Impact of Technology Readiness Levels on Aerospace R&D

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Who we are

- Boeing is about 160,000 people in five divisions
  - Boeing Commercial Airplanes (BCA)
  - Integrated Defense Systems (IDS)
  - Boeing Capital Corp. (BCC)
  - Shared Services Group (SSG)
  - Engineering, Operations, and Technology (E,O & T)
    - Includes Phantom Works

Role of R&D in BCA

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- **Description:** World leader in commercial aviation because of complete focus on airline operators and the passengers they serve.
- **Mission:** Products and services support to airline customers and allow passengers to fly where they want to go, when they want to go.
- **Strategy:** Deliver superior design, efficiency, and support to customers and passengers.
- **Strategy requires continuous improvement including insertion of new technology**
- **BCA adapts general flight-quality technology from Phantom Works to commercial aerospace environment**

Role of R&D in IDS

- **Description: Combines weapons and aircraft capabilities with intelligence, surveillance, communications, architectures, and integration.**
- **Mission: Understand enduring needs of customers, provide value-added solutions to meet requirements.**
- **Strategy: Use current and emerging technologies to improve the capabilities of existing products and delivering new solutions.**
- **Strategy requires continuous improvement including insertion of new technology**
- **IDS adapts general flight-quality technology from Phantom Works to commercial aerospace environment**

Role of R&D in Phantom Works

- **Description: Advanced research unit and catalyst for innovation for all of Boeing.**
- **Mission: Provide advanced systems solutions and breakthrough technologies that significantly improve the performance, quality, and affordability of aerospace products and services.**
- **Strategy: Technology teams provide engineering, information, and manufacturing technologies to all of Boeing. Strategy teams address specific new business markets.**
- **Both team sets examine potential of technologies with basic principals reported for fit with Boeing business or potential business.**
- **Selected technologies matured to “flight-quality”.**

Aerospace R&D Management before TRL's

- **Features**
  - Unique procedure per company
  - Product maturation defined in terms of passing tests
  - Which tests, in what order, was a matter of experience
- **Benefits**
  - Worked well enough once teams were experienced
- **Drawbacks**
  - Terms not well defined and no common terminology
  - Numerous In-Scope vs Out-of-Scope Debates
  - Considerable learning curve for development teams
  - Highly innovative items reset learning curve

R&D Structure at Boeing before TRL's

- Only two divisions, commercial and military
- Each did own R&D
- R&D of one not comparable with other

Pre-TRL Approach Example
F-3 Program

- Mid-1950's
- Eventually Successful
- Early versions plagued by insufficient thrust
  - Airframe contractor told by customer to develop airframe to exploit engine specified performance
  - Engine did not exist yet
- Painful Lesson
  - Customer: Next aircraft specified two engines
  - Airframer: Insisted on design around existing engine

Impact of Implementing Immature Technologies

- Technology maturation raises expected cost
- Tech maturation stretches planned schedule
- Real costs skyrocket and schedule loses meaning as technology maturation fails to follow plan and changes ripple through project design late in program cycle
- Failed technologies replaced by fall-backs
- Project (often) fails to meet requirements
- Program (often) canceled

History of TRLs

- Mid-70’s: Technology Management proposed by NASA
  - Assist new technology development
  - Improve communication among technologists
- 1980’s: Technology Readiness Levels (TRLs) developed by NASA
- 1990’s: United States Air Force applied TRLs
- 1999: GAO recommends all DoD use TRLs
- 2001: Deputy Under Secretary of Defense for Science and Technology issued memorandum that endorsed TRLs in new major DoD programs. Guidance for assessing technology maturity incorporated into Defense Acquisition Guidebook.
- 2003: DoD added detailed TRL guidance to DoD Technology Readiness Assessment Deskbook.

What TRL's Are

- A common language for discussing and quantifying technology maturity.
- A framework for evaluating technologies which provides a significant input to risk assessment of including a technology in an existing or new program.

