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Technology Development Life Cycle Processes

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Abstract

This report and set of appendices are a collection of memoranda originally drafted in 2009 for the purpose of providing motivation and the necessary background material to support the definition and integration of engineering and management processes related to technology development. At the time there was interest and support to move from Capability Maturity Model Integration (CMMI) Level One (ad hoc processes) to Level Three. As presented herein, the material begins with a survey of open literature perspectives on technology development life cycles, including published data on “what went wrong.” The main thrust of the material presents a rational exposé of a structured technology development life cycle that uses the scientific method as a framework, with further rigor added from adapting relevant portions of the systems engineering process. The material concludes with a discussion on the use of multiple measures to assess technology maturity, including consideration of the viewpoint of potential users.

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NOMENCLATURE

3-D	Three Dimensional
ACAT	Acquisition Category
AT	Technology Readiness Assessment Team
ATD	Advanced Technology Demonstrator
BDA	Bush Differential Analyzer
CMMI	Capability Maturity Model Integration
CTE	Critical Technology Element
DAB	Defense Acquisition Board
DDR&E	Director of Defense Research & Engineering
DoD	Department of Defense
DODD	Department of Defense Directive
DODI	Department of Defense Instruction
DOE	Department of Energy
DTI	Danish Technological Institute
DUSD(S&T)	Deputy Under Secretary of Defense for Science & Technology
EDM	Engineering Development Model
EIA	Electronic Industries Alliance
ENIAC	Electronic Numerical Integrator And Computer
IAM	ACAT-IA program for MAIS
ID	ACAT-I program (MDAP) with DAB as advisor to USD(AT&L)
IP	Independent Critical Technology Element Review Panel
IDAG	Interim Defense Acquisition Guidebook
IRI	Industrial Research Institute
ISO	International Standards Organization
IT	Independent Technology Readiness Assessment Evaluation Team
ITA	Independent Technical Assessment
LM	Line Manager
MAIS	Major Automated Information System
MDAP	Major Defense Acquisition Program
NASA	National Aeronautics and Space Administration
PDCA	Plan-Do-Check-Act cycle
PDSA	Plan-Do-Study-Act cycle
PM	Program Manager
PTE	Product Technology Element
PWB	Printed Wiring Board
R&D	Research and Development
SAE	Society of Automotive Engineers
S&T	Science and Technology
SDD	System Design and Development
SEI	Software Engineering Institute
SM	Product Senior Manager
SNL	Sandia National Laboratories
SRR	System Requirements Review
TDS	Technology Development Strategy

TES	Test and Evaluation Strategy
TL	Product Development Project Technical Lead
TMP	Technology Maturation Plans
TQM	Total Quality Management
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
U.S.	United States
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics
V&V	Verification and Validation
WBS	Work Breakdown Structure

1. INTRODUCTION

Technology providers in the “high-tech” society of today are likely to find themselves in a position for competing—at least in some sense—for a share of limited research and development (R&D) resources. For any organization that finds itself placed in such a position, effective strategic planning becomes a must if it is to survive in the long term. For the purposes of this document, it is possible to imagine a “high-tech” provider of having the lofty vision to be the provider of innovative, science-based systems engineering solutions that are developed in a way that inspires customer confidence. The question then becomes one of strategy. How will such an organization achieve this vision? What will reduce technology development process uncertainty—inspire funding “customer” confidence through higher success rates—and so “give an edge” over the competition?

It is strongly suggested that *formal process*, in fact, is a key factor from an organizational (multi-program), long-term perspective. This is particularly true where accountability and profitability are matters of concern; less so where entitlement is embedded in an R&D culture, which is often evidenced in the widespread use of ad hoc processes.

Given interest in the notion that technology maturation can be planned and follow a formal process, the question becomes: what process? Perhaps it is obvious and trite, but the answer for technology development is a process that implements the scientific method. Such an approach is followed herein in order to produce the description of a development framework for a multi-cycle technology maturation process that is suitable for use in high-risk ventures. Further process detail is sketched out by a tailored consideration of formal systems engineering approaches used in product development. The material concludes with a discussion on the use of *multi-dimensional* metrics of technology maturity (commonly referred to in a 1-D form as Technology Readiness Levels, TRLs) and the use of Technology Readiness Assessments (TRAs) in determining measures thereof. Consideration is also given to the viewpoint of potential users and their concerns for the TRL of Critical Technology Elements (CTEs) at the time said technology would be inserted into a product line.

2. BACKGROUND

While historical statistics regarding the performance of U.S. government-funded technology development projects are not generally available, it is easy to surmise that statistics from commercial sources provide an indicator—if not direct measure—of the general problem. As an example, consider the experience of the Danish Technological Institute (DTI). In 1972 DTI began administering the Danish Product Idea support scheme that had a mission to advise inventors and find partners for them. Between 1985 and 1990, out of approximately 5000 ideas, only 350 were retained as original and worth pursuing, 94 were deemed patentable and licensed to companies, 30 products were actually produced by the licensee, and 15 were still in production in 1991.[1] When presented with such statistics, there is at least one obvious question: What can be done to improve technology development process performance?

In 1992 the Industrial Research Institute (IRI) sponsored an investigation that tried to systematically identify causes of uncertainty in the R&D process, with an underlying assumption that "application of appropriate solutions" which reduce these uncertainties would "shorten project cycle times and improve the efficiency and productivity of the innovation process."[2] Using common TQM tools, 45 major causes of uncertainty in research were identified that were grouped into eight different categories; "customer requirements not defined" and "delays in decision" were the most frequently encountered causes of uncertainty. The eight categories were:

1. Market
2. Competitor
3. Technical (T)
4. Business Processes
5. Management Style
6. People/Culture
7. Communication
8. External Efforts

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[1] Jolly, Vijay K., *Commercializing New Technologies: Getting from Mind to Market*, Boston: Harvard Business School Press, 1997, p. 5.
[2] Burkart, Robert E., "Reducing R&D cycle time," *Research Technology Management*, Vol. 37 Issue 3, May/June 1994, pp. 27-32. See also Laidlaw, Frances Jean, "ATP's impact on accelerating development and commercialization of advanced technology," *Journal of Technology Transfer*, Vol. 23(2), June 1998, pp. 31-41.

Of particular interest here is the technical category, into which 13 of the causes of uncertainty were placed; they were:

- T1. Not invented yet
- T2. Science insufficient
- T3. Effort insufficient
- T4. Core competency mismatch
- T5. Skill mismatch
- T6. Customer interface insufficient
- T7. Product feature mismatch
- T8. Technical planning insufficient
- T9. Technical support insufficient
- T10. Manufacturing capability insufficient
- T11. Financially unfeasible
- T12. Economically unfeasible
- T13. Timing inappropriate

Out of the technical category, in order to have a reasonably narrow scope, the present “white paper” will explore one uncertainty: technical planning. Although the differences may be a bit fuzzy, the planning of concern herein is not program or project planning per se, nor of basic science, but of engineering research and development processes, of plans (and controls) related to technical tasks—technical goals, objectives, effects, and actions—required to use an organization’s capabilities (core competencies, core processes, and strategic assets) to turn an initial idea into a useable technology that has good potential (acceptably low risk) to be successfully inserted into a product.

3. DEFINITIONS

Technology can be defined variously as:[3]

1 a: the practical application of knowledge especially in a particular area
  b: a capability given by the practical application of knowledge
2: a manner of accomplishing a task especially using technical processes, methods, or knowledge
3: the specialized aspects of a particular field of endeavor

In contrast, a *product* is something produced—or a service—that is generally marketed or sold as a commodity. It is important to note that products are not equal to technologies (although these two terms are often confounded). A product is based on multiple technologies and a technology can form the basis for multiple products. A technology, on the other hand, is formulated on the basis of one or more physical principles and properties, and may build on other technologies as well (as in Figure 1).

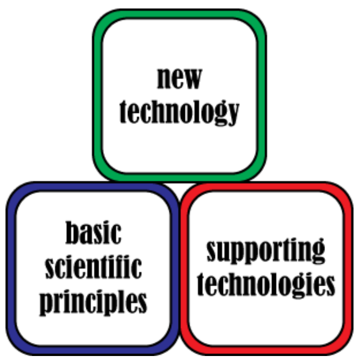

Figure 1. "Building blocks" of a new technology.

Consider a simple contrast: automotive technology vs. a Buick LaCrosse or a Toyota Celica; both cars are generally based on the same set of technologies, but have quite different product designs and characteristics. As another example (see Figure 2), consider lifting body technology as first developed and then applied in a product: the space shuttle.

Technology development can be thought of as a process that is intended to set forth or make clear by degrees or in detail, to work out the possibilities of, to acquire or cause to unfold gradually, knowledge in a particular area, including its practical application. Since *development* can also be related to the idea of *maturation*—where to be mature implies a condition of full development—

[3] Definitions presented here have been adapted from Merriam-Webster online dictionary at http://www.merriam-webster.com/ Retrieved on 04JUN09.

it is also possible, at least conceptually, to think of *maturity* as a measure for how developed a technology is (just as with anything else); the phrase *technology maturation* is, thus, synonymous with *technology development*. Another related term is *research and development* (R&D): "creative work undertaken on a systematic basis in order to increase the stock of knowledge … and the use of this stock of knowledge to devise new applications."[4]

A *life cycle* is a series of stages through which something passes during its lifetime (i.e., the process of maturation from conception through death). Since *technology* and *product* are different, it is asserted that their life cycles are also expected to be different by one or more measures.

