Quantity Distance
for the Kennedy Space Center Vehicle Assembly Building for Solid Propellant Fueled Launchers

Principal Authors
Steve Stover, Corey Diebler
Kennedy Space Center, FL

Wayne Frazier
Washington D.C.

ABSTRACT

The NASA KSC VAB was built to process Apollo launchers in the 1960's, and later adapted to process Space Shuttles. The VAB has served as a place to assemble solid rocket motors (SRM) and mate them to the vehicle's external fuel tank and Orbiter before rollout to the launch pad. As Space Shuttle is phased out, and new launchers are developed, the VAB may again be adapted to process these new launchers. Current launch vehicle designs call for continued and perhaps increased use of SRM segments; hence, the safe separation distances are in the process of being re-calculated.

Cognizant NASA personnel and the solid rocket contractor have revisited the above VAB QD considerations and suggest that it may be revised to allow a greater number of motor segments within the VAB. This revision assumes that an inadvertent ignition of one SRM stack in its High Bay need not cause immediate and complete involvement of boosters that are part of a vehicle in adjacent High Bay. To support this assumption, NASA and contractor personnel proposed a strawman test approach for obtaining subscale data that may be used to develop phenomenological insight and to develop confidence in an analysis model for later use on full-scale situations.

A team of subject matter experts in safety and siting of propellants and explosives were assembled to review the subscale test approach and provide options to NASA. Upon deliberations regarding the various options, the team arrived at some preliminary recommendations for NASA.

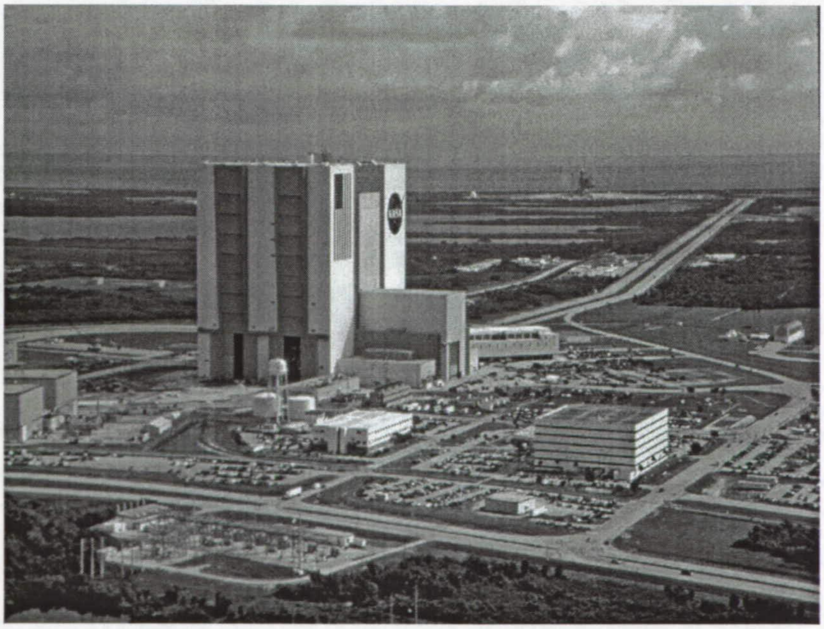

Figure 1.0 - Aerial View of KSC VAB Vicinity (view looking East)

INTRODUCTION

Note: This report has primarily been taken from the NASA Engineering and Safety Center, Document #: RP-06-31, "Review of the Test Plan to Update KSC VAB Propellant Safety Siting Methodology for Exploration Program"

The Vehicle Assembly Building (VAB) was built for processing Apollo launch vehicles in the 1960's and later adapted to process Space Shuttle launch vehicles. For the previous three decades, the VAB has served effectively as the location to assemble the Space Shuttle's solid rocket motors (SRM). Once fully assembled on a Mobile Launch Pad (MLP), the vehicle's External Tank (ET) is mated to the two SRMs. The Orbiter is then mated to the ET just prior to rollout to the launch pad. Additionally, the VAB is used as a safe haven for the Space Shuttle if severe weather forces the vehicle to return to shelter from the launch pad. As the Space Shuttle is phased out, and new launch vehicles are developed for NASA, the VAB may again be adapted to process these vehicles. Current launch vehicle designs call for continued use of SRM segments; hence the safe separation distances around the VAB are in the process of being re-examined in light of the new (increased) quantities of hazardous propellant that would be processed therein.

The VAB and its immediate environment are depicted in Figure 1.0-1. Specifically for the Space Shuttle Program (SSP), the Kennedy Space Center (KSC) Safety Office determined safe separation distances of 1,315 feet and 822 feet for the *inhabited building distance* (IBD) and the *intraline distance* (ILD), respectively. This calculation was made using Department of Defense (DoD) explosives safety standards for approximately 4.4 million pounds of polubutadiene-acrylic acid-acrylonitrile copolymer (PBAN) solid propellant. This represents the combined quantity of propellant of four complete solid rocket boosters (SRB) or 16 complete SRM segments. This determination was made using conventional QD approach, in that it assumed that once an ignition event occurred, all 16 SRMs were immediately involved no matter what their configuration or location in the VAB. The distances specified represent the minimum safe separation that must be maintained from the VAB as a potential hazardous site to minimize facility or equipment damage, injury, or death to personnel.

Exploration launch vehicle operations in the VAB, specifically the Crew Launch Vehicle (CLV) and the Cargo Launch Vehicle (CaLV)[1], are expected to involve greater quantities of PBAN propellants. KSC personnel and the Reusable Solid Rocket Motor (RSRM) contractor ATK, have revisited the VAB QD considerations and suggest that it may be revised to allow a *greater* number of motor segments within the VAB. This revision assumes that an inadvertent ignition of one SRM stack or segment need not necessarily cause immediate and complete involvement of other stacks or segments within the VAB (within the High Bay or an adjacent High Bay). To support this assumption, ATK personnel outlined a strawman test approach for obtaining subscale data to develop phenomenological insight and confidence in an analysis model for later use on full-scale situations. This test approach is generally referred hereafter as the "DPT (DTP)"

.