What TRL's Are Not

- TRLs supplement, but are not by themselves, a developmental program progress management or tracking system.
- TRLs are not product spec's

Aerospace R&D Management with TRL’s

- **Features**
  - Simple progress tracking framework
  - Applicable from part level through system level
  - Maturation still requires passing tests
  - Simple framework for order and timing of tests
- **Benefits**
  - Customers and suppliers understand requirements
  - Change impacts easier to determine
  - Facility needs easier to determine
- **Drawbacks**
  - Effectiveness highly dependent on customer and supplier involvement.

Major Program Example: Airborne Laser Program

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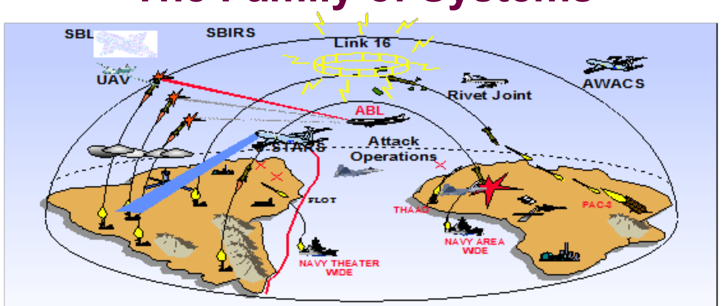
The Vision

Engage & destroy a Theater Ballistic Missile in 2003- on cost and on schedule

The Integrated Product Development Team - Team ABL

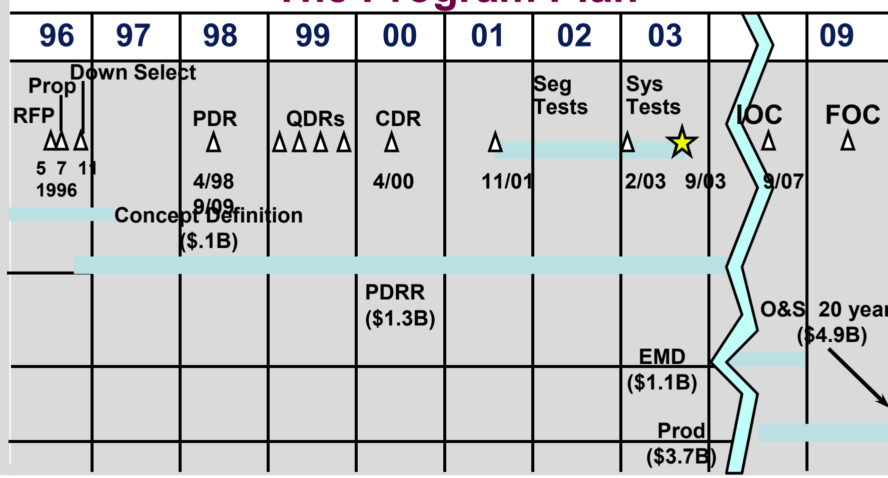
- Boeing
  - Team Leader
  - Aircraft and Integration
  - Command and Communication
- TRW
  - System Ground Support
  - COIL Laser
- Lockheed Martin
  - Beam Control (Acquisition, Tracking, and Pointing)
  - Fire Control

