The Quest for Practical DFSS (Design-for-Six-Sigma) Tools

PGMM Case Study

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ATK Advanced Weapons Division

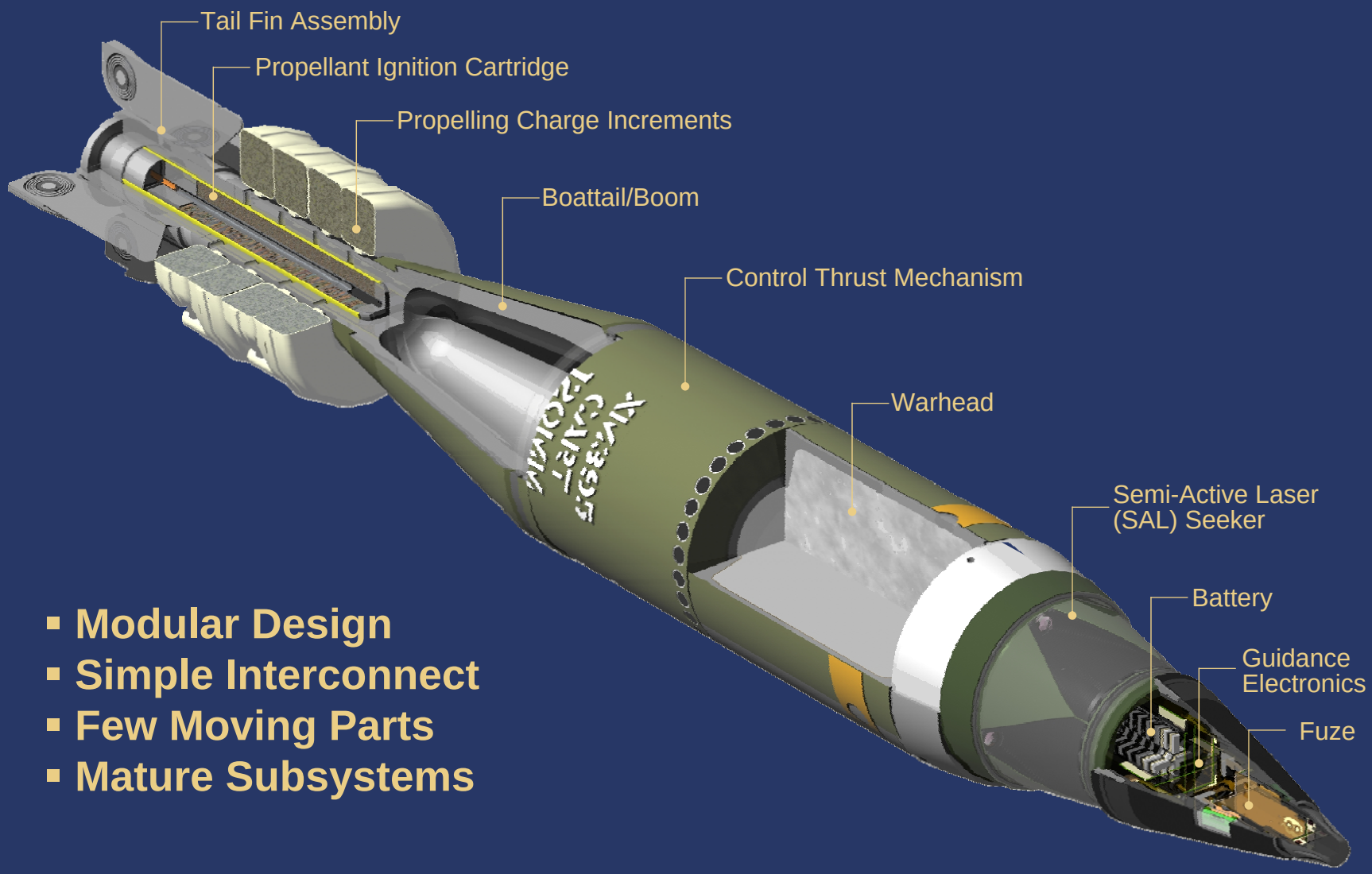
NDIA Systems Engineering Conference
26 October 206
San Diego, California

XM395 PGMM

Precision Guided Mortar Munition

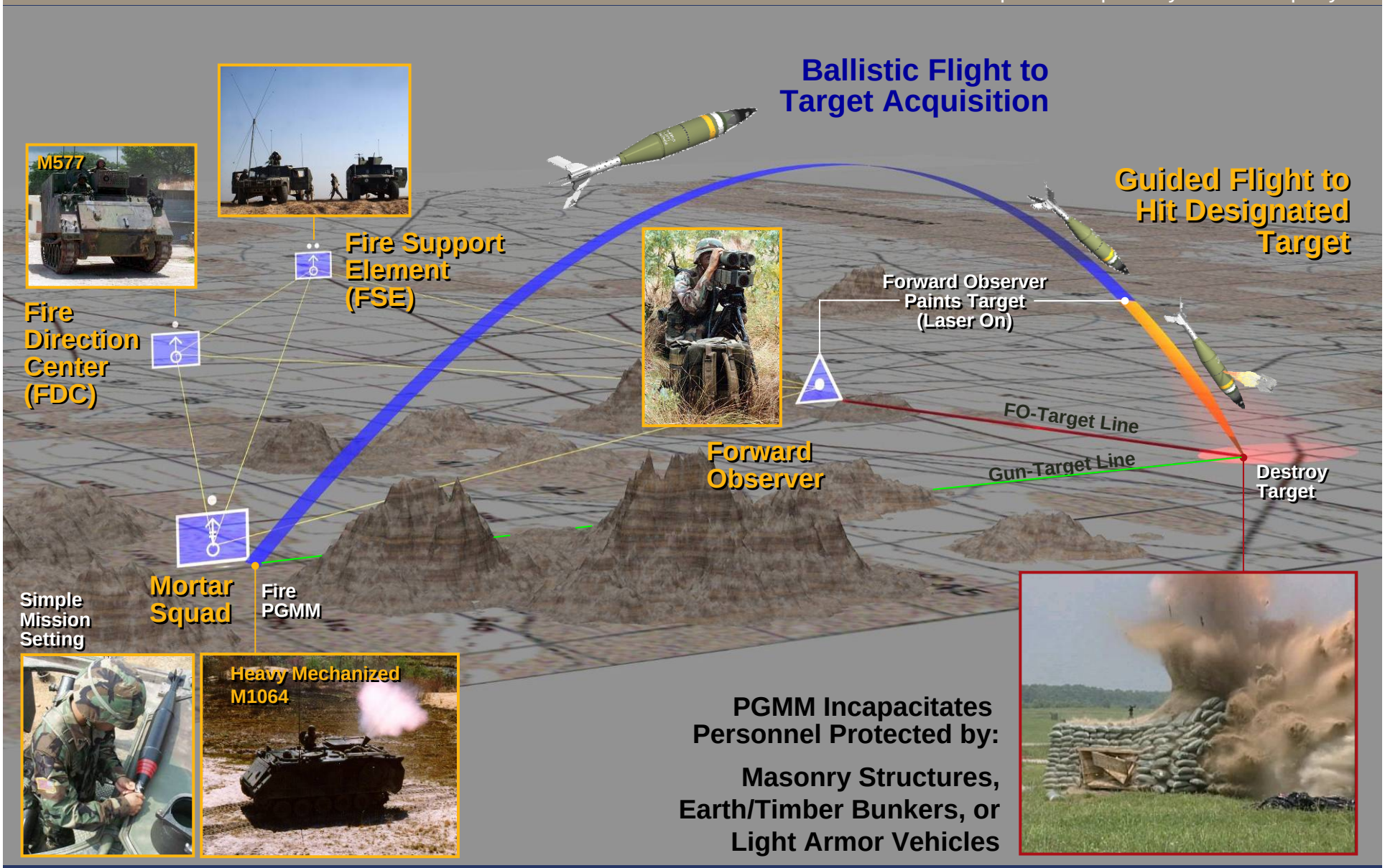
- **Swift, ballistic flight to target** – no midcourse guidance – laser guidance in terminal phase
- **Few moving parts** – high reliability in high-G gun environment
- **Accurate** – simple, responsive thruster control
- **Lethal** – large warhead overmatches all PGMM targets

PGMM Cartridge – Simple, Rugged, and Precise



- **Modular Design**
- **Simple Interconnect**
- **Few Moving Parts**
- **Mature Subsystems**

PGMM Operational Elements

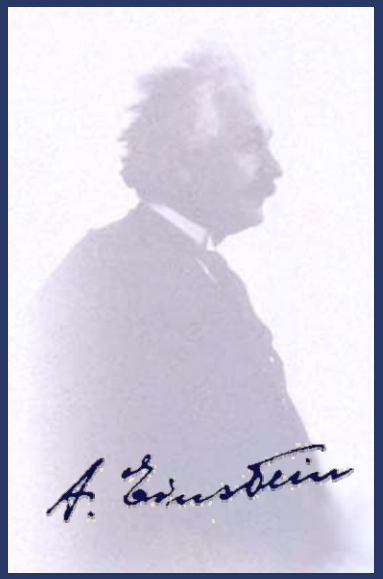


PGMM Incapacitates Personnel Protected by:

Masonry Structures, Earth/Timber Bunkers, or Light Armor Vehicles

PGMM Video

Wisdom for a Quest



The Best Design is the Simplest One That Works

Plan what is difficult while it is easy; do what is great while it is small.