Under the auspices of the NESC, a team of subject matter experts in safety and siting considerations of propellants and explosives was assembled to review the DTP approach and provide alternatives to the QD for the VAB. In addition to NASA team members, the team included experts from the DoD explosive safety organizations, as well as cognizant specialists who routinely support the Navy and Air Force SRM Programs. This NESC Consultation Team

---

[1] The CLV and CaLV were recently given names (Ares I and Ares V), but the new names will not be used in this report.

NCT) convened with personnel from KSC, ATK, Stennis Space Center (SSC), and NASA Headquarters (HQ) to review the basic set of necessary information. The NCT subsequently obtained further relevant information to arrive at recommendations for NASA as discussed below.

Scope

Since the original siting was performed more than 30 years ago, the experts discussed the current QD standards and methodology, and their interpretation with respect to the standards and methodology applied in the original evaluation.

No residual liquid propellant in the Orbiter or future launch vehicles was considered as part of the scope of this assessment. In the event that liquid propellant will be present in future vehicles in the VAB, a revised hazard analysis and a modified QD siting will be required.

The study did not evaluate the toxic or smoke effects of an inadvertent ignition of an SRM segment to the personnel within the VAB, or at distances beyond the VAB, or secondary effects of the plumes impacting any other hazardous or toxic material within the VAB. Toxic and smoke effects of burning SRM segments within the VAB have been addressed in several earlier studies, which the NCT reviewed as background. Those studies will be addressed in this report.

Also, since the Hazard Division 1.3 tables do not account for "flight" distances of propulsive segments or the throwing of firebrands as part of the QD calculations, these potential hazards from the burning SRM segments in the VAB were considered outside the scope of this study.

RESULTS AND DISCUSSION

Problem Description

The VAB is an ordnance operating facility because it is used to process and “stack” solid propellant filled SRM segments for the Space Shuttle Prorgram (SSP). Since solid propellant contains both a fuel and oxidizer material, an ignited fire involving the SRMs segments will burn vigorously. This could potentially spread heat, flame, smoke, combustion products to people and facilities in proximity. To protect the surrounding people and facilities from an incident involving inadvertant ignition of any solid propellant items in the VAB, NASA adopted a DoD explosives safety QD siting approach for managing explosives risk.

The NESC Consultation Team (NCT) considers that QD, in its simplest form, may be described as:

> *The establishment of safe separation distances from the hazardous facility to people and facilities to be protected, according to a set of formulas based on the type of explosive substances/articles present (characterized by their hazardous effects, such as blast overpressure, fragments/debris/firebrands, and thermal flux, and denoted by a United Nations [UN]/Department of Transportation (DoT) hazard class/division [Hazard Division]) and the quantity (weight) of the explosive substances/articles (material) present.*

Current KSC QD Methodology

The current KSC QD methodology is discussed below in light of Figures 2.0 and 3.0. For the current KSC VAB situation for SSP SRM processing, two High Bays are configured to process and stack the SRBs (see Figure 2.0). Each SRB consists of four stacked SRM segments (see Figure 3.0), and each SRB has two boosters on each side for a total of 2.2 million pounds of propellant for each complete vehicle. For two complete vehicles in two separate High Bays in the VAB, the total propellant weight is 4.4 million pounds. According to the QD tables, to determine the proper safe separation, all propellant in the VAB (4.4 million pounds, neglecting small amounts of pyrotechnics on the Orbiter or the ET), is assumed to be involved at once (worst-case). This assumption is made even though the Space Shuttle's SRMs could be physically separated by High Bay walls and interior open space (e.g. empty and unused office space). All propellant is also assumed to be concentrated in the nearest High Bay to the facility being protected. Using DoD (or NSS 1740.12) explosives safety QD tables for Hazard Division 1.3, the weight of propellant determines the required safety siting distance. Current VAB QD criteria for the UN hazard class 1.3 SRM segments for the SSP limits the total to 16 full segments[2] in the VAB to provide the required protection (1,310 feet, see Figure 2.0) from the nearest Shuttle stack to the nearest inhabited buildings, such as the cafeteria and the Operations Support Building (OSB). Inhabited building distance for Hazard Division 1.3 is the required distance to protect non-operational personnel from the direct hazards of an inadvertant event (e.g. thermal flux, firebrands, or other debris). Also, to be considered is that secondary injuries to personnel might occur as a result of flying glass and other debris, for example. Any additional propellant segments beyond 16 (4.4 million pounds) in the VAB requires a waiver to the NASA Explosives Safety Standards. KSC has one approved siting waiver for "rolling back" a full Space Shuttle stack from the launch pad in the event of a hurricane, when two other full flight sets could already be assembled in the VAB. This approved waiver is called the "safe haven" concept and is only used in the event of an approaching hurricane. This is judged to be a very rare condition and one in which the additional hazard of the extra propellant at IBD is acceptable since all nonessential KSC personnel within the inhabited distance arcs will be evacuated in a hurricane state of emergency. Thus, the only increased risk will be to the additional facilities that are within the increased IBD for three full flight sets (24 segments).

Figure 2.0, dated January 2005, is taken from the KSC Facility Master Plan and displays the official SSP QD siting for the VAB and surrounding buildings. Ordinarily, distances are measured from the corner of the building. However, the Shuttle SRBs must be positioned precisely within each of the High Bays. Since the location of the SRB stacks can be guaranteed, and the building walls will not contribute to the fragment or overpressure hazard, KSC measured QD distances from the stack locations.

