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DEVELOPMENT OF A VENTING SELECTION METHODOLOGY FOR FAST AND SLOW COOK-OFF MITIGATION

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14. ABSTRACT
Most high explosive warheads respond violently to unplanned cook-off in fires and do not comply with NATO insensitive munitions (IM) test STANAGs. The Program Executive Office for Ammunition (PEO Ammo) developed an IM strategic plan to establish methods for improving the IM characteristics of munitions. A design guide was developed to provide a venting decision methodology to assist Program Managers and systems developers in selecting the best venting concepts for application to their munitions. A structured framework was developed that incorporates customer's requirements and corresponding engineering metrics. The engineering metrics along with their rating were used to rank the effectiveness in achieving various munition requirements. By comparing candidate concept venting scores, one can see which venting concepts offer the greatest value to the customer. Several munition examples were run through the template to select the most appropriate venting approach. Based on the template output, the selected approaches were experimentally evaluated and demonstrated to show improved IM response under slow cook-off conditions resulting in a cost savings over using a standard experimental design approach.

15. SUBJECT TERMS
**Fast cook-off (FCO) Slow cook-off (SCO) High explosive warheads Insensitive munitions (IM)
Quality Function Deployment (QFD)**

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INTRODUCTION

The Program Executive Office for Ammunition (PEO Ammo) has been in the forefront of developing a strategic plan to effectively and efficiently move their portfolio of munition items towards insensitive munitions (IM) compliance. The PEO Ammo instituted a Plan of Actions and Milestones as a roadmap for the establishment and execution of munitions programs for which they have acquisition and life-cycle responsibility. Munitions in the portfolio were comprehensively reviewed to establish current IM compliance levels and then ranked to determine the appropriate application of funding and resources to provide the best return on investment. Five thrust areas were identified as major IM technology areas that would contribute towards a commonality of efforts, help integrate promising technologies, and leverage limited resources in order to achieve IM compliance. These areas are explosives, warhead venting, packaging, propellants, and modeling and simulation. Under the warhead venting thrust area, a design guide was prepared to aid Department of Defense Program Managers and Integrated Product Teams (IPTs) in identifying and selecting appropriate technologies to meet customer requirements. The guide provides a methodology, along with a template and examples for the selection and prioritization of venting concepts.

Most high explosive (HE) warheads respond violently to unplanned cook-off in fires and therefore do not comply with established IM requirements. The objective of warhead venting is to relieve internal pressures resulting from explosive burning during fast and slow cook-off (FCO and SCO) in order to preclude a warheads violent response (ref. 1). A variety of venting solutions have been applied to a broad range of gun and missile launched systems (ref. 2). There is also a body of work that has looked at specific techniques to model predictive IM behavior (ref. 3) and to experimentally develop both active (ref. 4) and passive (ref. 5) methodologies, along with the responses from different explosive types at various heating rates (ref. 6). It is clear that each explosive ordnance item is unique and consequently, each venting design feature must be tailored to a specific application. Several specific PEO ammunition munitions have incorporated warhead venting features. However, a generalized fact based methodology that prioritizes venting concepts based on munition requirements did not previously exist. The guideline provides methods and information useful for selecting and tailoring venting concepts to specific explosive ordnance items. The guideline also documents efforts to apply various venting concepts to certain munitions and thereby provides a useful resource to munition designers and developers.

DESIGN GUIDE METHODOLOGY

A structured framework was developed to down select a venting concept for a specific munition. The first step involved listing customer requirements with corresponding engineering metrics that impact these requirements. The engineering metrics, along with their rating, were then used in the second step where the venting concepts were rated for their effectiveness in achieving various munition requirements. By comparing the candidate concept venting scores, one can see which venting concept offers the greatest value to the customer.

A generic template was created as a framework in which to evaluate different warhead venting options for a given munition program. While the template provides customer requirements and metrics that are broad enough to address a wide spectrum of PEO Ammo munitions, the requirements of individual munitions can be uniquely addressed by selecting munition-specific customer requirements, weighing factors, interrelationship values, and interrelationship

scores. Several munition examples were run through the template to select the most appropriate venting approach. Based on the template output, the selected approaches were experimentally evaluated and demonstrated to show improved IM response under SCO conditions resulting in a cost savings over using a standard experimental design approach. Figure 1 presents a flow diagram of the basic IM warheads venting selection process.

