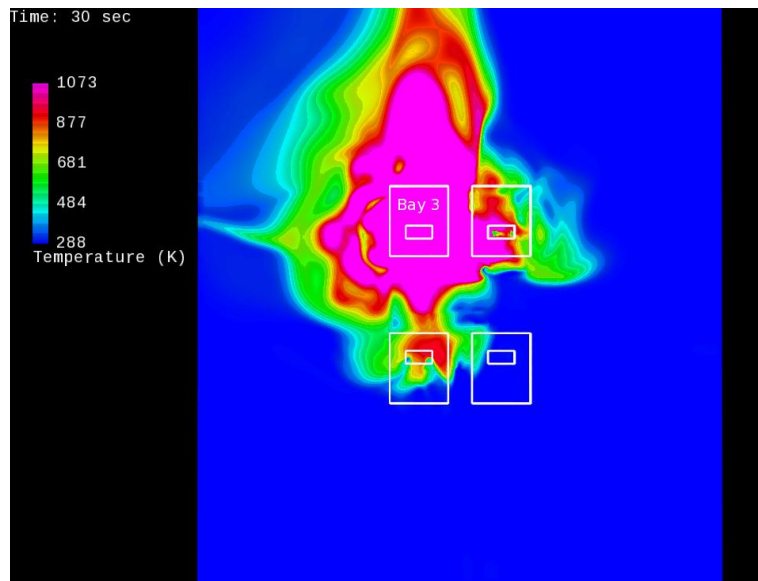


Figure 7.5-19. Exhaust Plume Temperatures at 1.7 m (66 in.) Above the VAB Floor at 30 seconds After Ignition of Boosters in High Bay 3 During Scenario 1d

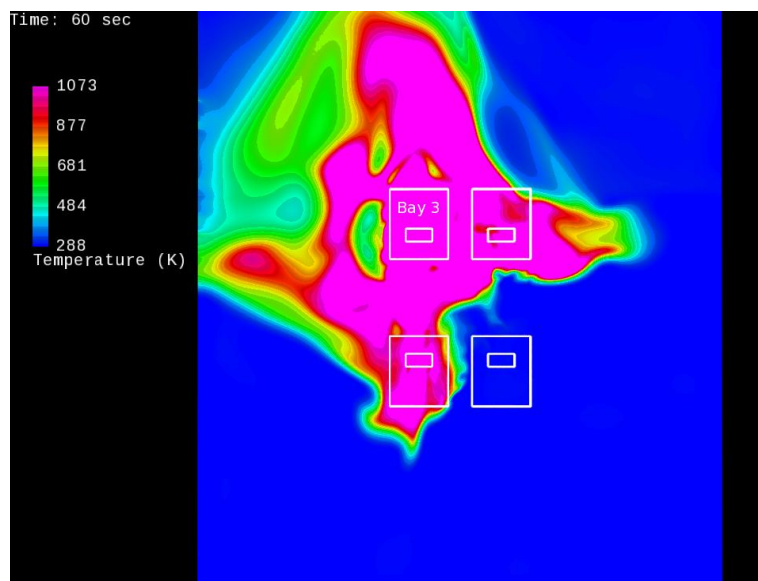



Figure 7.5-20. Exhaust Plume Temperatures at 1.7 m (66 in.) Above the VAB Floor at 60 seconds After Ignition of Boosters in High Bay 3 During Scenario 1d

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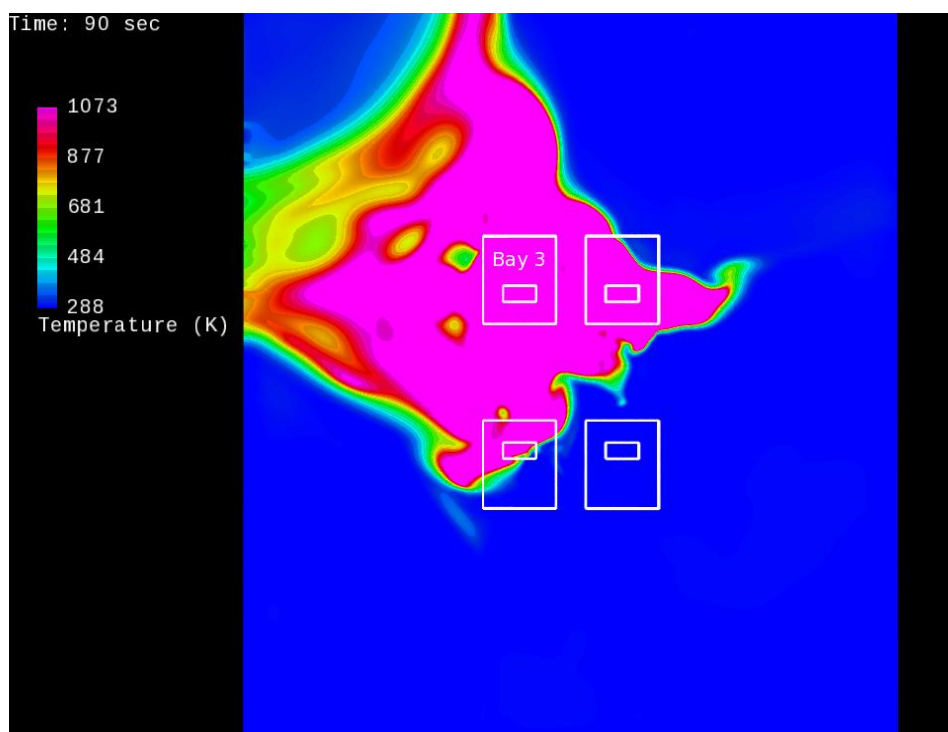



Figure 7.5-21. Exhaust Plume Temperatures at 1.7 m (66 in.) Above the VAB Floor at 90 seconds After Ignition of Boosters in High Bay 3 During Scenario 1d

Figures 7.5-16 through 7.5-21 show how quickly and to what extent these high-temperature exhaust plumes spread. These results were for the inadvertent ignition of the boosters in High Bay 3, but it is equally probable that the ignition could occur in any of the other bays. The results from High Bay 3 are applicable to the other bays by mirroring the results of High Bay 3 about the axes of symmetry to the other bays. When this is done, it indicated the potential for a significant high temperature region surrounding the VAB. Any personnel within these regions would likely perish under these conditions.

7.5.3 Calculating Safe Separation Distances to Prevent 2nd Degree Burns

The previous section presented results that showed fatality for personnel exposed to the regions of high-temperature exhaust plumes that extend beyond the original VAB bounds. Beyond these high-temperature regions, there are still regions of concern because personnel could be exposed to radiative heat fluxes that could cause 2nd degree burns. The NESC Human Exposure Sub-team investigated what exposure times to various radiation levels would result in 2nd degree burns and potentially their associated deaths. The Human Exposure Sub-team recommended that radiation levels and exposure times that would produce 2nd degree burns should be avoided

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and that the transition from 1st to 2nd degree burns should determine the safe separation distances from the VAB. Two methods were employed to determine the safe separation distances associated with the specified acceptable heat-flux levels: one by HAI, and a second by personnel from NAWCWD, China Lake.

7.5.4 HAI Determination of Safe Separation Distance to Prevent 2nd Degree Burns from Inadvertent Burning of Boosters

In this approach FDS, a CFD tool commonly used to model fire-driven flows, was used to determine the heat fluxes to vertical targets (representative of humans) at various distances from the exhaust plume leaving the VAB. The fluxes at these targets were used to determine a time- and space-dependent mapping of heat flux around the VAB. These heat fluxes were used to determine the burn levels of exposed personnel located around the VAB by applying a skin-burn model.

The computational domain used in these analyses is shown in Figure 7.5-22 with VAB (roof minus exterior wall panels) and boosters as indicated.

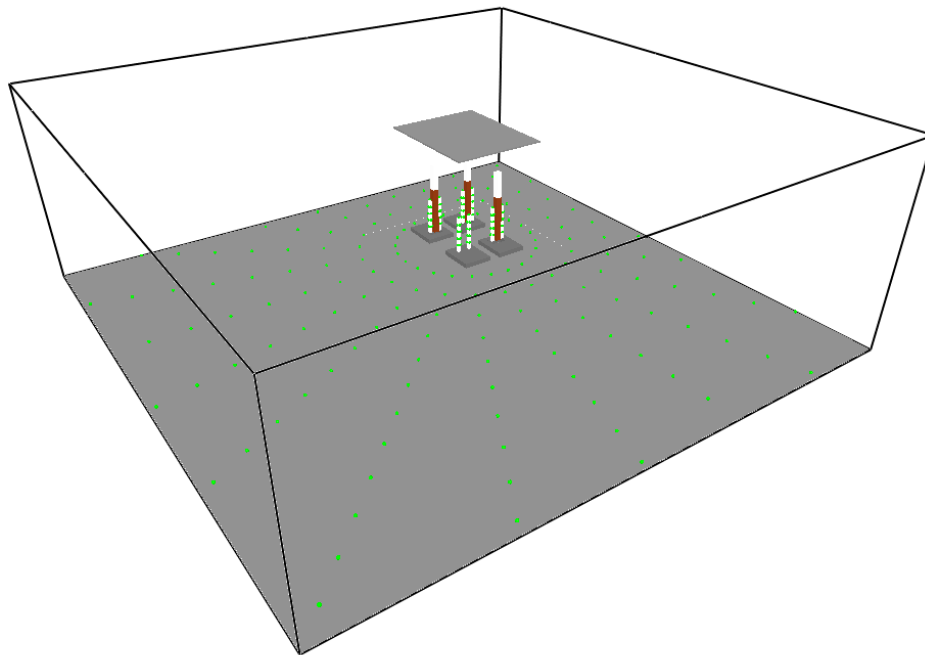



Figure 7.5-22. Smokeview Rendering of the Computational Domain for Scenario 1d Showing the VAB Roof, Motors, MLPs, Center Tanks with Cargo Modules, and Measurement Locations (Green) for Propellant Temperature (On Motors) and Radiant Heat Flux (On Ground Plane)

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The exhaust plume locations for two boosters burning in the VAB generated using this analysis are shown in Figure 7.5-23. In this depiction, the 70°C (158°F) region of thermal immersion injuries and/or fatalities contour is highlighted.