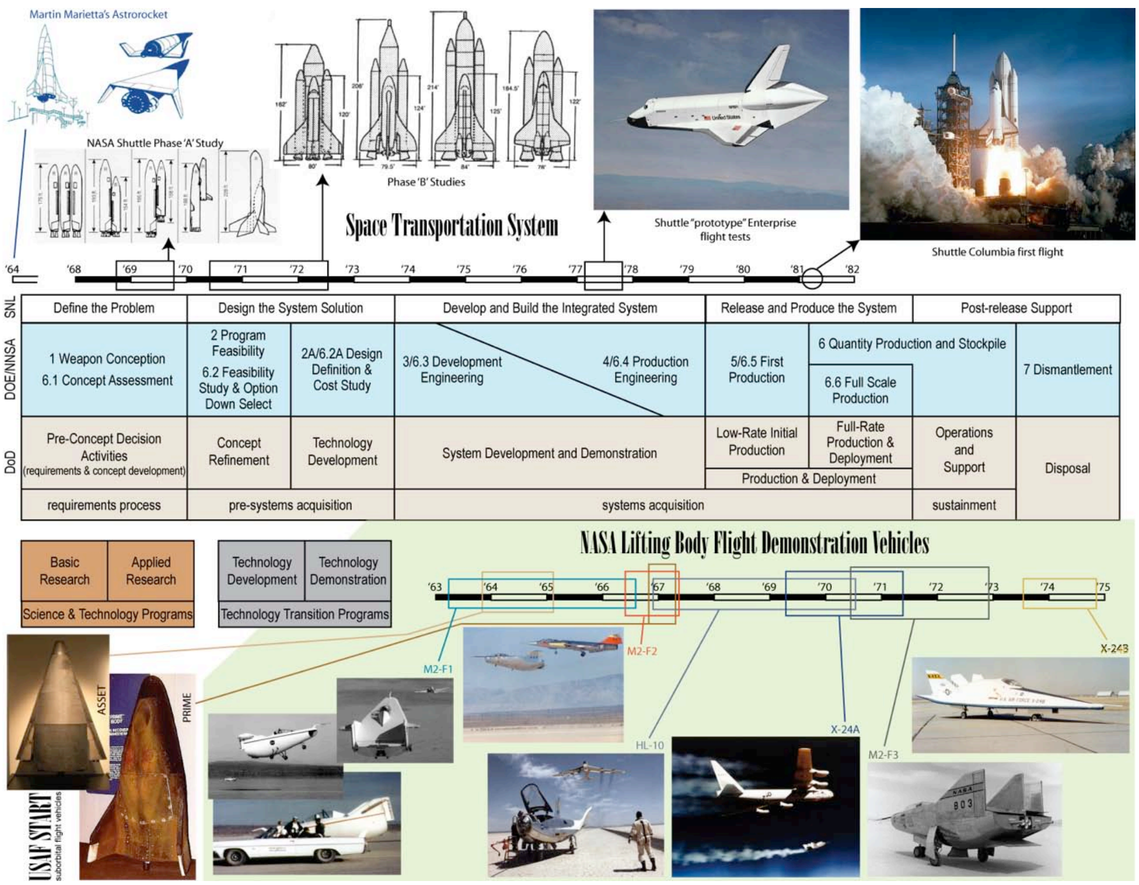

Figure 2. Illustration of the development of lifting body technology, contrasted with its insertion into the space shuttle product life cycle.

[4] Organization for Economic Co-operation and Development, *OECD Factbook 2008: Economic, Environmental and Social Statistics*.

4. EXISTING VIEWS (A BRIEF LITERATURE REVIEW)

Perhaps the most obvious technology development life-cycle view to take that can be found in the open literature base is consideration of technology from a "ware" perspective. In taking this view the developer envisions the various physical manifestations that the technology might go through as it matures, such as illustrated in Figure 3 below (although note the phase or step names may change depending on the domain or source reference followed; e.g., concept, demonstration/feasibility, pilot plant, and commercialization,[5] or basic R&D, process development, product development, production development, and production and sales[6]).

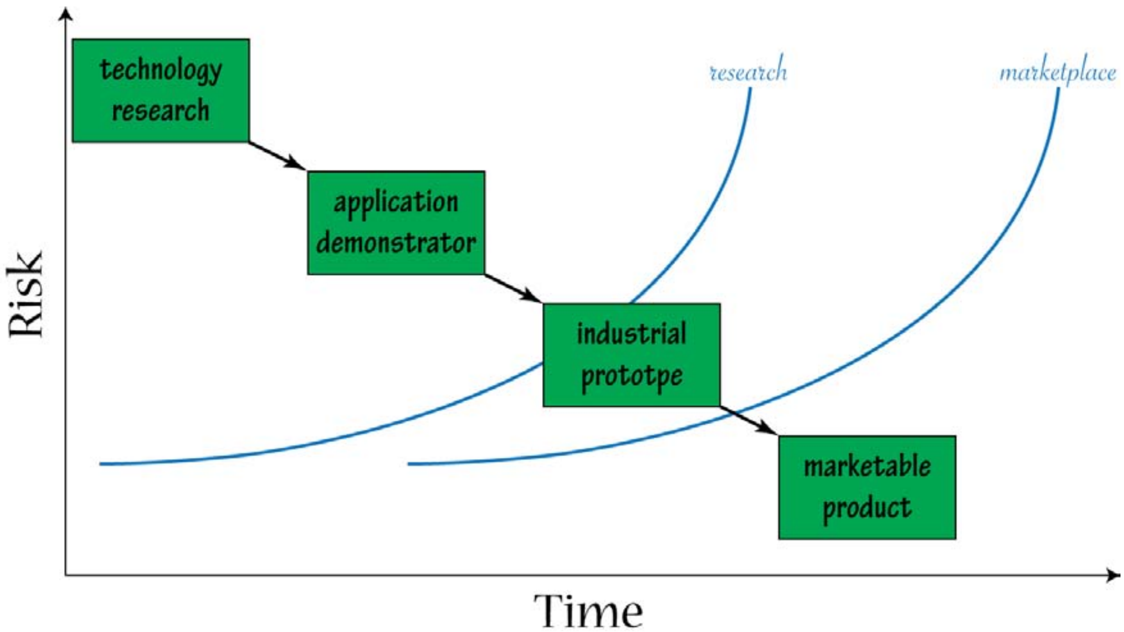

Figure 3. Technology development cycle.[7]

That said, however, one of the most prevalent views of a technology lifecycle is rooted in economics: how quickly and completely new technologies are adopted within a consumer market, as illustrated in Figure 4. From a business perspective, then, with an overriding concern for return on investment, technology development and deployment strategies focus on finding a way to enable early, rapid, and complete penetration of the market.

[5] Pittsburgh Mineral & Environmental Technology, Inc., "A White Paper on the Technology Development Life Cycle," May 2004, http://www.pmet-inc.com/resources/Tech.pdf, accessed 04JUN09.
[6] "H. Schmidt technology transfer model" as presented in Watanabe, Toshiya, et al., "Visualizing the invisible: a marketing approach of the technology licensing process," International Association for Management of Technology (IAMOT), Washington, DC, USA, April 3 - 7, 2004.
[7] Adapted from Wilson, Michael, "ICT Technology Lifecycles," World Wide Web Consortium (W3C) talk, 2001, http://www.w3c.rl.ac.uk/pasttalks/tech_lifecycles.pdf

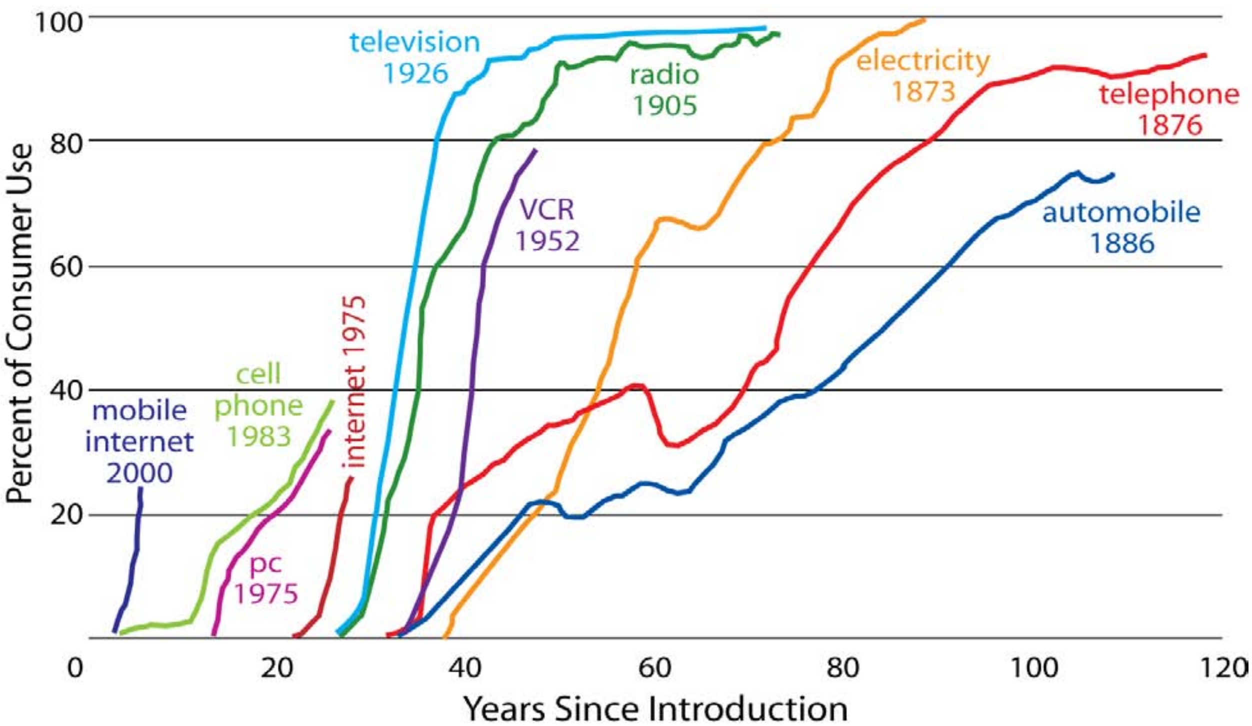

Figure 4. Typical trends in consumer adoption of new technologies.[8]