The Family of Systems

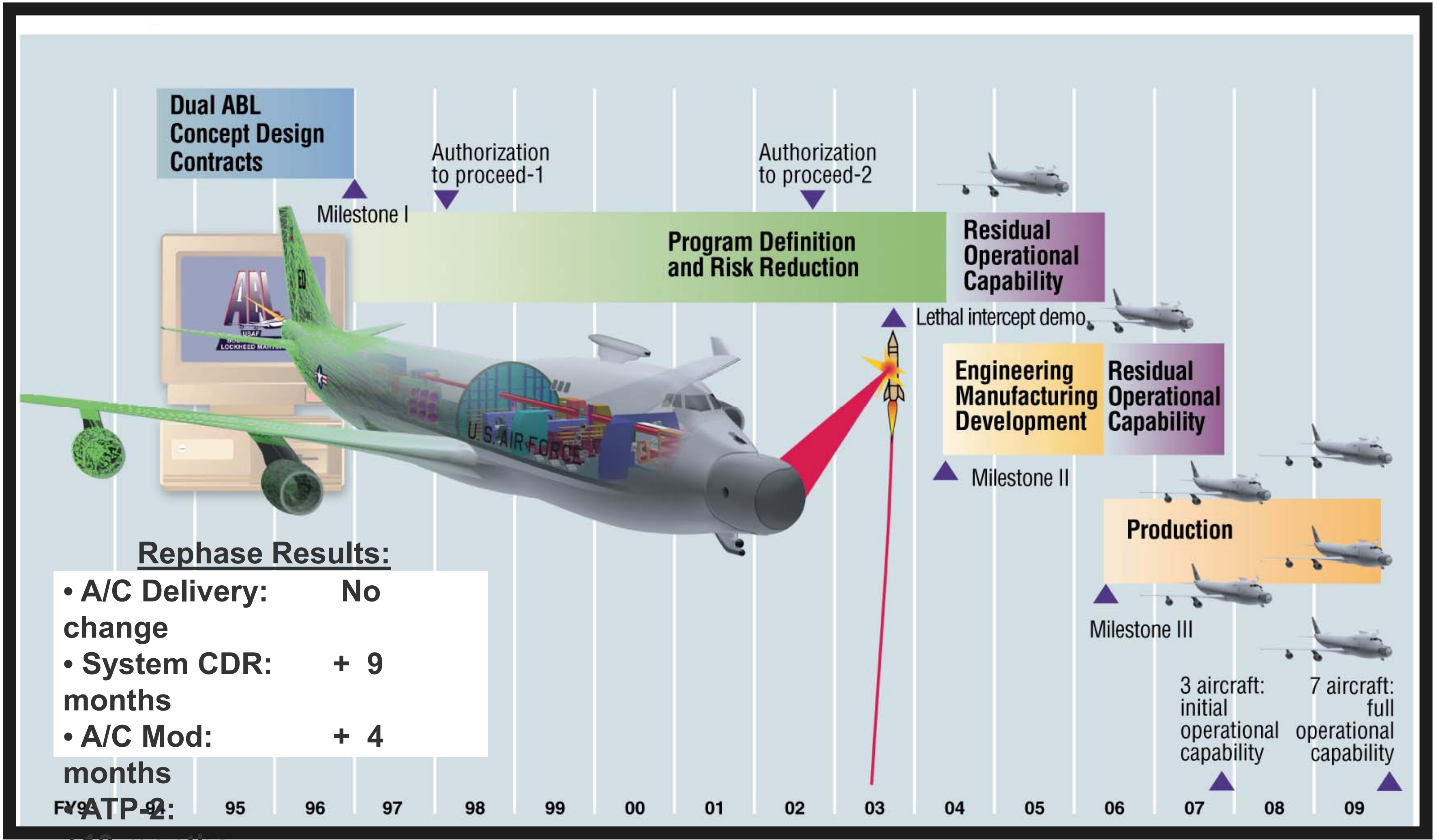


Fully integrated into the TMD multi-tier Architecture

The Program Plan



ABL Program Plan



Rephase Results:

- A/C Delivery: No change
- System CDR: + 9 months
- A/C Mod: + 4 months
- ATP-2: +13 months
- Lethal Shootdown: +12 months

Scope and Complexity

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Scope:
- $232M EAC (59% in-house labor/41% subs & matl)

Hardware:
- 927 drawings (13-Segment, 250-Turret, 501-BTA, 163-Racks/Cables)
  - Avg Sheets/Dwg = 2.5
  - Avg Hours/Sheet = 25 - 40
- 10 Electrical racks (not including 3 for TILL/BILL)