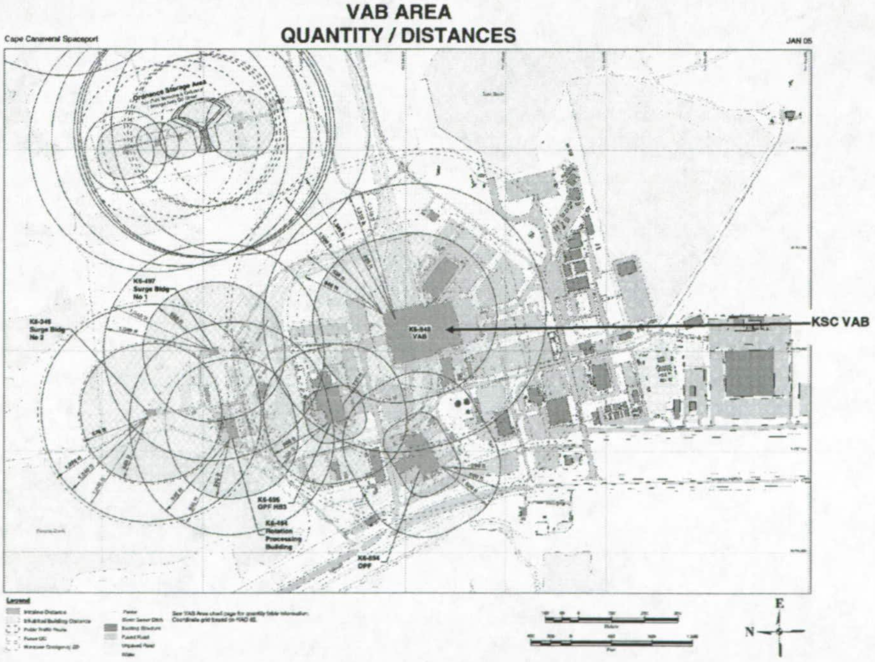

Figure 2.0 - SSP QD Map

---

[2] Two full flight sets of 8 SRMs in each of the High Bays used for stacking, for a total of 4.4 million pounds of propellant in both High Bays.

KSC has been able to comply with the current siting criteria for the SSP except for the Safe Haven waiver. However, with the VAB scheduled to be used for the CEV/CLV/CaLV processing, it is anticipated that parallel processing of both Space Shuttle and CEV/CLV/CaLV launch vehicles, or two CaLVs could result in more than 16 segments in the VAB at one time, thus violating existing QD safe separation distance.

For KSC to have the flexibility to process both Space Shuttles and CEV/CLV/CaLV, and still meet the fixed safety distances required to protect inhabited buildings, either the propellant must be characterized as a more benign propellant or the propellant weight involved in the inadvertant event must be reduced. Either approach will allow more propellant to be placed within the existing safe separation distances. However, since the PBAN propellant is a UN Hazard Division 1.3 classification propellant, KSC elected to pursue the reduction of total propellant weights involved in the inadvertant, worst-case event. This can be achieved by providing separation, insulation, and other barriers between stacks of SRMs in the VAB, or between bays within the VAB. These actions can delay or prevent the propagation of an event in one bay to another, such that only the total in one bay need to be considered as the Maximum Credible Evernt (MCE) for QD purposes. Limitation of propagation by such means as thermal barriers, insulation, water sprays, spacing, etc., must be confirmed by modeling and testing at either subscale or full-scale.

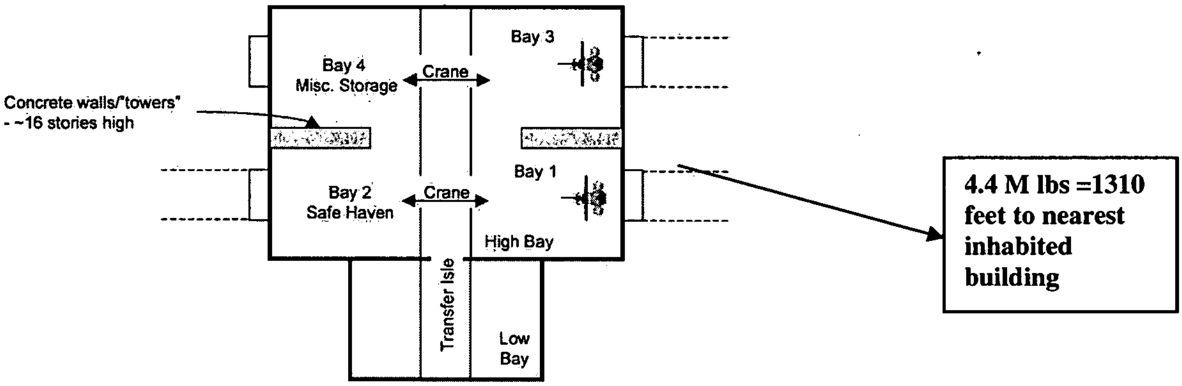

Figure 3.0 - Internal Layout of the KSC VAB

Proposed Solution

ATK, the RSRM contractor, suggested that the MCE might be limited to a single VAB High Bay instead of the total number of segments potentially residing in the VAB. The hypothesis that an inadvertant ignition in one High Bay would not propigate to another allowing KSC to decrease the weight, *W,* in the Safe Separation (QD) equation:

Safe Separation Distance = K- factor x cubic root of the explosive weight (W)

ATK generated a draft propellant test plan (hereafter called the "DTP") which could potentially validate the hypothesis. The DTP would determine if a single ignition event, whether a single segment or a single stack of several segments, would propagate to all segments in the VAB, be limited to only those within the bay, or be limited only to the initially burning segment.

The DTP consists of four phases. Specifically, these phases are:

- Phase I — Acquire Subscale Test Data
- Phase II — Model Validation using Rolf Jensen & Associates (RJA) Modeling Code

Phase III	Sympathetic Segment Ignition Assessment
Phase IV (option)	Conduct an Open Air Full-Scale Test

The NCT was assembled to review the DTP approach and provide alternatives to the QD for the VAB.

NCT Approach

The NCT did not provide any independent test or detailed engineering analyses since this was beyond the scope of the effort. The NCT was chartered to review the current state of knowledge with respect to QD and siting and address the specific needs at KSC with recommendations. This involved the following:

- Conducted a Technical Interchange Meeting (TIM) of KSC VAB vicinity.
- Site visit of VAB.
- Review of VAB QD siting history for SSP.
- Reviewed planned Exploration usage of VAB and impact on existing QD siting.
- Reviewed available prior studies of the VAB hazard reports.
- Re-evaluated hazard classification documents based on current criteria.
- In-depth review and discussion of proposed DTP.
- Collected prior accident data involving SRM mishaps.
- Examined KSC crane operations incidents and problem reports.
- Held in-depth review and discussion of proposed DTP.
- Developed detailed comments to improve the Test approach.
- Developed a report for NASA with Finding and Recommendations.