The series of actions through which new technologies are adopted—or new ideas are accepted—is generally known as the *diffusion process*. This concept is also referred to as the theory of *diffusion of innovations*, and was first studied by the French sociologist Gabriel Tarde (1890) and by German and Austrian anthropologists such as Friedrich Ratzel and Leo Frobenius. In the United States one early investigator was H. Earl Pemberton (ca. 1936), who provided examples of institutional diffusions for such things as postage stamps and compulsory school laws. Extensive pioneering studies in the diffusion of innovations were also undertaken in the 1950s at Iowa State University by sociologists.[9] On the basis of this work, George Beal, Joe Bohlen, and Everett Rogers together developed a technology diffusion model[10] that Rogers later generalized in his widely acclaimed book, *Diffusion of Innovations*,[11] now in its fifth edition (2003). The

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[8] Adapted from Vardi, Yossi, “After the gold rush, or: is it just the begging, you ain’t seen nothing yet,” presentation at *Telecommunications and Technology: After the Gold Rush* concurrent session, Milken Institute 2002 Global Conference, Beverly Hilton Hotel, Los Angeles, CA, April 24, 2002.

[9] See,for example, Bohlen, Joe M.; Beal, George M. (May 1957), "The Diffusion Process", *Special Report No. 18* (Agriculture Extension Service, Iowa State College) 1: 56–77.

[10] Beal, George M., Everett M. Rogers, and Joe M. Bohlen (1957) "Validity of the concept of stages in the adoption process." *Rural Sociology* 22(2):166-168.

[11] Rogers, Everett M. (1962). *Diffusion of Innovations*, Glencoe: Free Press.

diffusion process was given a firm mathematical foundation by Frank Bass.[12] This consumer- or market-oriented model generally takes the form of an "S" curve, such as shown in Figure 5, although its derivative, a "bell" curve, is also frequently used.[13]

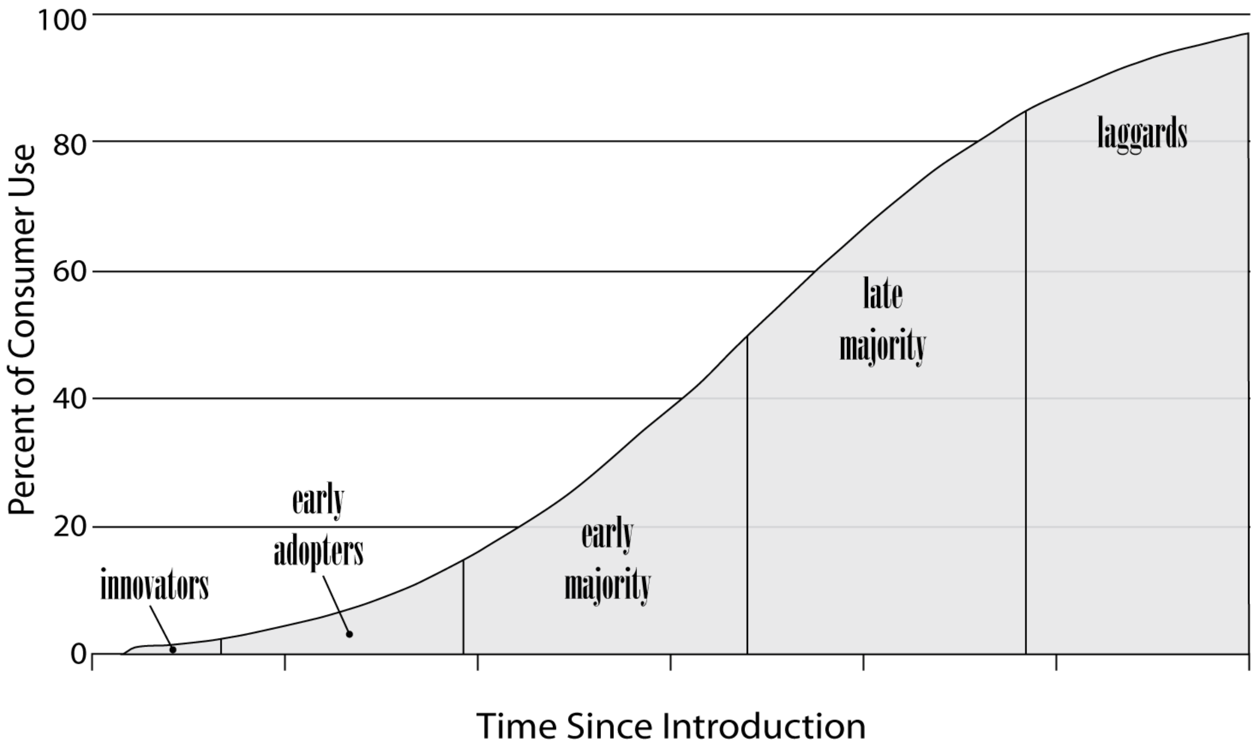

Figure 5. Technology diffusion model.[14]

The basic technology diffusion model has been extended to include cases with repeat purchasing (multi-generational models; i.e., cases involving continuous innovations or improvements that do not force a significant change of behavior by the customer; e.g., automotive technology).[15] The diffusion model has also been used as a framework for managing transition throughout the life cycle of a technology. For example, since 1996 the Software Engineering Institute (SEI) of Carnegie Mellon University has been applying a four-phase technology life-cycle model, as summarized in Table 1 below, to predictably and consistently mature and transition technology; note the intent to align with the Rogers diffusion model as indicated by the "users" listed.

[12] Bass, Frank (1969). "A new product growth model for consumer durables". *Management Science* 15 (5): p215–227.
[13] A bell curve may also be used to capture both the gain and then loss of market share due to technology displacement.
[14] Adapted from Wilson, 2001.
[15] Norton, J.A., and F.M. Bass, "A diffusion theory model of adoption and substitution for successive generations of high technology products," *Management Science*, Vol. 33, pp. 1069-1086, 1987.

Table 1. Technology Development and Transition Phase Summary[16]

Exploration	Maturation	Outreach	Support
Questions			
• What problem are we trying to solve and should the SEI and this program be solving it? • Whom should we partner with for development?	• What solution provides the most value? • How will people use it? Do we have an proof an intended users can use it? • What is the transition strategy?	• What mechanisms and value network are we developing for transition? • Whom should we partner with for transition?	• How do we support this technology? • How do we support the transition partners? • What improvements are most profitable or necessary?
Users			
innovators	early adopters	early majority	late majority
Strategic Focus			
• problem space • collaborators • technical direction	• technical credibility • value of solution • transitionability • strategic advantage for early adopters	• whole product and value network • transition partner prep • standardization	• meeting demand • self-sustaining transition • standards of excellence
Activities			
• identify needs • select high-payoff technology to meet identified needs • create leadership presence and identify collaborators	• mature the technology • trial use (pilot projects) to demonstrate value and transitionability • create transition plan	• package demonstrated technology for broad adoption • gather reference data and impact data to generate interest from target adopters • create products and partnerships to meet demand	• license technology to transition partners to meet demand • establish standards of excellence • update standards as warranted based on user experience

The idea of managing the phase transitions can also take on a particular focus, such as stakeholder management as illustrated in Figure 6 following below. A similar idea would be to consider the principal activities that have to be managed at different times in the technology lifecycle: technological feasibility; application feasibility; political feasibility; demand feasibility; market creation; and market share.[17]

[16] Adapted from http://www.sei.cmu.edu/news-at-sei/features/2003/3q03/feature-4-3q03.htm
[17] Wilson, 2001, p. 10.