Excerpted from *The Art of War/Sun Tzu*, Copyright 1991 by Thomas Cleary, Shambhala

Peter F. Drucker

"Effectiveness is the foundation of success – efficiency is a minimum condition for survival after effectiveness has been achieved. Effectiveness is doing the right things. Efficiency is doing things right."

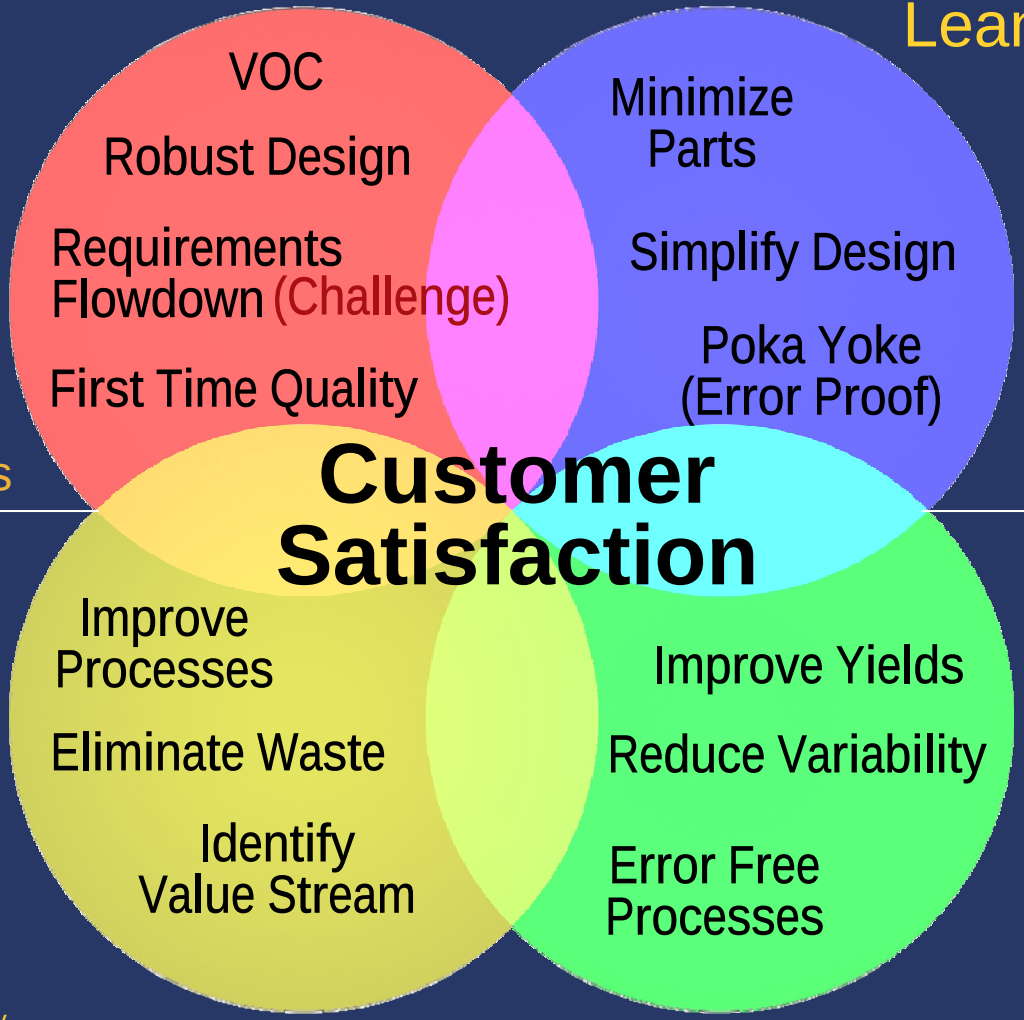
"Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease costs."

Excerpted from *Out of the Crisis*, Copyright 1986 by the W. Edwards Deming Institute

Six Sigma & Lean Enterprise Model for PGMM

DFSS, CDOV

Lean Design,™ DFA



Improve Effectiveness

Avoid Problems

Customer Satisfaction

Improve Efficiency

Fix Problems

Lean Manufacture

Six Sigma, DMAIC

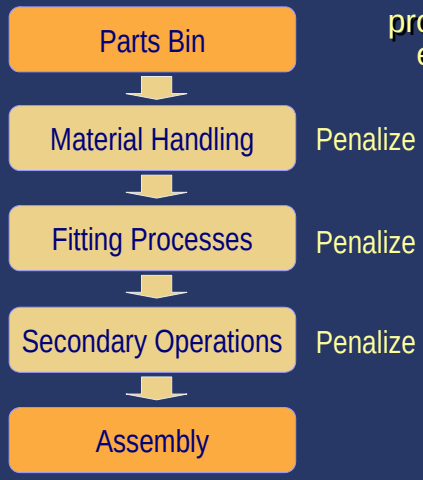
DFSS: Design For Six Sigma
DFA: Design for Assembly
CDOV: Conceive, Design, Optimize, Verify
VOC: Voice of the Customer
DMAIC: Define, Measure, Analyze, Improve, Control

Design for Assembly (DFA)

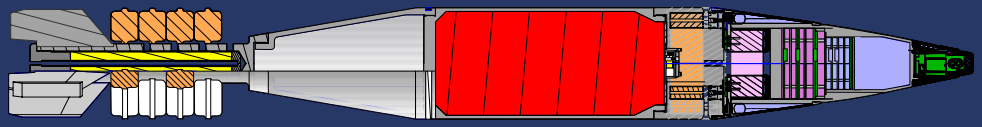
Design for Assembly

Analyze and penalize any non-value added process

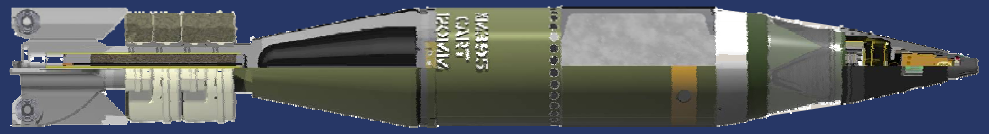
Aggressively eliminate unnecessary parts or processes at the earliest stages of the design



Pre-DFA Workshop ***>2000 Parts***



Current PGMM Design ***470 Parts***



Benefit: 20% Reduction in Product Cost

"Companies that implemented some form of DFA report significant savings. Part count is typically reduced **10-40%,** bringing down material and inventory costs with it. Assembly time falls **20-90%** and thus labor costs also come down. Reliability and servicability improve. Total costs fall by at least **20-50%**."

Design for Competitiveness, Advance copy by Bart Huthwaite

"DFMA survey by Galorath Inc. discovered that more than half of the respondents say **10 to 20%** savings when they used DFMA at the design stage."

