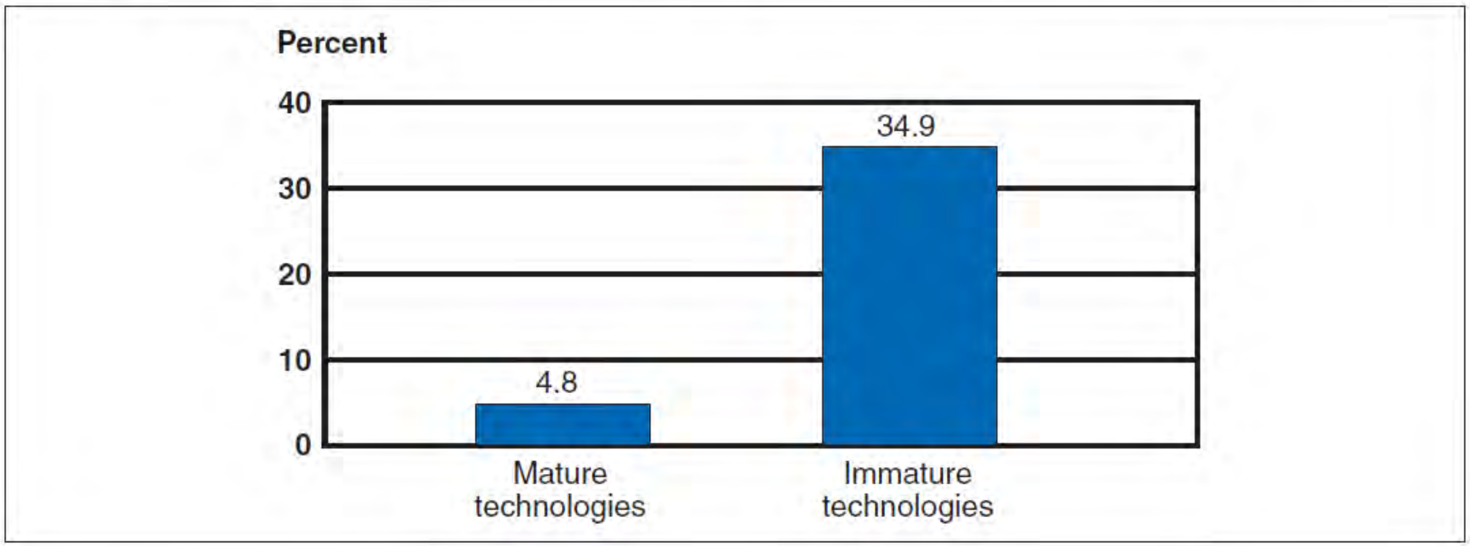
Presentation Purpose

- Information and opinions presented are that of the presenter and do not represent an official government or company position.

Average Program Research, Development, Test, and Evaluation Cost Growth from First Full Estimate

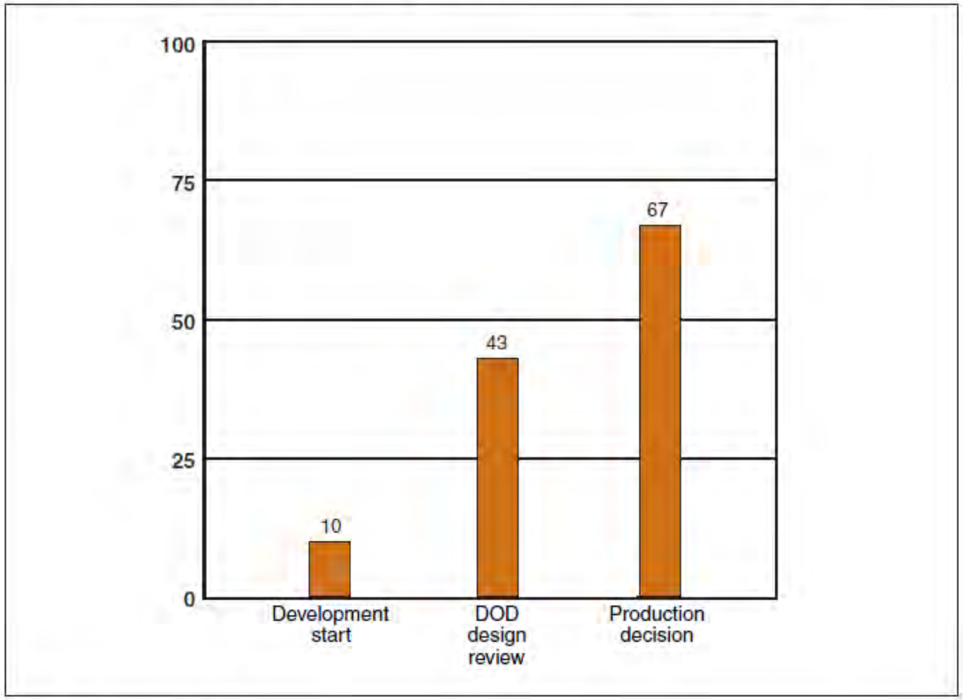


Source: GAO analysis.

1999	**GAO recommends DoD adopt NASA TRL to assess technology maturity**
2001	**DUD issues memorandum endorsing use of TRLs in new programs**
2006	**Legislation mandates DoD certify technology is at RL 6, before system design**
2007	**GAO issues report concluding premature application of technologies is reason for cost growth**

GAO Report to Congressional Committees, March 2006, Defense Acquisitions, Assessments of Selected Major Weapon Programs

