"Excalibur" Applying Unique Decision Support Tool to Explosives Selection

Quality Function Deployment (QFD)— A Step-by-Step Approach

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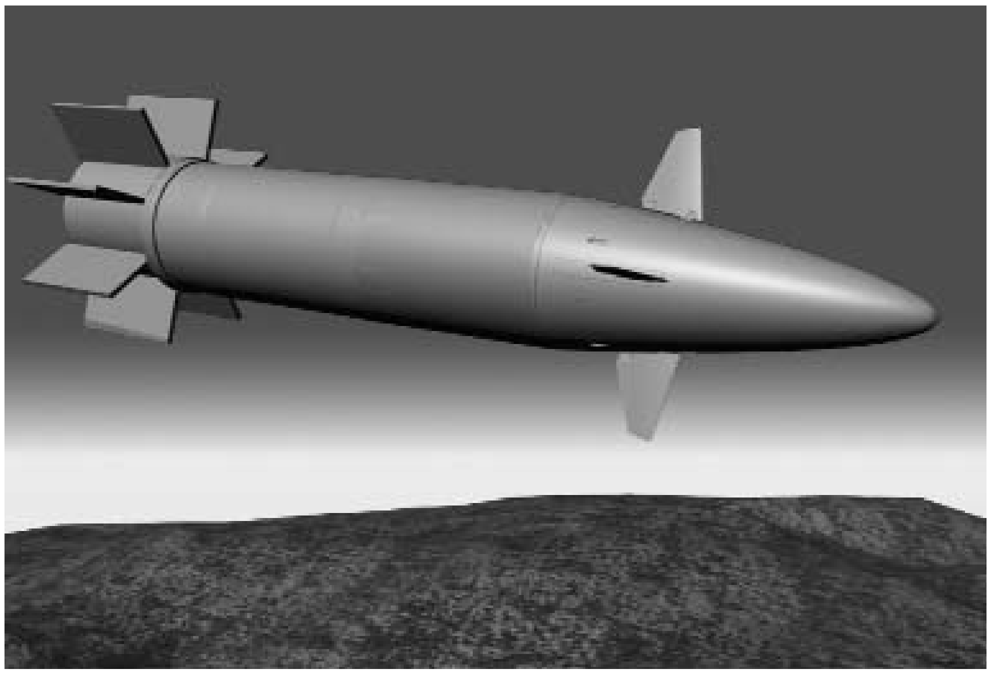

Since the invention of the cannon, the explosive fills used to drive lethal mechanisms have been the subject of ever increasing interest and study. Traditionally, munitions designers have used such explosives as Comp-B, TNT, or LX-14, depending upon the particular application. While these munitions passed various safety and rough handling tests in order to be certified for fielding, they may still experience a severe adverse reaction if caught in a fire or hit by bullets, fragments, or other battlefield threats. Indeed, many well-documented accidents/incidents happen over the years involving explosive ordnance.

In an effort to improve munitions survivability and safety, the Department of Defense (through the Joint Requirements Oversight Council) several years ago established a policy requiring all new munitions be capable of withstanding accidents, fires, or enemy attack. One method of addressing this requirement, the use of "Insensitive Munitions" (IM), including propellants and explosives, was mandated. Thus a new class of IM explosives has been developed over the past decade. Because these IM formulations differ somewhat from each other in a variety of ways (physical properties, explosive output, manufacturing process and cost, sensitivity and toxicity, etc.,) the explosive selection process

Recently, the Army's "Excalibur" artillery projectile development program, located at Picatinny Arsenal, N.J., used a decision support tool called Quality Function Deployment (QFD) to support their explosives downselect decision.