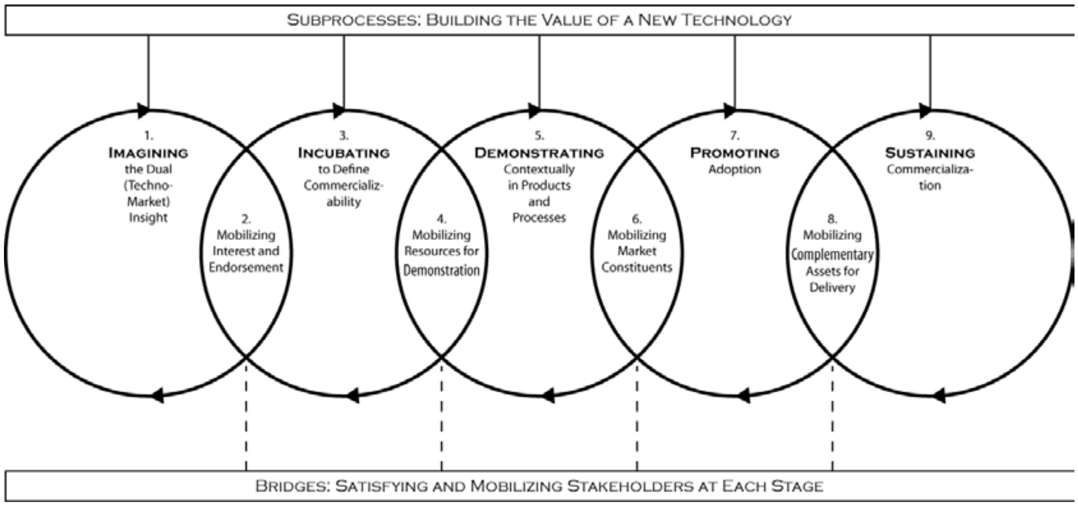

Figure 6. The process of technology commercialization; engaging the stakeholders.[18]

Where new technology survives by finding a niche market, and then moves "up market" through sustained innovation in response to the needs of a broader market, it can displace existing technologies and products (e.g., cellular phones vs. fixed-line telephony); such innovation has been termed "disruptive technology" in the popular work of Clayton Christensen,[19] although much work remains to be done to develop this "theory."[20]

For new innovations, it has been observed that the transition between the "early adopters" (or visionaries) and "early majority" (pragmatists) consumer groups often corresponds to failure for high-technology products; this transition has become to be known as the "chasm" due to the work of Geoffrey Moore.[21] This chasm has been explained on a requirements basis by thinking of the technology in terms of utility or performance vis-à-vis these different consumer groups. Following this line of reasoning, it can be envisioned that as the customer base grows, customer "requirements" will shift, as illustrated in Figure 7. Eventually the needs of the dominant customer (the one to please from a purely economics perspective) will have to take top billing. If the stakeholder list and their needs and requirements are not periodically reviewed, updated, and reflected in technology (and product) development, the risk becomes great for falling into the chasm (or in being displaced by a disruptive technology).

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[18] Adapted from Jolly, 1997, p. 4.
[19] Christensen , Clayton, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston: Harvard Business School Press, 1997. See also Utterback, James M., *Mastering the Dynamics of Innovation*, Boston: Harvard Business School Press, 1994.
[20] Danneels, Erwin, "Disruptive technology reconsidered: a critique and research agenda," J. Prod. Innov. Manag. 2004;21:246-258.
[21] Moore, Geoffrey A., *Crossing the Chasm*, New York, NY: Harper Business Essentials, 1991.

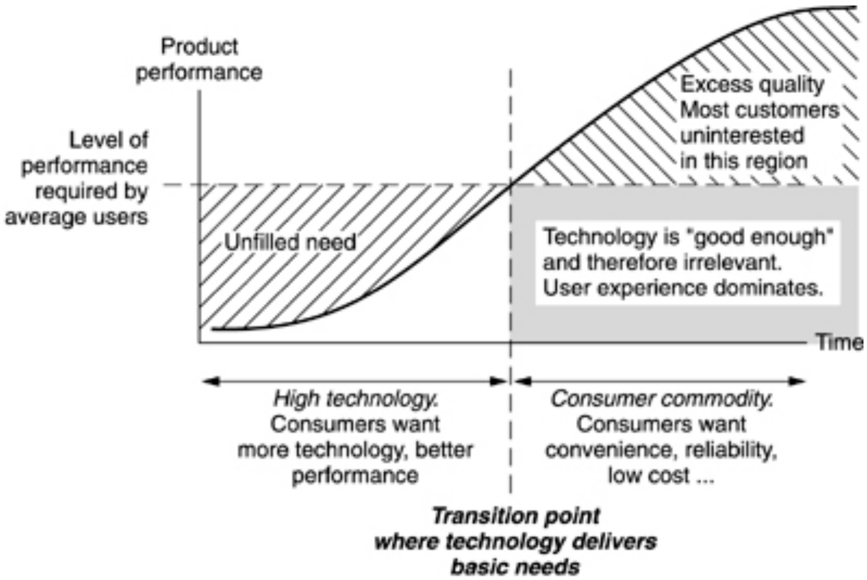

Figure 7. Technology performance requirements by consumer group.[22]

The idea of considering a technology in terms of utility or performance can also be used to transform a technology diffusion model away from a consumer market share view into more of a consumer requirements view, such as in Figure 8.

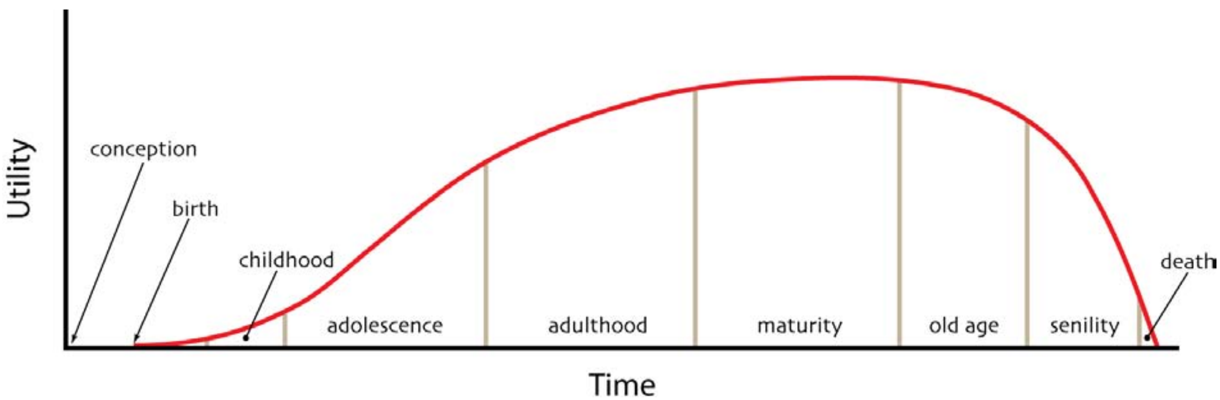

Figure 8. Technology life cycle: the "whale" chart.[23]

In addition to models of market share or consumer utility, technology life cycles have also been published that reflect, as to be expected, more of the business side of things. For example, Figure 9 conceptually illustrates a life cycle model concerned with R&D sunk costs, the timeline of recovering these costs, and the modes (e.g., types of licenses) of making the technology yield a profit proportionate to the costs and risks involved.

[22] From Norman, D.A., *The Invisible Computer: Why Good Products Can Fail, the Personal Computer Is So Complex, and Information Appliances Are the Solution. Cambridge, MA: MIT Press, 1998.*
[23] Adapted from Nolte, Bill, Norman Anderson, and Bob McCarty, "AFRL Systems Engineering Initiative: Risk Management for Science and Technology," presentation, 8th Annual Systems Engineering Conference, San Diego, CA, October 24-27, 2005.

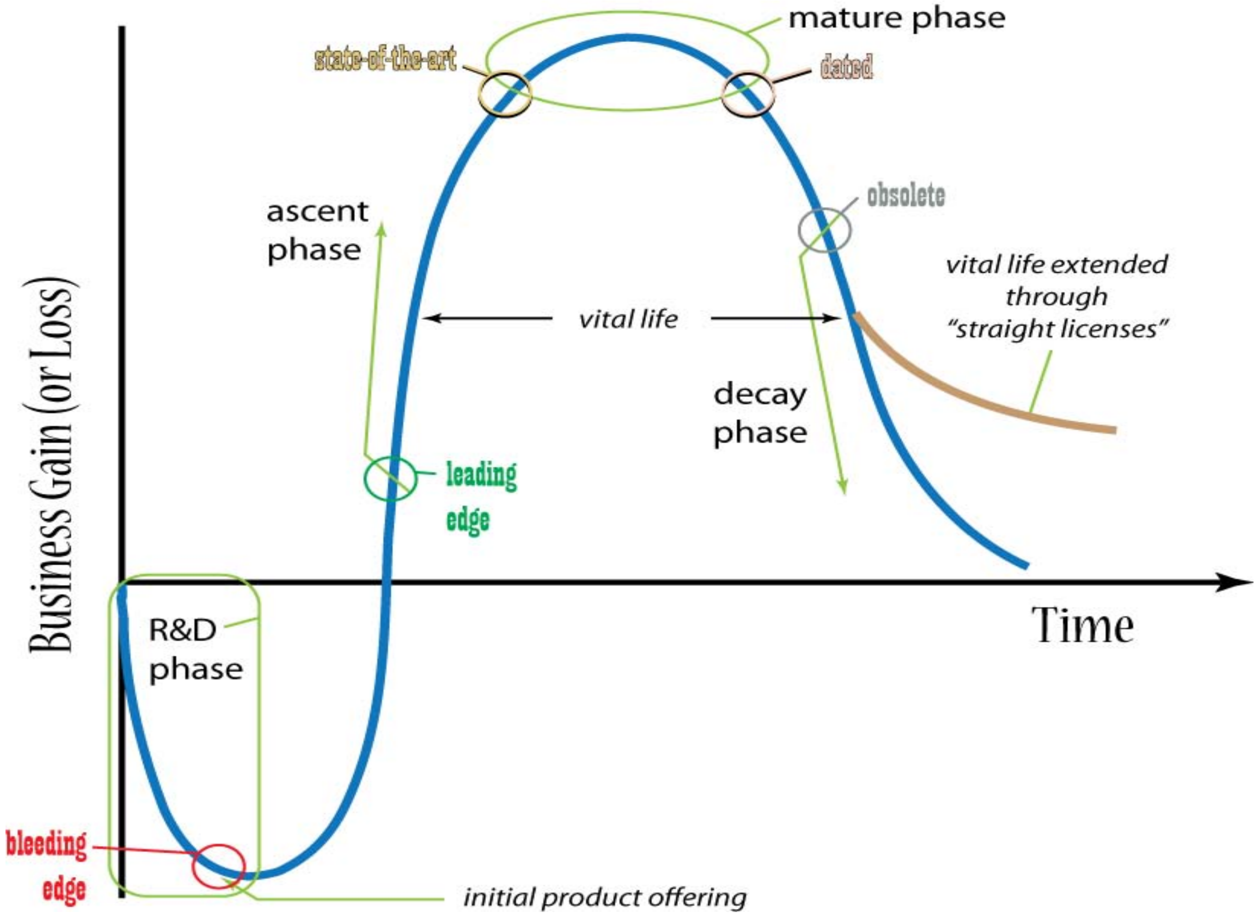

Figure 9. Management view of a technology life cycle.[24]