Software:
- 282 kSLOC at 2.3 SLOC/Hour (Flight-226k, Emulator-6k, RSim-15k, Test-35k)

Interfaces:
- 15 external ICDs (5-Lead, 15-Support)

Procurement:
- 23 Subcontracts ranging from $100K to $25M

≈ like NCSX in scope and complexity

Somewhat more mature technologies

TRLs in Definition and Risks

- Program Definition and Risk Reduction (PDRR) of a major development effort is characterized by:
  - Defining requirements to fill an urgent user need
  - Maturing and incorporating new technologies
  - Performing on an aggressive schedule
  - Using success-oriented budgetary projections

Place of TRLs in Key Management Tools

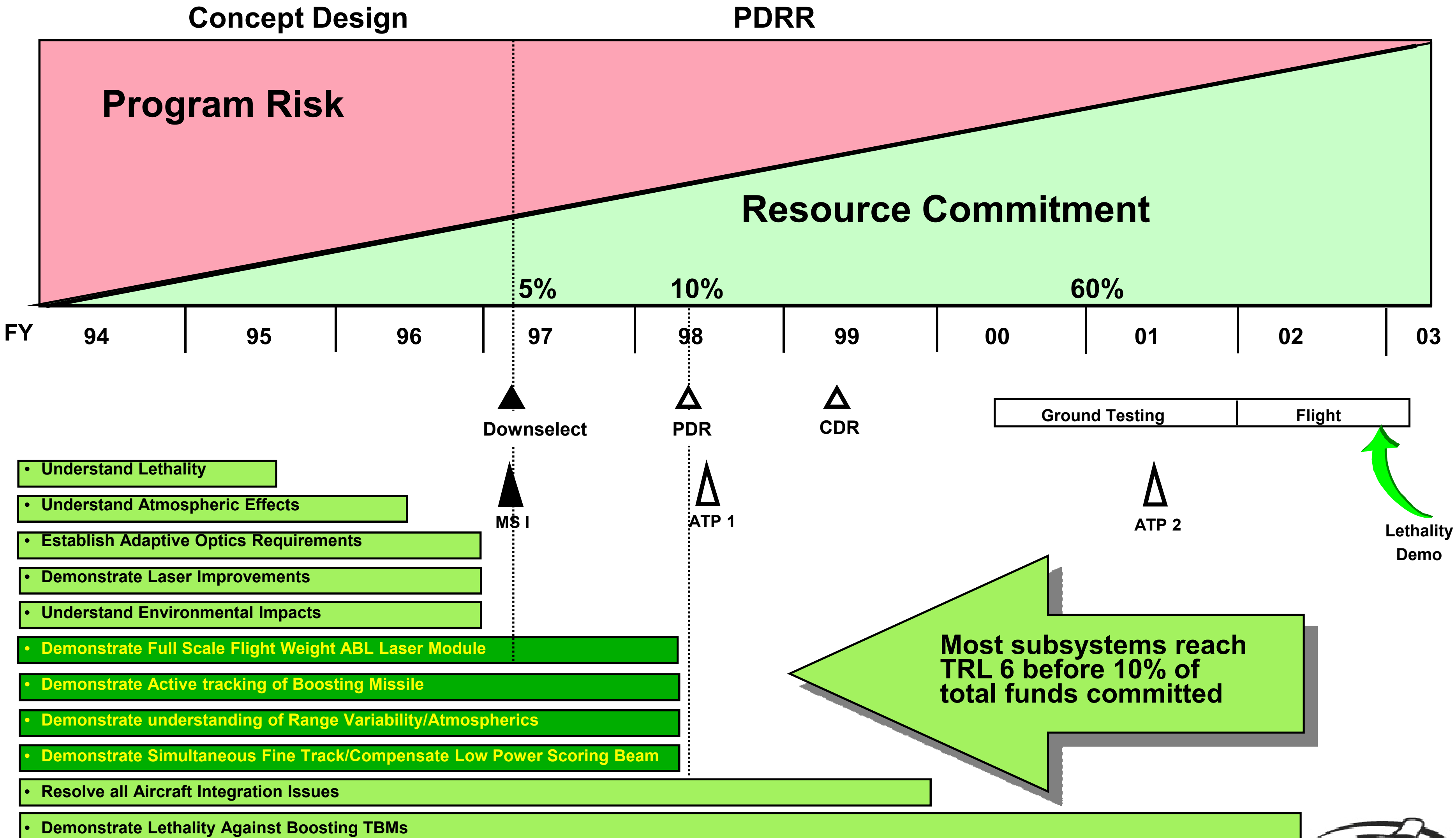
Project Management Tools	Extent of Use	Extent of Contribution to Success
Project Execution Plan	3.87	4.17
Project Schedule	4.64	4.63
Project Organizational Chart	3.72	3.28
Project Earned Value Report	2.91	3.13
Client Communication Log	4.31	4.34
Project Budget	4.64	4.61
Work Breakdown Structure	3.27	3.29