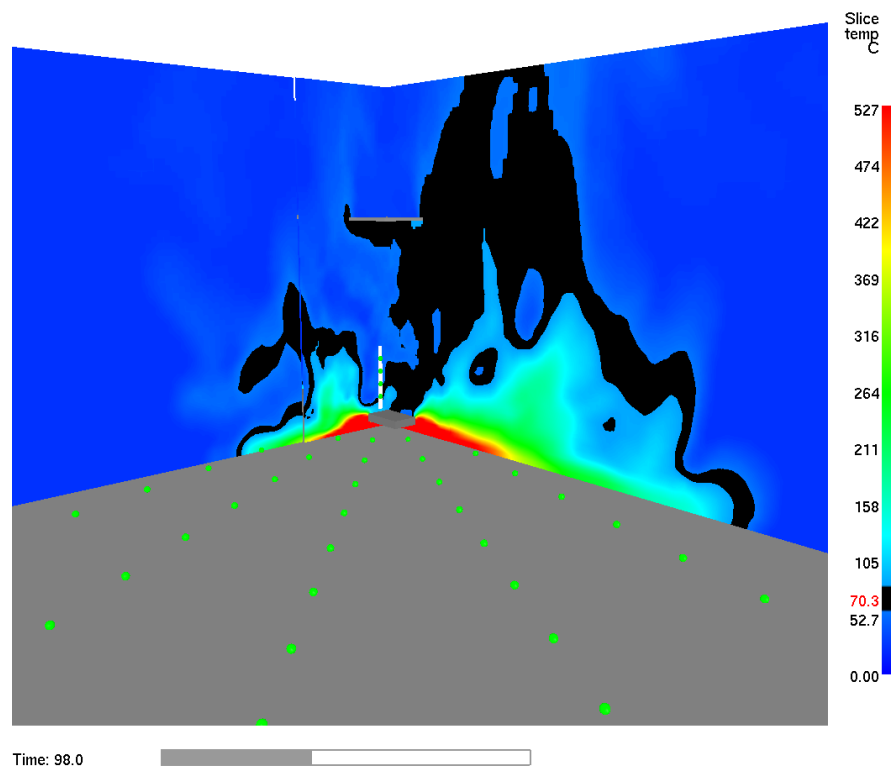



Figure 7.5-23. Plume Temperatures in Two Normal Planes at Bore Center Line for Two Boosters Burning at 98 seconds after Ignition with the 70°C (158°F) Contour Highlighted by the Black Area (Scenario 1d)

The FDS results presented in Figure 7.5-23 compare well with the OVERFLOW results presented in Figures 7.5-6 and 7.5-14.

Figure 7.5-24 shows the predicted heat flux to the ground plane for two boosters burning in High Bay 3 (the lower left bay). The values shown include both radiative and convective fluxes and are instantaneous (not time-averaged) values. The plot indicates regions of high flux at the ground plane for significant distances from the VAB center. Fluxes over 15 kW/m² over the duration of the booster burn have the potential to ignite combustible materials, and fluxes exceeding 1.7 kW/m² (no harm limit) would be likely to cause 2nd degree burns.

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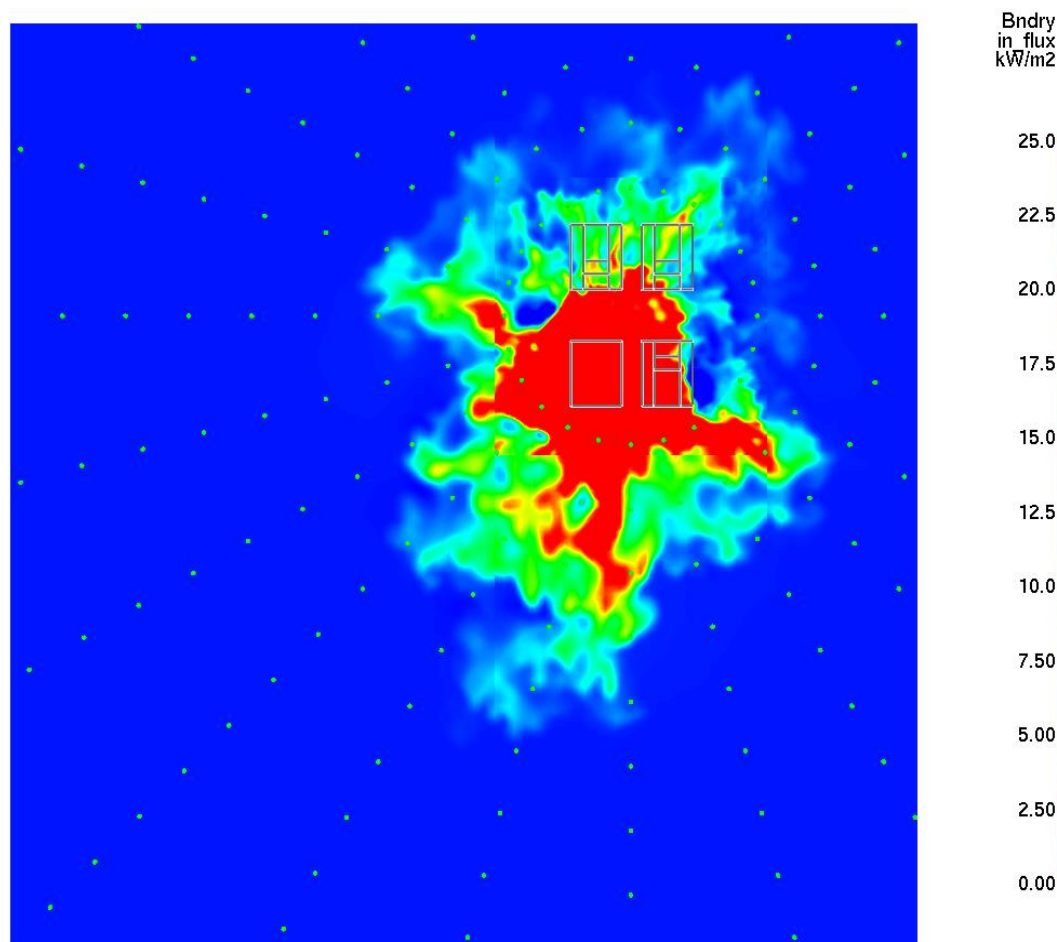



Figure 7.5-24. Incident Heat Flux at the Ground Plane for Two Boosters Burning in High Bay 3 at 92 seconds after Ignition (Scenario 1d)

Note: In this Figure High Bay 3 is in the lower left corner.

Figure 7.5-25 shows the FDS-predicted radiative flux to targets located along the line $x = y$ in Figure 7.5-24 at an elevation of 2 m (6.6 ft) and pointed toward the VAB center line. Note the y-axis for each plot is a log scale. Each line represents one of the measurement locations as shown in Figure 7.5-22. Each line of measurement locations shown on the ground plane in Figure 7.5-22 resulted in a similar set of curves, all of which were used as inputs to the burn model. It is noted that these curves only account for the radiative flux. As a reference, the no-harm limit for total heat-flux exposure, plume plus solar insolation, is 1.7 kW/m^2 . The rapid drop in flux exceeds that expected by the assumption of either a point source (radial distance⁻²)

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or a planar source (distance^{-1}) indicating that the shroud of colder smoke in the buoyant portion of the plume is acting to shield the hot core.