Figure 1: Percent of Programs That Achieved Technology Maturity at Key Junctures



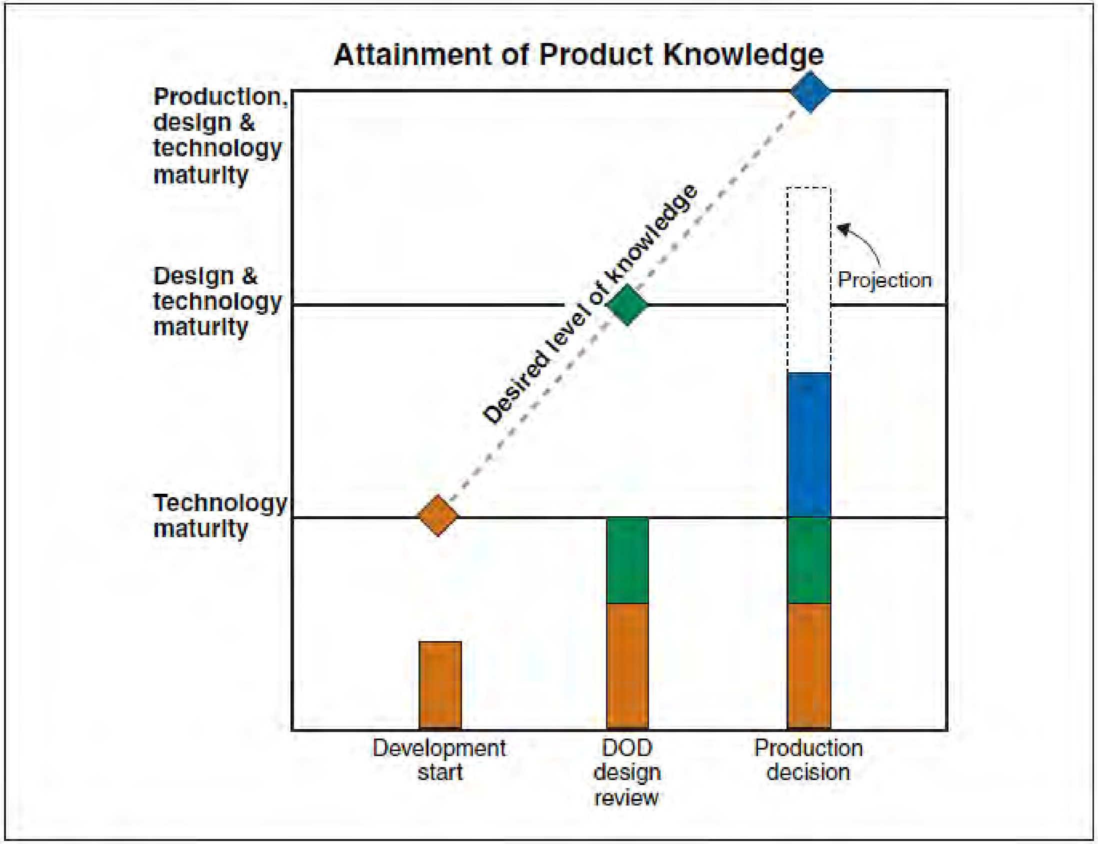
Source: GAO analysis of DOD data.

10%	**Programs demonstrated all critical technologies mature at start of product development**
43%	**Programs that attained Knowledge Point 1 (all critical technologies mature) at PoC**
67%	**Programs that attained KP1 at production decision**

GAO Report to Congressional Committees, March 2006, Defense Acquisitions, Assessments of Selected Major Weapon Programs

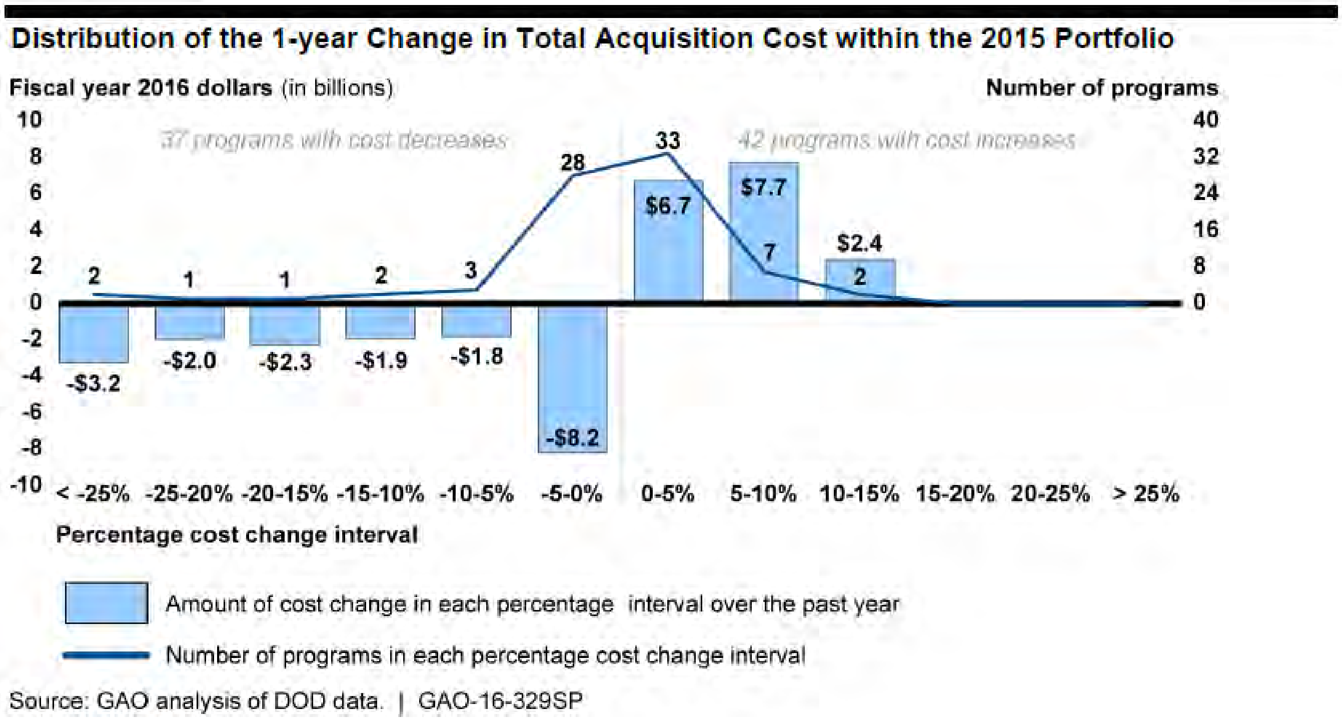
GAO, Knowledge Based Approach

Figure 3: Depiction of a Notional Weapon System's Knowledge as Compared with Best Practices



Source: GAO.

