# Systems Engineering approach to Technology Maturation for risk reduction using TRL, IRL, and MRL Standards

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“Research is what I’m doing when I don’t know what I’m doing.”

-Wernher von Braun

- Andrew Murrell, CSEP
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- Principal Systems Engineer, Northrop Grumman
- 2021 INCOSE-LA Director: Secretary
- Over a decade of experience in optical, electro-mechanical actuation systems, and research and development
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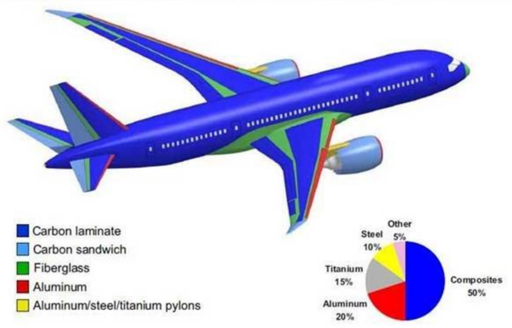
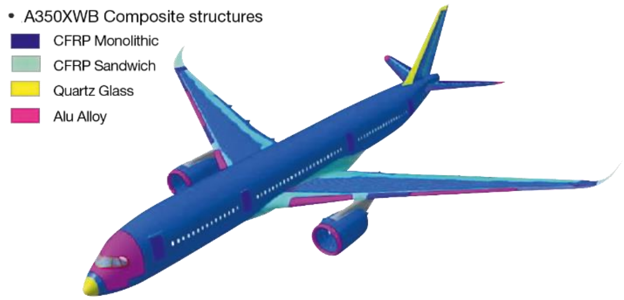
# Agenda

- Why it matters: Carbon Fiber in Aerospace
- Purpose
- Heilmeier’s Catechism
- Where research happens
- Technology Readiness Level
- Manufacturing Readiness Level
- Integration Readiness Level
- Department of Defense Research Level
- Technology Transition Model
- Technology Maturation Plan
- Transition to Business Unit (customer)
- Further Reading

# Why it matters: Carbon Fiber in Aerospace

- First Industrial use Carbon Fiber - 1964
- Composite Structures: 787 Fuselage and Wings
  - Dev Start - 2003
  - First Flight - 2009
  - Introduction - 2011
- Composite Structure: A350 XWB Fuselage and Wings
  - Dev Start - 2004
  - First Flight - 2013
  - Introduction - 2015
- Composite Wings: Mitsubishi Regional Jet (Spacejet)
  - Dev Start - 2007
  - First Flight - 2015
  - Introduction - TBD




# Purpose

- To develop a method to clearly and concisely define a project
- To convince investors of project benefit
- To provide measurable performance milestones and decision gates
- To develop a transition plan to the business unit
- Unilateral communication to customers on progress

# Heilmeier’s Catechism

- Source
- What are you trying to do? Articulate your objectives using absolutely no jargon.
- How is it done today, and what are the limits of current practice?
- What is new in your approach and why do you think it will be successful?
- Who cares? If you succeed, what difference will it make?
- What are the risks?
- How much will it cost?
- How long will it take?
- What are the mid-term and final “exams” to check for success?

Dr. Heilmeier - 1975 DARPA Director

# Where research happens

- What is Risk?
- Early Research and Development (TRL 1 and 2) – Highest Risk
  - Colleges
  - Startups
- ‘Valley of Death’ Research (TRL 2 to 6) – High to Moderate Risk
  - Colleges
  - Startups
  - Technology Centers
- Early production development (TRL 4 to 6) – Moderate Risk
  - Independent/Internal research and development programs
- Development (TRL 7+) – Lowest Risk
  - Customer funded development programs

# Where research happens

- Colleges
  - Often source of most original ideas
  - Have greatest access to new and novel ideas
  - Operations not contingent on production
- Startups
  - Often focus on a single idea with the intent to bring it to production
  - Operations contingent on investors
- Research Centers
  - Research arm of large companies
  - Mandated to drive acquisition and maturation of the above two research groups
  - Operation contingent on surplus revenue from Corporate
- Development Research
  - Are part of the Business Unit
  - Are driven by desire to increase market share
  - Focus on maturation of already demonstrated systems and concepts
  - Operation contingent on surplus revenue from Business Unit