Prior Studies of VAB Hazards and Explosive Safety

The following table, “Table 1.0 - Prior Studies”, summarizes the pertinent information from the prior studies and reports reviewed. The table highlights the results of these prior efforts relative to the current tasking in terms of output of the study and conclusions/recommendations. The output products noted include the type of hazard assessment involved (SRM or propellant), and whether and what kind of hazard analyses and/or hazard tests were performed. The conclusions/recommendations highlights the hazards identified, risks, hazard mitigations, and whether any additional analysis and/or testing were needed.

Table 1.0 - Prior Studies

Report	Study Products			Conclusions/Recommendations				
	Hazard Assessment	Hazard Analysis	Hazard Tests	Hazards Identified	Risks	Hazard Mitigation	Further Analysis	Further Testing
TWR-11389	SRM	None	Propellant ignitibility	Segment dropping, propellant impact	Personnel, VAB	Operational controls (132 actions to minimize personnel loss, propellant involvement, ignition, and building damage)	None	None
TWR-11389-1	SRM	SRM burning in VAB	None	Personnel exposure	Personnel	No propagation (assumed)	None	None
C. R. Gunn Report	SRM	None	None	Segment impact propellant impact	Personnel, VAB, STS Program	Restrict / Move processing out of VAB	None	None
KSC-DF-441	SRM	SRM burning in VAB	None	Propagation, propulsiveness, toppling	Personnel, VAB	Vent configuration	None	None
TWR-61148	SRM	None	None	Inadvertent Ignition	General	Operational controls	None	None
TWR-65550	Propellant	None	None	General	Ignition sensitivity	Operational controls	None	None
TWR-66175	SRM	SRM burning in VAB	Subscale segment	None	None	None	Improve model fidelity	Larger scale tests, Simulate VAB
TR-13340	SRM	SRM burning in VAB	None	Per TWR-11389 and TWR-61148	Per TWR-11389 and TWR-61148	Per TWR-11389 and TWR-61148	None	Additional SRM burn data
KSC-5600-7312	SRM	SRM burning in VAB	None	Heat and HCl	Personnel	Vent configuration	None	None

---

<u>Summary of Prior Studies Conclusions</u>

Pertinent conclusions and results extracted from historical reports include the following:

- Ignition of staged elements on the MLP from a segment burning in the transfer aisle cannot be ruled out.
- Forward segments can be propulsive with or without igniter for up to 45 seconds with a random, unstable trajectory and sufficient kinetic energy to penetrate tower walls.
- SRM stack will topple in approximately 13 sec due to heating of the aft skirt, making thermal and structural analyses indeterminate. Failure of primary structure in that high bay cell is probable, and tower wall penetrations are likely.
- Ignition of a full SRM stack will result in lift-off in 10 sec or less, and trajectories will be random and unstable.
- Future studies should be considered using models that can handle two phase (gas/particle) flow which will allow for a more accurate prediction of the particle phase temperature in the far field plume.
- Inability to simulate full-scale plume emissivity with the sub-scale tests hindered model validation. Future analysis could be combined with a larger sub-scale segment burn such as ½ scale or 1/3 scale.
- Data generated would be more useful if specific locations within the VAB were identified. Radiation level is highly location dependent due to blockage from interior structures within the VAB.

- Insufficient data exists to describe the plume size, heat flux, duration, rate of flame propagation and toxic smoke propagation for segments stacked on the MLP and for a segment suspended from the crane in order to look at the MLP conditions with one aft segment on the MLP, two aft segments, three segments stacked, six segments stacked, and two full stacks.
- Insufficient data exists to describe the heat flux required to ignite a segment through the case, through the pie covers on the forward end of the segment, through the nozzle plug, and through a sheet of Velostat over the aft end of a segment.
- It bears investigating whether or not the current QD limits for the VAB have been drawn too conservatively, not taking into account the rather slow release of energy contained in the RSRM segments by virtue of their design plus increased quantities on the basis that the VAB bays are separated such that an RSRM inadvertent ignition in one bay is not necessarily going to burn propellant assets in other bays. The worst possible scenario could involve sequential ignitions rather than simultaneous inadvertent ignitions.

Approach KSC VAB Siting Safe Separation and QD

The objective is to realistically determine safe separation/hazard arc distances from the VAB to surrounding buildings for various configurations of SRM segments in the VAB.

Safe separation/hazard arc distances are usually based on QD considerations. These considerations are linked by the relationship:

Safe Separation Distance = K- factor x cubic root of the explosive weight

The K factor is determined by United Nations Hazard Classification (Hazard Divisions 1.1, 1.2, 1.3, etc.). Each hazard class/division has associated K factors. There are different K factors depending on whether the exposed target site is an inhabited building, public transportation route, and whether intermagazine distances and intraline distances apply.

DoD 6055.9-STD "Department of Defense Ammunition and Explosives Safety Standards, October 5, 2004", presents the methods for determining K factors once the hazard classification is known.

The use of a W value less than the total weight of propellant based on all of the items not reacting or not reacting simultaneously is justified in a process to establish the MCE. In the process to establish the MCE, experimental results and analytical modeling are used to prove that a W value less than the total weight is appropriate. The DoD has a well-defined process for establishing the MCE. Unfortunately, it does not appear that NASA has such a defined process, although it does mention, and agree in principle, to use of the MCE approach.

Alternate Heat Flux Approach

During the NCT discussions, another approach was considered. This alternate approach would directly use the flux from burning motor segments, not the propellant weight, to determine safe separation distances. Weight is a realistic parameter to use when siting facilities for Hazard Division 1.1 materials because these materials can react by mass-detonation/mass explosion. The detonation/explosion reactions occur quickly in less than a few hundreds microseconds consuming much, if not all, of the mass in that time. This extremely rapid consumption of all material produces blast and fragment hazards. In contrast, fire reactions occur over much longer times and the consumption rate is dependent on factors such as surface regression rates (often called linear burning rate, or simply burning rate which is a function of pressure) and burn surface. In the case of burning, all material is not consumed "instantly" as is the case in detonation/explosion. Additionally, the total thermal flux experienced at a location outside the VAB would only have contributions from SRMs involved in the fire at that time, and their individual contributions to the total thermal flux would be based on their specific (different) distances from the particular locations.