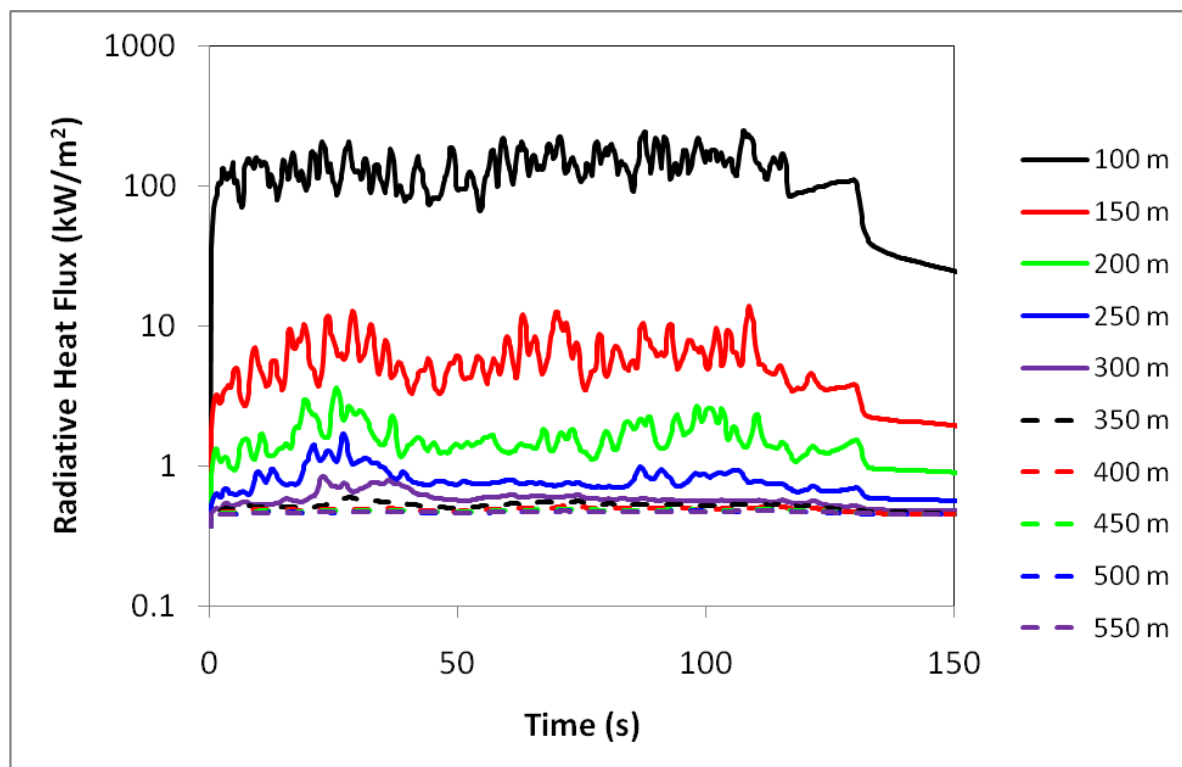



Figure 7.5-25. Radiative Heat Flux along Line $x = y$ for One Motor Pair (Scenario 1d)

Figure 7.5-26 presents the result of the skin response model computations given the heat-flux data from Figure 7.5-25 plus the maximum ambient solar insolation. A computation was performed using the data points in the quadrant containing the burning boosters. Since the initiating boosters could be located in any of the High Bays, the data points from that quadrant were reflected across the symmetry axes to the other three quadrants. The resulting burn map is shown in Figure 7.5-26.

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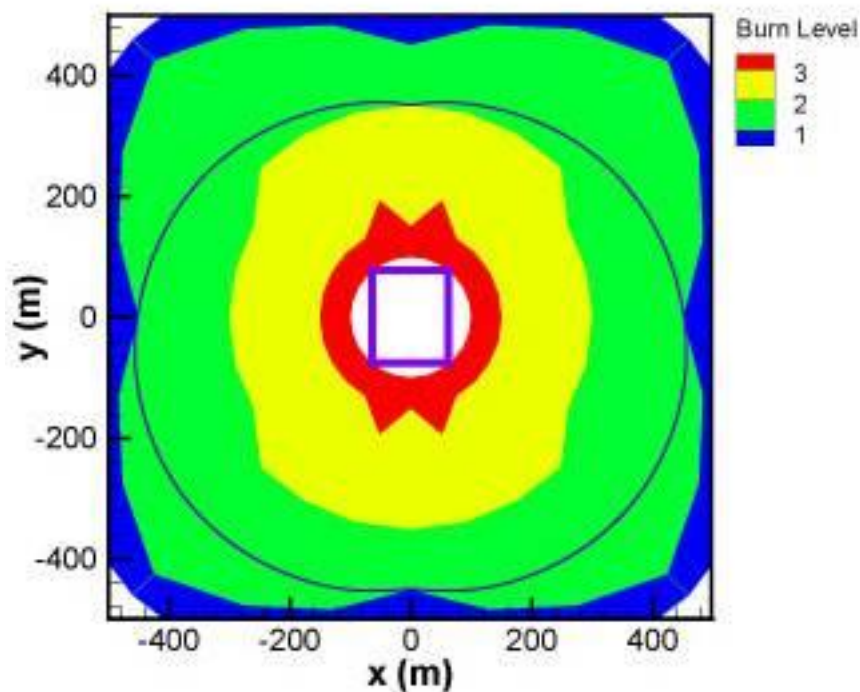



Figure 7.5-26. Contour Map of Burn Level as a Function of Position Around the VAB for One Motor Pair (Including 1.5 Safety Factor that Effectively Decreases Exposure Time and Solar Insolation) for Scenario 1d

Note: The yellow region is the area where 2nd degree burns would occur. The blue oval indicates the existing QD arc.

Distances in the Figure 7.5-26 are measured from the VAB centroid. The purple rectangle represents the VAB with High Bays 3 and 1 located at the bottom of the purple rectangle. The blue oval is an approximation of the current QD arc as determined by the DoD tables based on $k \text{ factor} \times (\text{weight})^{1/3}$, with the arcs drawn from the centers of High Bays 1 and 3. The levels of burn are indicated by colored regions, with the blue being the region of no harm, the green being regions where combinations of heat fluxes and exposure times would produce 1st degree burns, the yellow regions where 2nd degree burns would occur, and the red where 3rd degree burns would occur.

Figure 7.5-26 shows that if two boosters are burning, regardless of the High Bay location, the safe separation line, based on the prevention of 2nd degree burns criterion, lies within the existing QD arcs established for the SSP. Even though there are eight 5-segment boosters within the VAB with a total combined weight of approximately 5.4 million kg (12 million lbs) of hazard division 1.3 classification solid propellant, the safe separation distance for inadvertent

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combustion of boosters is within the current QD established for SSP with four 4-segment boosters (approximately 2.2 million kg (4.8 million lbs) of propellant). The underlying reason for this circumstance is that the current Scenario 1d analysis shows only two boosters would burn; the other boosters would not ignite before the first two boosters burned out. The heat flux from these two burning boosters, the heat flux-exposure time burn results, and the prevention of 2nd degree burns criterion would result in the contours as shown in Figure 7.5-26.

It is of interest to assess the extent of the safe separation zone if four 5-segment boosters burned at the same time, even though the OVERFLOW analysis indicates that only the initial two boosters would burn. Figure 7.5-27 presents the results for such a possibility.

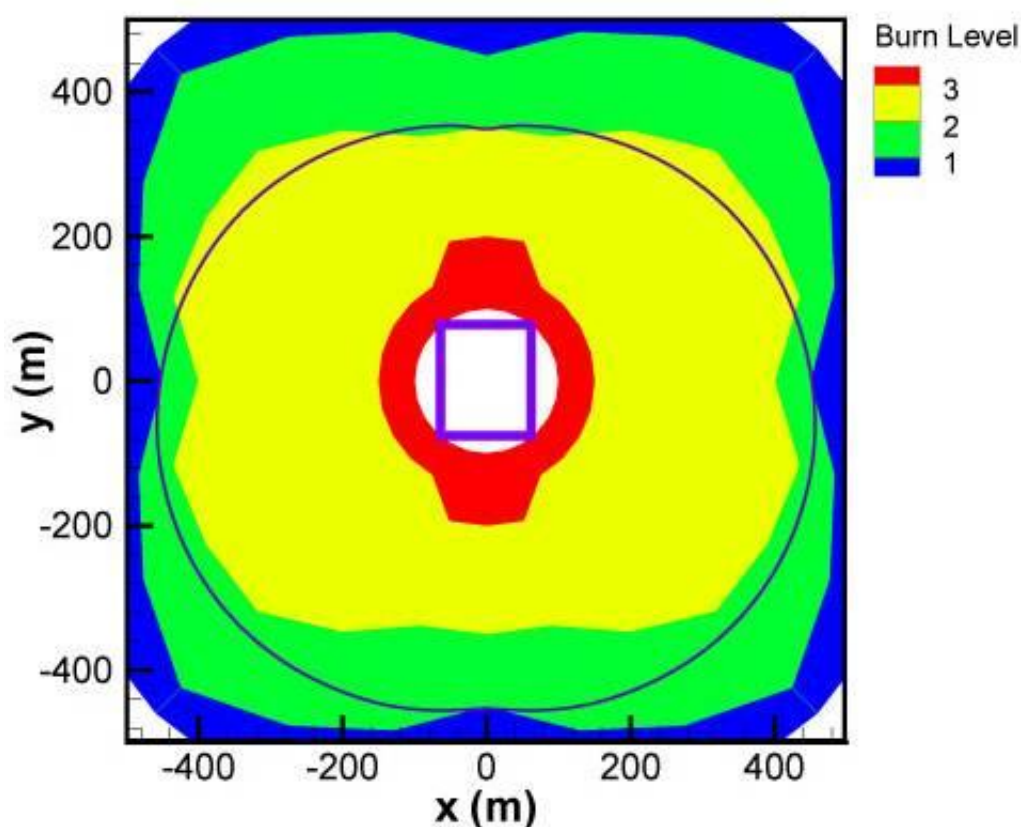



Figure 7.5-27. Contour Map of Burn Level as a Function of Position Around the VAB with Four Boosters Burning (Including Safety Factor and Solar Insolation)

For the case of four 5-segment boosters burning, it can be seen that the transition from 1st to 2nd degree burns occurs for the most part within the current QD arc, but there are two regions that

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fall outside the QD arc. This occurs in large part because the current QD arc in the DoD weight-based approach is drawn with 400-m (1,312-ft) radius circular arcs drawn from High Bays 1 and 3 (residing in the lower part of the purple rectangle).