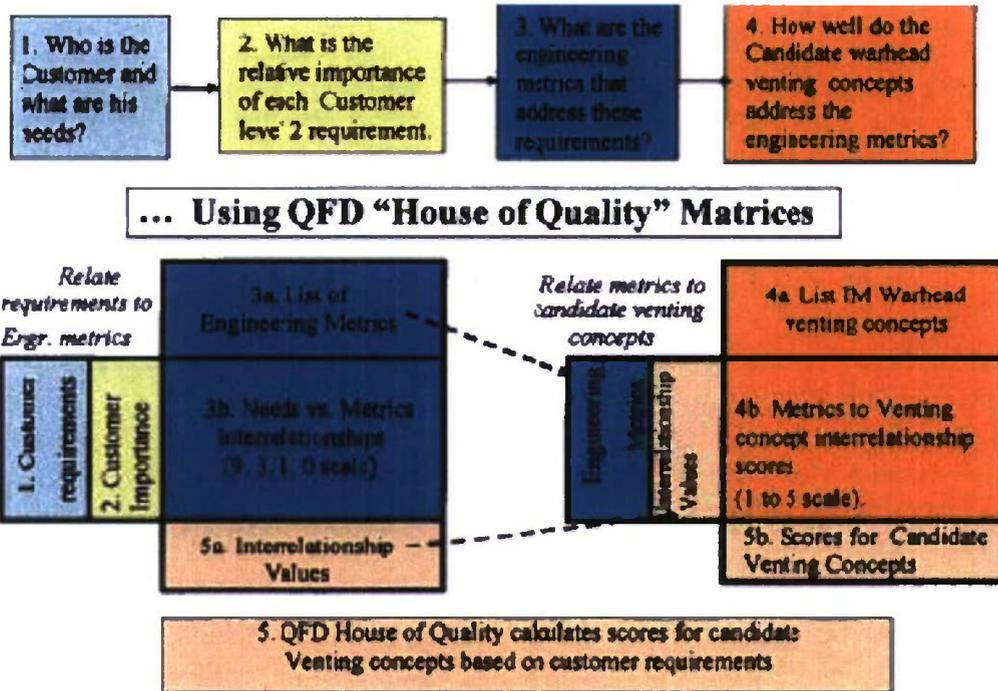


Figure 1
IM warhead venting selection process

Customer Requirements

Every munition has specific requirements that relate to IM, performance, safety, logistics, and environmental effects among others. It is necessary that these requirements be addressed as part of an overall systems engineering design solution.

Engineering Metrics

A list of attributes that could impact each of the munitions requirements; such as vent area, location of vents, paths to vent, retention of total explosive volume, etc.; is determined.

Concepts Identification

A list of potential warhead venting concepts is developed. This list is developed through brainstorming with a large body of technical experts. A typical list would include a large variety of concepts, such as venting through the fuze well, split shell, base release, scoring, vent holes, heat fusible or weakened bodies (e.g., preformed fragments in a plastic matrix), and active venting.

Quality Function Deployment

A quality function deployment (QFD) is a decision support tool that uses a matrix format to help determine and organize customer requirements, and to help assign proper weighing factors and performance parameters to those requirements in a structured framework to evaluate potential solutions to a problem. A two-step QFD approach was applied to down select a venting concept for a specific munition. The first step involves listing the customer's requirements and corresponding engineering metrics that impact these requirements. The engineering metrics, along with their rating, are then used in the second step of the QFD where the venting concepts are rated for the effectiveness in achieving various munition requirements. By comparing the candidate concept venting scores at the conclusion of the QFD, one can see which venting concepts offer the greatest value to the customer.

Using a matrix format, the QFD method first collects and prioritizes the "customer requirements" for the system being evaluated. These needs generally relate to battlefield performance, IM response, safety, and reliability needs of the soldier in the field, as well as the schedule, environmental impact, and cost concerns of the munition development program itself. Customer requirements are prioritized by approaching weighted points among all the munition system requirements.

Next, a set of engineering metrics is determined. As used in this context, a metric is a feature or quality of a warhead that a) relates specifically to one or more customer needs and b) whose value can be measured or assessed relative to possible warhead venting solutions. The engineering metrics are shown in the rows running across the top of the first matrix (matrix 1). Using the QFD matrix, each metric is compared to each customer requirement to determine if a strong, moderate, weak or no relationship exists between them (a quantitative 9/3/1/0 scoring method is typically used to determine the interrelationships). The engineering metric score, for each metric, is then determined as the product of the customer need priority points times the interrelationship value with a given metric, summed down the metric column.