Xerox Palo Alto Research Center

Bell labs Holmdel Complex

# Technology Readiness Level

- Source

| | TRL | Definition | Hardware Description | Software Description | Exit Criteria |
|---|---|---|---|---|---|
| Early | 1 | Basic principles observed and reported. | Scientific knowledge generated underpinning hardware technology concepts/applications. | Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation. | Peer reviewed publication of research underlying the proposed concept/application. |
| Early | 2 | Technology concept and/or application formulated. | Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. | Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data. | Documented description of the application/concept that addresses feasibility and benefit. |
| Valley | 3 | Analytical and experimental critical function and/or characteristic proof of concept. | Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction. | Development of limited functionality to validate critical properties and predictions using non-integrated software components. | Documented analytical/experi-mental results validating predictions of key parameters. |

# Technology Readiness Level

- Source

Valley

| TRL | Definition | Hardware Description | Software Description | Exit Criteria |
|---|---|---|---|---|
| 4 | Component and/or breadboard validation in laboratory environment. | A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment. | Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted. | Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment. |
| 5 | Component and/or breadboard validation in relevant environment. | A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases. | End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed. | Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. |
| 6 | System/sub-system model or prototype demonstration in an operational environment. | A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions. | Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated. | Documented test performance demonstrating agreement with analytical predictions. |

# Technology Readiness Level

- Source

|  | TRL | Definition | Hardware Description | Software Description | Exit Criteria |
|---|---|---|---|---|---|
| Development | 7 | System prototype demonstration in an operational environment. | A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space | Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available. | Documented test performance demonstrating agreement with analytical predictions. |
|  | 8 | Actual system completed and "flight qualified" through test and demonstration. | The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space). | All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed. | Documented test performance verifying analytical predictions. |
|  | 9 | Actual system flight proven through successful mission operations. | The final product is successfully operated in an actual mission. | All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment. | Documented mission operational results. |

# Manufacturing Readiness Level

- Source

| | MRL | Definition | Description |
|---|---|---|---|
| Early | 1 | Basic Manufacturing Implications Identified | This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., funded by budget activity) begins in the form of studies. |
| | 2 | Manufacturing Concepts Identified | This level is characterized by describing the application of new manufacturing concepts. Applied research translates basic research into solutions for broadly defined military needs. Typically this level of readiness includes identification, paper studies and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging. |
| Valley | 3 | Manufacturing Proof of Concept Delivered | This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. This level of readiness is typical of technologies in Applied Research and Advanced Development. Materials and/or processes have been characterized for manufacturability and availability but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality. |
| | 4 | Capability to produce the technology in a laboratory environment | This level of readiness acts as an exit criterion for the Materiel Solution Analysis (MSA) Phase approaching a Milestone A decision. Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. At this point, required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for building prototypes and mitigation plans are in place. Target cost objectives have been established and manufacturing cost drivers have been identified. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required. |

# Manufacturing Readiness Level

- Source

Valley

| MRL | Definition | Description |
|---|---|---|
| 5 | Capability to produce prototype components in a production relevant environment | This level of maturity is typical of the mid-point in the Technology Development Phase of acquisition, or in the case of key technologies, near the mid-point of an Advanced Technology Demonstration (ATD) project. Technologies should have matured to at least TRL 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost. |
| 6 | Capability to produce a prototype system or subsystem in a production relevant environment | This MRL is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the Engineering and Manufacturing Development (EMD) Phase of acquisition. Technologies should have matured to at least TRL 6. It is normally seen as the level of manufacturing readiness that denotes acceptance of a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design has been completed and producibility assessments and trade studies of key technologies and components are complete. Prototype manufacturing processes and technologies, materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems and/or subsystems in a 2-4 production relevant environment. Cost, yield and rate analyses have been performed to assess how prototype data compare to target objectives, and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system development plans. The Industrial Capabilities Assessment (ICA) for Milestone B has been completed. Long-lead and key supply chain elements have been identified. |