The contours shown in Figures 7.5-26 and 7.5-27 address the safe separation distances for preventing 2nd degree burns, but it must also be remembered that direct exposure to the exhaust plumes that exist within these safe separation zones should also be considered.

7.5.5 The NAWCWD, China Lake Approach to Determining Safe Separation Distances from Radiation from Burning Boosters

A second approach was used to calculate thermal radiation from the exhaust plumes that had been determined using the results of the OVERFLOW calculations. This second approach used the radiant heat transfer model within the CFD package Star-CCM+. Post processing was performed to compute the 2nd degree burn exposure time limits. As seen in the results in Section 7.5.1, the exhaust plumes do not propagate symmetrically from the VAB. Plume flow exceeded the computational domain used in the OVERFLOW calculations of Section 7.5.1 (approximately 344 x 428 m (1130 x 1405 ft) on a side). Jets escaping the domain made it difficult to determine the exposure limits in those areas. By extrapolating the flow field beyond the OVERFLOW CFD domain, it was possible to estimate the extent of the plumes and exposure limit contours.

This study also included several sensitivity analyses that addressed the effects of aluminum oxide particle size distribution, low-temperature gas absorption coefficients, and aluminum oxide refractive indices. None of these variables were found to produce significant changes in the results and findings.

These predictions yielded exposure limit contours within the domain used in the OVERFLOW calculations for various simulation times and for extrapolated results for regions outside the OVERFLOW domain. The extrapolated results are shown in Figure 7.5-28.

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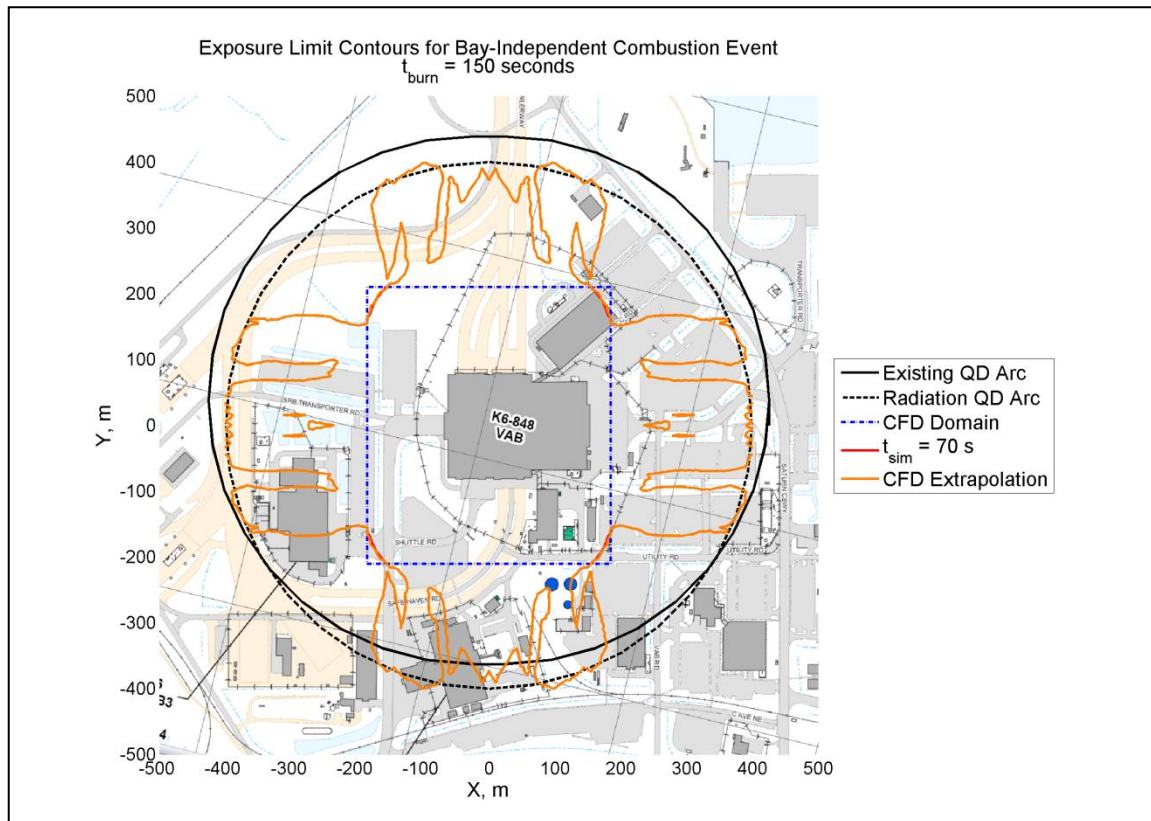



Figure 7.5-28. Exposure Limit Contours (Extrapolation), High Bay-independent Combustion Event, $t_{sim} = 70$ seconds

The blue box in Figure 7.5-28 represents the domain used in the OVERFLOW calculations. To simulate the exposure limit contour associated with a combustion event occurring in any of the four possible High Bays, the High Bay 3 results were mirrored about the domain x- and y-axes. The resulting exposure limit contour plot can be seen as Figure 7.5-28. Based on these exposure limit contours, a radiation safety arc can be established with a radius of 400 m (1,312 ft), as measured from the VAB center.

Since the existing VAB QD arc is 400 m (1,312 ft) (as measured from the center of High Bays 1 and 3), the radiation exposure safety limit arc largely lies within the existing QD arc. The radiation safe separation arc exceeds the existing QD arc only at the bottom of the plot (Western region). Most of the buildings encompassed by the 400-m (1,312-ft) radiation-determined safe separation distance are also encompassed by the QD arc determined for the SSP.

The 400-m (1,312-ft) safe separation distance includes a 7-m (23-ft) portion (corner) of the Operations Support Building (OSB) cafeteria that had not been previously included in the QD arcs for the SSP. The portion of the cafeteria within the 400-m (1,312-ft) arc is shown in detail

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in Figure 7.5-29. Because the building is at the extreme distance (>390 m (1,279 ft)), the intensity of heat flux diminishes with the square of distance, and the building may offer some level of protection from direct exposure, this corner may be considered safe as is, or with minor modifications.

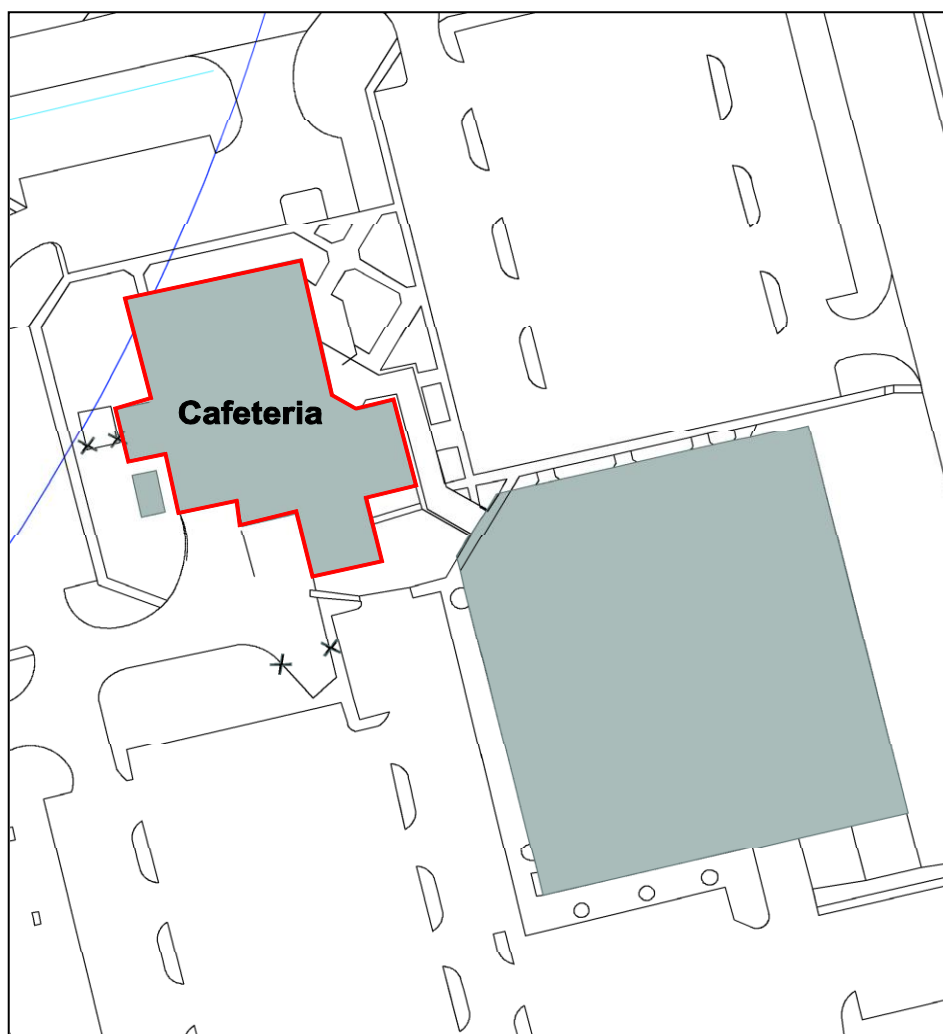



Figure 7.5-29. View Showing the 400-m (1,312-ft) Safe Separation Distance Arc (Blue Segment Intersects Upper Left Corner of the Cafeteria) (Source: Justin Oliveira)