The second matrix (matrix 2) is generated by first identifying a set of candidate warhead venting concepts (also referred to as munition design features that enable venting to occur). These are listed across the top of the matrix 2 table. At the intersection of each candidate concept with each engineering metric, a score is assigned. This score of 1 through 5 (or alternatively 0, 1, 3, 9) is assigned to represent poor through excellent ability of the candidate venting design concept to satisfy each engineering metric. The product of the score for each metric times the interrelationship score is summed down the candidates venting concept column resulting in a final "score" for each alternative. The highest ranking alternative becomes the leading candidate for consideration as the warheads venting solution for that munition.

Definitions

The following definitions were tailored to define the major elements of the QFD as presented in the guide:

Customer Requirements - Munition system attributes that are weighted by the customer. Level 1 requirements cover broad capability areas and level 2 requirements define specific needs.

Relative Importance - A weighted numeric value assigned to each customer requirement that establishes the importance of each customer requirement as compared one to another.

Engineering Metrics - Munition design attributes that address the customer's requirements. For this QFD, they contribute to the ability of the confined energetic materials to vent, thereby, reducing IM response.

Interrelationship Value - The numeric value (1, 3, 9) assigned in step 1 to show how strongly an engineering metric effects a customer's requirement. See body of table 1.

Engineering Metric Score - Rates which the engineering metric has the most potential to impact a customer's requirement. The number is calculated by multiplying the relative importance of each customer requirement by the interrelationship value and then summing down the columns for each engineering metric. Each engineering metric gets an engineering metric score and is calculated at the bottom of table 1.

Candidate Venting Concept - A munition design feature that has the primary purpose of enabling energetic decomposition gases to escape the warhead case or any feature that precludes the energetic/warhead from reacting violently in SCO and FCO. They can also accurately be called solution alternatives. Candidate venting concepts are listed across the top row of table 2.

Interrelationship Score - The numeric value (1 through 5) that is assigned in step 2 to show how well a candidate venting concept would enable the engineering metric to be achieved.

Candidate Venting Concept Score - Candidate venting concept scores are shown on the last row of table 2. The best candidate venting concept will have the highest score. The score is calculated by multiplying the engineering metric score by the interrelationship score and then summing down the column for each candidate venting concept.

GENERIC QUALITY FUNCTION DEPLOYMENT

A generic QFD template was created as a framework in which to evaluate different warhead venting options for a given munition program. While the template provides customer requirements and metrics that are broad enough to address a wide spectrum of PEO Ammo munitions, the requirements of individual munitions can be uniquely addressed by selecting munition-specific customer requirements weighting factors, interrelationship values, and interrelationship scores. The QFD process is done in two steps for this application. Step 1 relates the system requirements to the engineering metrics. Step 2 relates the metrics to the candidate warhead venting concepts. Step 1 of the warhead venting QFD template is shown in table 1 (fictitious numbers were included for illustration). Table 1 is presented in two parts (a and b) that would appear next to each other in a standard Excel document.

The two left columns in table 1 list the customer requirements and specific customer needs. Level 1 requirements are general in nature and cover broad areas such as logistics, environmental effects, life-cycle costs and maintenance, and impact on other IM requirements. Level 2 requirements are specific needs to be addressed as subsets to each level 1 requirement. For instance, life-cycle considerations may include development costs and schedules, manufacturability of the IM mitigation technique, and future demil costs. The subset of performance may include lethality, reliability at extreme environmental conditions, or the ability to survive launch stresses.

The third column is "relative importance," and is unique to each individual munition program's specific requirements. For instance, survival in a high g-load environment may be less important for missile launched weapons application than for a gun launched system, while low unit costs solutions may be more important for high volume/low tech munitions than for sophisticated high-tech systems. The remaining columns are the engineering metrics that contribute to the ability of the confined energetic materials to vent without negative munition system effects. These may include, but are not limited to size and location of vent areas, interior venting paths, fuze venting methodologies, fuze release mechanisms, active venting techniques, explosive confinement, or material cost and availability.