Another complicating factor is the flux-time profile can be different for different formulations of Hazard Division 1.3 propellant, i.e., 1,000 lbs of two different propellants: a heavily metallized propellant versus a non-metallized propellant (e.g. a reduced signature propellant). When the heavily metallized propellant burns, the metal (i.e., aluminum powder) is reacted to metal oxide at very high temperatures. The radiation from this high temperature metal oxide is significantly higher than the radiation from the combustion plume of the non-metallized propellant.

Based on these considerations, health/hazards risks should be more fully addressed by considering flux-time-distance rather than considering weight (or the cube root of weight) and applying a K factor. This approach would require determination of the maximum number of RSRM segments burning at any time (the MCE), and then determine the heat flux-distance contours for that time, as opposed to just applying the standard QD criteria.

The safe separation distances would be based on the Society of Fire Protection Engineers publication entitled, Society for Fire Protection Engineers Engineering Guide, "Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation," March 2000. The fluxes used would be determined for radiation from RSRM segments and would be analogous to fluxes determined from pool fires as used in the publication entitled, Society of Fire Protection Engineers Engineering Guide "Assessing Flame Radiation to External Targets from Pool Fires", June 1999. An attempt was made to estimate the flux-distance profiles from burning RSRM segments, but the assumptions made and some assumed values had associated large uncertainties. As a result, it was decided that direct flux measurements from burning test articles should be made and the flux should not only be measured at various distances, but also at different view angles.

Hazards Quantity Considerations (i.e., the W)

As mentioned previously, the QD relationship used to establish hazard arcs for the VAB is given by the following expression:

$$D = k\sqrt[3]{W} \qquad \textbf{(EQ. 1)}$$

where *D* is the safe separation distance, *k* is a weighting factor, and *W* is the weight of the energetic material. The hazard classification (1.1 versus 1.3) of the energetic material determines the *k* factor that is used in this relationship.

When multiple RSRMs are present in VAB the weight used in the QD equation (EQ. 1) may be established by an approved Maximum Credible Event analysis. This condition occurs when it can be shown that not all of the RSRMs will burn at the same time. This is possible when building design and/or physical barriers prevent propagation of the burning reaction to adjacent motor stacks, or if these reactions can be delayed in time so that they are not simultaneous.

Current QD arcs for the KSC VAB were established based on an earlier determination that the PBAN based RSRM propellant meets the criteria for a Hazard Division 1.3 hazard classification. It is also assumed that simultaneous combustion of up to 16 RSRM segments (4.4 million pounds) contained within the VAB could occur. It may be possible to reduce the QD arcs by revisiting the specific assumption that all RSRM motors will burn simultaneously within the VAB. Proving that simultaneous burning was not credible using the process of establishing a Maximum Credible Event was the hypothesis of the approach this team was formed to review.

Analysis of future VAB operations shows that the maximum number of segments contained in the VAB at any given time will not exceed 40, with no more than 10 RSRM segments in each High Bay. It may be possible to show that bay-to-bay propagation can be averted and that the maximum number of RSRM segments considered in the determination of the hazard arc can be reduced to 10 (the projected maximum number allowed per bay).

Summary of Test Approach and Model Verification

The test approach was built to investigate if bay-to-bay propagation would occur in the event of an inadvertent ignition of a RSRM segment. The outlined test approach has three phases.

Phase I: Acquire Subscale Test Data

The DTP suggested developing a measured database that a pre-existing computer model of the VAB would attempt to replicate to assess model accuracy. The model, developed in 2005 by Rolf Jensen & Associates (RJA), used a modified version of the NIST FDS computational fluid dynamics (CFD) code to simulate VAB internal conditions during an inadvertent ignition of RSRM segments for emergency egress purposes.

Phase II: Model Validation using RJA Modeling Code

RJA would be asked to demonstrate the accuracy of their computer model by attempting to replicate the results of the tests from Phase I. Assuming that the model would be validated, RJA would then be expected to run full-scale simulations of burning RSRM segments to generate VAB internal temperature profiles during a fire.

Phase III: Sympathetic Segment Ignition Assessment

Using the temperature profiles created from the Phase II full-scale simulations as inputs, the tester would then perform detailed 3D heat transfer modeling to determine if and when the ignition and burn of various segment stack configurations will result in the sympathetic ignition of additional stacks located in the same bay or in an adjacent bay.

A fourth "scale-up" phase was discussed, but was not included as part of the original DTP. This phase was to address any scalability issues in transitioning from the 5-inch subscale test of Phase I to the full-scale modeling of Phase II.

The results of the proposed DTP would then be used as the technical rationale for changing the VAB QD. Before the plan was activated, NASA asked the NESC to review the DTP and provide any comments or recommendations to assure the proper approach would be taken.

NCT's Top Level Comments to the DTP Approach

The NCT reviewed the overall goals and objectives. The NCT's intent was to determine whether the testing outlined can provide the data necessary to allow establishment of new hazard arc/safe separation distances from the VAB and surrounding buildings for the various RSRM storage and handling configurations under consideration.

The NCT believes that the DTP should address these questions:

- Can inadvertent ignition event be limited to no more than 10 RSRM segments, contained in a single High Bay?
- Can propagation from a High Bay event to an RSRM located in the transfer aisle be prevented?
- Can propagation from a transfer aisle event to adjacent bays be prevented?
- Can barrier materials be used to mitigate or prevent propagation of RSRM burning to adjacent bays?
- If the inadvertent ignition does propagate to adjacent bays, is the time delay sufficient to reduce peak heat flux and, therefore, keep the MCE to no greater than 10 RSRMs (and therefore, reduce the QD).