Design News, 16 August 1999

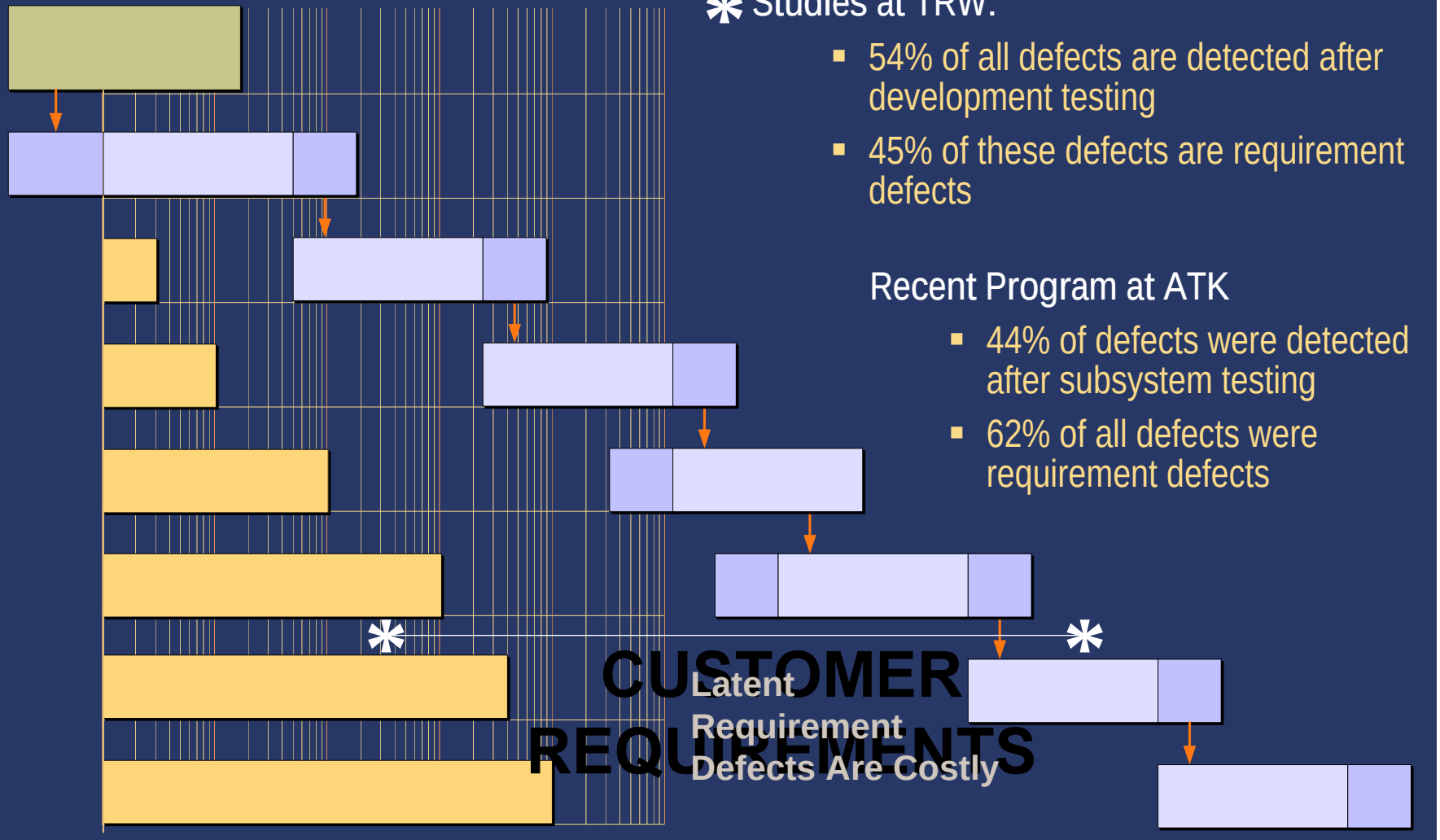
Project Objectives

Objectives

1. Vigorously apply several DFSS tools to the PGMM (Precision Guided Mortar Munition) program
2. Refine and evaluate the tools (provide lessons learned, resource planning guides)
3. Support timely execution of major PGMM program milestones (SRR, SDR, PDR)

DFSS Tool	Status	ATK Technical Excellence Standard
Stakeholder Analysis	Complete	2. Data Based Decision Making
Operational Crosswalk	Complete	3. Consideration of System-Level Issues and Interactions
Requirements Discovery and Management	Complete	1. Requirements Defined and Tracked
QFD (Quality Functional Deployment)	Complete	3. Consideration of System-Level Issues and Interactions
FMEA (Failure Modes Effects Analysis)	In-Process	3. Consideration of System-Level Issues and Interactions
System-Wide Defects Tracking	In-Process	2. Data Based Decision Making
Producibility Scorecard	In-Process	7. World Class Process Control at ATK and our Suppliers

Traditional Approach to Product Development



- Studies at TRW:
  - 54% of all defects are detected after development testing
  - 45% of these defects are requirement defects

Recent Program at ATK

- 44% of defects were detected after subsystem testing
- 62% of all defects were requirement defects

Latent Requirement Defects Are Costly

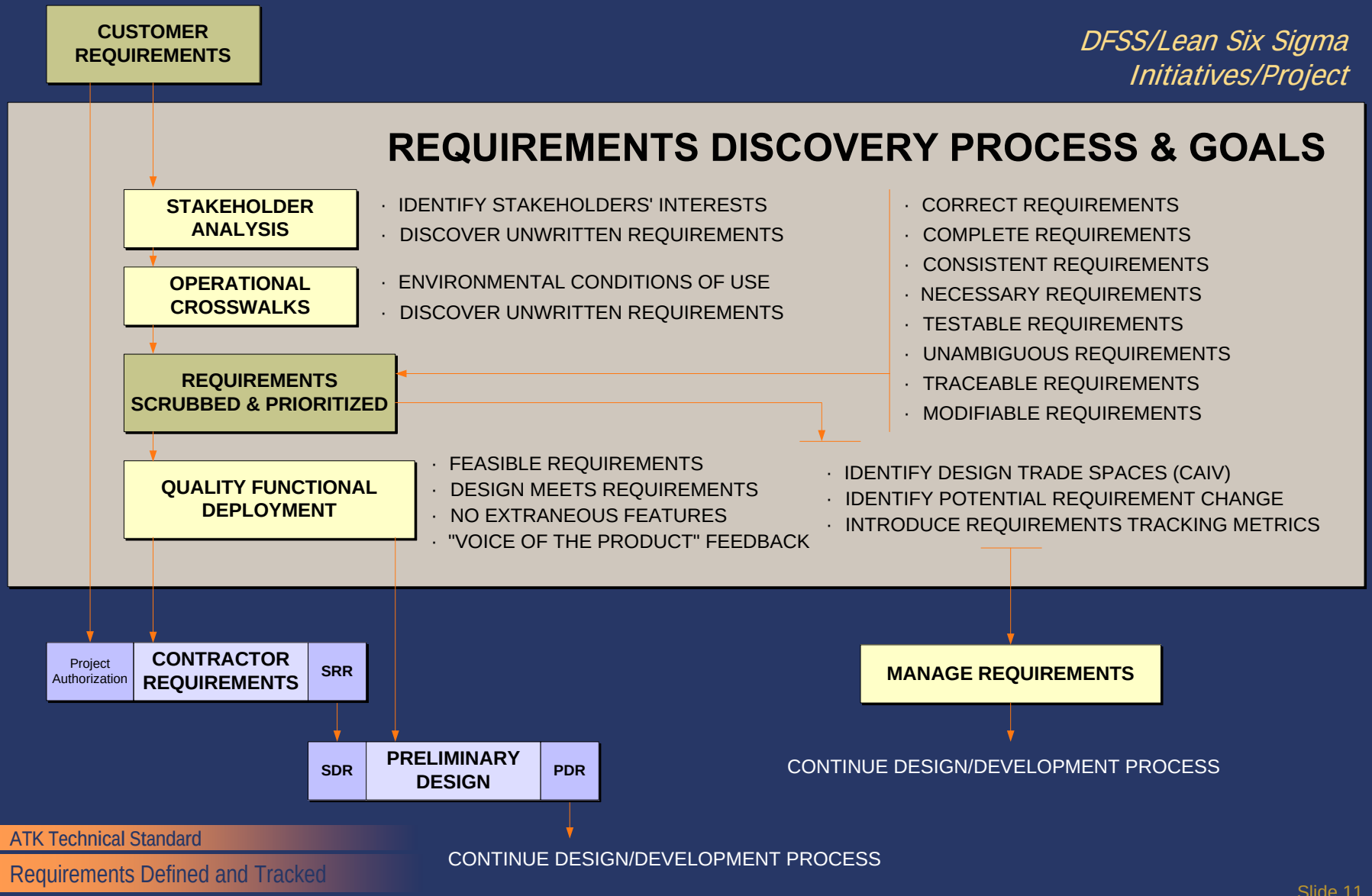
Design for Competitiveness, Advance copy by Bart Huthwaite

1

Project

CONTRACTOR

New Approach to Product Development



ATK Technical Standard

Requirements Defined and Tracked

Interdisciplinary Cross-Functional Project Team

Team of 19 Peers

- **Planned the Project**
- **Reviewed Approaches**
- **Participated in Exercises**
- **Evaluated Process**

ATK Cross-Functional Engineering Team

	Systems Engineering	Analysis & Simulation	Systems Design	Mechanical Design	Software Design	Electrical Design	Manufacturing	Business Development	Subcontracts	Project Advisor	Project Advisor
ATK PGMM Program IPT Leads											
PGMM Technical Director											
Systems CPT Lead	■										
Analysis, Software, Simulation IPT Lead		■									
Nose Assembly IPT Lead			■								
Midbody Assembly IPT Lead				■							
Tail Assembly IPT Lead											
Systems Software, HIL											
Weapon Integration, Logistics IPT Lead											
Munition Integration & Test CPT Lead											
US Army IPT Leads											
ARDEC – System Performance Specification											
OPM Mortars – Test & Evaluation											
ARDEC – Test & Evaluation											