# Manufacturing Readiness Level

- Source

Development

| MRL | Definition | Description |
|---|---|---|
| 7 | Capability to produce systems, subsystems, or components in a production representative environment | This level of manufacturing readiness is typical for the mid-point of the Engineering and Manufacturing Development (EMD) Phase leading to the PostCDR Assessment. Technologies should be on a path to achieve TRL 7. System detailed design activity is nearing completion. Material specifications have been approved and materials are available to meet the planned pilot line build schedule. Manufacturing processes and procedures have been demonstrated in a production representative environment. Detailed producibility trade studies are completed and producibility enhancements and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. Yield and rate analyses have been updated with production representative data. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Manufacturing plans and quality targets have been developed. Production tooling and test equipment design and development have been initiated. |
| 8 | Pilot line capability demonstrated; Ready to begin Low Rate Initial Production | This level is associated with readiness for a Milestone C decision, and entry into Low Rate Initial Production (LRIP). Technologies should have matured to at least TRL 7. Detailed system design is complete and sufficiently stable to enter low rate production. All materials, manpower, tooling, test equipment and facilities are proven on pilot line and are available to meet the planned low rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and ready for low rate production. Known producibility risks pose no significant challenges for low rate production. Cost model and yield and rate analyses have been updated with pilot line results. Supplier qualification testing and first article inspection have been completed. The Industrial Capabilities Assessment for Milestone C has been completed and shows that the supply chain is established to support LRIP. |

# Manufacturing Readiness Level

- Source

Development

| MRL | Definition | Description |
|---|---|---|
| 9 | Low rate production demonstrated; Capability in place to begin Full Rate Production | At this level, the system, component or item has been previously produced, is in production, or has successfully achieved low rate initial production. Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into Full Rate Production (FRP). All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials, parts, manpower, tooling, test equipment and facilities are available to meet planned rate production schedules. Manufacturing process capability in a low rate production environment is at an appropriate quality level to meet design key characteristic tolerances. Production risk monitoring is ongoing. LRIP cost targets have been met, and learning curves have been analyzed with actual data. The cost model has been developed for FRP environment and reflects the impact of continuous improvement. |
| 10 | Full Rate Production demonstrated and lean production practices in place | This is the highest level of production readiness. Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment, facilities and manpower are in place and have met full rate production requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing. |

# Integration Readiness Level

- Source

| | IRL | Definition | Description |
|---|---|---|---|
| Semantic | 1 | An Interface between technologies has been identified with sufficient detail to allow characterization of the relationship. | This is the lowest level of integration readiness and describes the selection of a medium for integration. |
| | 2 | There is some level of specificity to characterize the Interaction (i.e. ability to influence) between technologies through their interface. | Once a medium has been defined, a “signaling” method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept. |
| | 3 | There is Compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact. | IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process. |

# Integration Readiness Level

- Source

| | IRL | Definition | Description |
|---|---|---|---|
| Syntactic | 4 | There is sufficient detail in the Quality and Assurance of the integration between technologies. | Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it. |
| | 5 | There is sufficient Control between technologies necessary to establish, manage, and terminate the integration. | IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating. |
| | 6 | The integrating technologies can Accept, Translate, and Structure Information for its intended application. | IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one. |
| | 7 | The integration of technologies has been Verified and Validated with sufficient detail to be actionable. | IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability. |

# Integration Readiness Level

- Source

| | IRL | Definition | Description |
|---|---|---|---|
| Pragmatic | 8 | Actual integration completed and Mission Qualified through test and demonstration, in the system environment. | IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment. |
| | 9 | Integration is Mission Proven through successful mission operations. | IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system, and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9. |

# Department of Defense Research Level

- Source

| | DoD Level | Definition | Description |
|---|---|---|---|
| Early | 6.1 | Basic Research | Systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and/or observable facts without specific applications toward processes or products in mind. |
| Valley | 6.2 | Applied Research | Systematic study to gain knowledge or understanding necessary to determine the means by which a recognized and specific need may be met. |
| | 6.3 | Advanced Technology Development | Includes all efforts that have moved into the development and integration of hardware for field experiments and tests. |
| | 6.4 | Demonstration and Validation | Includes all efforts necessary to evaluate integrated technologies in as realistic an operating environment as possible to assess the performance or cost reduction potential of advanced technology. |