Scales:
- **Extent of Use - 5 (Always Used) to 1 (Never Used)**
- **Contribution to Success - 5 (Critical to Success) to 1 (No Value)**
- **Mean reported, standard deviation range was .70 - 1.21**

Compiled from the Program Management Research Instrument results, using responses from 100 senior-level project managers from large architectural and engineering consulting firms, with a minimum of 10 years experience.

- Thomas Zimmerer and Mahmoud Yasin (1998)

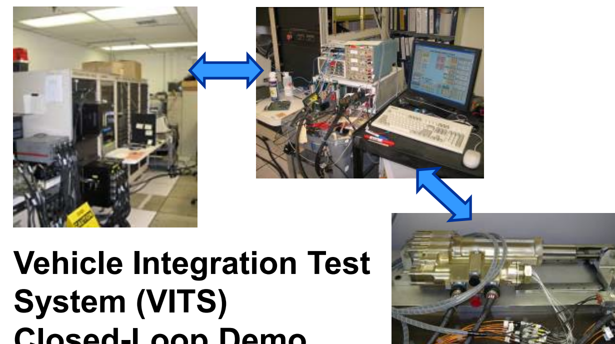
Time of TRLs in Schedule



Subsystem Example: Fly-by-Light

1999-2003	Air Vehicle Management Technologies	TRL 2&3 → TRL 4
2003-2006	Control of Multi-misson UAV Systems	TRL 4 → TRL 5&6
2006-2009	Air Vehicle Electromagnetic Environmental Effects Immunity Devel. Phase	TRL 5&6 → TRL 6
2009-2012	Air Vehicle Electromagnetic Environmental Effects Immunity Validation Phase	TRL 6 → TRL 7