Table 1
Step 1 of the QFD

QFD for Warhead Venting (first half of Matrix 1)		Engineering Metrics								explosive metric		
Level 1 rqt	Level 2 Rqt	Relative Importance	Vent Area	Location of vent(s)	non-fuze release pressure & temp	symmetry of venting locations	Interior Paths to Vent	HE Surface Paths to Vent	Warhead/ Fuze vent method (physical separation)	energetics to above that of the main charge (thermal management)	Fuze release thermomech props related to T & P	energetic materials insensitivity impact (active venting)
Improve IM Cook-off Performance	Create sufficient venting to prevent catastrophic pressure build-up in order to provide the best opportunity for a type V reaction in SCQ (prevent body from blowing up).	9	9	9			9	3			9	
	Create sufficient venting to prevent catastrophic pressure build-up in order to provide the best opportunity for a type V reaction in FCO (prevent body from blowing up).	9	9	9			1	9			9	
	Prevent fuze from violently initiating the main charge (SCO)								9	3		
Impact on other IM rqt	Maintain or Enhance other IM responses (Bl, Ft, SD, SCJ)	3	3	1			1	3				3
maintain munition battlefield performance	survive launch stresses											
	Lethality reliable under environmental extremes reliable shell life											1
Low Cost	low developmental cost and schedule											
	low manufacturing cost (simple/robust)											
Safety	Low Demil Cost											
	Producibility + Refurbishment											
	Safe to Produce											3
Logistics	Safe to Demil											1
	Safe to Handle											1
Environmental	Minimize Logistics Impact											3
	limit environmental impact (including noxious emissions) during manufacture											
Metric score		0	0	0	0	0	0	0	0	0	0	0

Table 1
(continued)

QFD for Warhead Venting (second half of Matrix 1)		Engineering Metrics															
Level 1 Rqts	Level 2 Rqts	Relative Importance	general														
			Strength of the body as a function of vent design	Retain total HE volume	Warhead case material effects	function under operational axtrame temperatures	material temp behaviour (component level)	Ease of Systems Integration	materials aging data	non-complex venting solution	materials costs	low noxious emissions when burning	materials availability				
Improve IM Cook-off Performance	Create sufficient venting to prevent catastrophic pressure build-up in order to provide the best opportunity for a type V reaction in SCO (prevent body from blowing up).							3									
	Create sufficient venting to prevent catastrophic pressure build-up in order to provide the best opportunity for a type V reaction in FCO (prevent body from blowing up). Prevent fuze from violently initiating the main charge (SCO)							3									
Impact on other IM Rqts	Maintain or Enhance other IM responses (BT, FI, SD, SCJ)			3													
maintain munition battlefield performance	survive launch stresses	9								3							
	Lethality	9	9	9													
	reliable under environmental extremes				9												
Maintain or reduce Life Cycle Cost	reliable shelf life									9							
	low developmental cost and schedule										9	3					
	low manufacturing cost (simple/robust)										9	9					
Safety	Low Demil Cost										1		1				
	Producibility + Refurbishment										9					9	
Logistics	Safe to Produce																1
	Safe to Demil Safe to Handle																
Environmental	Minimize Logistics Impact								9								
	limit environmental impact (including noxious emissions) during manufacture															9	
Metric score		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The individual cells in table 1 are filled in with an interrelationship value as determined by an IPT or by appropriate subject matter experts (SME). The following numbers are used to assign the strength of the correlation; strong (9)/moderate (3)/weak (1)/none (0 or blank). The bottom row, which is the engineering metric score, is calculated by multiplying the relative importance times the interrelationship value and summing the columns.

Step 2 of the warhead venting QFD template is shown in table 2. Here the set of candidate warhead venting concepts are evaluated relative to the engineering metrics. The two columns at left show the engineering metrics and their engineering metric scores as determined from step 1 of the QFD (table 1). The next several columns list the candidate warhead venting concepts. Their relative ability to satisfy each metric is indicated in the matrix cells, based on a scale of one to five. Candidate venting concepts listed here are more specific direct solution alternatives and may explore subsets of generic solutions such as relative size or placement of venting holes, or the interaction of a combination of venting concepts such as vent holes with melt-out liners, or both active and passive vent techniques.