7.6 Ignition of Boosters Due to Radiation from Exhaust Plumes to Casing and Heat Transfer through Casing, Insulation, and Liner to the Solid Propellant

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In all of the scenarios discussed in this report, it was assumed that ignition of other boosters following inadvertent ignition of the first pair would be due to failure of the nozzle plug, with subsequent penetration of gases into the booster bore and transfer of energy to the solid propellant surface. Ignition of boosters via radiation from exhaust plumes and subsequent heat transfer through the booster casing, insulator, and liner was recognized as another possibility. However, preliminary investigations of exhaust plume flow and location led to choosing the through-the-bore ignition as the most likely cause of ignition of other boosters. As part of the Scenario 1d study, this assumption was examined. Two separate analyses were performed: a relatively simple spreadsheet analysis performed by NAWCWD, China Lake, and one by HAI using FDS analysis. The results of the two analyses are presented in the follow section.


7.6.1 NAWCWD, China Lake Analysis of Ignition Occurring through the Booster Casing

This effort consisted of two parts. The first part used the OVERFLOW results to calculate heat fluxes to the booster case. The second part used a one-dimensional (1D) transient analysis that started with various heat fluxes to the casing surface and then determined heat conduction through the steel casing, insulator, and liner and into the solid propellant.

The calculations of peak radiant flux from the plume to the booster case gave results of 275 kW/m² at the booster top segment and 303 kW/m² at the bottom segment. These values were compared to values from 340 to 375 kW/m² obtained from the SSP Full Scale Motor (FSM)-14 firing with a sensor 34 m (112 ft) from the nozzle exit.

The 1D heat transfer through the case, insulator, and liner into the propellant was calculated for three different heat-flux values at the steel case external surface: 110, 295, and 360 kW/m². These values are in the typical range of calculated and experimental values.

The results of these calculations are presented in Figures 7.6-1 through 7.6-3.

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110 kW/m²

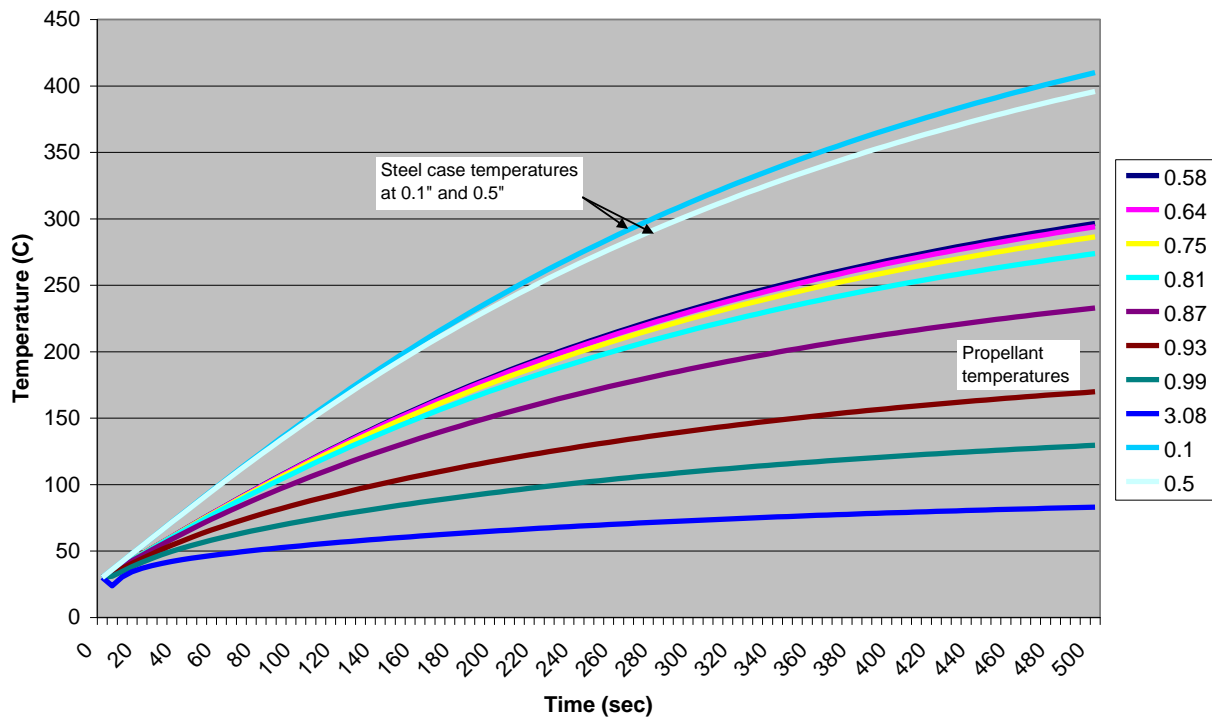



Figure 7.6-1. Time-temperature Profiles for Steel Booster Casing and Propellant Depths Ranging from Propellant-insulator Interface ($x = 1.5$ cm (0.58 in.)) to depth of 6.4 cm (2.5 in.) ($x = 7.8$ cm (3.08 in.)) for 110 kW/m² Incident Heat Flux

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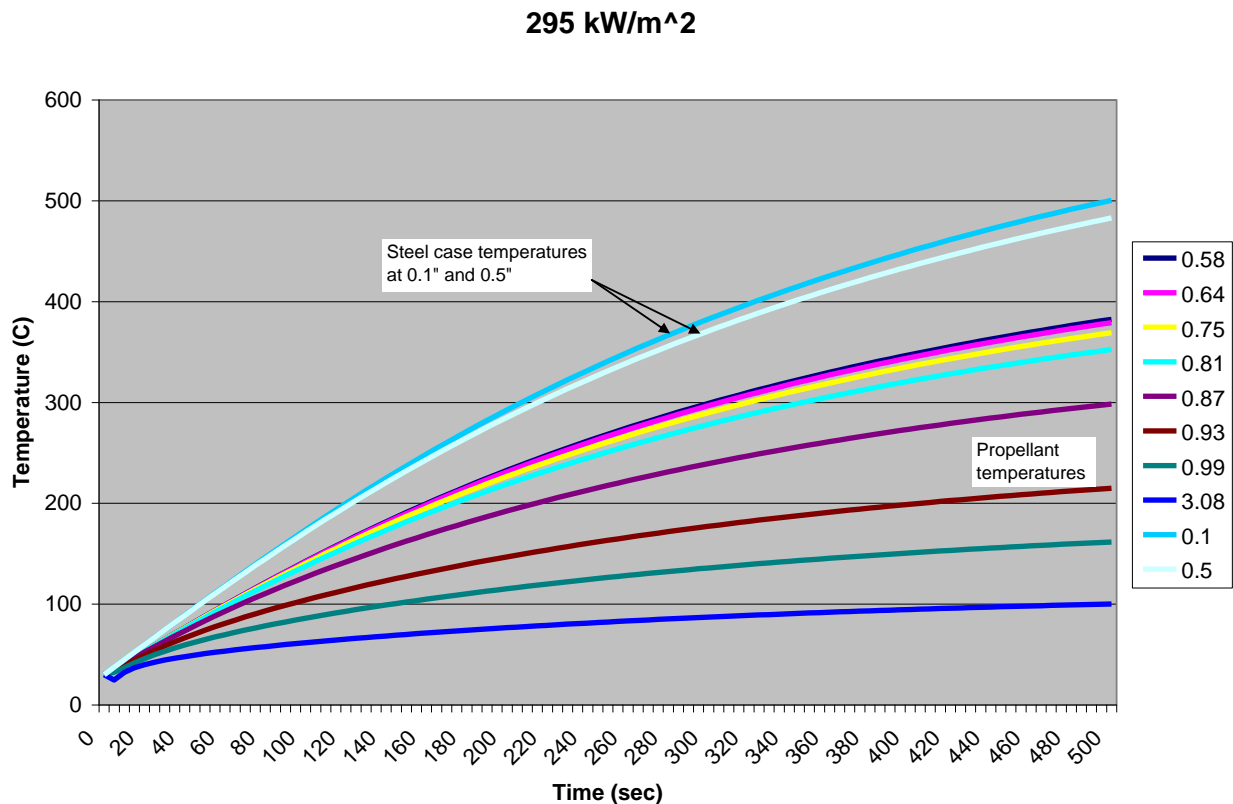



Figure 7.6-2. Time-temperature Profiles for Steel Booster Casing and Propellant Depths Ranging from Propellant-insulator Interface ($x = 1.5$ cm (0.58 in.)) to depth of 6.4 cm (2.5 in.) ($x = 7.8$ cm (3.08 in.)) for 295 kW/m² Incident Heat Flux