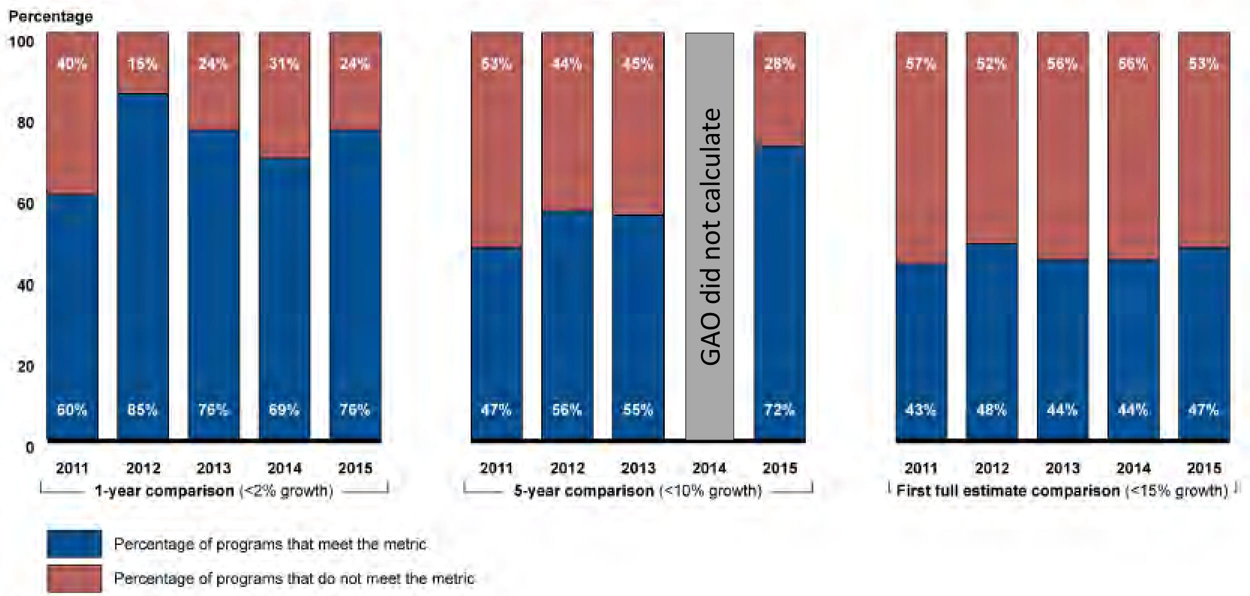
GAO Report to Congressional Committees, March 2006, Defense Acquisitions, Assessments of Selected Major Weapon Programs



1 **Most programs not fully following Knowledge Based acquisition approach as recommended**
2 **Many programs conducting H/W and S/W development during production**
3 **DoD is making progress as Knowledge Based acquisition is implemented**
4 **80% of cost growth attributed to programs with initial IGEs > 5 years ago**

GAO Report to Congressional Committees, March 2016, Defense Acquisitions, Assessments of Selected Major Weapon Programs

Figure 5: Comparison of the Cost Performance of DOD's 2011-2015 Portfolios



Source: GAO analysis of DOD data. | GAO-16-329SP

Metrics are measure of cost performance on % basis over three defined periods: Preceding year, Preceding 5 years, Since first full estimates were established

76%	**Meet the threshold for less than 2 percent growth in the past year**
72%	**Meet the threshold for less than 10% cost growth in past 5 years**
47%	**Meet the threshold for less than 15% cost growth since full estimate (2008)**

GAO Report to Congressional Committees, March 2016, Defense Acquisitions, Assessments of Selected Major Weapon Programs

Proof of Concept + Product Development
$1,000 M x 3 Prime Contractors
Two Phases: PoC -> Product Development

- Original acquisition concept
- Support from System Engineering and Program Management
- Multiple contractors, independent concepts
- PoC results in System TRL 5-6, possible down select, transition to PD
- PD results in System TRL 8-9, production decision, possible down select

1 Qtr Delay

Accelerated Product Development
40% Schedule Compression
One Phase: Product Development
$750 M * 3 Prime Contractors

- Directorate impatience with prolonged schedule
- Suggests parallel technology maturity and system development efforts
- Does not address viability of concepts
- Tepid support from SEPM (reduced budget, increased risk)

1 Qtr Delay

Proof of Concept + Test Option
30% Schedule Compression
Two Phases: Proof of Concept -> Test
$350 M * 3 Prime Contractors

1 Qtr Delay

Technology Risk Reduction
60% Schedule Reduction
Technology Readiness Assessment
$230 M * 3 Prime Contractors

Not System Level Dev.

- SEPM responds
- Addresses budget constraint, considers GAO recommendations, legislation
- Proposes ID of “critical technologies’ for maturation
- Program renamed “Technology Risk Reduction”

Critical Technologies are the at-risk technologies that are essential to successful system development

- Does the technology directly impact a system functional requirement?
- Do the limitations in the understanding of the technology result in a potential schedule risk; i.e. the technology may not be ready for insertion when required?
- Do limitations in the understanding of the technology result in a potential cost risk; i.e. the technology may cause significant cost overrun?
- Are there uncertainties in the definition of the end state requirements for this technology?
- Is the technology new or novel?

- **Congress takes cost overruns seriously, wants answers and mitigation plans**
- **GAO responds with annual reports and continued recommendation of Knowledge Based Acquisition**
- **NASA's contribution is well defined TRLs**
- **Congress has legislated based on GAO recommendations and NASA TRLs (2006)**
- **DoD has made significant progress in reigning in overruns across the portfolio**
- **Programs that fail to fully implement Knowledge Based Acquisition continue to overrun**

Technology Readiness Level	Description	Hardware Software	Demonstration Environment
1. Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties	None (Paper studies and analysis)	None
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.	None (Paper studies and analysis)	None
3. Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Analytical studies and demonstration of nonscale individual components (pieces of subsystem).	Lab
4. Component and/or breadboard. Validation in laboratory environment.	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in a laboratory.	Low fidelity breadboard. Integration of nonscale components to show pieces will work together. Not fully functional or form or fit but representative of technically feasible approach suitable for flight articles.	Lab
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.	High fidelity breadboard. Functionally equivalent but not necessarily form and/or fit (size weight, materials, etc.). Should be approaching appropriate scale. May include integration of several components with reasonably realistic support elements/subsystems to demonstrate functionality.	Lab demonstrating functionality but not form and fit. May include flight demonstrating breadboard in surrogate aircraft. Technology ready for detailed design studies.

White Papers

Concept Reviews

M&S

Existing / Mass Model Technologies Lab Demo

Combined New Technologies Lab Demo

1. **TRL Provides a scale against which to measure the maturity of a technology**
2. **TRLs range from 1, Basic Technology Research, to 9, Systems Test, Launch, and Operations**
3. **Typically, a TRL of 6 is required for a technology to be integrated into an operational system**

(Continued From Previous Page)

Technology Readiness Level	Description	Hardware Software	Demonstration Environment
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.	Prototype—Should be very close to form, fit and function. Probably includes the integration of many new components and realistic supporting elements/subsystems if needed to demonstrate full functionality of the subsystem.	High-fidelity lab demonstration or limited/restricted flight demonstration for a relevant environment. Integration of technology is well defined.
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.	Prototype. Should be form, fit and function integrated with other key supporting elements/subsystems to demonstrate full functionality of subsystem.	Flight demonstration in representative operational environment such as flying test bed or demonstrator aircraft. Technology is well substantiated with test data.
8. Actual system completed and "flight qualified" through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Flight qualified hardware	DT&E in the actual system application
9. Actual system "flight proven" through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.	Actual system in final form	OT&E in operational mission conditions

Source: GAO and its analysis of National Aeronautics and Space Administration data.