Table 2
Step 2 of QFD

Part 1 of QFD Matrix 2: Metric warhead venting solution alternatives										
Metrics	Rank	Preformed frags in plastic matrix.	Reduced Inthread Scoring	Adapter Splitshell	Active shaped charge vent	Bigger vent hole w/HDPE liner	More vent holes w/HDPE liners	Thicker HDPE liner	Current design w/HDPE liner	
Vent Area	100									
Location of vent(s)	201									
Non-fuze release pressure	201									
Symmetry of vent locations	0									
Interior Paths to Vent	0									
HE Surface Paths to Vent	97									
Warhead/ Fuze vent method (physical/ energetic)	147									
Ignit temp above main charge.	27									
Fuze release thermomech props related to T & P	27									
Energetic matl insensitivity impact (active venting)	189									
High body/vent strength	53									
Retain total HE volume	90									
Warhead case material effects	51									
System function under extreme temperatures	18									
Good venting material temperature behaviour	18									

QUALITY FUNCTION DEPLOYMENT EXAMPLES

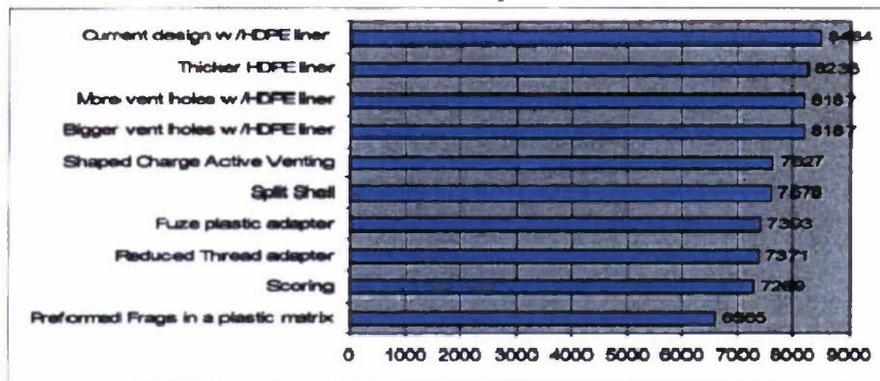
Two munitions representing important PEO Ammo ordnance families were selected for evaluation of warhead venting alternatives using QFD methodology. These munitions are the M934A1 (120-mm mortar round) and the development XM982 Excalibur (155-mm artillery projectile). Their QFD analyses are discussed next.

XM982 Excalibur 155-mm Artillery Projectile

Metrics were selected to measure how well the warhead venting alternatives meet the customer needs. Both broad categories (level 1) and customer specific needs (level 2) were ranked with a total of 100 points. Level 1 needs were ranked to get a general feel for how important different requirement categories are to the customer. Level 2 needs were ranked to match the same number of points as its associated level 1 need. Using the generic QFD template as a guideline, the interrelationships between each metric and customer need were imputed into the matrix. Warhead venting IPT and subject matter experts adjusted the values as necessary to address the specific needs of the XM982 munition. The "overall scores" for each metric is the product of the customer requirement times the interrelationship value, summed down the column for each metric.

The metrics were then related to potential XM982 warhead venting design alternatives (table 3). These alternatives were selected and evaluated by subject matter experts with specific consideration to the XM982 projectile. The warhead venting concepts being compared were performed fragments in a plastic matrix, scoring the warhead case, reduced thread adapter, plastic fuze adapter, split shell, shaped charge active venting, bigger vent holes with high-density polyethylene (HDPE) liner, more vent holes with HDPE liner, thicker HDPE liner, and current design with HDPE liner. Each concept was compared against each metric to decide on its interrelationship score. Interrelationship scoring was determined by the warhead venting IPT. The relative score for each warhead venting produced the overall highest score. The SCO test results showing a type V reaction are presented in figure 2.

Table 3
Results of XM982 warhead venting QFD



Warhead in oven



Vent hole reaction



Results showing type V reaction

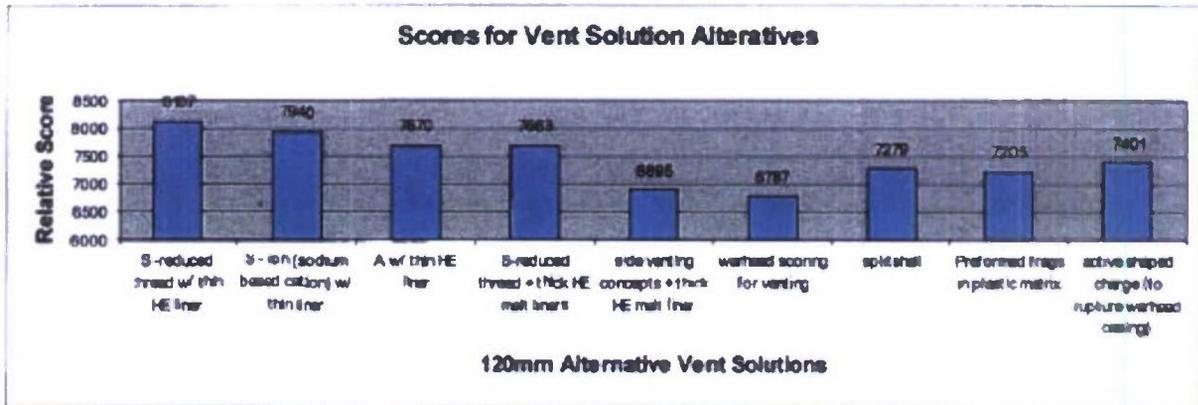
Figure 2
Excalibur warhead undergoing SCO testing at 50°F/hr