In fact, the use of advanced economic analyses techniques such as "discounted cash flow" and "compound real options valuation" have been shown to be of benefit in technology development as an aid to decision making, risk assessment, infusion planning, probabilistic cost estimation, schedule uncertainties, and program-level decision tree analysis.[25]

Figure 10 provides another example that is intended to portray the perceptions of a technology in terms of a marketing view that can drive both internal R&D funding and consumer confidence (sales). Referred to as a "hype" cycle by Jackie Fenn,[26] an analyst at the U.S. research firm Gartner Group, this type of technology life cycle model is related to the classic diffusion of innovation work by Rogers introduced earlier.

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[24] Adapted from United Nations Industrial Development Organization (UNIDO), *Manual on Technology Transfer Negotiation: A Reference for Policy-Makers and Practitioners on Technology Transfer*, Vienna, 1996, as referenced by http://en.wikipedia.org/wiki/Technology_Life_Cycle (accessed 10JUN09).
[25] Tralli, David. M., "Valuation of technology development using a novel workflow approach to compound real options," *2004 IEEE Aerospace Conference*, Big Sky, Montana, 06 March 2004.
[26] Fenn, Jackie, "When to Leap on the Hype Cycle," Gartner Group, January 1, 1995.

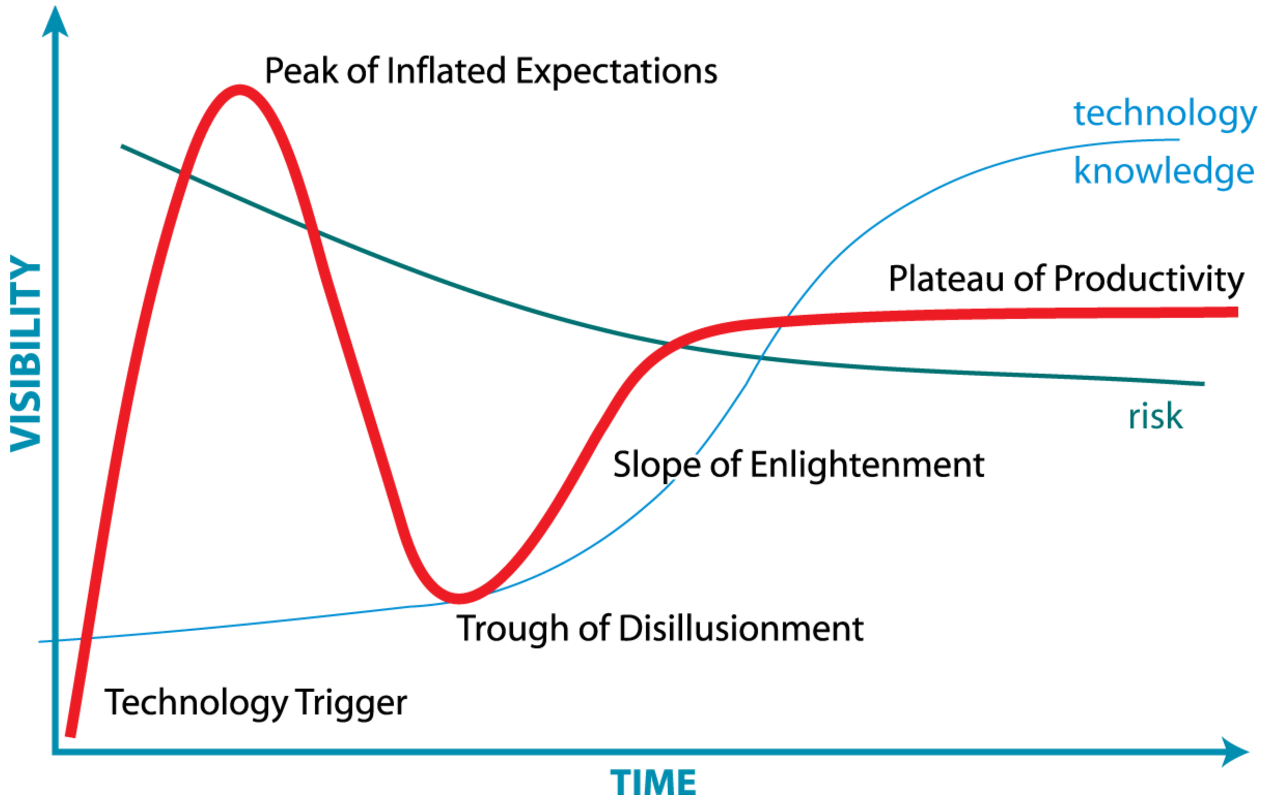

Figure 10. A "hype" cycle representation of the maturation of a specific technology.[27]

However interesting (or not) this material may be, it is too broad, and even esoteric, from the standpoint of determining what constitutes a sufficient plan for technology development, particularly for the intended R&D focus. Perhaps the literature base reviewed was not extensive enough—or was not covering the right material—but, nevertheless, given this material, the conclusion that must be drawn is that either what makes a good R&D technical plan is so key to success that it remains locked up as company proprietary information, or it is part of the "fuzzy front end" that has been commonly accepted as the way R&D is carried out.[28]

[27] Adapted from http://en.wikipedia.org/wiki/Technology_hype (accessed 10JUN09).
[28] Smith, Preston G., and Donald G. Reinertsen, *Developing Products In Half The Time*, Van Nostrand Reinhold, New York, 1991.

5. STRUCTURED TECHNOLOGY DEVELOPMENT

As in the introduction, the focus here will be on the R&D process that might variously be called *technology research & application demonstration* (Figure 3), *imagining, incubating, & demonstrating* (Figure 6), *conception*, *birth*, and perhaps *childhood* (Figure 8), or the *R&D phase* (Figure 9). Strictly speaking, this work is pre-product (although it may take on a product-like persona) and so pre-commercialization, and thus it takes place prior to the *innovator* stage (see Figure 5). It can also be said to be post-science or post-basic-research in the context of Figure 1, although technology maturation activities may end up requiring further scientific advancement if they are to proceed (i.e., R&D uncertainty cause T2 raises its head).

Recalling the earlier definition provided for *technology development* that included the idea of "…make clear by degrees … cause to unfold gradually…"—implying iterative improvement understanding of how to practically apply some particular bit of knowledge—the notion arises that an R&D phase will include some number of process cycles (or stages)[29] that produce the desired progress. The questions raised by this view would include:

> **What is a cycle?**
>
> **How many cycles?**
>
> **What determines successful completion of a cycle?**

"It depends" is a fair, but next to useless response to these questions. The correct answers are tied to how risk is being managed for the particular technology development activity. While this could (and perhaps should) be elaborated on, for present purposes, risk will be either low or high (e.g., low or high cost, no injury or death possible, etc.). The answers to the questions under low-risk conditions will be collectively referred to as part of an "alchemist's paradigm" while the answers when operating under high-risk will be "science-based, systems engineering paradigm."

[29] Although there are similarities, this is not, strictly speaking, iterative or incremental development, nor is it reference to the spiral model (at least in its original form).

5.1 Technology Development by Alchemy[30]

The best-known goals of the alchemists were: the transmutation of common metals into gold or silver; the creation of a "panacea", or the elixir of life, a remedy that would cure all diseases and prolong life indefinitely; and the discovery of a universal solvent. In the Middle Ages, alchemists also invested much effort in the search for the "philosopher's stone", a legendary substance that was at that time believed to be an essential ingredient for these goals. The basic approach was experimental.

> *The first essential in chemistry is that you should perform practical work and conduct experiments, for he who performs not practical work nor makes experiments will never attain the least degree of mastery.* Jabir ibn Hayyan, 8th c.[31]

The basic method used was endless attempts at dissolving or coagulating various materials together (Latin dictum: *SOLVE ET COAGULA*), hoping that the outcome would (at last!) give the desired result. By analogy, a more contemporary (and eventually useful) example is given by Thomas Edison’s approach toward finding a commercially viable incandescent lamp.

> *Before I got through, I tested no fewer than 6,000 vegetable growths, and ransacked the world for the most suitable filament material.* Thomas A. Edison, 19th c.[32]

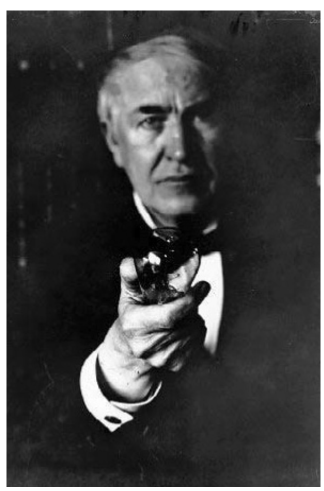

Figure 11. Thomas Alva Edison and his light bulb.