System Test, Simulated Environment

Initial Test

Operational Test

System Acceptance Test

TECHNOLOGY READINESS LEVEL 5 HARDWARE MATURITY CHECKLIST					
DoD TRL 5 Definition	**Criteria**	**Met[1]**	**Not Met[2]**	**N/A[3]**	**Certification Authority**
Breadboard Test **Component and/or Breadboard Validation in Relevant Environment.** Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in simulated environment. Examples include "high fidelity" laboratory integration of components.	1. High fidelity lab integration of the hardware technology "system" completed and ready for testing in realistic simulated environments. *Results from testing in laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the Breadboard system refined to more nearly match the expected system goals?*	☐	☐	☐	Director in consultation with PM and System Engineering certify that technology has met all applicable TRL 5 Hardware Maturity Criteria and has thus achieved TRL 5 status.
	2. Preliminary hardware technology "system" engineering report completed that addresses: a. Performance (including how measured performance translates to expected performance of final product) b. Integration c. Test and Evaluation d. Mechanical and Electrical Interfaces *Provide preliminary hardware technology "system" engineering report.*	☐ ☐ ☐ ☐	☐ ☐ ☐ ☐	☐ ☐ ☐ ☐	
	3. Detailed design drawings have been completed. Three view drawings and wiring diagrams have been submitted.	☐	☐	☐	
	4. Pre-production hardware available. a. Prototypes have been created. b. Production processes have been reviewed. *Update ROM integration cost estimate and provide first order schedule for integration with end user(s).*	☐ ☐	☐ ☐	☐ ☐	
	5. Form, fit, and function for application has begun to be addressed in conjunction with end user development staff. *Provide details of efforts to date.*	☐	☐	☐	
	6. Cross technology effects *(if any)* identified and established through analysis. *Provide documentation of effects.*	☐	☐	☐	
	7. Design techniques/codes have been defined to the point where most off nominal conditions/problems defined. *Provide details on how this technology will solve wide range of operational problems.*	☐	☐	☐	
	8. Scaling studies have continued to next higher assembly from previous assessment. *Describe scaling to new functional capability and regions of operational area.*	☐	☐	☐	
		☐	☐	☐	

1. For each criterion that HAS been met provide relevant background information for verification as noted.
2. For each criterion that HAS NOT been met provide the status and an estimate when the criteria will be met.
3. For each criterion marked N/A provide supporting documentation for this selection.

1 TMA is used to determine technology maturity via TRL scale

2 TRL is lowest level of fidelity of technology maturation

Technology Maturity Assessment (TMA)