# Department of Defense Research Level

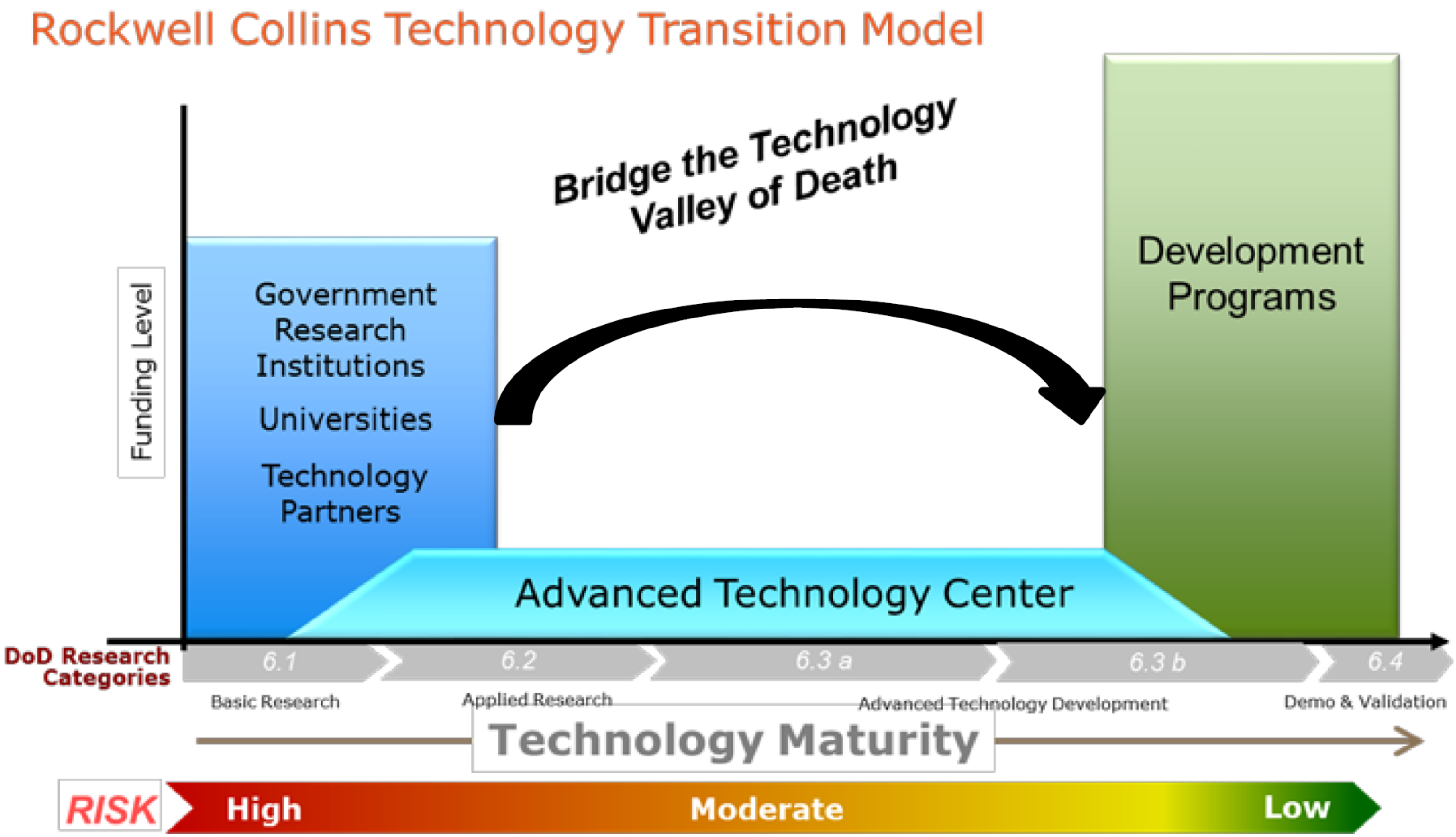
- Source

Development

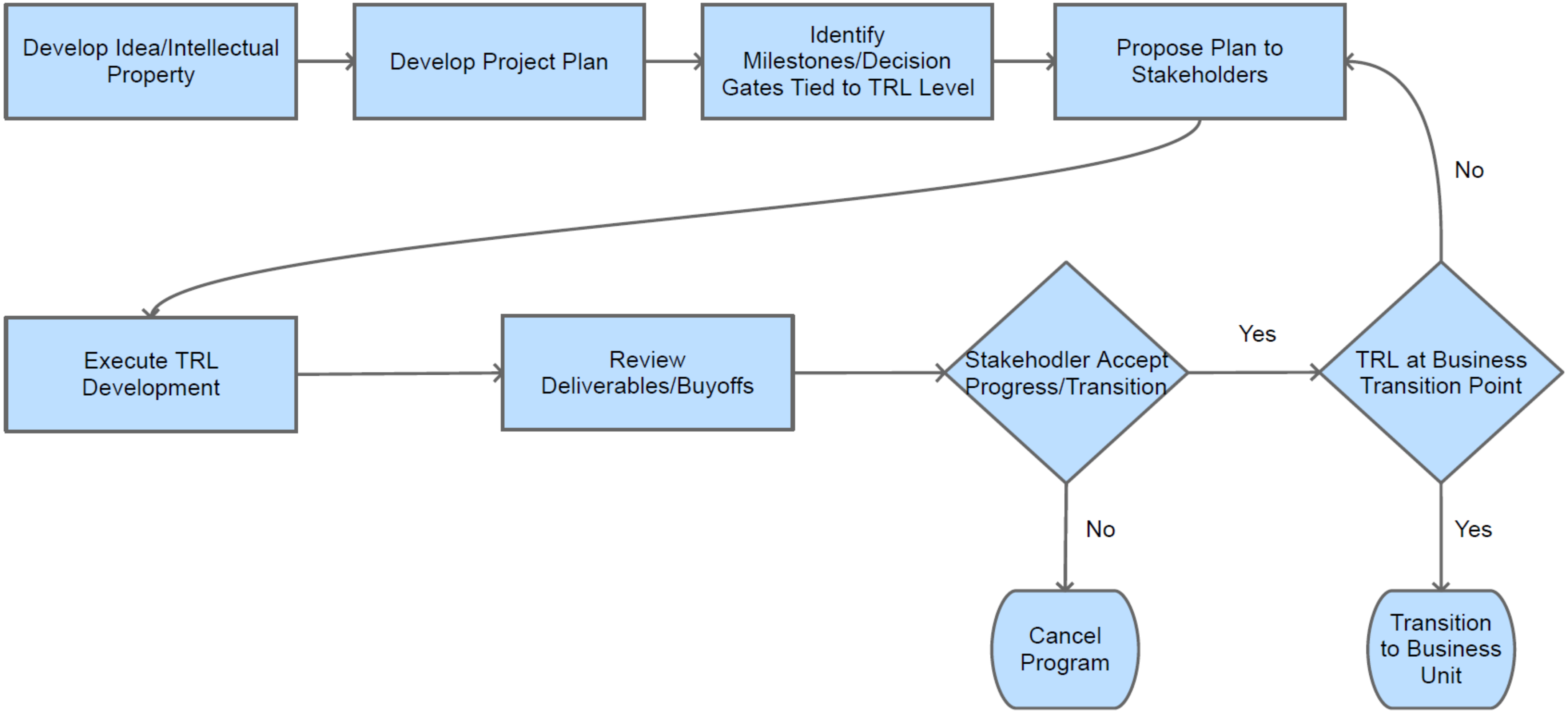
| DoD Level | Definition | Description |
|---|---|---|
| 6.5 | Engineering and Manufacturing Development | Includes those projects in engineering and manufacturing development for Service use but which have not received approval for full rate production. |
| 6.6 | RDT&E Management Support | Includes R&D efforts directed toward support of installation or operations required for general R&D use. Included would be test ranges, military construction, maintenance support of laboratories, operations and maintenance of test aircraft and ships, and studies and analyses in support of R&D program. |
| 6.7 | Operational System Development | Includes those development projects in support of development acquisition programs or upgrades still in engineering and manufacturing development, but which have received Defense Acquisition Board (DAB) or other approval for production, or for which production funds have been included in the DoD budget submission for the budget or subsequent fiscal year. |

# Technology Transition Model

- [Source]()