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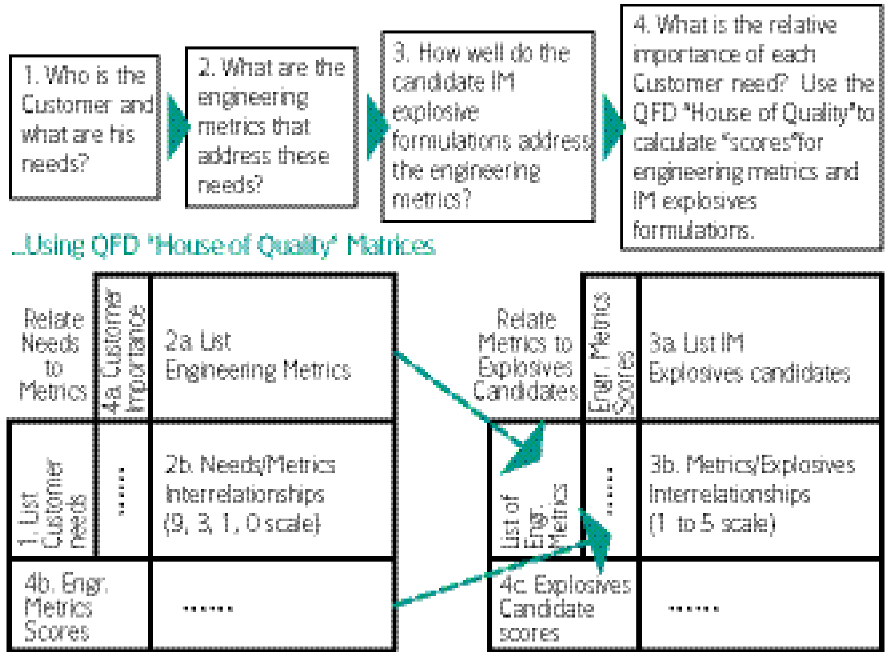
for a given munition has become more complex. How, then, do we determine which of these many explosives formulations is best to use for a particular munitions design?

FIGURE 1: **Four-step QFD Process for IM Explosive Selection**



To deal more effectively with this challenge, some munitions-design teams used Quality Function Deployment (QFD) as a decision support tool for their explosive downselect process. QFD provides an organized, step-by-step approach to comparing how well a particular solution addresses customer needs. Recently, the Army's "Excalibur" artillery projectile development program, located at Picatinny Arsenal, N.J., used QFD to support their explosives downselect decision. They established a multi-functional QFD team consisting of explosives design experts, munitions systems analysts and engineers, and a QFD facilitator. To assure all relevant parties were represented, team members were drawn from the Army (including the authors of this article), Navy, government, and contractor organizations.

The QFD Approach

The QFD team tackled the problem using the four-step process described in Figure 1.

Step 1

Determine who the customers are and what they need. We decided there were two sets of customers involved with the IM explosive decision:

- The warfighter who uses the munition.
- The Program Manager who is responsible for developing and manufacturing the munition.

The user/warfighter's military needs are captured in an Operational Requirements Document (ORD), written specifically for this munition. The ORD provides a detailed description of the military environment in which the munition has to survive and operate safely and reliably. The Program Manager's needs were determined through discussions with the Excalibur design team and include such factors as technical maturity, schedule risk, manufacturing complexity, environmental health concerns, and life cycle costs. An overall set of customer needs was created from the combined user and Program Manager requirements.

Step 2

Determine a set of engineering metrics that address every customer need. The key here is for engineers to be able to evaluate how effectively each metric addresses individual customer needs. One or more metrics must be determined that relate strongly to meeting each need. A metric is a characteristic or quality of the explosive that can be measured or assessed. A total of 43 engineering metrics were used to address Excalibur customer requirements.

A QFD matrix (also called the "House of Quality") is used to compare customer needs on one axis to engineering metrics on the other axis. Our QFD team filled in the matrix by comparing each metric to each need to determine where strong, moderate, weak, or no interrelationships exist. We assigned numerical values of 9, 3, 1, and 0 to represent strong, moderate, weak, and no interrelationships, respectively (using numerical values allows a quantitative evaluation to be made). Figure 2 shows a partial listing of this QFD matrix.

Step 3

Compare how well each explosive formulation under consideration satisfies the engineering metrics. To make an accurate assessment, our team first had to compile a database of technical information (consisting of physical and chemical characteristics, manufacturing methods, production costs, test results, toxicity, etc.,) on each explosive. Data on 13 explosives formulations (11 IM plus TNT and Comp-B "baselines") were collected. Subject matter experts on our team used a second QFD matrix to compare engineering metrics on one axis to explosives candidates on the other axis. A numeric scale of 1 through 5 was assigned to represent poor through excellent ability of the explosive to satisfy each metric. Figure 3 shows a partial listing of this second matrix.