ATK Technical Standard

Peer review process

Stakeholder Analysis

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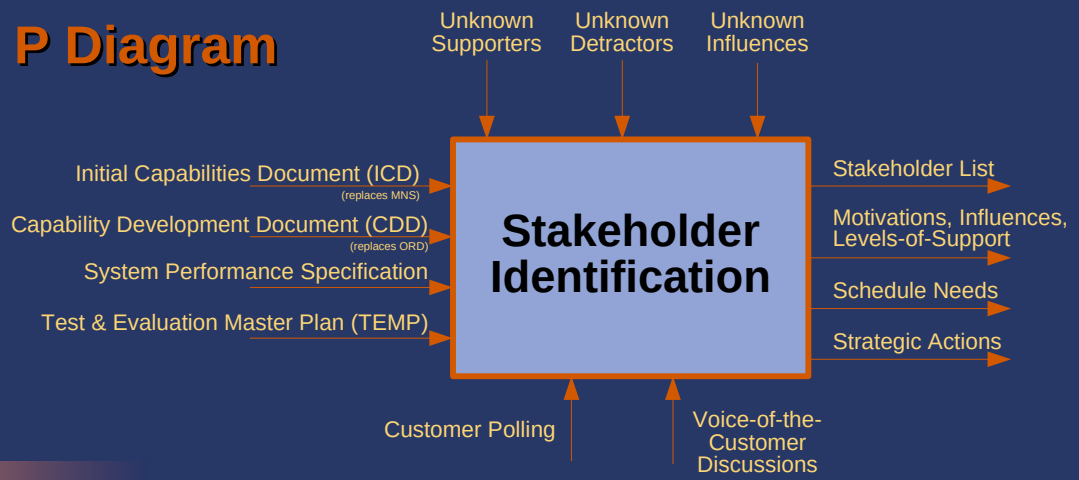
Database Information	Database Example
Interest Category	Seeker Subsystem
Organization	US Industry
Stakeholder	BAE Systems
Location	Nashua, NH
Role	SAL Seeker Supplier
Motivation	Expand SAL Seeker Product Base
Level of Support [+3 For, -3 Against]	3
Level of Influence [+5 High, +1 Low]	2
Stakeholder Effect	6
Strategic Action	- -

Lessons Learned

- This tool has utility for Program Managers, Business Development teams, and Engineering leadership
- Database protects against knowledge base turnover
- Helps to ensure that no stakeholder's interest is ignored – develops complete set of stakeholders

P Diagram



To:

PY126: Customer Satisfaction

PY401_2 Requirement Identification

Operational Crosswalks

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Light Forces

Heavy Mechanized Forces

- MFCS – Mortar Fire Control System
- MMS - Mortar Mission Setter
- Mortar Extraction Tool
- LRRS _ Loose Round Restraint System
- Helicopter Transport
- Vehicle Weapon Racks
- Autoloaders/Breechloaders

FCS NLOS-M
(Future)

Stryker
BCT-MC
Soltam Vb
(Current)

Dismounted
M120 Mortar
(Current)

Dismounted
M120 Mortar
(Future)

M1064A3
Mortar Carrier
M121 Mortar
(Current)

Palletized
Mortar Rounds

Requirements Discovery

Requirement Discovery Process – An Allegory

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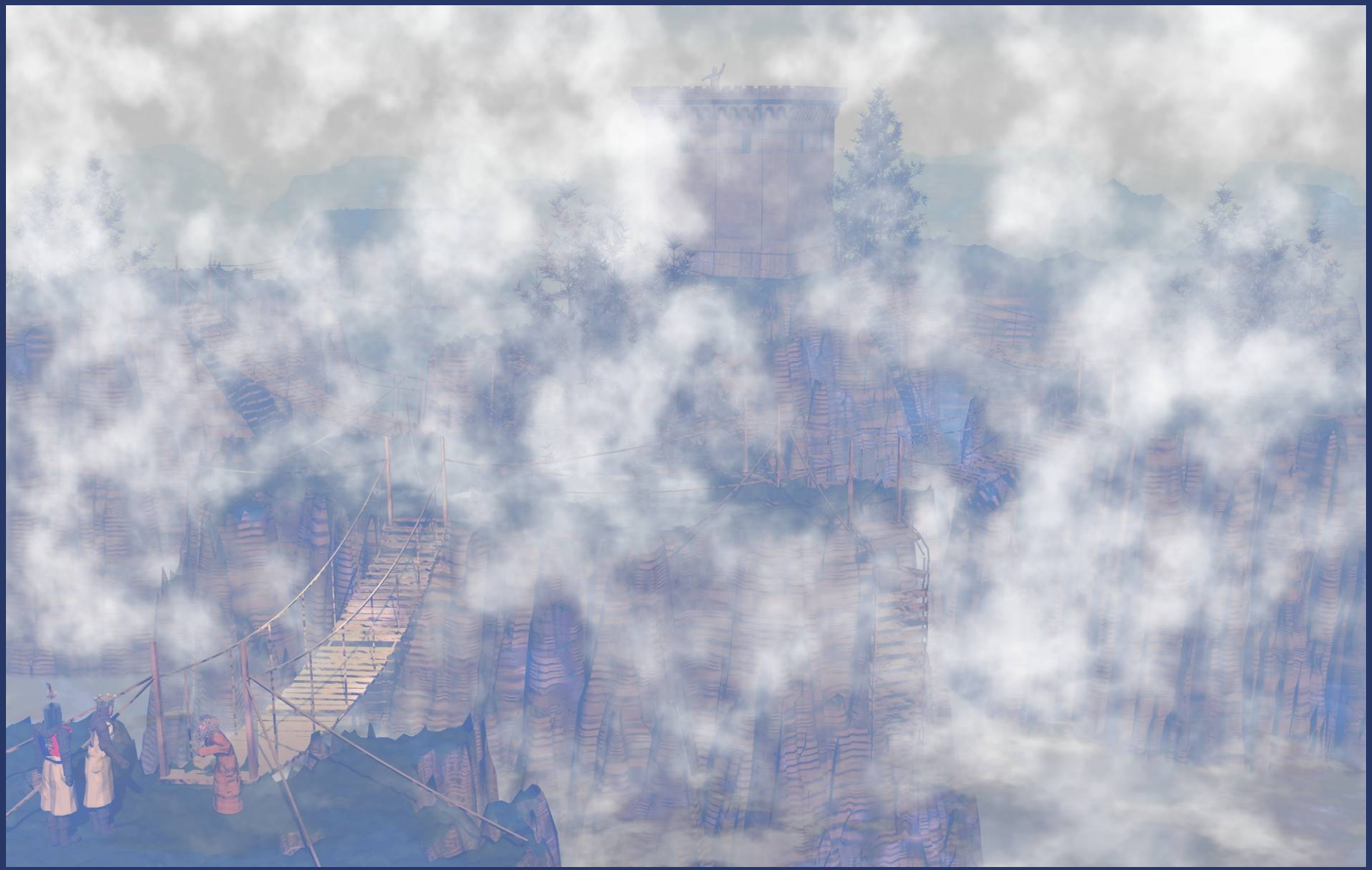