[30] http://en.wikipedia.org/wiki/Alchemy
[31] http://en.wikipedia.org/wiki/Geber
[32] Wei, James, *Product Engineering: Molecular Structure and Properties, Topics in Chemical Engineering*, Oxford University Press, USA, 2007, p. 18.

Under this paradigm, the answers to the questions are as follows:

What determines successful completion of a cycle? When the goal is met (e.g., the discovery of a process that will produce gold, silver, panacea, or a universal solvent by successful transmutation, or the discovery of a carbon filament that will last for at least 15 hours).

How many cycles? Indeterminate.

What is a cycle? One experiment.

The alchemist's paradigm is known by a variety of other names, such as *fly-fix-fly, trial-and-error*, *build-test,* and *black art* (or even *expert opinion* in many cases). To put it another way, Thomas Edison displayed a placard over his desk with a famous quote from Sir Joshua Reynolds: "There is no expedient to which a man will not resort to avoid the real labor of thinking."[33]There is a time and place for fly-fix-fly, but it must not be a choice made because it is the easy—low thought energy—way. Rather it should be selected on the basis of a conscious decision in cases where the alternative—a science-based, systems engineering approach—is not practical or possible. The "not practical" comes about, for example, in the design of low-cost, low-risk items (like Edison's light bulb) that probably only merit a simple analysis, or even just a "try it and see if it works" approach. The "not practical" is also an issue for large, complex problems, where individual component behaviors and their interactions might be understood, but where system analysis techniques are simply too costly or impractical for the design cycle involved (e.g., in cases that would require many years of computational effort). The "not possible" arises where rigorous design methodologies do not exist or where the underlying scientific principles have not been developed.

There is one more trait to beware of that alchemists tend to share in common: a lack of documentation (both in terms of plans and reports). Even when fly-fix-fly is warranted, this tendency means that experiment sequences are often unfocused, peer reviews are few and far between, and lessons learned are generally lost in the long term (not a good thing in the context of this paper).

[33] "Aeronautics: real labor," Time, Monday, December 08, 1930. Retrieved from http://www.time.com/time/magazine/article/0,9171,752631,00.html 17JUN09.

5.2 Science-based Technology Development

This paradigm approaches technology development as if it were a high-risk venture (if there is much to it, maybe it always is so?).

> *Fifteen years is about the average period of probation, and during that time the inventor, the promoter and the investor, who see a great future for the invention, generally lose their shirts. Public demand even for a great invention is always slow in developing. That is why the wise capitalist keeps out of exploiting new inventions.* Gleason Archer, 20th c.[34]

If, however, for no other reason, it might be pointed out that this paradigm is part of one the "high-tech" company vision offered in the introduction: to be "the provider of innovative, science-based systems engineering solutions." The second part of this vision, "systems engineering," will be addressed in the next section. But for consideration here, what is a "science-based" solution and how might it be developed? As the paradigm name implies, this approach uses science—that is, the scientific method—and so provides a means to give preliminary answers to the basic questions posed earlier:

5.2.1 What is a cycle?

One cycle contains the four basic elements of the scientific method:

1. **characterization**

   A cycle begins by first characterizing the need that is to be satisfied. This includes development of an understanding of the current situation and a vision of the desired future state, along with identification of specific goals, events and actions that would effect this transition. For a mature process, technology characterization is generally expressed in terms of requirements (or a technology development performance specification).

2. **hypothesis**

   The second step is where invention takes place. With reference to how a stated need will be fulfilled, the hypothesized solution is described and characterized in terms of the underlying, basic scientific principles and supporting technologies, and the innovative way they will be assembled together to give the functionality

[34] Archer, Gleason (1938), *History of Radio to 1926*, as quoted in Jolly, 1997, p. 1.

and performance claimed for the new invention (cf. the simple view of Figure 1). This technology description and characterization is documented the form of models, be they iconic, analogue, or symbolic.[35] Note that the set of models must include an innate predictive capability for both the behavior of the system (invention) and its parts in terms of measures that can be verified and validated (i.e., the models must be testable). When development has reached a sufficient level of maturity, technology "hypotheses" (models) are generally documented in the form of a technology application manual and a supporting technical (or "integrated") data package.[36]

3. **predictions**

   In the third step, the models of step 2 are assessed in order to predict the behavior of the technology while it is being used (functioning) to meet—and under conditions expressed by—the need. Test predictions are recorded in some form of experiment (test) requirements or planning documentation.

4. **experiments**

   As the last step, experiments are designed and performed to test and evaluate the correctness of the hypothesis (i.e., veracity of the model(s) in predicting the actual observed actions or effects). "Test" involves both observation (measurement) and data collection. "Evaluate" includes both data analyses and determination of whether or not the results match the predictions (and, so, whether or not the hypothesized technology solution will satisfy the stated need). Experiment (test) results are documented in some form of experiment (test) report, which, at least by reference, includes all of the associated plans, procedures, observations, and raw data, as well as the analyses and conclusions.

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[35] These three terms form a general classification scheme for different model taxonomies as follows. Iconic models—represent reality and look like the real thing, but may employ, e.g., a change in scale or materials; includes sketches or drawings, 3-D constructs, and virtual reality. Analogue models—a simplification of reality (limited detail) focused on key elements that make no pretense of looking like the real thing; includes schematic models (graph theory), 2-D contour maps, and functional relationships displayed on graphs. Symbolic models—an abstraction of reality that represents ideas by means of a code and is used for analyzing performance and predicting events; includes numbers and mathematical (deterministic and stochastic) models, words (verbal description), and musical notation.

[36] See, for example, IEEE-1220 §4.7 and EIA-632 Table C.12.

It is important to notice the shift that has taken place in the role that experiments play. For the alchemist, the hoped for outcome of the experiment (e.g., turning lead into gold) is the goal. For the technology developer, the outcome of the experiment is used to validate the system models—the supported assertion that the new technology will meet the need—with the goal to provide adequate assurance that the models are suitable for use as *product* design tools.

It might also be noted that the four basic elements of the scientific method summarized above show up in other ways that are of some interest here. In particular, Walter Shewhart circa 1924 followed the scientific method in developing recommendations for how Western Electric Company engineers could improve the quality of telephone hardware at the Hawthorne manufacturing plant. Both W. Edwards Deming and Joseph Juran—founders of the modern quality improvement movement—studied at Hawthorne under Shewhart, and continued the development of his ideas.

One of Shewhart's ideas that is well represented in the quality community is variously called the "Shewhart cycle," the "Deming Wheel," the "Plan-Do-Study-Act (PDSA) cycle", or the "Plan-Do-Check-Act (PDCA) cycle," depending upon which source is consulted. Corporate implementations may, for a variety of reasons, recast the cycle into other terms as well. One such example describes the cycle in five elements: plan the work, evaluate risks/hazards/threats, develop/implement controls, perform the work, and improve the process; here the first three elements are *plan*, the fourth is *do*, and the last is *study* and *act*. Regardless of the nomenclature used, it should be understood that the Shewhart cycle is really nothing more than a tailored, repartitioned scientific method proffered under the guise of continuous process improvement.[37]

Figure 12. The Shewhart cycle.

[37] See, for example, Best, M., and D. Neuhauser, "Walter A Shewhart, 1924, and the Hawthorne factory," *Quality and Safety in Health Care*, 15(2), April 2006, pp. 142-143.

As a result of the quality crusade led by Deming and Juran, the Shewhart cycle has become deeply embedded at many levels in quality standards such as ISO 9001 and SAE AS9100. Of particular interest here is §7.3 of these two standards, entitled *Design and Development*. Grouped by PDSA category, the subsections are:

Plan

7.3.1 Design and Development Planning

Do

7.3.2 Design and Development Inputs

(Note that the actual Design and Development Process itself goes here—which is not, in fact and appropriately so, defined by quality management standards. HOWEVER, note also that no matter how good the "wrapper" is, the "recipe" or process of doing design and development ultimately controls the quality of the product. Being ISO-9001 certified does nothing if this key process is ad hoc—i.e., CMMI Level 1.)

7.3.3 Design and Development Outputs

Study

7.3.4 Design and Development Review

7.3.5 Design and Development Verification

7.3.6 Design and Development Validation

Act

7.3.7 Control of Design and Development Changes

ISO 9001 is of general interest (at least beyond the academic) in that contract requirements—particularly in the aerospace industry—will almost always stipulate compliance with "the appropriate national or international consensus standards," and often specifically identify ISO 9001 as "appropriate." Note that it would also be possible to make similar comparisons with quality assurance regulations and standards for other industries (e.g., nuclear power, bio-medical, transportation), but that would belabor the point. The bottom line is that "high-tech" development contracts will generally require program and project plans to include implementation of a PDSA cycle (verifying that they do so is another question altogether).

Figure 13. Quality management view of design & development: "then a miracle occurs."

5.2.2 What determines successful completion of a cycle?

When the results of the experiments match the model predictions. Otherwise, the cycle has to be repeated with appropriate corrections to the characterization, hypothesis, and predictions prior to conducting new experiments.