Step 4

Ask customers to prioritize all their needs. The Excalibur Program representative fulfilled the role of the customer and ranked all the needs (by apportioning approximately 1,000 points among them). Once these rankings were inserted into the first QFD matrix, the relative importance, or score of every engineering metric was automatically calculated. (The score for a given metric is the product of the customer importance times the interrelationship value with that metric summed down the metric column.)

Figure 2 (bottom row) lists these scores. The engineering metric scores were then transferred to the second QFD matrix, resulting in a calculated score for each IM explosives candidate (bottom row of Figure 3, p. 40). The explosive with the "highest score" becomes the leading candidate for use in the Excalibur warhead.

Assessment of the QFD Selection Process

The process of collecting and analyzing the various sets of customer requirements, engineering metrics, and explosives candidates (together with the technical database) evolved over several months. We completed the final evaluation during an intensive two-day meeting, where explosives and manufacturing experts as well as the Excalibur Program Manager representatives painstakingly examined, compared, and agreed upon all data entries to the QFD matrices. As a result of this analysis, the IM explosive candidate receiving the highest score in the QFD process was selected for further development as the Excalibur warhead explosive.

How did we feel the QFD approach worked in this application? Let's look at

FIGURE 2: **Excalibur Explosive QFD Matrix No. 1**

Customer needs vs. engineer metrics.

(9, 3, 1 corresponds to strong, medium and weak relationship between metric and need)

Customer needs		Customer importance	thermal & chemical characteristics						physical & mechanical characteristics								sensitivity characteristics							
			thermal stability (DSC, STANAG-4515)	thermal stability@75degC (TB-700)	ignition temp (e.g. Woods metal bath)(MIL Std-650)	thermal conductivity	coefficient of thermal expansion	melting point	viscosity assessment	density	hydroscopic properties	irreversible growth characteristics (Mil Std-1751)	exudation characteristics (Mil Std-1751)	bulk modulus	yield strength	compressive strength	gap test -NOL Large Scale (mil std-1751)	impact sensitivity (Mil Std 1751)	ABL friction sensitivity (Mil Std 1751)	SCO (variable confinement cookoff test) (STANAG-4491)	Electrostatic Sensitivity (Mil Std-1751)	critical diameter (Mil Std-1751)	setback sensitivity assessment	risk of dangerous voids (Army & Navy Rqts)
Operational Performance (675): Effectiveness (300)	penetrator performance	100								1		3	1	1	1	1							3	
	blast/frag effects	200								3		3	1											
IM survivability (100)	withstand being in a fire Fast Cookoff	17	1		1	1	3	1												3				
	withstand being in a fire Slow Cookoff	17	3		1	3	9	1												9		1		
	withstand bullet and fragment impact.	33										1	1	1	1		1							1
	withstand sympathetic detonation conditions	34								1		3	1	1	1		3							1
Safety (100)	rough handling	25										3	3											
	weapon firing/hot tube	50	9		9	3	9	3				9	9	1			1						9	9
	EMP, lightning	25																						
Reliability (175)	controlled storage	25	1				9	9				3	3											
	uncontrolled storage	25	1				9	9				3	3											
	hot/cold environments	25					9	3				3	3											
	fuzetrain detonation transfer	100					3	3		1		3	3				3					3		
Product Management (350): Schedule risk (100)	2002 –test quantities needed	33																						
	2004 –LRIP quantities needed	33																						
	2007 Full rate production quantities needed	34																						
Production safety (100)	production safety	40						3										9	9		9			3
	Processibility	30	3					3		3														
	transportation safety	30																						
Environmental/health (75)	Environment hazard waste (air, water or soil)	19		9				3				3	3				1	3	3		3			
	toxicity - acute & subchronic/carcinogens	19											3											
	haz. explosive biproducts (test/train/war)	18																						
	haz. UXO biproducts	19																						
Life cycle costs (75)	Non-recurring costs	35							9		1		1											1
	recurring costs	40						3	9		1		1											9
Engineering Metrics scores = sum (cust importance x metric interrelationship)			658	270	484	218	1629	1339	765	834	165	2175	1656	217	167	100	515	450	450	204	450	333	750	1002

some of the perceived positives and negatives of the QFD analysis:

Positives/Strengths

- Consensus was reached as to the best explosives candidate for the Excalibur warhead.
- Facts and data replaced personality clashes as the basis for judgment.
- Decision related directly to customer needs—not to arbitrary decision making by managers or to vested interests.
- Politically sensitive decision was delegated to objectivity through the ability of QFD method to transfer discussions to a set of quantitative engineering criteria.
- Permanent record of the decision process was retained.

Negatives/Risks

- Considerable amounts of engineering, cost, and schedule data must be gathered upon which to base a decision. The commitment to do this must be made early-on, to minimize downstream schedule and cost impacts.
- It may require a significant expenditure of time, thought, and perseverance for a group of experts to assemble and complete the QFD matrices.
- The assignment of weighting factors to the customer's requirements/needs could have been conducted earlier in the process to allow more time for the QFD team to understand how the weightings might affect results. This would improve the decision process as far as which explosives candidates should be submitted for consideration. It will also allow time for the customers to better evaluate the consequences of their decisions.

  For example, if the customers weigh any one requirement extremely high, it could render all other requirements essentially meaningless as evaluation factors. An initial sensitivity test could be run to see if any "overriding" requirements exist. The customers may not have intended such an override situation to exist and might want to attribute a greater balance among their needs. Care should also be taken to ensure that all customer groups are identified and given an opportunity to influence the weighting factors.
- Explosive candidate scores revealed very little difference existed (less than 2 percent separating the top four explosives scores), calling into question the significance of selecting one candidate over another. The reason for doing the QFD approach in the first place was that all 11 IM candidates appeared generally acceptable for this munitions application, and QFD was used to select among close alternatives. Since the munitions were generally similar in performance, it should be expected that their scores would reflect this fact. An unacceptable explosive would not be considered in the first place.
- In the absence of detailed, specific, or accurate data, best engineering/expert judgment must be relied upon (and even experts can be wrong). A total of eight explosives experts (representing the Army, Navy, government, and contractor organizations) were used to evaluate data for this effort during the final two-day meeting.
- Sometimes the performance of the IM candidates in the actual munition configuration can only be estimated, which can lead to erroneous assessments of performance. Ideally, all IM candidates should be evaluated/tested in the specific munition configuration of interest prior to conducting the QFD analysis. Due to perceived schedule and funding constraints, however, this is not always possible, so "expert assessments" of how effectively the IM explosive candidate might work (e.g., based on how well it performed in other munitions configurations) are used to predict expected performance.

  If later testing demonstrates reduced or unacceptable performance of the selected candidate, the QFD matrix must be reviewed to determine the next best candidate. It should not automatically be assumed that the second-highest-scoring IM candidate should be used, since it may be that both candidates have the same fatal flaw in their design.

In an effort to improve munitions survivability and safety, the Department of Defense established a policy requiring all new munitions be capable of withstanding accidents, fires, or enemy attack. The use of "Insensitive Munitions" (IM), including propellants and explosives, was mandated. Thus a new class of IM explosives has been developed over the past decade.

An Explosive "Setback"

Recently, the IM explosive selected from the QFD rankings seriously failed a setback safety test and was discarded from further consideration in the Excalibur program. The question could be asked:

"Was this the result of a flaw in the QFD process?" We made a thorough review of the QFD data and found that matrices relating to the user need—"safety during weapon firing"—showed several engineering metrics that were strongly related to this need. The two most relevant to test failure were "setback sensitivity assessment" and "risk of dangerous voids." Since at the time the QFD was completed no IM candidate had conducted setback sensitivity tests in the actual Excalibur weapon configuration, this was an area where "expert assessment" played a strong role. Our experts based their opinions on the available data collected, which was based on the explosive's past performance in other munitions. Although no specific data were provided on setback test results, the "top explosive" candidate had claimed successful performance/selection in other munitions; i.e., it had been selected as the explosive fill for two Navy projectile programs. This prompted our explosives experts to assign a value of 4 (indicating "desirable, exceeds, pretty good") out of a maximum of 5 as to how well this explosive satisfied both the set-