Requirement Discovery Process – An Allegory

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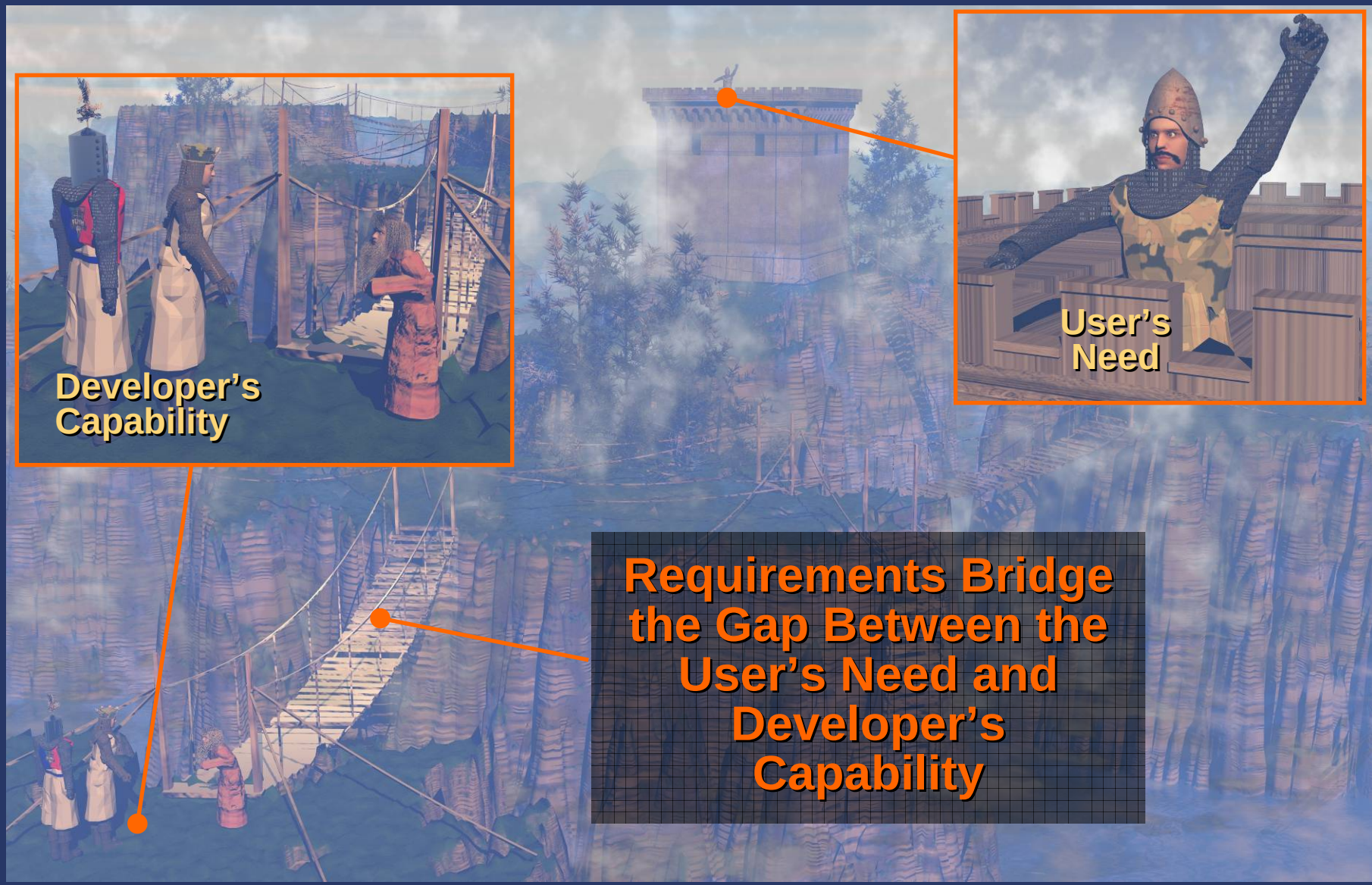

Requirement Discovery Process – An Allegory

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Requirement Discovery Process – An Allegory

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Performance Requirements Walkthrough

Requirements Walkthough

Consolidated Walkthrough Review

3.3.5.2 KPP 2 - Lethality

Verbatim from Customer Performance Specification

REFERENCE: System Performance Specification Draft 31-Jan-03

OWNER: USAIC – Jurgen Becker

DESCRIPTION:

3.3.5.2 KPP 2 – Lethality. The XM395 cartridge SHALL have the ability to incapacitate or fractionally casualtize personnel protected within and by point targets (described below), given a two round XM395 engagement. Specific levels of effectiveness Probable Incapacitate (Pi) SHALL meet Block I requirements detailed in Table-I of Appendix B.

EVALUATION:

[X] INCOMPLETE	[ ] INFEASIBLE	[ ] UNTESTABLE
[ ] INCONSISTENT	[ ] UNMODIFIABLE	[ ] UNTRACEABLE
[ ] INCORRECT	[ ] UNNECESSARY	[ ] AMBIGUOUS

CROSS-REFERENCE: CTP 9. Draft ORD Para. 4.1.1.1.1, 4.1.1.1.2

ISSUE:

Why two rounds or less? Why not specify single round, when we are assuming (in evaluation) independence in probability? How do we assign how the laser designator operation influences lethality? How do we model delivery errors?

PRIORITY:

[9] MISSION/SAFETY CRITICAL	[X] NON-NEGOTIABLE	[X] UNLIKELY TO CHANGE
[ ] USEFUL	[ ] NEGOTIABLE (CAIV)	[ ] MAY CHANGE
[ ] DESIRABLE	[ ] FLEXIBLE	[ ] MOST LIKELY TO CHANGE

CORRECTIVE ACTION:

Probability of collapse is now also included for the Earth & Timber bunker. We would like to have guidance on how to constrain or define the operational conditions and "real world" error sources under which we are to perform. Can we refer to an error budget within the spec (Section 4)?

SOURCE: ORD

RATIONALE:

The user wants to envision how many rounds they will need to kill a target (hence two rounds specified).

METHOD OF VERIFICATION:

4.3.5.2 Lethality. To be verified via analysis and test of XM395 subsystem and system flight hardware against all targets specified in Section 3.3.5.2. The input data for the lethality analysis will be based upon the Probability of Incapacitation (Pi), 30 sec defense casualty criteria.

Note: Since we are verifying performance through modeling, we are most interested in validating our models. Further discussion needed.

Verbatim from Customer Performance Specification

SUPPORTING ANALYSIS:

Performance Requirements Walkthrough

Information Capture Directly from Customer

Requirements Walkthough

Consolidated Walkthrough Review

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X	INCOMPLETE		INFEASIBLE		UNTESTABLE
	INCONSISTENT		UNMODIFIABLE		UNTRACEABLE
	INCORRECT		UNNECESSARY		AMBIGUOUS

Feedback To Customer From Contractor

CROSS-REFERENCE: CTP 9. Draft ORD Para. 4.1.1.1.1, 4.1.1.1.2

ISSUE:

Why two rounds or less? Why not specify single round, when we are assuming (in evaluation) independence in probability? How do we assign how the laser designator operation influences lethality? How do we model delivery errors?

Notes to Formulate Action Plan

PRIORITY:

9	MISSION/SAFETY CRITICAL	X	NON-NEGOTIABLE	X	UNLIKELY TO CHANGE
	USEFUL		NEGOTIABLE (CAIV)		MAY CHANGE
	DESIRABLE		FLEXIBLE		MOST LIKELY TO CHANGE

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Note: Since we are verifying performance through modeling, we are most interested in validating our models. Further discussion needed.

SUPPORTING ANALYSIS:

Requirements Walkthrough Statistics

Requirements Discovery

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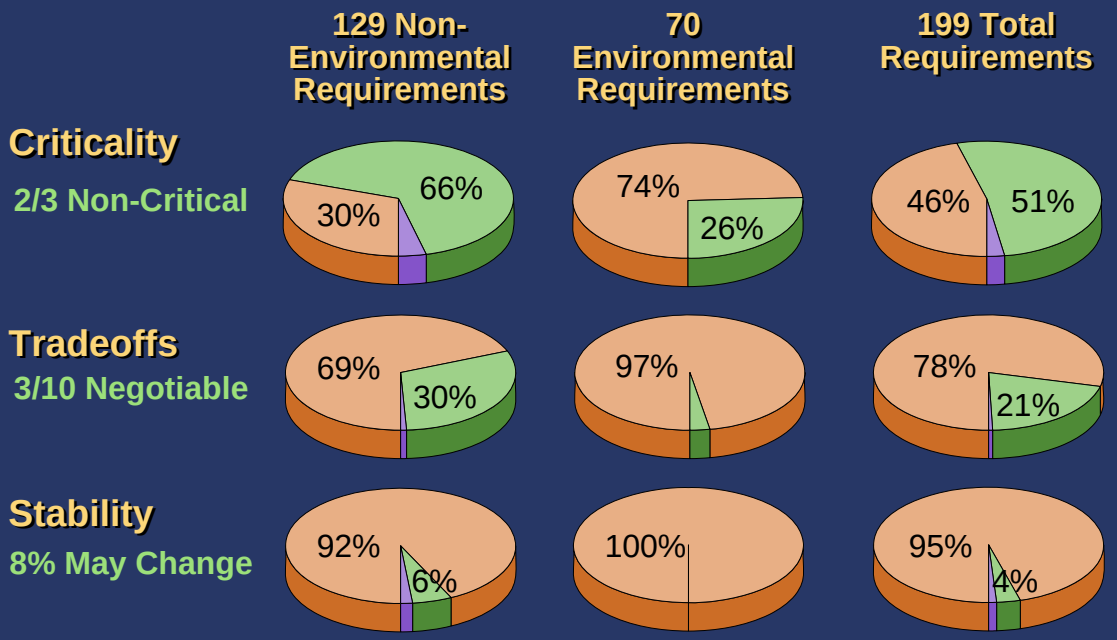
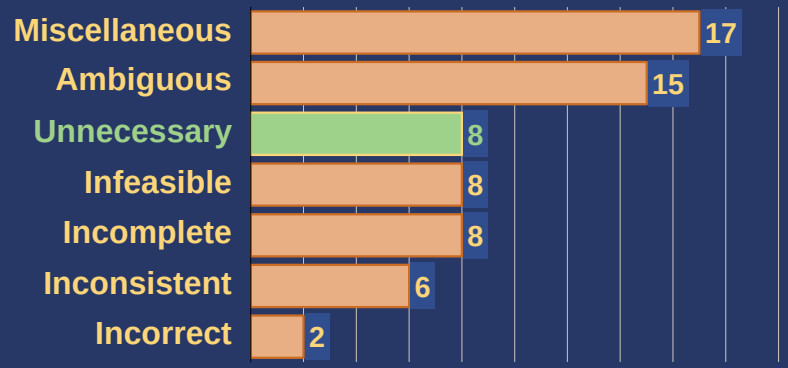
Customer Priorities	129 Non-ENV REQ	70 ENV REQ	199 Total REQ
Mission/Safety Critical	39	52	91
Useful	85	18	103
Desireable	5	0	5
Non-Negotiable	89	68	157
Negotiable	39	2	41
Flexible	1	0	1
Unlikely to Change	118	72	190
May Change	7	0	7
Most Likely to Change	2	0	2