TECHNOLOGY READINESS LEVEL 6

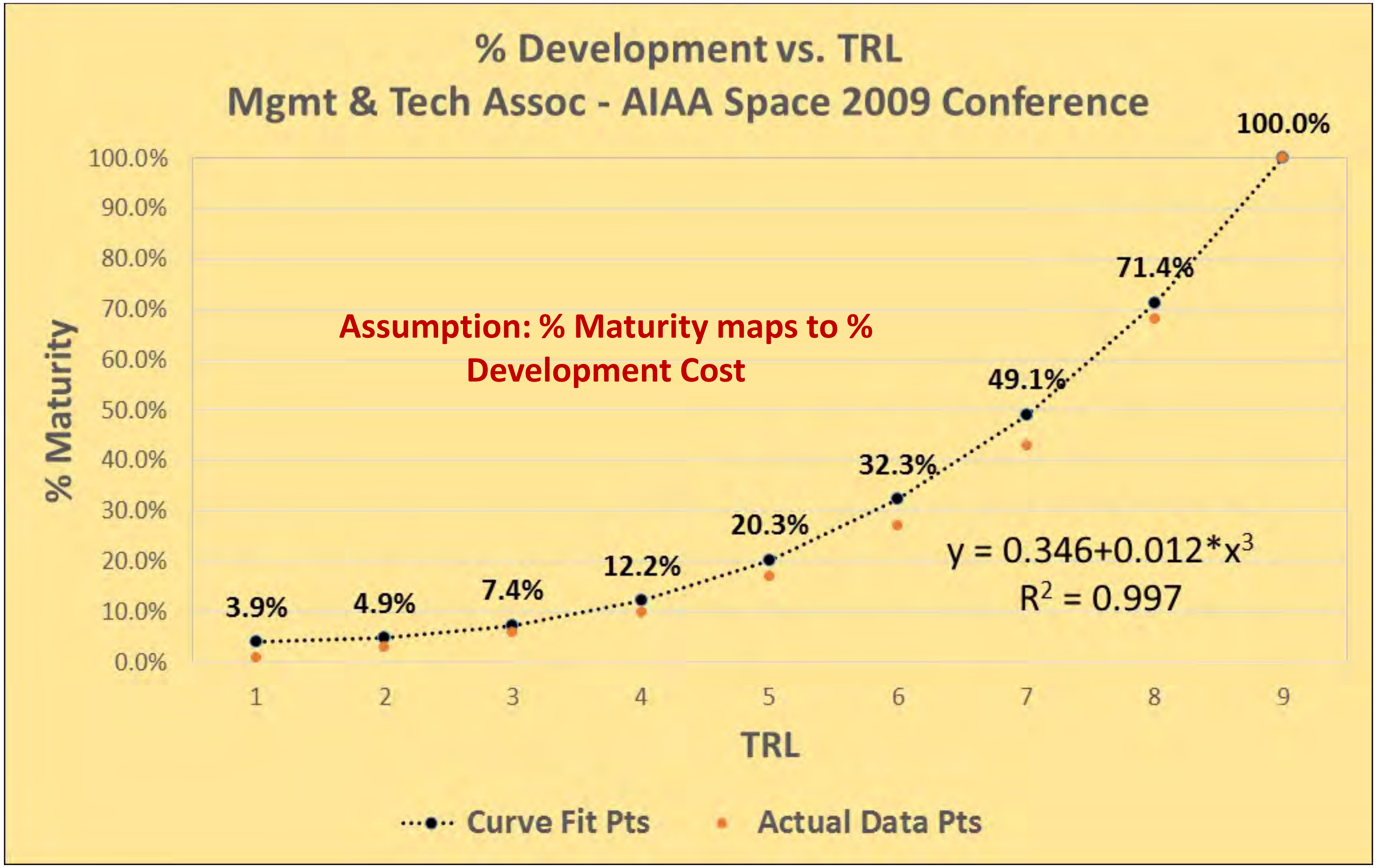
HARDWARE MATURITY CHECKLIST

DoD TRL 6 Definition	Criteria	Met[1]	Not Met[2]	N/A[3]	Certification Authority
Demo Prototype in Relevant Environment **System/Subsystem Model or Prototype Demonstration in a Relevant Environment.** Representative model or prototype system, which is well beyond the breadboard tested for level 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.	1. Materials, process, design, and integration methods have been employed. *Results from laboratory system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?*	☐	☐	☐	Director in consultation with PM and System Engineering certify that technology has met all applicable TRL 6 Hardware Maturity Criteria and has thus achieved TRL 6 status.
	2. Scaling issues that remain are identified and supporting analysis is complete. *Provide description of issues and resolution.*	☐	☐	☐	
	3. Production demonstrations are complete. Production issues have been identified and major ones have been resolved. *Provide documentation of data, issues and resolutions.*	☐	☐	☐	
	4. Some associated "Beta" version software is available.	☐	☐	☐	
	5. Most pre-production hardware is available. *Provide documentation of identified shortfalls to end user(s) and/or testing organization.*	☐	☐	☐	
	6. Draft production planning has been reviewed by end user and developer. *Update ROM integration cost estimate and update integration schedule with end user(s), MDA/DE, and MDA/DPBI.*	☐	☐	☐	
	7. Draft design drawings are nearly complete.	☐	☐	☐	
	8. Integration demonstrations have been completed, including cross technology issue measurement and performance characteristic validations. *Verification report compiled and reviewed by system engineer and testing organization.*	☐	☐	☐	
	9. Have begun to establish an interface control process. *Provide process documentation to system engineer for review.*	☐	☐	☐	
	10. Collection of actual maintainability, reliability, and supportability data has been started. *Provide RAM data to system engineer.*	☐	☐	☐	
	11. Representative model or prototype is successfully tested in a high- fidelity laboratory or simulated operational environment. *Provide performance estimate and verification of capability enhancement with data collected.*	☐	☐	☐	
	12. Hardware technology "system" specification complete. *Submit hardware technology "system" specification for approval.*	☐	☐	☐	
	13. PDD documentation updated to reflect data in items 1 through 4, 7 through 9, 11 and 12.	☐	☐	☐	

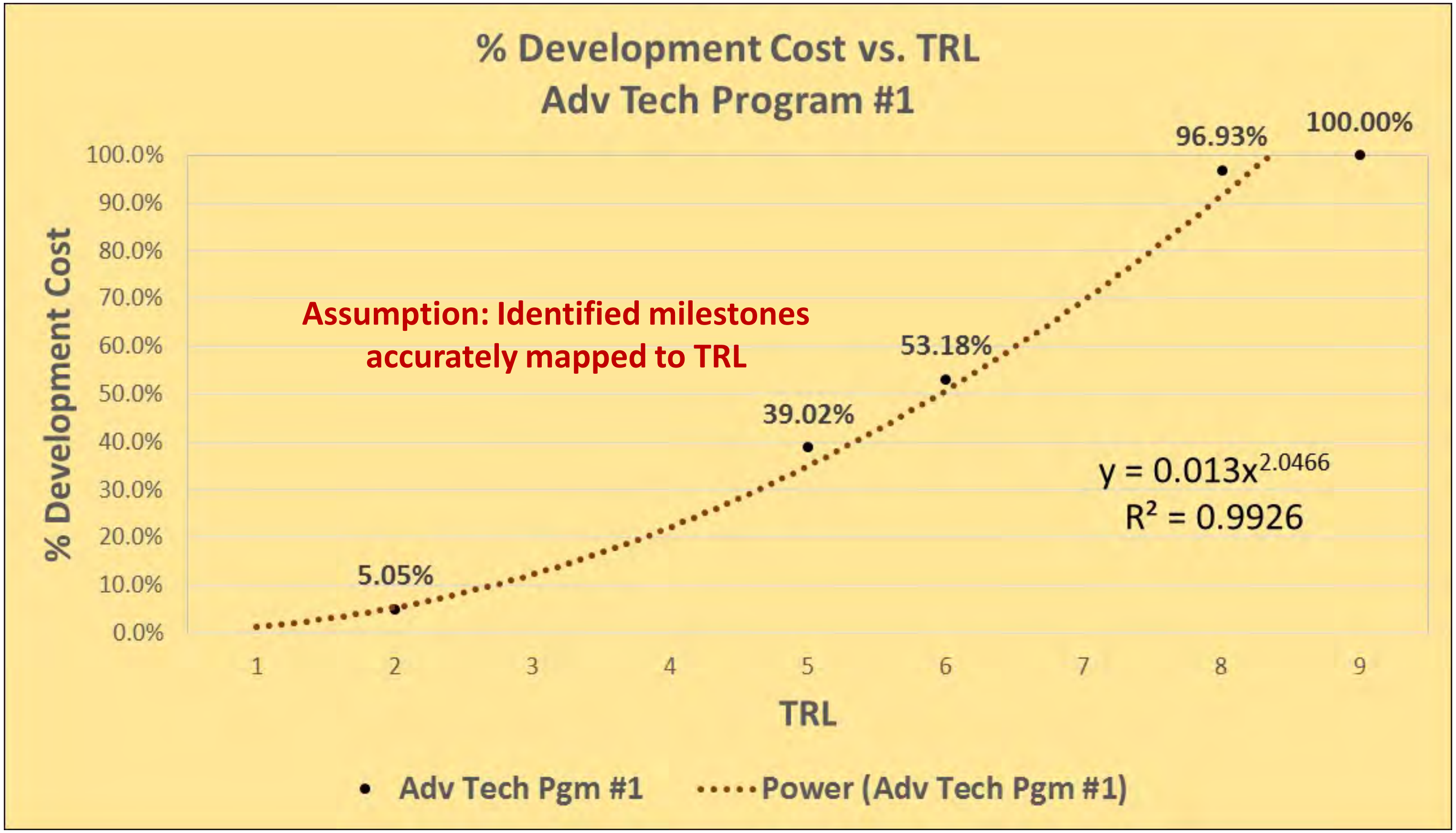
1. **For each criterion that HAS been met provide relevant background information for verification as noted.**
2. **For each criterion that HAS NOT been met provide the status and an estimate when the criteria will be met.**
3. **For each criterion marked N/A provide supporting documentation for this selection.**