The NCT also believes the coupled experimental/analytical program should include:

- Laboratory-scale tests to establish propellant properties that are not presently well known
- Scaled thermal tests that simulate proper VAB configuration
- Large-scale tests to provide information that small-scale tests cannot

- Modeling efforts that include model validation and prediction of full-scale events

And finally, the NCT believes small- and large-scale test programs must be well integrated with the computational effort.

Recommendations

The scope of this assessment was to perform a focused review of proposed DPT and provide guidance as to the adequacy of the testing approach, and recommend changes to the testing approach as appropriate. The NCT provided the following recommendation.

The recommendations presented below are grouped into two themes for clarity. The first group of recommendations (R-1 to R-6) directly addresses the "DPT" itself.

R-1. KSC and ATK should collectively mature the DPT with appropriate subject matter expertise involvement.

R-2. Tests should be conducted at various scales to characterize the combustion and heat release from atmospheric burning of a RSRM. For model validation purposes, it is important to accurately characterize the extent of aluminum combustion in both small scale (5.0 inches) and in RSRM exhaust plumes. If it is determined that the majority of the combustion does not occur within the motor, an equilibrium model should not be used for the aluminum combustion. In this case, the computational tool should be able to account for incomplete aluminum combustion in a RSRM.

R-3. Some experimental determination of computational parameters should be done prior to the small-scale validation experiments. The precise nature and types of data collected during these parameter determination experiments should be determined by a consensus between the modelers and the experimentalists.

R-4. Laboratory scale experiments should be conducted initially to provide critical parameter values required by the computational model prior to undertaking small-scale (5.0-inch), large scale, and/or RSRM-scale test validation. The precise nature and types of data collected during these parameter determination experiments should be established by a consensus between the modelers and the experimentalists.

R-5. KSC should evaluate the use of mitigation technologies (i.e., thermal barriers, flame barriers, water curtains, thermally insulating nozzle plug and open grain covers) to limit the MCE in the VAB and to reduce the flux from the segments burning in the VAB.

R-6. KSC, via the use of the DTP, needs to establish a MCE that defines the realistic maximum weight of propellant that could be simultaneously burning in the VAB. Data collected from a properly executed test program is needed to determine this MCE.

The three additional recommendations below highlight aspects of the QD siting effort associated with the Threat Hazards Assessment.

R-7. KSC should develop a thorough and comprehensive configuration-controlled VAB Site Plan document conforming to applicable standards including NSS 1740.12. *(O-1)*

R-8. In addition to siting the VAB, KSC needs to conduct a complete propellant hazards assessment of the entire VAB for the Exploration Program to completely understand and mitigate the potential hazards from propellant operations, including the toxic effects from an inadvertent ignition. Prior to the use of the VAB by the Exploration Program, KSC should re-evaluate their Threat Hazards Assessments conducted for the VAB and the SSP in order to help establish the MCE. ***(F-4**, F-5, **O-2)***

R-9. KSC should pursue alternative methods to address the required safe separation distance for the VAB containing Hazard Division 1.3 motor segment. The NCT has identified two alternate approaches to be pursued in parallel: (1) based on MCE, and (2) based on heat flux. Heat flux can be determined from the testing and modeling effort discussed in this report. *(F-4, F-6, O-6)*

SUMMARY AND CONCLUSIONS

The NCT took a comprehensive approach to examine factors influencing the QD for the future use of the VAB. These include:

1. Examining prior studies of VAB hazards and explosive safety.
2. Examining the anticipated VAB processing scenarios for launch vehicles (including near-term co-processing scenarios with Shuttle and CLV, and later co-processing of CLV and CaLV).
3. Evaluating current methods used by NASA to estimate QD and safe separation distances.
4. Assessing the hazard classification status of the solid propellant.
5. Examining the prior SRM accidents along with current state of knowledge of the phenomenology of solid propellant ignitability and burning.
6. Addressing the use of subscale and large scale testing with associated modeling to achieve the ultimate objective of developing appropriate QD for use at the VAB.

All of the above were interrelated and necessary to establish the overall framework for conducting this effort. Subsequently, the NCT documented several noteworthy facts, findings, observations, and recommendations for use by NASA in follow-on activity for establishing the VAB QD when the Exploration suite of launch vehicles is baselined.

FUTURE WORK

The NCT notes that the KSC VAB represents a unique and complex operational situation given its gigantic scale and the large quantities of propellant involved, unlike any other application within the U.S. aerospace industry. This situation is not readily addressed by the prescribed recipes for estimating safe separation distances in the available standards documents. Instead, the particulars of the VAB situation must be accounted for in establishing these distances, and supported by the appropriate tests and analyses.

Due to the uniqueness of the application, forward work by NASA will require a comprehensive and coordinated effort that includes Government and contractor organizations with the necessary technical skills, capabilities, and facilities that can support both the testing and modeling components necessary to establish meaningful safe separation distances. Additionally, NASA policy for application of QD siting methodology will also have to be revisited and updated.

With respect to the DPT itself, the NCT believes that a varied complement of testing is needed that addresses several aspects of the QD situation including, but not limited to:
(a) phenomenological questions about the ignited motor and/or segment(s) combustion fire/plume effects, (b) potential for fire propagation to adjacent stacks and/or segment, and (c) resolving fundamental parameter knowledge gaps or uncertainties necessary for modeling of large scale fire and heat propagation within and outside of the VAB boundaries. The task of developing test

matrices that are closely tied to prioritized objectives is non-trivial, where early testing may influence the details of subsequent testing and modeling. The NCT believes that small-scale testing, supported by modeling, is insufficient by itself to address the full scale QD siting problem. The particulars of a large-scale or full-scale test would be contingent upon the questions posed and left unanswered in the subscale testing and analysis work. An extensive review of prior studies also pointed to a paucity of test data and high fidelity modeling for the purposed of establishing an appropriate QD for the VAB.

Overall, the forward work to address the QD for the VAB will lead to advancing the state-of-the-discipline for assessing the hazards/consequences associated with the processing and use of large SRMs, and is of interest both for NASA and the DoD. The practice at KSC will necessarily advance in terms of threat hazards assessment (THA), risk assessment and mitigations, engineering and operational rigors, as well as institutionalizing the new knowledge and information into NASA practice. The present opportunity is timely for establishing a sound basis for all future QD siting at KSC VAB needed for large SRM-based vehicles.