Contractor Feedback (64 Issues)



- The PGMM Performance Specification was very well written by OP-Mortars, USAIC, and ARDEC
- Only 64 issues (32% of 199 requirements)
- The 64 issues spawned 58 Actions (9 of which were critical).

Clear, Quantitative Requirements

Earth And Timber Bunkers [Req-Id = 13708-2]

The cartridge shall defeat earth and timber bunkers (collapse) or incapacitate (30-second defense casualty criterion) a two-man, randomly located team within a structure as defined by TM 30-78 given a two-round or less engagement.

Rationale: The ability to efficiently defeat the threat soldiers protected by bunkers allows the maneuver commander to keep his soldiers from defeating this threat using traditional direct fires systems. The precision effects from the PGMM will significantly reduce the large numbers of HE mortar rounds/field artillery rounds being fired as stated in the PGMM AoA which reduces the logistical resupply requirements dramatically. PGMM will reduce collateral damage due to the decrease of actual mortar and artillery rounds required to accomplish the same mission using HE.

Maximum Range [Req-Id = 13717-2]

The cartridge shall engage targets from the mortar system as far as 7200m (gun-to-target line impact measurement per TOP 3-2-825) in nominal weather defined by standard meteorological data at sea level (temperature = 15ºC; pressure = 1013 millibars; no precipitation; no wind; no humidity; and air density = 1225 grams per cubic meter).

Rationale: Current mortar munitions have a maximum range of 7.2 km. Giving the PGMM the ability to reach 7.2 km allows the force commander to accurately engage targets throughout the area of operations at current range capabilities without changing current tactics and procedures to accommodate shorter-range munitions.

MFCS Link [Req-Id = 15280-2]

The cartridge shall link to the MFCS Commander's Interface via the Mortar Mission Setter (MMS).

Rationale: The current and Future forces will depend heavily on digital systems to integrate and control fires in support of the maneuver commander. The future MBCs, MFCSs, and UA FCS network will be digitally linked for situational awareness (SA) and fire support information. The PGMM may receive target information directly from those systems without additional user input.

- **Excerpted from PGMM PIDS**
- **Managed in Teamcenter Requirements**

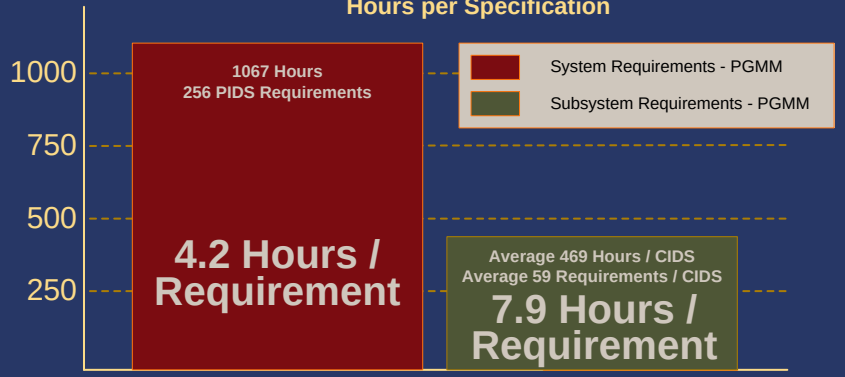
ATK Technical Standard

Clear Requirement Understanding

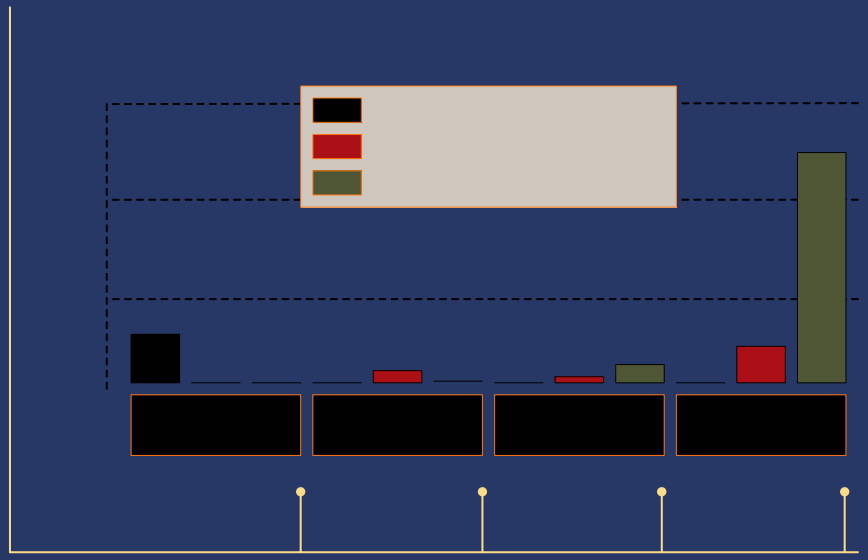
Requirements Discovery - Results

Resource Planning

Hours per Specification



Hours include: Requirements Discovery, Flowdown, Development, Management and Audits up to PDR where the specifications were baselined and put under formal configuration control.



Potential Benefits

- Fewer Revisions to Specifications during the requirement development phase
- Clear understanding of the customer's requirements and rationale
- Eliminates unneeded requirements

ATK Technical Standard

Clear Requirement Understanding

Lessons Learned

- Publish and Maintain an Operational Concept and System Diagrams
- System Requirements should be 90% mature by SDR
- Rationale statements expose bad assumptions and improve requirement quality
- A requirements management tool reduces requirement development time
- Have a configuration management process in place by SDR
- Conduct requirements audits before specifications are released to formal configuration control

Accomplishment - Requirement Reduction

Reduced Customer Requirements

- 199 “SHALL” requirements in US Army SPS (System Performance Specification)
- Deleted 17 requirements (8.5%)
- Relaxed another 5 requirements (2.5%)

} 11%

Significance

- Eliminated requirement to meet safety and reliability performance for one environmental requirement (unnecessary)
- Relaxed a second environmental requirement to be met in an in-package, un-powered condition rather than in an un-packaged, powered condition
- Avoided fuze redesign cost of ~$300K to safely reset after exposure to the second environment
- Avoided special testing at government facility to verify redesign
- Eliminated the second environment potential non-compliance from risk register

PGMM Requirements Audit and Defect Tracking

REQUIREMENTS MANAGEMENT

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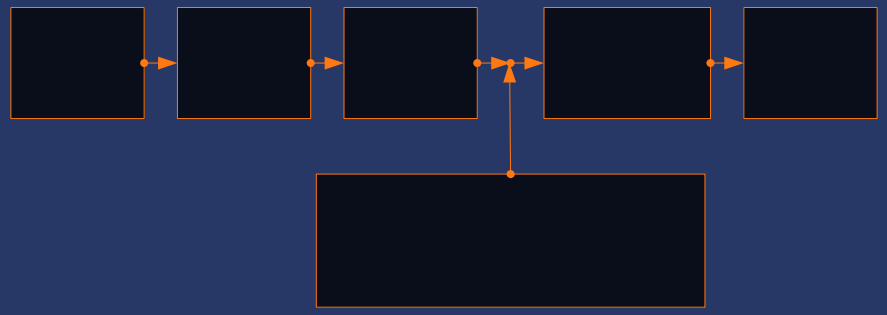
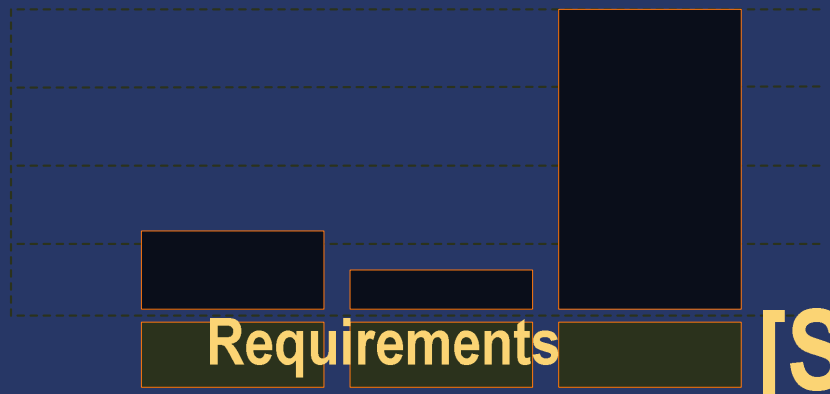
Process