1

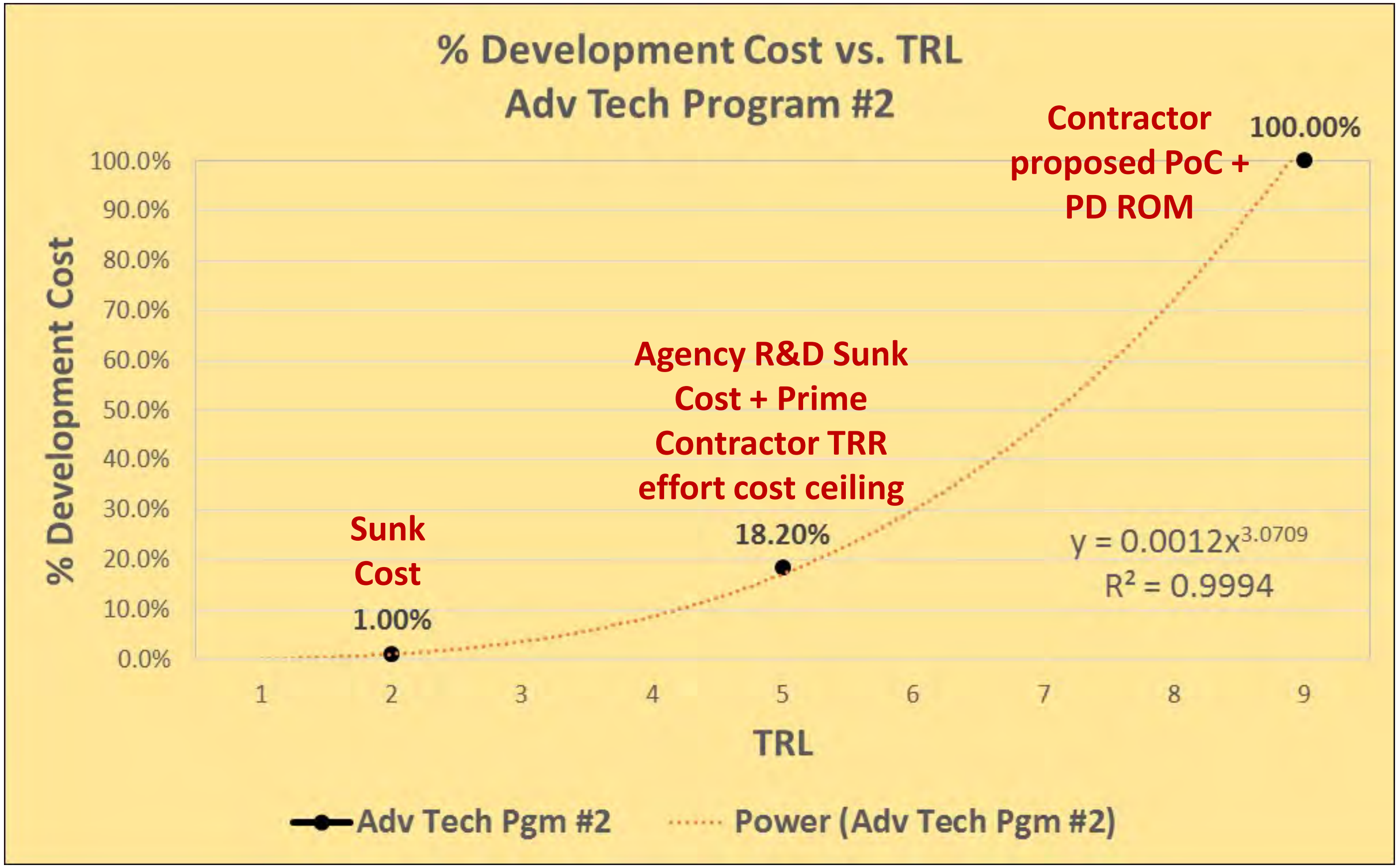
- **TRL is the accepted measurement of technology maturity**
- **Knowledge Based Acquisition requires TMAs**
- **Lowest fidelity of technology maturation measurement is its integer TRL**
- **Technology Readiness is not the same as System Readiness**



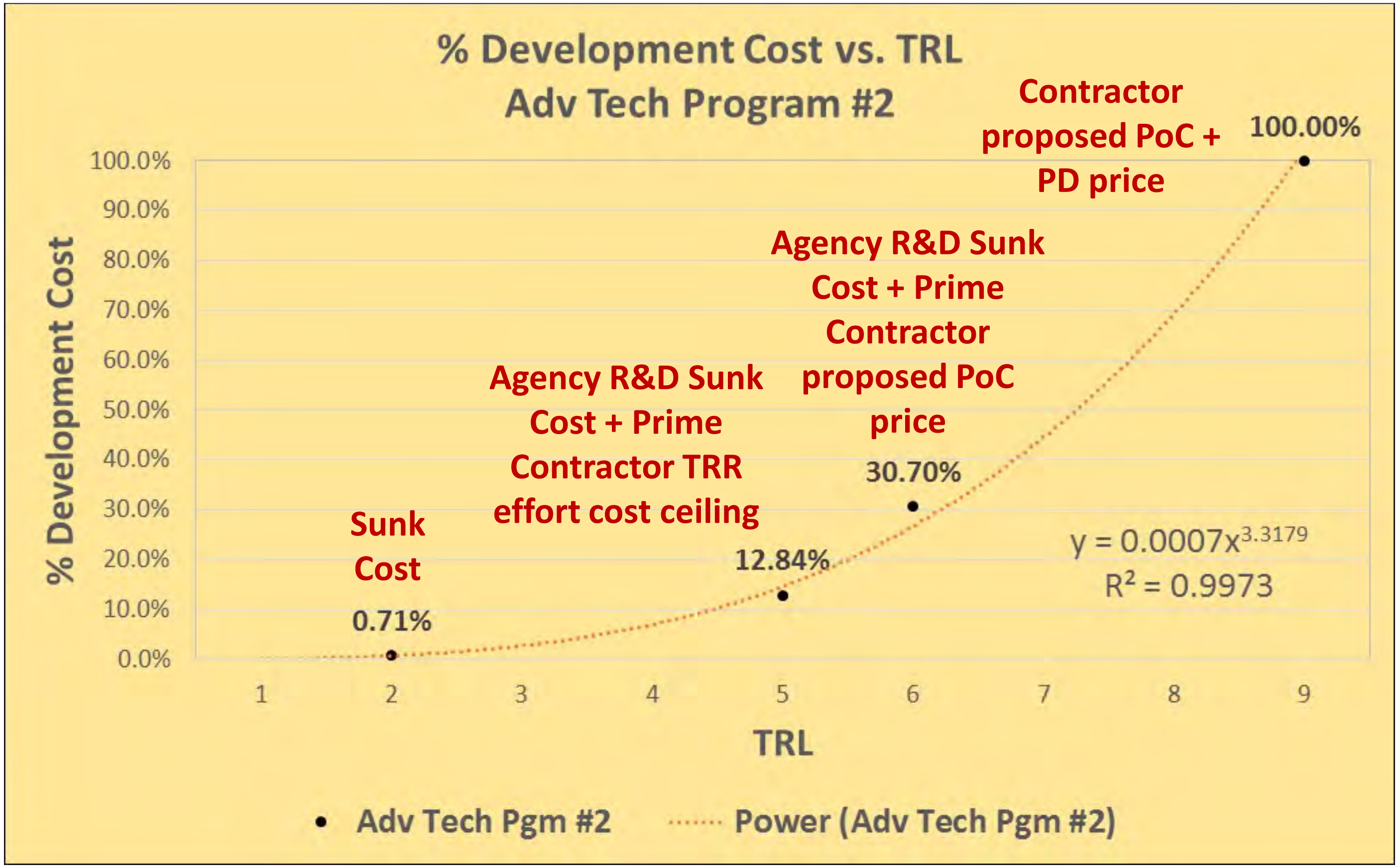
1 AIAA SPACE 2009 Conference & Exposition14 - 17 September 2009, Pasadena, CA
2 Estimating Technology Readiness Level Coefficients
3 Dr. Edmund H. Conrow, CMC, CPCM, CRM, PMP*