The final part of the *experiments* element of the scientific method includes an assessment (*study* in PDSA terms) of that cycle's characterization, hypothesis, and predictions in terms of the outcome or results of the experiments. Criteria for conducting this assessment should be part of the planning that begins the cycle, although it should certainly be firmly established **prior** to conducting the experiments. The output of this technical assessment would, in practical terms, be a recommendation to project management to either: repeat the cycle following revisions to the technology model(s) (re-cycle); continue to the next cycle; or abandon or indefinitely shelve the technology in that it is, e.g., unworkable, or the underlying science is insufficient (uncertainty cause T2), or a necessary supporting technology has not been invented yet (or insufficiently matured; uncertainty cause T1).

Of course the technical review should be coordinated with a project review. Management may choose to agree with and support execution of the recommendations stemming from the technical assessment, or they may choose to abandon or shelve the technology development effort for their own reasons such as: the envisioned application (product) is unlikely to be economically feasible (uncertainty cause T12); the planned technology development cycle is not financially feasible (uncertainty cause T11); or, in the greater scheme of things, it is not the best time to conduct the next cycle (uncertainty cause T13). The upshot is, at this point (or gate[38]) in the technology development life cycle, work may continue, terminate, hold, or repeat (*act* in PDSA terms).

Although related to the question of "How many cycles?" found in the next step, it is useful at this juncture to delve into the idea of cycle **technical** completion criteria (general project management criteria are another topic altogether); that is, what might suitable cycle metrics or measures be? (The next step itself—the "How many cycles?" question—will determine the starting point, the desired end point or goals for the overall technology development effort, and how to break the difference up into manageable chunks or cycles.) Three high-level metrics and suggested measures are discussed below, which basically fall out of the following three questions:

- How complete are the technology requirements?
- How complete are the technology models?
- How complete is the technology maturation assurance documentation?

Notably there is **no** hardware *metric*, although the models generally include hardware as a useful form of an iconic model, and hardware development may form one measure of development of the model metric. Additional metrics will be proposed later in this document when systems engineering is discussed.

5.2.2.1 Requirements.

When a new *technology* development project first kicks off, it is generally to be expected that any understanding of customers, applications, and requirements will be weak. Early in the

[38] It is, in a way, ironic to note that what is a well understood, well published methodology—the scientific method—of which this assessment is a part, can be capitalized on by entrepreneurs when business manager's forget their third-grade science lessons. For example, Robert G. Cooper, in his book *Winning at New Products* (1986), "pioneered," "developed" and published the "carefully designed" "stage-gate model", was able to register the trademark "Stage-Gate", and built up an international training and consulting company around the "Stage-Gate® Product Innovation process." See http://www.stage-gate.com/

development, the focus is on clarifying the need and developing high-level requirements (measures of effectiveness and performance). As the capability of symbolic models is developed, predicted behavior serves as requirements pro tem, against which early iconic models (e.g., hardware) can be evaluated. Finally, by the time a technology has developed to the point that it is mature enough for low-risk insertion into a product, the customer, user, and other stakeholders should be known, a set of functional performance and operational (e.g., interface or integration and environmental) requirements and constraints (development specification) should have been established and placed under configuration management control, and associated verification and validation requirements established. Thus, in collecting these ideas together, a measure for the requirements metric might be the documented evolutionary development of requirements in a sequence such as: the need for a technology; model-based requirements; pseudo-customer[39] functional and functional-performance requirements; pseudo-customer operational (e.g., interface and environmental) requirements; other stakeholder constraints; and, finally, a technical development specification.

5.2.2.2 Models.

Models play a key role in the scientific method. As already noted, models may be iconic, analogue, or symbolic. While computer-based mathematical models are what first comes to mind for most people these days, the lifting body flight demonstration vehicles of Figure 2—and the functional or phenomenological graphs presenting lifting body wind tunnel test results (not shown)—are both models in their own right. For the technology developer, the task is to identify the appropriate models for the particular technology under development in light of the technology's anticipated use. (Remember, a predictive capability is required.)

Model development generally starts from observations and moves toward the mathematical. An initial symbolic model may be nothing more than a word description captured in several pages worth of information that outlines the new technology in terms of identifying the key underlying scientific principles and supporting technologies, and the innovative way they will be assembled together. Early development may come by, e.g., producing a phenomenological model that is

[39] The present paper was drafted from the point of view of a technology development program that has yet to be inserted into a product. If a new (or improved) product has selected the technology prior to full maturation, the "pseudo" would be dropped.

nothing more than a simple correlation table that presents the results of experimentation or experience. As the level of understanding advances, these results may be cast in mathematical terms to enable manipulation and further derivations in support of the problem at hand. With increased knowledge, behavioral models may eventually be described in terms of the underlying physical laws, and they can increase in fidelity by moving from a first-order effects model to one that includes second-order (or higher) effects.

WHAT GOES UP MUST COME DOWN

elevation	range
10	900
20	1500
30	1900
40	2200
50	2100

$$R = \frac{V^2 \sin 2\Theta}{g}$$

$$m\frac{du}{dt} = -D\cos\phi - L\sin\phi$$
$$m\frac{dw}{dt} = -mg - D\sin\phi - L\cos\phi$$
$$I\frac{d\omega}{dt} = (-D\sin\alpha - L\cos\alpha)d$$
$$\frac{dx}{dt} = u$$
$$\frac{dy}{dt} = w$$
$$\frac{d\Theta}{dt} = \omega$$
$$\Theta = \alpha + \phi$$

Figure 14. Increasing model complexity.

Such a model development sequence, while intending to be a typical example, is not meant to be restrictive or prescriptive. That is, this sequence is referring specifically to efforts needed to understand and predict, project, or draw conclusions about the functional performance and key characteristics (including costs!) of the technology under development. Note that prior to expending much effort on a system-level (invention) modeling effort, appropriate models should already be available for the underlying scientific principles and supporting technology in order to avoid undue risks (uncertainty causes T1 and T2), although some projects may have a sufficiently high level of risk acceptance that allows a concurrent development path to be followed.

Because of its importance, a further word about application-appropriate model development is in order. The idea is to support sufficient development of the technology such that it can be successfully used in a product—but no further—in order to avoid unnecessary sunk costs (cf.

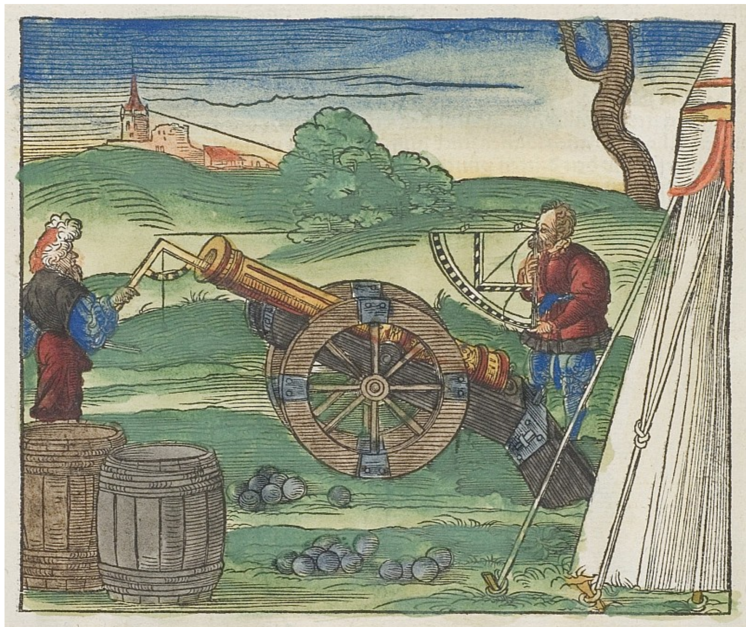
Figure 7). To illustrate this point, consider some "high points" of gun range prediction technology, as outlined below.

Figure 15. "Faule Mette" bombard, 29-inch caliber, City of Brunswick, 1411.

The effective siege cannons of the mid-15th Century were known as bombards.[40] These very-large cannon had calibers of 20- to 36-inches. In the Turkish siege of Constantinople under the command of Sultan Mehmed II in 1453, one bombard—called "Basilica"—was capable of firing a stone ball weighing 1,600 pounds a mile away. Bombards were, however, very large and heavy, and so were only moved with great difficulty (Basilica required some 200 men and 60 oxen). Operationally, the bombards were generally placed roughly parallel to the ground as close to the walls as was considered reasonably safe (i.e., where earthworks or other defensive measures could protect gun operators)—typically 100 yards—on heavy wood mounts, and were

[40] See, for example, Manucy, Albert, *Artillery Through the Ages*, United States Government Printing Office, Washington, DC, 1955.

anchored fast by stakes driven in the ground. That is, operationally there was **no** need for any range prediction technology.



Quelle: Deutsche Fotothek

Figure 16. Gunner's quadrant.

In the early 17th Century, King Gusav II Adolf (Gustavus Adolphus) of Sweden—known by some as the "father of modern warfare"—greatly changed the face of artillery by making a deliberate shift to the use of mobile pieces; his 9-pounder demiculverin was classed as the "feildpeece" *par excellence*, while his 4-pounder was light enough that only two horses were required to pull it in the field. With easily moved artillery, range prediction technology became useful. The operational theory of the day was simple: a cannon at 45° elevation would fire ten times farther than it would when the barrel was level (zero-degrees elevation). The implementing technology was likewise simple, and was called a *gunner's quadrant*: one end of a quadrant was laid in the gun barrel and a plumb bob was used to indicate the elevation; the elevation scale was appropriately divided into equal parts; increasing the elevation by one mark was believed to increase the range by one-tenth of the 45° elevation range. This approach proved sufficient when compared to the accuracy of the guns of that time.