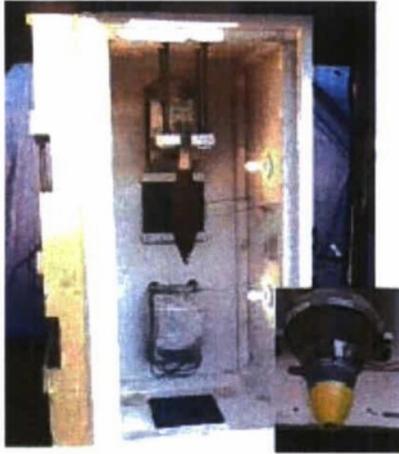
M934A1 120-mm Mortar

First, customer needs were related to the M934A1 set of metrics. As with Excalibur, these metrics were selected so that they can also measure how well the warhead alternatives meet the customer needs. Using the generic QFD template as a guideline, the interrelationships between each metric and customer need were determined. Warhead venting IPT and subject matter experts adjusted the values as necessary to address the specific needs of the M934A1 munition. The "overall scores" for each metric is the product of the customer requirement times the interrelationship value, summed down the column for each metric.

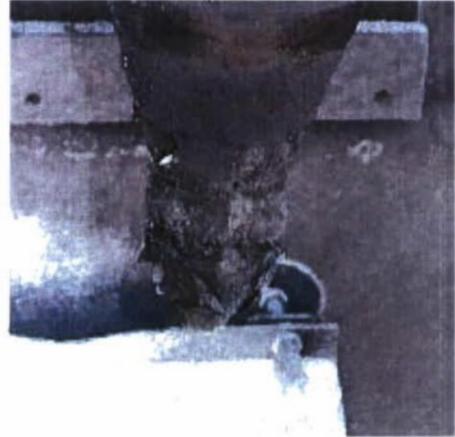
The metrics were then related to potential M934A1 warhead venting design alternatives. These alternatives were selected and evaluated by the IPT and SME, with specific consideration to the M934A1 munition. The warhead venting concepts being compared are reduced thread with thin HE liner, ion (sodium-based cation) with thin liner, thin HE liner, reduced thread plus thick HE melt liner, side venting concept plus thick HE melt liner, warhead scoring for venting, split shell, preformed fragments in plastic matrix, and active shaped charge (to rupture warhead casing). Interrelationship scoring was determined by the warhead venting IPT. The relative score for each warhead venting concept is shown graphically in table 4. The warhead venting concept known as "S" - reduced thread with thin HE liner - was a close winner over the other alternatives. The warhead venting concept using the HDPE liner produced the overall highest score. The SCO test results showing a type V reaction are presented in figure 3.

Table 4
Results of M934A1 warhead venting QFD





Mortar in oven, close-up of fuze vent (insert)



Results showing type V reaction

Figure 3
120-mm mortar undergoing SCO testing at 50°F/hr

CONCLUSIONS

A design guide was developed to provide a venting decision methodology to assist Program Managers and systems developers in selecting the best venting concepts for application to their munitions. A quality deployment function tool was used to provide a structured framework that integrates the customer's munitions requirements with the corresponding engineering metrics that impact these requirements. The engineering metrics, along with their ratings were used to assess the effectiveness in achieving various munition requirements. By comparing the candidate concept venting scores, one can see which venting concepts offer the greatest value to the customer. Several munition examples, including the XM982 Excalibur 155-mm artillery projectile and the M934A1 120-mm mortar were run through the template to select the most appropriate venting approach. Based on the template output, the selected approaches were experimentally evaluated and demonstrated to show improved insensitive munitions response under slow cook-off conditions resulting in a cost savings over using a standard experimental design approach.

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