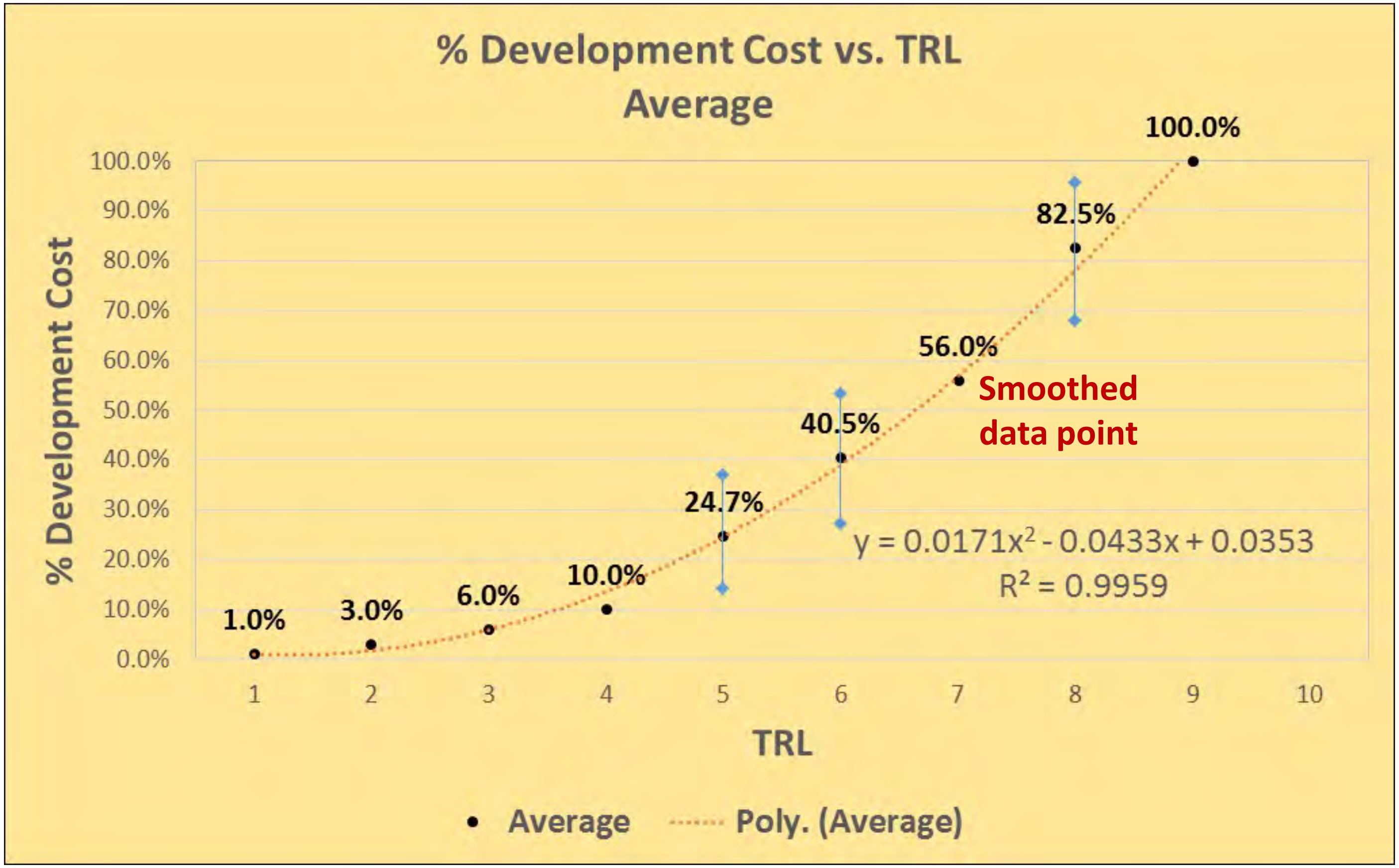
1	Basic Technology Research, Begin Research to Prove Feasibility mapped to TRL 2
2	Technology Development, Research to Prove Feasibility Complete mapped to TRL 5
3	Technology Demonstration mapped to TRL 6
4	System IOC, System Commissioning mapped to TRL 8 and 9 respectively



1	**Concept definition presentation mapped to TRL 2**
2	**Technology Risk Reduction effort complete mapped to TRL 5**
3	**Product Development complete, production decision mapped to TRL 9**



1	**Concept definition presentation mapped to TRL 2**
2	**Technology Risk Reduction effort complete mapped to TRL 5**
3	**Proof of Concept complete mapped to TRL 6**
4	**Product Development complete, production decision mapped to TRL 9**