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360 kW/m²

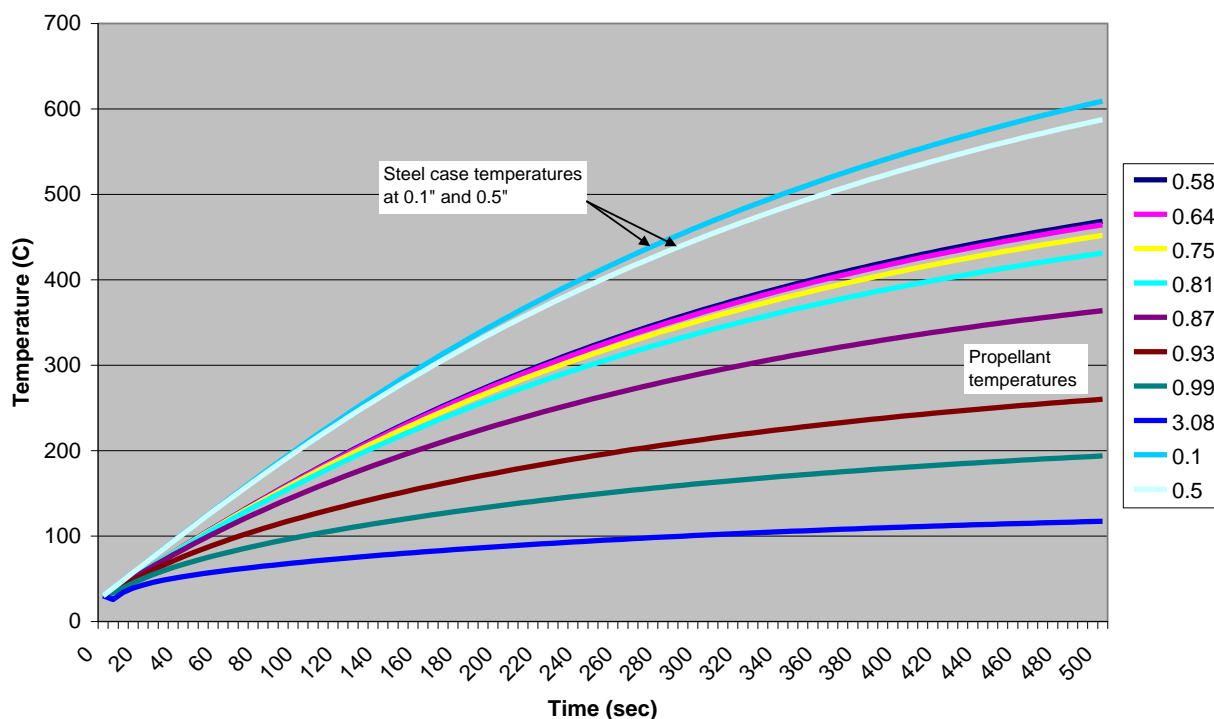


Figure 7.6-3. Time-temperature Profiles for Steel Booster Casing and Propellant Depths Ranging from Propellant-insulator Interface ($x = 1.5$ cm (0.58 in.)) to depth of 6.4 cm (2.5 in.) ($x = 7.8$ cm (3.08 in.)) for 360 kW/m² Incident Heat Flux

Figures 7.6-1, -2, and -3 show that the propellant temperatures are too low ($< 260^{\circ}\text{C}$ (500°F)) to achieve ignition of the propellant in the time that boosters are burning (approximately 125 seconds). The ignition temperature is higher than 260°C (500°F) at these fluxes.


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Table 7.6-1. Time to Reach 260°C for Three Flux Levels

External Flux to Booster Casing, kW/m ²	Time to Reach 260°C (500°F), seconds
110	370
295	238
360	180

7.6.2 HAI Analysis of Ignition Occurring through the Booster Casing

As part of the FDS simulations described in Section 7.5.4, radiation from the exhaust plumes to other booster casings was investigated. The ten locations with the highest propellant temperatures were determined. The propellant temperature histories are plotted in Figure 7.6-4.

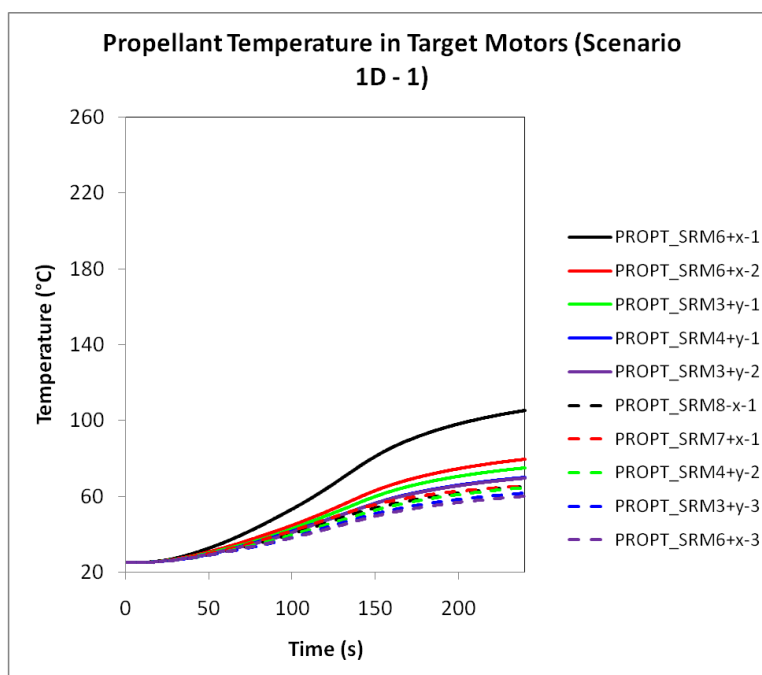



Figure 7.6-4. Highest Predicted Propellant Temperatures at SRM Measurement Locations for Two Boosters Burning

Note: Heating continues beyond the 2-minute burn duration due to thermal carry-over from the heated steel case.

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These temperatures are below the 260°C (500°F) ignition criterion and would be insufficient to cause propellant ignition. An analysis was also performed for four, six, and eight 5-segment boosters burning and the temperatures predicted remained too low to cause propellant ignition from heat transfer through the casing.

7.7 Comparison of Scenario 3d to Scenario 1d


Scenario 3d: Two 4-segment stacks are initially burning within one VAB High Bay. The VAB interior and exterior walls have been removed.

Scenario 1d: Two boosters are initially burning in the VAB. The VAB interior and exterior walls have been removed.

The NESC Modeling Team also considered the question of whether the accidental ignition of 4-segment stacks might be a worse case scenario than inadvertent ignition of two fully assembled 5-segment boosters. This concern arose because a 4-segment stack would have plume coming from the top of the uncompleted stack and from the bottom through the nozzle, and the 4-segment stack burns for about 4.5 minutes versus 130 seconds for a 5-segment booster.

To address this, Scenario 3d was performed using OVERFLOW to see if the energy release from 4-segment stacks might cause ignition of 5-segment boosters in the adjacent High Bays. The analysis assumed that, as occurred in Scenario 1d, the VAB walls would be lost during the initiation of the event. The analysis used flow data provided by ATK Space Systems for both the flow from the opening at the top of the stack and the flow through the nozzle. Since the flow rate through the nozzle is decreased (versus the flow rate from a normal booster), the ground plume does not travel as quickly to the adjacent High Bays. The plume from the top of the 4-segment stack travels upward toward the ceiling and exits the VAB around the sides far above the 5-segment boosters located in the adjacent High Bays (see Figure 7.7-1).

While a 4-segment stack burns for approximately 4.5 minutes, the OVERFLOW calculations for Scenario 3d were run for only 25 seconds of burn time. At that time it was decided that Scenario 1d was a worse case than Scenario 3d if ignition through the bore was considered. However, ignition through the booster casings due to radiation was not investigated for Scenario 3d.

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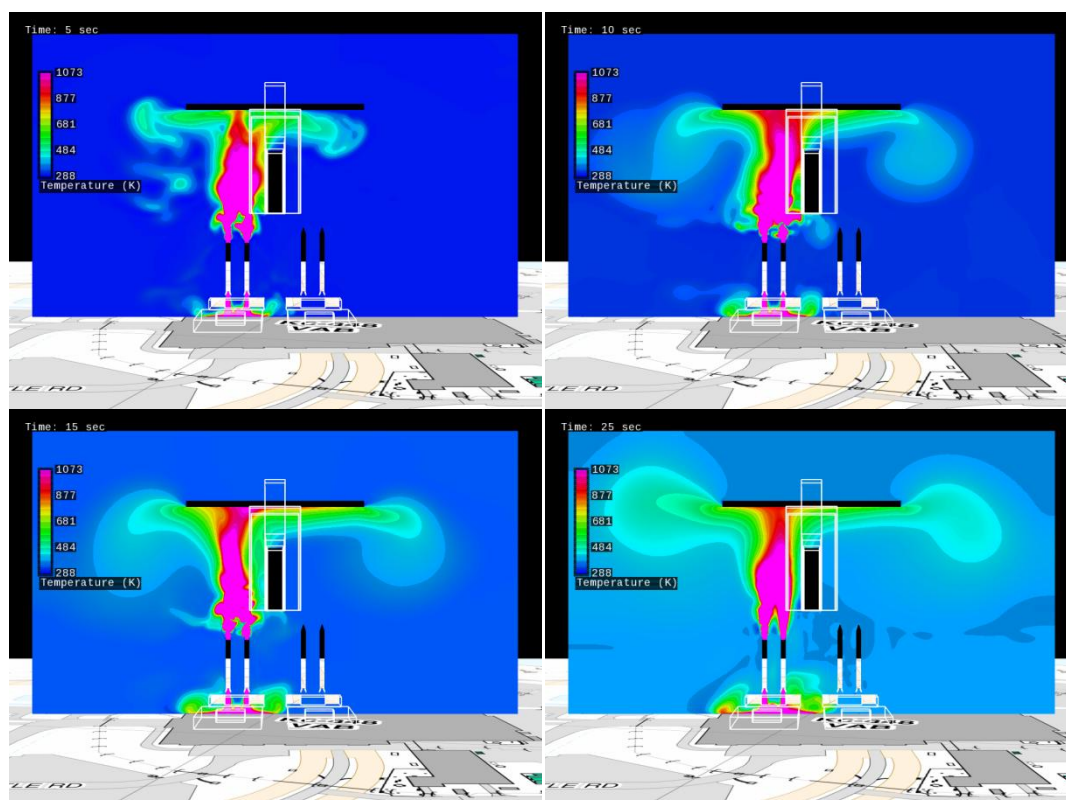