ATK Technical Standard

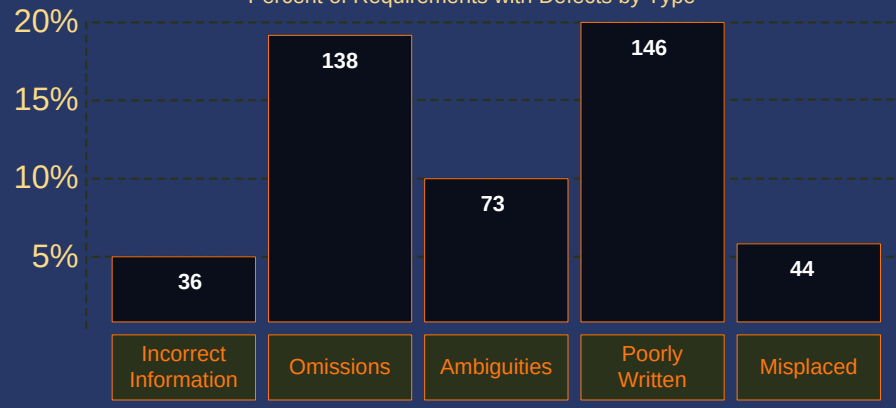
Early elimination of deficiencies

Results

- 946 System and subsystem requirements audited
- 46% had at least 1 potential defect
- 87% of potential defects realized a change to the requirement

PGMM System and Subsystem Requirements Audit

Percent of Requirements with Defects by Type



Requirement Defects	Examples
Incorrect Information	Incorrect Test Standard Incorrect Paragraph Reference Incorrect Environmental Levels
Omissions	Missing Test Standard Missing Requirement Missing Verification
Ambiguities	More Than One Interpretation
Poorly Written	Multiple "Shalls" in One Requirement Spelling and Grammar Requirement Not Clear
Misplaced	Requirement in Wrong Section Requirement Applied to Wrong Subsystem

Quality Functional Deployment (QFD)

9 Mission/Safety Critical

3 Useful

1 Desirable or Deleted

9 Critical Subsystem

3 Necessary Subsystem

1 Helps Satisfy Requirement

House of Quality Exercise Completed 27 Jan 2005

~42 x ~150 = ~6300 Evaluations

System Performance Requirements

Critical Subsystem for Meeting Requirement or Requirement Drives Subsystem Design

If this requirement changes, which subelements are most affected?

Sort		Category	Paragraph	Priority	Title	Requirement
1	1	Lethality	3.3.5.1.	Deleted	KPP 1 – Precision.	The XM395 cartridge SHALL have the ability to engage point targets with 2 rounds or less.
1	2	Lethality	3.3.5.2.	9	KPP 2 – Lethality.	The XM395 cartridge SHALL have the ability to incapacitate or fractionally casualtize personnel protected within and by point targets (described below), given a two round XM395 engagement. Specific levels of effectiveness Probable Incapacitate (Pi) SHALL meet Block I requirements detailed in Table-I of Appendix B.
2	6	Range	3.3.5.3.1.	9	Minimum Range.	The XM395 cartridge SHALL be able to operate from the mortar system out to 1000m (T), 500m (O) (Gun to target line).
2	7	Range	3.3.5.3.2.	9	Maximum Range.	The XM395 cartridge SHALL be able to maneuver to engage targets. The maximum range (straight-line distance between the mortar system and target location) SHALL not be less than 7200m.
2	8	Range	3.3.5.3.3.	9	Range Overlap.	Each cartridge SHALL have, at a minimum, a range overlap of 20% between zones.
3	9	Compatibility	3.3.1.	9	XM395 Design.	The XM395 cartridge design SHALL include the propelling charges, ignition cartridge & fuze and SHALL utilize a 5-zone, 4-charge system.
3	10	Compatibility	3.3.3.	9	XM395 Firing Procedures.	The XM395 cartridge SHALL be compatible with current firing, misfire and handling procedures, per TM 9-1015-250-10, for current US 120mm firing platforms to include the Stryker BCT-MC (Brigade Combat Team – Mortar Carrier).
3	11	Compatibility	3.3.4.	9	Laser Compatibility.	The XM395 cartridge SHALL operate in conjunction with all current Department of Defense (DoD) fire support 1064mm laser designators.
3	12	Compatibility	3.3.5.4.	9	KPP 4 – Compatibility.	The XM395 cartridge SHALL be compatible with all 120mm firing platforms (M121, M120 towed, and Stryker BCT-MC (Brigade Combat Team – Mortar Carrier)) and munition handling systems. The maneuver Commander requires the capabilities of the first three KPPs without the addition of personnel or equipment to the organization.
3	13	Compatibility	3.3.5.4.1.	9	Maximum Chamber Pressure	The XM395 projectile, when conditioned to 145°F and fired at maximum charge, SHALL not produce an average chamber pressure greater than 16,630 psi (114.6 Mpa).
3	14	Compatibility	3.3.5.4.2.	3	No Damage to Mortar Tube	The XM395 cartridge SHALL not in any way damage or adversely affect the M121 mortar tube as a result of it being fired.
3	15	Compatibility	3.4.11.4.	3	Compatibility with Material Handling Equipment.	The pallet SHALL be compatible with being lifted, transported and stacked by a standard forklift and handjack, using approaches from all four sides of the pallet.
3	16	Compatibility	3.5.10.1.	3	Special Tools.	No special tools SHALL be required.
3	17	Compatibility	3.5.10.2.	3	Maintenance and Support Equipment.	The XM395 PGMM will be supported in accordance with the standard Army Maintenance System, the Standard Army Tools, and Test Measurement and Diagnostic Equipment (TMDE).

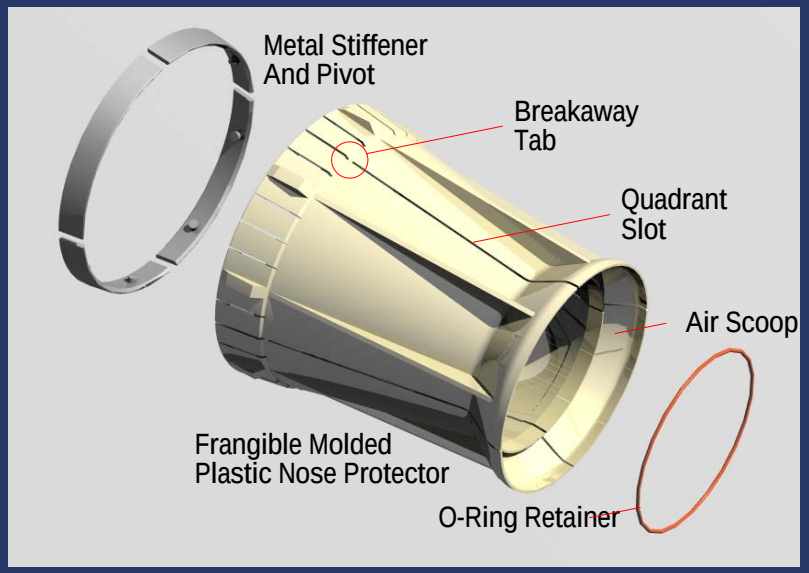
	Length	Weight	Extraction Tool	Packaged Cartridge / Cartridge / Nose / Fuze	Test Port	SAL	ISEU / Battery & PC	G&C Processor	ISA	G&C SW	Nose Protector	Midbody / WIM	Warhead Assy	CTM	Turnbuckle
1															
2		9		3		9		3	3	9		9	9	9	
6										9		3			
7	1	3				1	3							3	
8						1			1	9				1	
9				9								3			
10				9								3			
11						9		3		9					
12	9	9		3											
13		9													
14													9	3	
15															
16	3	3	3	9											
17		3	9	3											

	Tail / Boattail Boom Assy	Fin Assy	Obturator	Ignition Cartridge	Propelling Charge	Factory Assembly / Monopack	Nose Dunnage	Propelling Charge Cover	Assembled Pallet / Pallet	Pallet Adapter	Pallet Dunnage	IM dunnaage	Mission Setter / Mission Setter HW	Mission Setter SW	MFCS / MFCS HW	MFCS SW
1																
2		3												1		3
6				3												
7	9	9	3	1	9											
8				3	9											3
9				9	9											
10				9	9											
11																
12		3											3			3
13					9											
14		9														
15						9			9	9						
16																
17																

ATK Technical Standard

System-Level Interactions

QFD, DFA Flagged Nose Protector



- QFD characterized nose protector as a net liability in meeting requirements.