ACKNOWLEDGMENTS

NESC Consultation Team (NCT) List

The NESC consultation effort relied on the expertise of several JANNAF communities. The individuals who contributed this effort are listed below.

Last Name	First Name	Position/Team Affiliation	Center/Contractor
Core Members			
Boggs	Thomas L.	Member/Explosives Safety	Sverdrup/China Lake/Naval Air Warfare Center
Bowman	Howard L.	Member/Explosives Safety	China Lake/Naval Air Warfare Center
Covino	Josephine	Member/SRM Hazards, Propellant Chemistry	Department of Defense Explosives Safety Board (DDESB) Staff
Frazier	Wayne R.	Deputy Lead/Solid Propulsion and Explosives Safety	NASA HQ OS&MA
Laker	Travis S.	Member/Modeling	China Lake/Naval Air Warfare Station – Weapons Division
Merrill	Claude E.	Member/Accident Investigations, Propellant Hazards	Sverdrup/Air Force Research Laboratory (AFRL)
Rahman	Shamim A.	Lead/Rocket Propulsion Testing	NASA SSC
Raines	Nickey G.	Member/Hazardous Test Facility Siting	NASA SSC
Tomei	Edmardo J.	Member/Chief Engineer, Space Launch Operations	The Aerospace Corporation
Ward	Jerry M.	Member/Explosives Safety/Hazards, Testing & Analysis	DDESB Staff
Washburn	Ephraim B.	Member/Propagation Modeling	China Lake/Naval Air Warfare Center

Last Name	First Name	Position/Team Affiliation	Center/Contractor
Advisors And Observers			
Diebler	Corey	Advisor	KSC S&MA
McVay	Greg	Advisor	Sverdrup/SSC
Worden	Jim	Advisor	Sverdrup/SSC
Bellinger	Frank	Observer	HQ/OS&MA
Greulich	Owen	Observer	HQ/OS&MA
Key Support and Logistics			
Chun	Peggy	NESC Systems Engineer Office (SEO)	NASA DFRC
Bruno	Cynthia	NESC Management and Technical Support Office (MTSO)/Program Analyst	NASA LARC
Belitz	Jaime	Scheduler	LARC/Swales
Derby	Terri	Administrative Assistant	LaRC/Swales
Moran	Erin	Technical Writer	LaRC/Swales

Many thanks to ATK; Dr. Bob Bennett, Jim Rosanski, Jeff Cook, Mart Cook, Dr. Ben Goodman and a host of others.

REFERENCES

1. ATK Thikol, “KSC Motor Integration”, by Motor Integration Team, briefing excerpt ATK Thikol, pp 285-333.
2. Boggs, T.L., Atwood, A.I., Lindfors, A.J., Mulder, E.J., and Pritchard, R.W., “Hazards Associated with Solid Propellants”, Chapter 1.9, pp. 221-264 in Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics, edited by Yang, Brill, and Ren, Progress in Astronautics and Aeronautics, Volume 185, 2000.
3. Chemical Propulsion Information Agency (CPIA), “Joint JANNAF/DDESB Workshop on Hazards Classification of Large Rocket Motors, 4-8 June 2001, Alexandria, VA” JSC CD-18, June 2001, Shock & Impact Section, vu-graph 2D hydrocode calculations of accidents.
4. DDESB Memorandum for Record, Subject: Class/Divisions 1.3/1.4 Radiation and Quantity Distance Criteria, DDESB-KT, 19 July 1989.
5. Department of the Air Force, Strategic Air Command, Explosive Safety Siting SAC/AFSC Vandenberg 85-S10 Memorandum – New Vehicle Parking Lot North of SLC-6, dated Dec. 12, 1985.

6. Elwell, E.L., Irwin, O.R., and Vail, J.R.W., Project SOPHY—Solid Propellants Hazards Program", Air Force Rocket Propulsion Laboratory, AFRPL-TR-67-211, Vol. I, August 1967).

7. Gartling, D.K., Hogan, R.E., and Glass, M.W., "COYOTE – A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part I – Theoretical Background," SAND94-1173 Unlimited Release, *Sandia National Laboratories*, Albuquerque, New Mexico, January 24, 2003.

8. Gartling, D.K., Hogan, R.E., and Glass, M.W., "COYOTE – A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part II – User's Manual," SAND94-1179 Unlimited Release, *Sandia National Laboratories*, Albuquerque, New Mexico, January 24, 2003.

9. Gunn, C.R., et al., "Safety Review of Solid Rocket Motor Processing in the Vehicle Assembly Building". Briefing to the Director of KSC on January 23, 1980.

10. Kase, D.W., et al., "Hazard Analysis of Solid Rocket Motor Assembly Operations for Kennedy Space Center Vehicle Assembly Building," Thiokol/Wasatch Division Report TWR-11389, Contract NAS8-30490, dated June 3, 1977.

11. KSC Hazard Report, Hazard # LL-0005, Rev. B, dated 07/07/04. Master #: K-SPC-00256-S-PS, dated 11/09/87.

12. NSWC TR 85-344: "Solid Rocket Booster Command Destruct System Hazard Study", Volume 1, Naval Surface Weapons Center, Swisdak, M.M., Jr.; Peckham, P.J.; Tasker, D.G.; Bazil, R.H.; Deiter, J.S.; and Hinckley, W.M., October 9, 1985.

13. NSWC TR 85-346: "Solid Rocket Booster Command Destruct System Hazard Study: Volume 2, Propellant Cylinders", Naval Surface Weapons Center, Peckham, P.J., October 9, 1985.

14. NSWC TR 85-348: "Solid Rocket Booster Command Destruct System Hazard Study: Volume 3, Shock Initiation Studies", Naval Surface Weapons Center, Tasker, D.G., October 9, 1985.

15. NSWC TR 85-350: "Solid Rocket Booster Command Destruct System Hazard Study: Volume 4, Mechanical Properties", Naval Surface Weapons Center, Bazil, R.H.; Deiter, J.S., October 9, 1985.