FIGURE 3: **Excalibur Explosive QFD Matrix No. 2**

Engineering Metrics and IM Explosive Candidates (Partial list)

	Compare Engineering Metrics to Explosives Candidates	**baselines** metrk score	**CompB**	**PAX-28**	**PAX-21**	**PAX-2A**	**PBXN-9**	**PBXW-114**	**PBXN-112**
thermal & chemical characteristics	thermal stability (DSC, STANAG-4515)	658	3	3	3	3	3	3	3
	Thermal stability @ 75degC (TB-700)	270	3	3	3	3	3	3	3
	ignition temp (e.g., Woods metal bath)/Mil Std-650)	484	3	3	3	4	4	4	4
	thermal conductivity	218	3	3	3	3	3	3	3
	coefficient of thermal expansion	1629	4	3	3	4	4	3	3
	melting point	1339	3	3	3	3	4	4	4
physical & mechanical characteristics	viscosity assessment	765	4	4	4	3	3	3	3
	density	834	3	3	3	3	3	3	3
	hydroscopic properties	165	3	3	3	3	3	3	3
	irreversible growth characteristics (Mil Std-17	2175	3	3	3	3	3	3	3
	exudation characteristics (Mil Std-1751)	1656	2	3	3	3	3	3	3
	bulk modulus	217	3	3	3	3	3	3	3
	yield strength	167	3	3	3	3	3	3	3
	compressive strength	100	3	3	3	3	3	3	3
sensitivity characteristics	Gap test - N.O.L Large scale (mil std-1751)	515	2	5	4	4	3	4	3
	impact sensitivity (Mil Std 1751)	450	3	3	3	3	3	3	3
	ABL friction sensitivity (Mil Std 1751)	450	3	3	3	3	3	3	3
	SCO (variable confinement cookoff test) (STANAG-4491)	204	2	2	2	2	4	3	3
	Electrostatic Sensitivity (Mil Std-1751)	450	3	3	3	3	3	3	3
	critical diameter (Mil Std-1751)	333	3	3	3	3	3	3	3
	setback sensitivity assessment	750	2	3	3	4	4	4	4
	risk of dangerous voids (Army & Navy Rqts)	1002	2	4	4	3	3	4	4
performance characteristics	Detonation velocity	600	3	3	3	3	3	3	3
	Brisance (plate dent test)	600	3	3	3	3	3	3	3
	Gurney constant	1800	3	2	4	4	4	4	4
	CJ pressure	600	3	3	3	3	3	3	3
	Accelerated aging	906	4	3	3	5	4	4	5
IM tests (for other applications)	Fast cook-off test	51	1	3	5	3	4	5	4
	Slow cook-off test	51	1	3	4	1	4	4	4
	Bullet impact test	99	3	3	5	3	3	5	5
	fragment impact test	99	1	3	3	1	2	2	1
	sympathetic detonation test	102	1	3	4	2	1	4	3
schedule risk	time needed to mature, facilitize, and produce explosive	300	5	4	5	5	5	4	5
	Materials availability	900	2	3.5	3	5	5	5	5
costs	Non-recurring costs: mature, and facilitize explosive	315	2	4	4	3	3	5	5
	Recurring costs: explosives production/ LAP	360	5	5	5	4	4	4	4
	Recurring costs: O&S and demil	360	5	4	4	4	4	4	4
	Cost to remediate hazardous emissions	465	2	4	4	4	4	4	4
environmental/ toxic hazards	Hazardous production/ LAP/ UXO/ demil wastes (air, water, soil)	680	2	4	4	4	4	4	4
	Hazardous detonation byproducts	162	3	3	3	3	3	3	3
	carcinogenic emissions	509	5	5	5	4	4	4	4
	acute toxicity emissions	509	4	3	4	3	3	3	3
	sub-chronic toxicity emissions	509	4	3	4	3	3	3	3
		Explosive Candidate Score	74707	79525	84381	85582	86109	86678	87117

Numbers 1–5 correspond to poor-to-excellent ability for the explosive to satisfy the requirements of the metric.