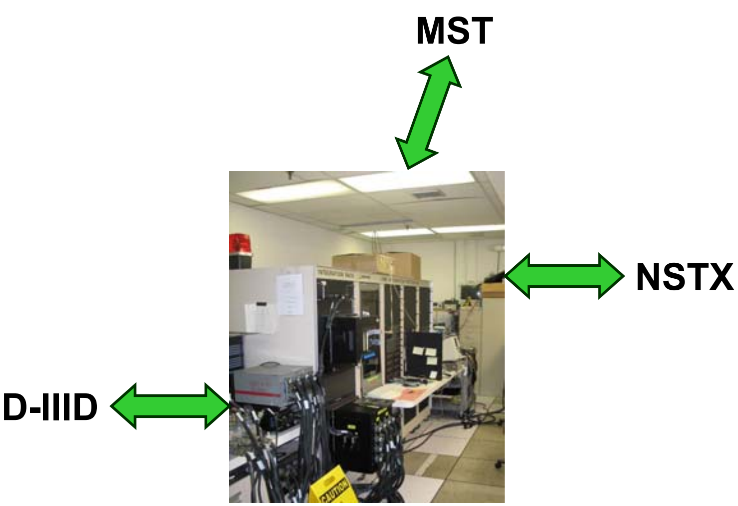
Open-Loop Network Demo



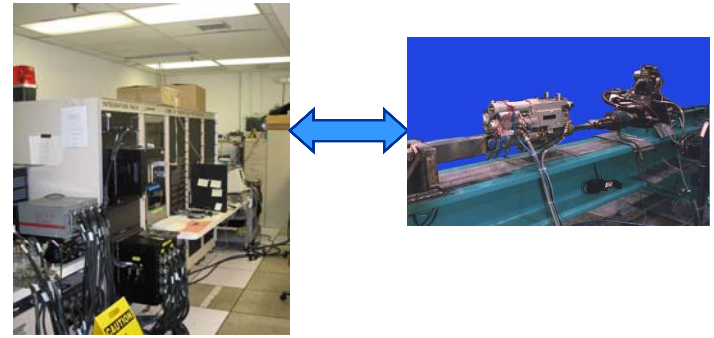
Vehicle Integration Test System (VITS) Closed-Loop Demo

Prediction: Flight Control Laws to Plasma Control Laws

- **Develop plasma stability control in a virtual lab (e.g. DoE VLT) with mixtures of scientists and engineers, real hardware and simulations**
- **VITS does not care if it pushes an actuator against a load or a magnet current against an inductance**



Mon, Wed, Fri



Tue, Thu

Aerospace Plans for TRLs

- Being incorporated into proposal risk management procedures
- Being incorporated into program management procedures merging technology and application readiness
  - Procedure 5157 in Boeing
- Both incorporations include aspects of other readiness measures, e.g.
  - Manufacturing
  - Integration (not yet firmly defined)
  - System
  - Cost