16. NSWC TR 85-352: "Solid Rocket Booster Command Destruct System Hazard Study: Volume 5, Fragmentation", Naval Surface Weapons Center, Hinckley, W.M., October 9, 1985.

17. Olson, E. and Vittitow, P, "Large Rocket Motor Hazard Classification Overview". Briefing Charts from JANNAF PSHS meeting, dated April 9, 2002.

18. Report "9734.3-4007" on Minuteman "bonfire test" (circa mid-60s) as described by Claude Merrill (he will provide a copy of the full report).

19. Rolf Jensen & Associates, Inc., "Special Study Vehicle Assembly Building Solid Rocket Motor/Inadvertent Ignition Venting Study", KSC-5600-7312, NASA KSC, May 3, 2005.

20. Row, H. H., et al., "SRM/VAB Inadvertent Ignition Effects Study," Report No. KSC-DF-441, dated September 1981.

21. Schwartz, D., Bennett, R., Graham, K., Boggs, T., Atwood, A. and Butcher, G., "Current Efforts to Develop Alternate TB700-2 Test Protocols for the Hazard Classification of Large Solid Rocket Motors", briefing charts from JANNAF PSHS meeting April 9, 2002.

22. Smith, J. R., et al., "Space Shuttle Explosive Equivalency Study, Volume I, *Executive Summary*, Volume II, *Technical Discussions*, Volume III, *Appendices*," Contract NASW-2472, The Aerospace Corporation Report ATR 74(7338)-1 prepared for NASA, March 15, 1974.

23. Society for Fire Protection Engineers Engineering Guide, "Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation," March 2000.

24. Society of Fire Protection Engineers Engineering Guide "Assessing Flame Radiation to External Targets from Pool Fires", June 1999.

25. ST/SG/AC.10/11/Rev. 4 "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria" United Nations, New York and Geneva, 2003.

26. ST/SG/AC.10/11/Rev. 4, "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria" United Nations, New York and Geneva, 2003.

27. Sverdrup Technology, "Quantity Distance Study and Supporting Hazard Analysis", Advanced Solid Rocket Motor Program, Contract No. NAS13-290, prepared by Sverdrup Technology for NASA Stennis Space Center, dated June 1990.

28. Thornton, J., et al., "RSRM Propellant Inadvertent Ignition - An Update", ATK Thiokol Propulsion, TR13340, November 19, 2002.

29. Thornton, J., et al., "Shuttle SRM Propellant Chemistry – PSM/PHA Specific Assessment", ATK Thiokol Propulsion, TR-65550, October 12, 1993.

30. Tomei, E. J., "Propellant Explosive Hazards Study". Volume I, *Executive Summary*; Volume II, *Technical Discussions*; and Volume III, *Appendices*. The Aerospace Corporation, TOR-0089(4025-04)-1, Contract F04701-88-C-0089, October 1989.

31. United Nations Manual of Tests and Criteria. ST/SG/AC.10/11/Rev. 4/Amend. 1 ISBN 92-1-139109-1. Available from United Nations Publications, Room DC2-853, 2 UN Plaza, New York, New York 10017 USA.

32. United Nations Recommendations on the Transport of Dangerous Goods. Model Regulations. 14th revised edition ST/SG/AC.10/1/Rev. 14 ISBN 92-1-139106-7. Available from United Nations Publications, Room DC2-853, 2 UN Plaza, New York, New York 10017 USA.

33. Vorwerk, R. F. and Weals, F. H, "624A Solid-Propellant Motor Impact Test", TPR 381, U. S. Naval Ordnance Test Station, China Lake, California, October 1964.

34. Weals, F.H. and Wilson, C.H., High Explosive Equivalency Tests of Rocket Motors" U.S. Naval Ordnance Test Station, China Lake California, Technical Progress Report 413, NOTS TP 3910, November 1965.

35. Weaver, J. R. and Bieringer, G. F., "Titan IV SRMU Failure Debris Analysis", RTI/5180/26-14F, Research Triangle Institute, Cocoa Beach, Florida, September 30, 1993

36. Wentworth, B.T., "Special Study-Vehicle Assembly Building SRM/Inadvertent Ignition Venting Study," Report No. KSC-5600-7312, prepared by Rolf Jensen and Associated (Orlando, Florida), dated May 3, 2005.

37. Wilson, T.R., "KSC VAB Quantity-Distance Study: NESC Chief Engineer Review", briefing charts to the NESC Review Board on Sept. 29, 2005.

Briefings at NESC TIM at KSC (January 31, 2006)

38. Bennett, Robert R., "RSRM Hazard Classification," presented at NESC-led Technical Interchange Meeting, January 31, 2006.

39. Cook, Mart, "Segment Stacking in the Vehicle Assembly Building," presented at NESC-led Technical Interchange Meeting, January 31, 2006.

40. Diebler, Corey, "NESC VAV QD Study: Background and Summary," presented at NESC-led Technical Interchange Meeting, January 31, 2006.

41. Frazier, Wayne and Bellinger, Frank, "Constellation Program Vehicle Background Information," presented at NESC-led Technical Interchange Meeting, January 31, 2006.

42. Rozanski, J., and Bennett, Robert R., "VAB/RSRM Fire Model Validation & Sympathetic Segment Ignition Assessment," presented at NESC-led Technical Interchange Meeting, January 31, 2006.

List of Governing Standards/Documents

43. DoD 6055.9-STD: "DoD Ammunition and Explosives Safety Standard", Undersecretary of Defense for Acquisition, Technology, and Logistics, October 5, 2004.

44. DOE M440.1-1: Dotts, J. E., and Kim, B., "DOE Explosives Safety Manual – Version 4", Lawrence Livermore National Lab, December 7, 2004.

45. NSS 1740.12: "Safety Standard for Explosives, Propellants, and Pyrotechnics", NASA Office of Safety and Mission Assurance, August 1993.

46. TB 700-2: "DoD Ammunition and Explosives Hazard Classification Procedures", Joint Technical Bulletin, January 5, 1998.