Figure 7.7-1. Instantaneous Temperature Contours on a Cutting Plane through High Bays 3 and 1 from 5–25 seconds for Scenario 3d

7.8 Summary and Conclusions for Scenario 1d

1. Because the VAB external wall panels fail during the inadvertent ignition of the first two boosters, the exhaust plumes and associated energy expand well outside the original VAB confines.
2. This expansion and release of energy prevent the ignition of the other boosters. Only the original two boosters burn.
3. The exhaust plumes expand out to approximately 200 m (656 ft) as measured from the VAB center with some jets expanding out even further. Personnel within these areas will be fatalities or severely injured.
4. Temperatures and fluxes within portions of the plume extension are sufficient to ignite combustible materials.
5. Two different heat-flux analyses were conducted and the conclusions were similar. In one analysis, the safe separation distances were within the existing QD arcs associated with the

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SSP. In the other analysis, the safe separation distance was outside of the existing QD arc on the western portion where the current QD arcs already encompass existing buildings such as the two Orbiter Processing Facility (OPF) buildings. Based on these analyses, 400 m (1,312 ft) from the VAB center was chosen to be the safe separation distance. This safe separation distance, determined using the heat-flux approach for eight 5-segment boosters (Scenario 1d) in the VAB, is within the existing arcs determined for SSP using the DoD weight-based QD tables, or slightly outside the existing QD arc in already impacted areas. The 400-m (1,312-ft) safe separation distance includes a 7-m (23-ft) portion (corner) of the cafeteria that had not been previously included in the QD arcs for Space Shuttle. Because the building is at the extreme distance (>390 m (1,279 ft)), the intensity of heat flux diminishes with the square of distance, and the building may offer some level of protection from direct exposure, this corner may be considered safe as is or with some very minor modifications.

6. Radiation from the exhaust plumes to the booster casing is not sufficient to cause ignition due to conduction through the casing for Scenario 1d.

8.0 Findings, Observations, and NESC Recommendations

The following Findings, Observations, and NESC Recommendations are based on the work described in this report, primarily the efforts focusing on Scenario 1d (two 5-segment boosters in each VAB High Bay for a total of eight 5-segment boosters). This report describes analyses and experiments in support of the determination of safe separation distances from the VAB to the surrounding buildings and personnel from heat flux resulting from inadvertent ignition and combustion of solid propellant boosters in the VAB. The safe separation distance analyses are based only on the response of humans to the temperature and heat fluxes from the combustion event(s) and do not consider ballistic, acoustic, or toxic gas hazards. At the beginning of this study, it was determined that this effort was to consider only combustion of the boosters in their original location on the MLP. Considerations defined as being out of scope for this effort include the following:

- Analysis of boosters going propulsive within the VAB or toppled from their original location.

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- Structural response of the VAB and ramifications (e.g., building collapse, fragment throw), other than:
 - Destruction of interior cinder block walls (e.g., flow considerations).
 - Failure of exterior VAB wall panels (e.g., venting and increased radiation view factors).
- Hazards from toxic species in the booster exhaust plume.
- Hazards associated with related hardware and facility hypergolic liquid fuels (e.g., explosion and toxic plume).
- Interactions between a hypergolic fire and one or more boosters.
- Increased burn area due to damage of propellant and associated increase in energy release rate.
- Egress of personnel from the VAB or the surrounding area.
- Mitigation studies (e.g., improved nozzle plug, strengthened internal walls between adjacent High Bays, installation of larger sprinkler systems, or changes in VAB venting strategy).
- Acoustic hazards associated with boosters burning in the VAB.

While these considerations are important and may contribute to the establishment of a modified safe separation distance, they were not considered in this study and are not reflected in the following Findings, Observations, and NESC Recommendations. These considerations may contribute to the probability of occurrence, the evolution of the accident, the severity of the consequences, and/or the safe separation distances.

8.1 Findings


The following NESC team findings were identified:

- F-1.** Configuration of the booster segments (i.e., all-up 5-segment boosters versus partial stacks versus individual segments) determines the energy release rates and burn times and is an extremely critical determinant in the heat-flux-based analytic approach.
- Previous studies based safe separation distances on the weight of propellant contained in the VAB. Using this approach, the configuration of booster segments in the VAB is not important. However, when using a heat-flux-based approach the configuration is extremely important because it determines the energy-release rate and burn time. These determine the ignition of other boosters, how many boosters are burning, and the heat flux-exposure time at

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distance, which in turn determine the safe separation distance (see Sections 7.2 and 7.5).

- F-2.** The safe separation distance from the VAB (calculated from this program) is based on preventing 2nd degree burns.
- Second degree burns occur as a result of the radiative heat-flux levels over the duration of the accident. Death is likely to occur when a person's body is covered with large areas of 2nd degree burns. Because of uncertainties in the data and models for skin injury, as well as variations in human response to burns due to factors such as age, a safety factor of 1.5 was applied to the computed skin damage to accommodate the range of conditions (as recommended by *SFPE Engineering Guide*, March 2000. See Section 7.4.3). The analyses applied the flux-exposure times from the exhaust-plume calculations and mapped regions where 1st, 2nd, and 3rd degree burns were likely to occur. The distances where 1st degree burns transitioned to 2nd degree burns determined the locations of the safe separation arcs.
- F-3.** Concrete masonry walls separating High Bays 3 and 1 and High Bays 4 and 2 fail due to pressure from ignited boosters.
- Contrary to assumptions made in previous VAB solid booster hazard studies, the concrete masonry interior walls separating High Bays 3 and 1 and High Bays 4 and 2 are found to fail due to pressure build-up when boosters ignite in any of the bays. This allows the exhaust plume to flow from one High Bay to another as opposed to channeling the flow across the transfer aisle (see Sections 7.3–5).
- F-4.** Exterior wall panels fail quickly due to overpressure when boosters inadvertently ignite within the VAB.
- Contrary to assumptions made in previous VAB solid booster hazard studies, the exterior wall panels fail quickly due to overpressure when boosters inadvertently ignite within the VAB. The panel failure allows the exhaust plumes to vent from the VAB, significantly reducing the thermal exposure to boosters in adjacent High Bays (see Section 7.5).
- F-5.** Venting of exhaust plumes from the VAB prevents the ignition of additional boosters in the VAB.

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- This event is discussed in Scenario 1d (see Section 7.5). Note that the inadvertent ignition of two boosters could initially occur in any of the High Bays. Any safe separation considerations should reflect this possibility.

F-6. The safe separation distance that was determined using the heat-flux approach for eight 5-segment boosters in the VAB is a circle with a 400-m (1,312-ft) radius from the VAB High Bay center.

- This circle with a 400-m (1,312-ft) radius from the VAB center encompasses the 1st degree to 2nd degree burn transition thresholds that were determined from the independent human-response-to-radiation analyses conducted in this study (see Sections 7.5.4 and 7.5.5). Personnel located at distances greater than this distance will not receive 2nd degree burns in the unlikely event of booster ignition in the VAB.


F-7. The 400-m (1,312-ft) safe separation distance is largely within the existing arc determined for the SSP four 4-segment boosters using the DoD weight-based approach.

- The safe separation distance—determined using the heat-flux approach for eight 5-segment boosters (Scenario 1d) in the VAB—is slightly different from the existing QD arc determined for four 4-segment boosters in High Bays 3 and 1 for the SSP (400-m (1,312-ft) radius circles from High Bays 3 and 1 with tangents connecting the two circles). The circle with the 400-m (1,312-ft) radius is within the SSP QD arc, except for a small region to the West of the VAB (see Sections 7.5.4–5).

F-8. The 400-m (1,312-ft) safe separation distance encompasses portions of some existing buildings.

- For example, portions of the two OPF buildings are included within the 400-m (1,312-ft) safe separation distance and within the QD arc determined for the SSP. The 400-m (1,312-ft) safe separation distance includes a 7-m (23-ft) corner of the OSB cafeteria that is outside the original SSP QD arc (see Section 7.5.5).

F-9. Exhaust plumes expand so rapidly and the temperatures are so high, any personnel within the open area of approximately 200 to 300 m (656 to 984 ft) from the VAB center will quickly expire due to exposure to the exhaust plumes.