			Nose Protector		
Spec	Requirement	Customer Priority	Protect SAL Window	Survive Environments	Aero-dynamically Separate After Launch
3.5.11.4	Training	3	1		
3.3.2	Weather Conditions	9	1		
3.6.5	Corrosion, Sand, Dust, Fungus	9	1		
3.3.6	Finish (non-reflective, corrosion resistent…)	3	3		
3.5.11	Visual Identification	3	3		
3.6.8	Temperature (operating, transport, storage)	9		(1)	
3.5.7.4	Propellant Burning Embers	3		(1)	
3.6.2	Safe to Handle & Fire - Temperature	9		(9)	
3.5.8.2	Short Rounds	9			(9)
3.5.8.3	Cartridge Parts Separation	3			(9)
			39	(93)	(108)
			Overall Effect		(162)

- Two DFA Sessions tried to eliminate this ugly baby
- Finally, optical window testing at supplier characterized SAL sensor performance with smears and scratches typical of handling – confirmed low risk in elimination
- **Cost Avoidance:** Aerodynamic flight testing at Yuma to confirm separation ~$100K

Quality Functional Deployment (QFD) - Results

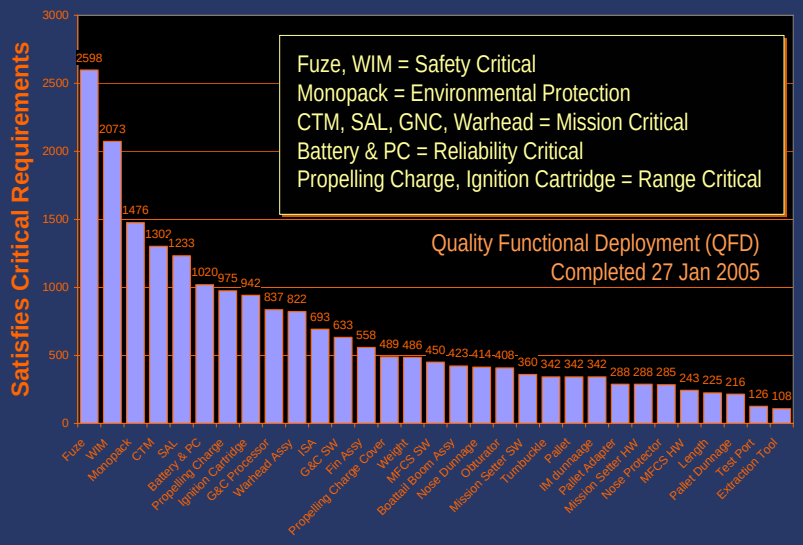
Potential Benefits

- Check for Extraneous Design Features
- Identify Critical Features
  - Satisfies multiple requirements
  - Satisfies critical requirements
- Relate Conflicting Requirements
- "Voice of the Product" Feedback
- Demonstrates Design Compliance
- Organization for Requirement Flowdown
- Communicates Design to Whole Team

Lessons Learned

- Most of the benefits are realized with construction of the first HOQ
- Need to map key requirements to key features
- Size to a manageable HOQ matrix
- Mapping to subsystem is too coarse
- Early application can help direct concept trades

Key Subsystems



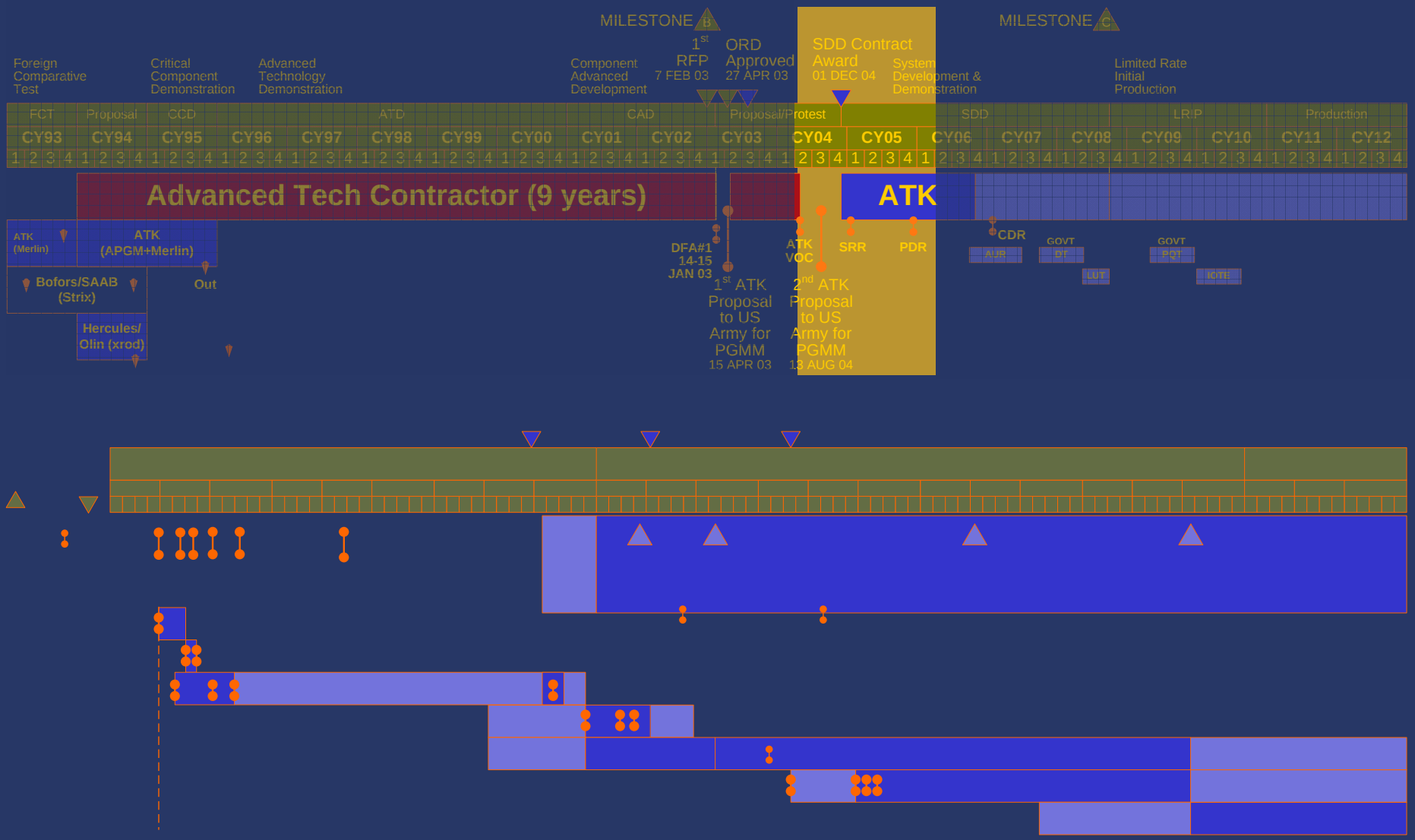
Resource Planning

- QFD Cost ~100 contractor engineering hours
- Average ~ 1 hour per 6x10 evaluation

Design for Six Sigma Tool Phasing

Project Summary

An advanced weapon and space systems company



Quest for Practical DFSS Tools Summary

Objective: Vigorously apply DFSS tools to PGMM, refine and evaluate them, establish metrics for defect tracking

Approach: Interdisciplinary cross-functional project team for framing approach, burden project funding; applied ATK Technical Excellence Standards with good results.

- ☑ **Project Objectives Met:** Tools applied, lessons learned, planning guidelines defined, defect tracking established
- ☑ **Major PGMM Program Milestones Met:** SRR, SDR, and PDR were held on schedule, within budget, and with high quality
- ☑ **Simplification Achieved:** Eliminated or relaxed 11% of US Army system performance requirements; cost avoidance well over $450K
- ☑ **Forged Strong Customer Relationship:** DFSS Tool application facilitated communication across the design team

Questions?