Highest scoring explosive

back sensitivity and risk of dangerous voids assessments (evidently, as with the stock market, past performance in other munitions may not be an indicator of future success). However, our assessment does not appear to have been unreasonable, based on the data available.

It does not appear that the QFD process was at fault, but it suffered from a lack of relevant test data in key areas. Moreover, the QFD matrices and data tables enabled an efficient post mortem of this problem to be conducted. One cautionary note: the second-highest-scoring IM candidate had essentially the same sensitivity data as the top-scoring explosive. This suggests it may not be the best alternative explosive candidate for Excalibur, and that additional testing together with a careful scrutiny of lower scoring candidates would be prudent.

Participant's Perspective

From a participant's perspective (provided by an explosives expert who participated in this QFD exercise), a number of issues contributed to the difficulty of this effort. A more rigorous systems engineering/testing approach would have been extremely helpful to more accurately tie the system requirements to the explosive characteristics used for the QFD.

For instance, some important engineering metrics were eliminated, or only roughly assessed, as a result of lack of detailed test data (for example, specific setback data). To await results of further testing would have forced a delay in the selection process and possibly impacted the Excalibur program schedule and increased costs. Having the additional data available, however, might have significantly improved this particular selection.

A more rigorous systems engineering approach would have benefited the selection process in several ways:

- The amount of data requested for customer needs versus engineering matrix could be reduced.
- The amount of time and effort expended for the evaluation could also be reduced.
- The timing of the final QFD data review should coincide with completion of data collection, rather than be prematurely set to coincide with a preset program schedule date. Prior determination of key design parameters and test data would result in a more accurate focus to the explosive selection process.
- Given the time to properly conduct data collection, the prioritization and deployment of customer/system requirements could be conducted in a more rigorous and quantitative fashion. This would reduce emphasis on qualitative judgment based upon experience (such as the setback data previously mentioned).
- Prioritization of customer needs should have been done much earlier in the QFD process, before the explosives candidates were provided. Lack of early knowledge of the key user needs may have resulted in a potentially best-choice explosives candidate not even being submitted for consideration.

The eight explosives experts assessing the QFD data may have been too many and resulted in an overly long and detailed evaluation time. The team should be more limited in size and comprise an odd number of individuals to avoid ties on ranking metrics and overly detailed discussions on minor variables.

To help reduce the long and arduous final QFD discussion and ranking period, explosives candidates should be limited to no more than two of each explosive type. A formal QFD prescreening process, limited to a small amount of major engineering metrics, could be used for this activity.

After completion of the pre-selection process, some critical safety and performance tests should be run on the remaining candidates using actual system hardware to provide greater assurance of accurate correlation of engineering metrics to the end-item requirements.

Taken as a whole, these adjustments would allow for a more accurate determination of the best characteristics and energetic material to meet end-item needs.

Overall Application of QFD Methods

We believe the QFD process contributed to the Excalibur IM explosive selection by organizing customer needs and facilitating the assessment of how well engineering metrics meet these needs and how well the explosives candidates satisfy the metrics. However, the QFD process itself cannot make up for a lack of critical test data. When lack of data was noted, the options exercised were to: 1) eliminate the engineering metric for which data were unavailable, or 2) have technical experts "assess" how well they believed the explosive candidate would perform based on what data were available.

These assessments were apparently not accurate enough to reliably predict performance in certain key areas such as setback tests. The IM explosive candidate selected for further testing suffered a catastrophic test failure and was discontinued. The Excalibur program is following the QFD rankings to select its follow-up choice. While we are still learning about applying QFD to explosives selection, the transparent nature of the QFD process made it relatively easy to review the data after the fact as to possible causes of the setback test failure. The overall application of QFD methods to the explosives selection area should be viewed as a positive contribution.

As a final caution, keep in mind that QFD matrices and results are often unique to the particular set of users' needs being investigated. They should not automatically be applied to another customer's needs (even if they appear somewhat related) without a careful review.

Editor's Note: The authors welcome questions or comments on this article. Contact Rhinesmith at rrhine@pica.army.mil; Williamson at bwilliam@pica.army.mil; and Niles at jniles@pica.army.mil.