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- Within the 400-m (1,312-ft) safe separation distance, exhaust plumes (with temperatures >1000 K (1,340°F)) quickly expand more than 200 m (656 ft) from the VAB center (see Section 7.5).

F-10. Ignition of additional boosters following the inadvertent ignition of the first pair is more likely to occur due to exhaust products that cause the nozzle plug to fail and allow the exhaust products to enter the booster bore resulting in ignition, rather than due to absorption of radiation from the exhaust plumes of the first burning boosters through the cases of other boosters.


- This finding is based on calculations, not experimental data. A literature search found some references to ignition through the case in studies of fast cook-off of tactical missile motors engulfed in fuel fires. No studies were conducted on motors approaching the size and construction of booster motors (see Section 7.5).

F-11. Experimental data on the ignition of propellant at the low fluxes typical of hazard scenarios closely match the extrapolation of experimental data from high fluxes typical of operational ignition of boosters/motors. This extrapolation was done early in the program before experimental data were available at low heat fluxes.

- Because propellant ignition data were not available at the low-heat fluxes typical of inadvertent ignition, extrapolations of two orders of magnitude in time and one order of magnitude decrease in heat flux were made. These extrapolations represented a significant technical risk until data were obtained at the lower heat fluxes.

F-12. Two burning 5-segment boosters are a more severe threat for inadvertent ignition by exhaust products entering the bores of other boosters than are two 4-segment stacks (no top segment/cap) burning.


- The two 5-segment boosters burning result in exhaust plumes impinging on the floor and spreading to the adjacent High Bays while the two 4-segment stacks (minus the top segment/cap) burning have exhaust plumes exiting through the nozzles and the tops of the uncapped stack. While analyses indicated that the two boosters burning in one High Bay would not cause ignition through the casing of other boosters in other bays, ignition through the casing was not studied for radiation from two 4-segment stacks burning (see Section 7.5).

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8.2 Observations

The following observations were identified by the NESC team:

- O-1.** KSC applied the DoD weight-based methodology to establish QD arcs for the SSP, but do not follow normal DoD exclusion methods.
 - When DoD defines a hazard arc/safe separation distance, non-essential personnel are usually excluded within that arc or space, especially if there is a possibility of death(s) occurring. Personnel not part of the hazardous operation that generates the hazard arc are not allowed within the hazard arc. Typically, this is enforced by fencing at the perimeter and in some instances, using security personnel. While there is fencing around the VAB with guard posts, it is within the arc and there is no fencing at the arc perimeter. This allows nonessential personnel to be within the hazard arc (e.g., personnel in parking lots adjacent to the VAB, tour buses, and workers in the VAB) who are not associated with the hazardous operation. Findings F-6 and F-7 show that personnel within the safe separation distance would suffer 2nd (and in some instances 3rd) degree burns and fatalities in the event of an inadvertent booster ignition, given the current configuration of the facilities.
- O-2.** Personnel within the 400-m (1,312-ft) safe separation distance may be afforded some protection by “shelter-in-place” by staying within buildings (e.g., the OPF buildings) or behind barricades.
 - The analyses for 2nd degree burns and the resulting contours assumed the affected personnel would have direct exposure to the radiation. Any means of reducing the exposure to heat flux increases the chances of survival. The reduction afforded by buildings and barricades was not addressed in this study.
- O-3.** While safe separation distance analyses do not consider the probability of an inadvertent ignition (assumes a probability of one), the probability of an inadvertent incident may be reduced by policy, procedures, and training (see Section 6.1).
- O-4.** Other considerations outlined at the beginning of the Findings, Observations, and NESC Recommendations section, deemed out of scope for this study, may have serious consequences.
 - This study only addressed safe separation considerations of thermal hazards to humans resulting from inadvertent ignition of boosters that remain within the


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VAB (boosters do not go propulsive or topple) and the associated exhaust plumes and radiation. The other, out-of-scope considerations should be addressed as part of an MCE analysis.

- O-5.** Analysis of Scenario 3 (inadvertent ignition of uncapped stacks during the stacking operation) was not fully completed in this study (e.g., the possibility of ignition of adjacent boosters due to radiation from plumes exiting the nozzles and upper portion of the stacks).
 - While exhaust plumes exiting the nozzles of the 4-segment stacks and entering the bores of boosters in adjacent High Bays were considered, ignition through the booster casings due to radiation from the plumes exiting the nozzles and the tops of the 4-segment stacks was not analyzed.
- O-6.** In the Scenario 1d (two boosters burning, no interior walls in VAB, no external wall panels) analysis, the extent of the plumes exceeded the domain \pm approximately 200 m (656 ft) of the OVERFLOW CFD calculations (see Section 7.5).
- O-7.** While this study excluded consideration of the toxicity of the exhaust plumes, it did show the location of the exhaust plumes.
 - This study did not consider wind strength and direction nor did it include other weather effects. This would need to be considered for a toxicity-of-plumes study.
- O-8.** This study used SSP SRM design segments because the Ares I booster system design has not been finalized. The booster configuration used was the 5-segment SSP RSRM design.
 - Near the end of this study, a 5.5-segment booster design was identified. Analyses of this design was started, but not completed.

8.3 NESC Recommendations

The following NESC recommendations were identified and are directed toward KSC unless otherwise identified:

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- R-1.** NASA HQ and KSC should establish a minimum safe separation distance of 400 m (1,312 ft) from the VAB High Bay center and make the area within this radius an exclusionary zone. *(F-2, F-6, and O-1)*

- R-2.** The area within the safe separation distance (hazard arc) around the VAB should be deemed an exclusion zone and provided with physical security (fences and controlled access or guards) to prevent unprotected non-essential or transient personnel uncontrolled access to areas within the hazard arc. *(F-2, F-6, F-9, and O-1)*

- R-3.** While reduction of exposure to heat flux due to “shelter-in-place” or shelter behind barricades was not considered in these analyses, it should be considered in any formal site plan. *(F-6, F-8, and O-2)*


- R-4.** Any facility within 1.5 times the safe separation distance arc should have an established plan (including considerations such as “shelter in place,” HVAC shutdown, and egress corridors) to control and protect its occupants in the event of inadvertent ignition within the VAB. *(F-2 and F-6)*

- R-5.** KSC should continue to enforce policies and procedures and provide training and certification programs to reduce the potential of inadvertent ignition of boosters. *(O-3)*

- R-6.** Since the analyses dealing with ignition of boosters caused by thermal radiation to the booster casing and subsequent heat transfer through the casing, insulation, and liner to the propellant have not been validated by experimental data, it is recommended that such data be generated. Concurrent with the publication of this final report, experimental work is addressing this lack of data. *(F-10)*

- R-7.** Future work should examine the possibility of ignition through the booster casing for Scenario 3d (two 4-segment stacks burning in one High Bay, with no internal or external walls). *(O-5)*

- R-8.** If CFD analyses were to be conducted in the future to assess the extent of potential hazards to individuals not associated with VAB operations, a domain greater than the extent of the ground plume should be used. The domain should extend approximately 500 m (1,640 ft) from the VAB center. *(F-6, F-9, and O-6)*

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- R-9.** Several hazard considerations were deemed out of scope for this study. It is recommended that analyses of these out-of-scope items should be undertaken to complete the safe separation distance or MCE determination. *(F-6, O-4, and O-7)*
- R-10.** If the VAB configuration significantly changes, or a booster system containing more than 5 segments or having a design radically different than the existing SSP SRM design were to be considered instead of the 5-segment boosters addressed in this study, the methods used in this study should be applied to the new VAB configuration and/or the booster system. *(F-1, F-2, F-3, F-4, F-5, F-6, and O-8)*

9.0 Alternative Viewpoints


No Alternative Viewpoints were provided to date for this assessment.

10.0 Other Deliverables

There are no Other Deliverables for this assessment.

11.0 Definitions of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment team to correct a root cause or deficiency identified during the investigation. The recommendations may


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be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.

Root Cause One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

12.0 Acronyms List


ARC	Ames Research Center
CEV	Crew Exploration Vehicle
CFD	Computational Fluid Dynamics
CxP	Constellation Program
DDESB	Department of Defense Explosives Safety Board
DoD	Department of Defense
FDS	Fire Dynamics Simulator
FSSIM	Fire and Smoke Simulator
HAI	Hughes Associates, Inc.
HQ	Headquarters
HULVUL	Hull Vulnerability
IBD	Inhabited Building Distance
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LaRC	Langley Research Center
MCE	Maximum Credible Event
MLP	Mobile Launch Platform
MSFC	Marshall Space Flight Center
MTSO	Management and Technical Support Office
NAWCWD	Naval Air Warfare Center Weapons Division
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OPF	Orbiter Processing Facility
ORM	Operational Risk Management
OSB	Operations Support Building
OSMA	Office of Safety and Mission Assurance
QD	Quantity-Distance
RAC	Risk Assessment Code
RSRM	Reusable Solid Rocket Motor

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S&MA	Safety and Mission Assurance
SEO	Systems Engineering Office
SFPE	Society of Fire Protection Engineers
SSC	Stennis Space Center
SSP	Space Shuttle Program
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
TIM	Technical Interchange Meeting
VAB	Vehicle Assembly Building

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