TRL Application Issues

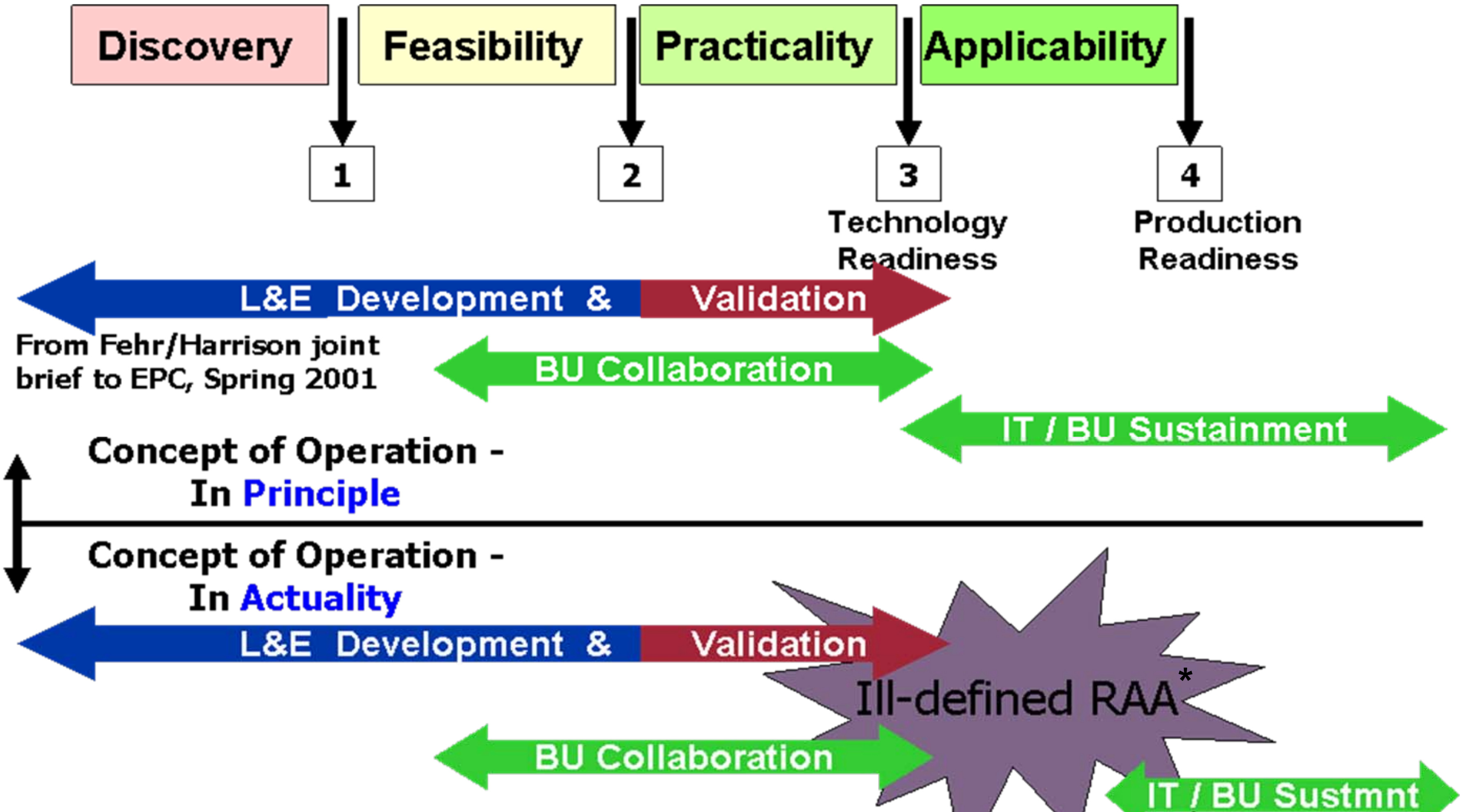
- Understanding "Relevant Environment" (TRL = 5, 6) and "Operational Environment (TRL = 7) is Crucial
  - Often missed: TRL 9 item in one application may be TRL 4 in another
  - "Environment" can include any or all of:
    - Physical Environment
    - Logical Environment
    - Data Environment
    - Security Environment
    - Use and User Environment
  - "Operational Environment" must consider unusual and emergency scenarios

TRL Insights into Aerospace Maturation Challenges

- TRL's highlight "Hand-Off" risks
- TRL's smoothed early maturation (Levels 1 – 6)
- TRL 6 to 7 transition still often difficult

  (System Demonstration in Relevant Environment to System Demonstration in Operational Environment)