1 CER maps well TRL 1 through 7

2 CER maps less well TRL 8 and 9

TRL	Cum % Dev. Cost
1	0.9%
2	1.7%
3	5.9%
4	13.6%
5	24.6%
6	39.1%
7	57.0%
8	78.3%
9	100.0%

Contractor	Starting Point	Starting Point BY15 ($M)	Complexity Factor	TRL 5 Factor	IGE BY15 ($M)	IGE FY17 ($M)	IGE FY18 ($M)	IGE FY19 ($M)	IGE TY ($M)	Contr Prop	Delta (Prop-IGE) $	Delta (Prop/IGE) %
One of the Big Ones	Similar Component	$173.5	1.5	24.7%	$64.29	$27.0	$27.5	$14.0	$68.6	$60.0	($8.6)	87.5%

CeBoK: Equation for an Analogy

Analogies have a basic formula, described below:

$E = A * F = A * P_e/P_a$

Where:

E = cost estimate for the current program

A = cost of the analogy

F is factor or ratio

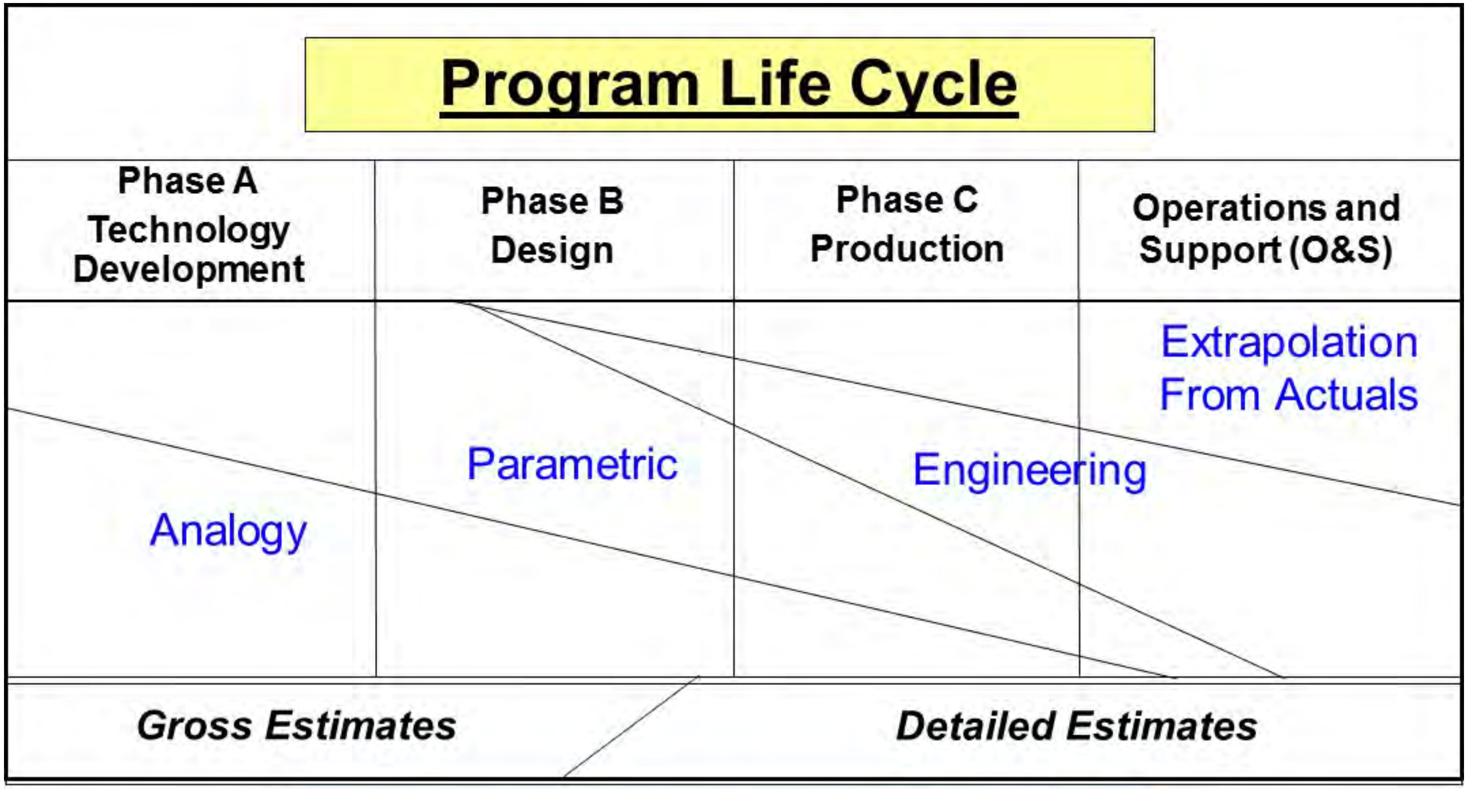
P_e is parameter for the estimated system

P_a is parameter for the analogy system

Prerequisites:

- A must be actual for a successful program and must be a justifiable analogy for E
- P must be an acceptable or intuitively valid cost driver

basis	none	very weak	weak	strong	very strong
risk	indeterminate	high	medium	low	low
uncertainty	high	high	high	varying	defined
identical (in progress)			EVM EAC (tradi-tional)	EVM EAC (progress-based)	+ Prediction Interval (PI)
identical (no learning)		expert testimony	actual cost	average	+ PI
identical (learning)			pseudo-learning curve	learning curve	+ PI
comparable		expert testimony	exact analogy	average	+ PI
different	expert opinion	scaled analogy	adjusted analogy	CER	+ PI
related cost	expert opinion	factor (apocryphal)	factor	CER (cost-on-cost)	+ PI



Integrated Defense Acquisition, Technology and Logistics Life Cycle Management Chart, Defense Acquisition University (DAU), https://ilc.dau.mil/.

Cost Reimbursement contract that provides for a fee award amount based on a judgmental evaluation by the government

Sufficient to provide motivation for excellence in contract performance

Factors that can be incentivized:
- Cost
- Delivery
- Performance (Achieved TRL)

CFAF is the perfect vehicle for incentivizing contractor performance where a specific TRL level is the goal.

- **TRL cannot be used directly to estimate cost**
- **There is a relationship between TRL and % development cost**
- **Analogy is the recommended methodology for estimating Early Stage programs and TRL is a useful factor**
- **TRL 6 represents only 40% of development cost**
- **Programs with a TRL goal are well suited for CPAF type contract vehicle**

Technology Readiness Level (TRL) vs. Percent Development Cost