# Technology Maturation Plan

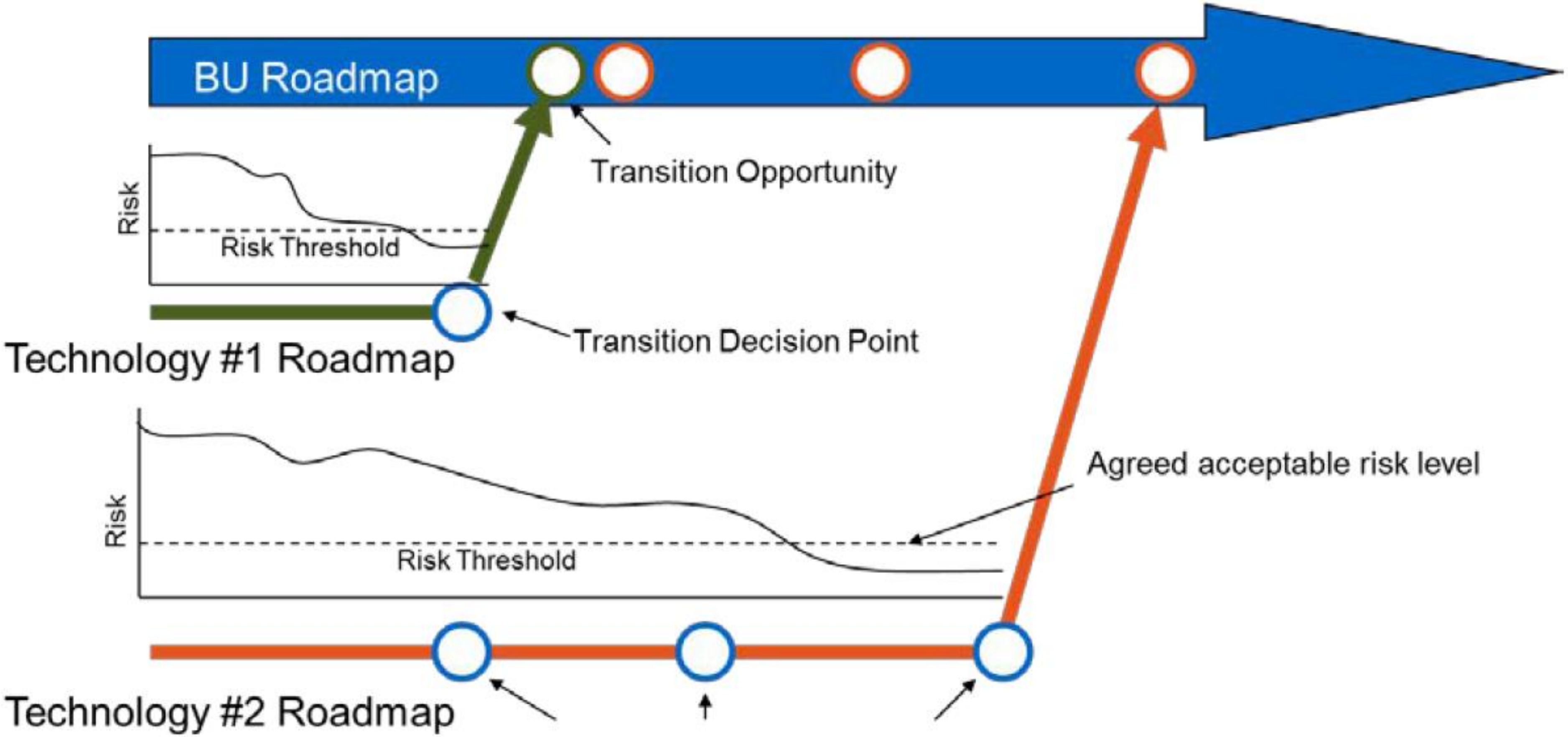


# Transition to Business Unit (customer)

- The Technology Transition Plan (TTP) is the ultimate goal of all successful research projects
- Is the 'final exam' of Heilmeier's Catechism
- Confidence of the Business Unit to bid the new technology
  - Does not mean all issues are solved
  - Often means that some or all of the research team will be support technology transfer to the BU (and possible transfer with the technology)
  - Continued development is driven by different leadership and funding sources
- If the goal of the research is not for a 'customer' to make money then the project will reach a dead end
- Is critical that your every step of the way your customer has buy in
  - Negotiate and arrange technology transfer before research completion
  - Consider program manager best practices (Stakeholder analysis, requirement reviews, design reviews,, demonstrations, etc)
  - You will need to change your scope to facilitate your customer's needs
- A successful project has a

# Transition to Business Unit (customer)

- Source



# Further Reading

- Similar presentation was given in 2018
- By Andrew Murrell and Vice President John Borghese of the Rockwell Collins Advanced Technology Center (Now Collins Aerospace inside Raytheon)
- IRR415_RC_Sys Engr Approach to Aerospace_Tech_Maturation-Dev_pgms-TRL-IRL-MRL_Stds A
- Located in INCOSE-LA Connect
  - INCOSE Membership is required to access this presentation