The 6-7 Transition Problem

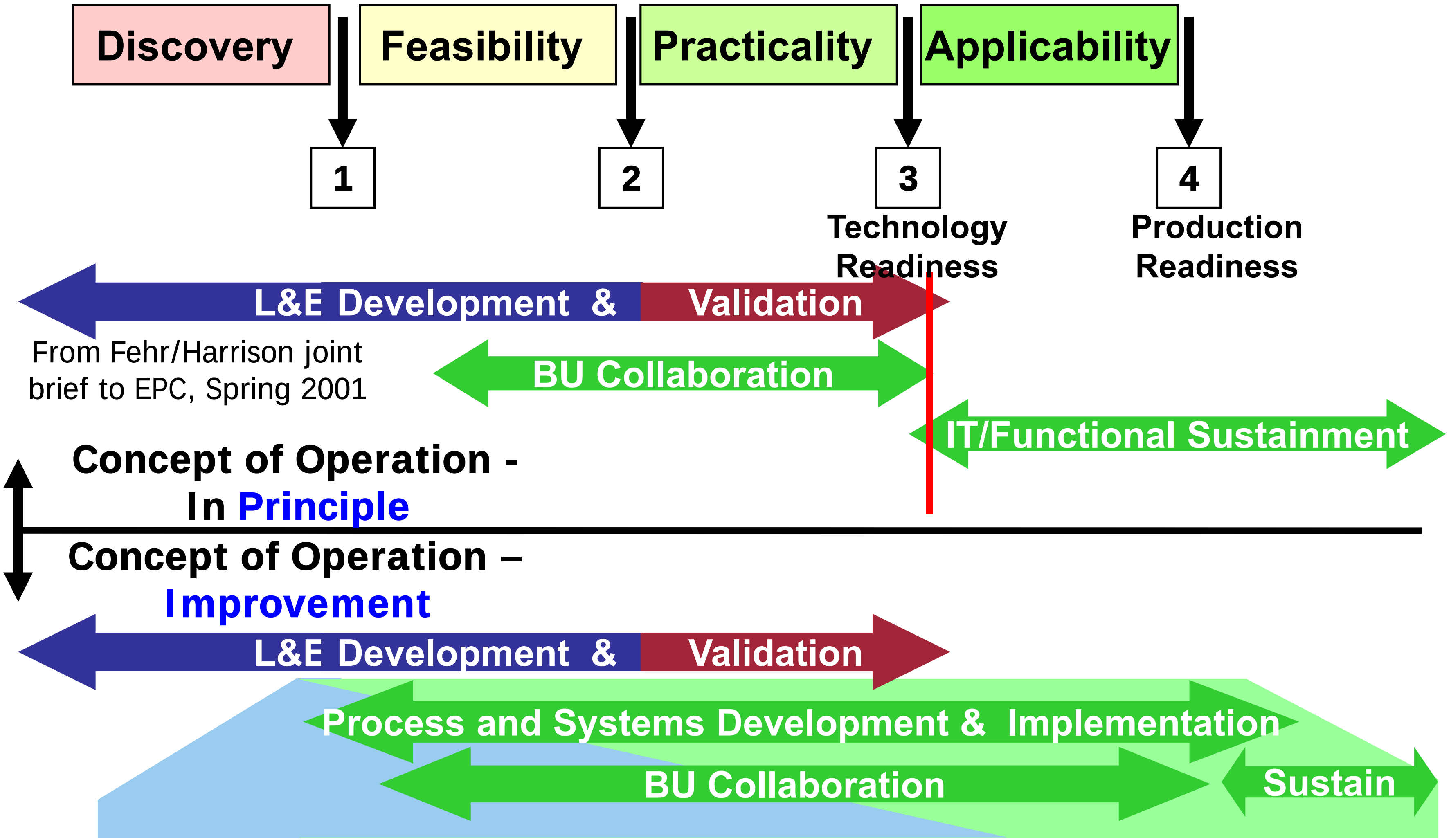


* RAA = Responsibility, Authority, Accountability

Solution Approach
Step 1: Relate to TRLs

Boeing Maturity Stage	Discovery			Feasibility		Practicality	Applicability		
TRL	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
TRL Summary	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof-of-concept	Component and/or breadboard validation in a laboratory environment	Component and/or breadboard validation in a relevant environment	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	System prototype demonstration in a space environment	Actual system completed and “flight qualified” through test and demonstration (ground or space)	Actual system “flight proven” through successful mission operations

Solution Approach
Step 2: Relate to Functional Groups



TRL Tailoring

- TRL concept allows flexibility in definitions in the levels according to the needs of different agencies
- DoD definitions differ slightly from NASA definitions
- DoD tailored definitions for different technology areas
  - General
  - Software
  - Biomedical
  - Fissile Nuclear Fuel
- DoE - Incorporation of TRLs into Technical Business Practices at Sandia National Lab (proposed)
- 2002 – TRLs adopted by British MoD for technology management within program and project management

Conclusion

- TRLs simplify aerospace R&D by providing a common language for understanding technology maturity and by providing a framework for assessing technology risk.
- Aerospace industry both adopted and expanded on TRL concept