By the 20th Century and World War-II, range prediction technology had lagged behind gun technology; the need for calculus had arrived. The Ballistic Research Laboratory of the Ordnance Department, located at Aberdeen, Maryland, was tasked with the preparation of firing and bombing tables for the U.S. Army. However, at the start of the war, for a given gun, projectile, and powder charge under some set of operational (atmospheric) conditions, it took 5 days to calculate a single trajectory using a mechanical calculator, or 30 minutes using a Bush Differential Analyzer (BDA; think 100 tons of whirling machinery), of which there were two in the world (Aberdeen and the University of Pennsylvania). Even with the BDA it took one month to produce a complete gun trajectory table for field use, and accuracy was generally considered to be unacceptable (~1% error).

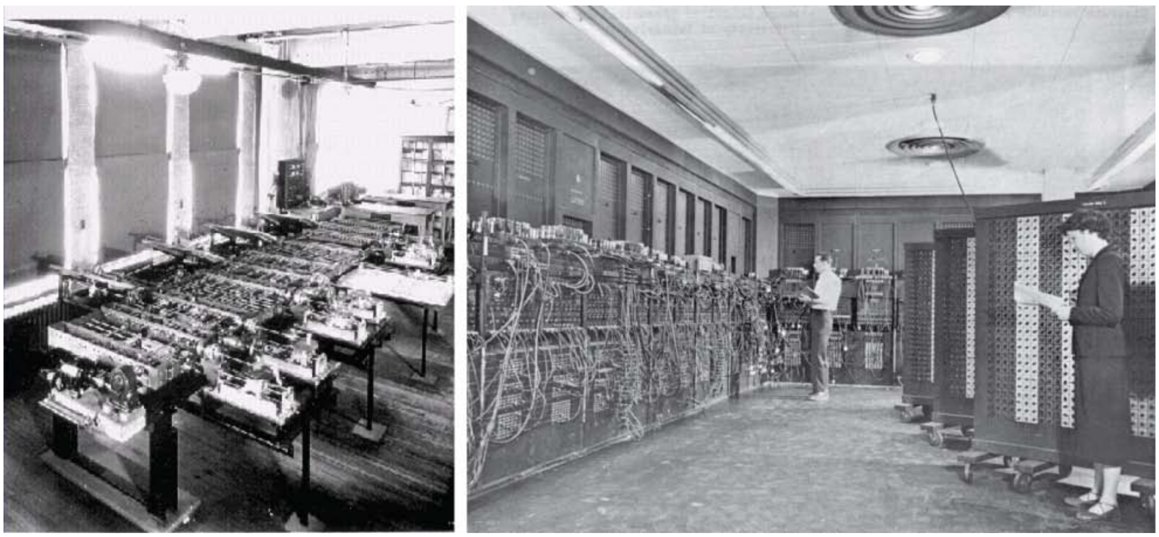


Figure 17. The Bush Differential Analyzer (left) and ENIAC.

To overcome these limitations, the Army contracted with the University of Pennsylvania on June 5, 1943, for six months of "research and development of an electronic numerical integrator and computer and delivery of a report thereon." Thus the ENIAC was born (the unknowing "prototype" from which most other modern computers evolved). While it did not place the computational power necessary for accurate ballistic calculations directly in the field—something which did not take place until recent decades—it did provide the means to meet the demand for trajectory calculations of the mid- to late-1940s.

The point of all this is that it is important to initially have some vision of how a technology will be used (a vision that should develop toward the concrete as the technology matures), and so to identify corresponding performance levels for said technology and the necessary fidelity required of the supporting models. The output of ENIAC (or of a mechanical calculator) would have done nothing for Sultan Mehmed II or King Gusav II Adolf; the accuracy of their guns (e.g., circular error probability) was simply too poor to ever benefit from such trajectory calculations.

Measures for the model metric would include progress in developing and documenting: analogue models (e.g., analogies, functional relationships, physical architectures and descriptions, and phenomenological models), symbolic models (e.g., predictive models containing first- and second-order effects), and iconic models (e.g., drawings and 3-D constructs such as a benchtop testbed, breadboard, brassboard, and advanced technology demonstrator, as defined below).

3D Construct (Hardware) Types[41]

Benchtop—A test bed assembled for initial evaluation of a new technology (or components thereof) that are in the least developed state; i.e., a benchtop configuration is less advanced in development than a breadboard.

Breadboard—A research configuration of a system composed of integrated components that provide a functional representation of the key elements of a technology; it does not replicate the actual configuration of an operational system, and has major differences in known or notional physical layout; typically configured for laboratory use and so is not generally suitable for field testing. A breadboard is less advanced in development that a brassboard.

Brassboard (aka engineering development model (EDM) or pre-prototype)—A research configuration of a system that is suitable for field testing, and that replicates both the functions and the physical configuration of an operational system with the exception of non-essential aspects such as packaging. A sequence of brassboard models may appear with increasing fidelity (e.g., brassboard and advanced brassboard). A brassboard is more advanced in development than a breadboard, but is less so in comparison to an advanced technology demonstrator.

[41] These definitions are provided for purposes herein. Note that the term *prototype* is deliberately not included in this list (although it is perhaps the most often used term that—in a very loose sense—can refer to any of the iconic models defined here). In a strict acquisition sense, a prototype is intended to be—for all practical purposes—the final version of the product. It should be just like the finished product in every way, from how it is manufactured, to its appearance, packaging, and instructions. It is used for final evaluation of a product's design, performance, and production potential (e.g., qualification). As such it is not possible to define, let alone produce, a prototype until the system development and demonstration phase in a product lifecycle.

Advanced technology demonstrator (ATD)—The highest form of iconic model or 3-D construct used in technology development prior to technology insertion into a product line.

5.2.2.3 Assurance Documentation.

The old adage applies: if it isn't written down it didn't happen. In contrast with alchemy, a basic expectation of the scientific method—called full disclosure—is the documentation, archival, and sharing of all models, data (e.g., verification and validation data), and methodology (e.g., test plans and procedures) so they are available for careful scrutiny by others, even to the point of enabling them the opportunity to verify results by attempting to reproduce them. (Of course management may choose to restrict access to this information, but it does not obviate the need for it nor for the review.) Note that lab notebooks or the like do **not** count; this is not a format that is suitable for disclosure.

So what is meant here by *assurance documentation*? Clearly both the requirements and model metrics discussed above include documentation such as performance specifications, an application manual, guide or handbook, and a technical data package. There is certainly a need to provide assurance that such material is complete and correct, but this is more the domain of configuration or records management. Such documentation—and related quality concerns—is **not** part of this assurance documentation metric. As was stated earlier, for the technology developer, experiments are used to validate the system models with the goal to provide adequate assurance that they are suitable for use as *product* design tools. *Assurance documentation*, then, refers to the set of experiment (test) plans and reports that collectively provide the evidence that the hypotheses (models) are, first, maturing, and, when fully developed, are capable of meeting the need (requirements).

One measure for the assurance documentation metric would be the publication of experiment (test) reports. It is to be understood that the heart of such reports is the analysis showing how closely the results matched predictions made with the hypotheses (models) in support of the need (requirements). It also almost goes without saying that due reference will be made to the associated requirements and modeling documentation, as well as the original test plans. As it might be expected that a number of tests or experiments will be conducted in any one development cycle, many of which could be at a level of detail too esoteric for someone simply interested in an overall assessment of how the technology is maturing, a project may choose to produce periodic or post-cycle technology development reports that summarize how knowledge related to the technology has been advanced.

5.2.3 How many cycles?

The number of cycles required will be determined by the problem domain and on what constitutes a reasonable problem decomposition. The term *domain* is used here to refer to the extent or degree of model complexity required in terms such as the number of parameters that must be treated to yield the desired accuracy in predicting functional performance within the intended operational environment. *Decomposition* in this case refers to the problem domain, and not to the proffered problem solution; for example, modeling may begin by considering first-order effects under invariant environmental conditions, then perform further development to capture second-order effects, and finally extend the work to treat the expected range of operational conditions—which would give three cycles (as an example).

Let’s take a **partial** and **very brief** case study, and begin by referring back to Figure 2. It should go without saying that the investigation by NASA into lifting body technology began with “paper” studies that then progressed into wind tunnel tests. Eventually the program expanded to add flight demonstration vehicles—but, **note**, these were not product (e.g., the space shuttle)! Strictly speaking they were iconic models, 3-D constructs used to develop, test, and verify analogue and symbolic models that would later be used as the engineering basis on which the space shuttle design relied.

Because of the extent of the performance and operational (environmental) envelope—e.g., from low-speed landing at sea level to hypersonic speeds on atmospheric reentry from space—the flight demonstration experiments were divided into two, perhaps obvious, categories: reentry and atmospheric flight. Reentry testing was performed by the U.S. Air Force using surplus ballistic missiles and the unmanned “Asset” and “Prime” test bodies. NASA (with Air Force support) performed the atmospheric testing using the M2-F1, M2-F2, HL-10, X-24A, M2-F3, and X-24B test vehicles. The flight envelope for the atmospheric test vehicles was also gradually explored, beginning with low-speed, low-altitude tests with the plywood-covered M2-F1 (pulled by a Pontiac and then a DC-3!), and then expanded into a sequence of ever more demanding air-dropped tests of advanced test vehicles.

So how would you count the cycles? Three? Paper, wind tunnel, and flight tests? Four? Paper, wind tunnel, reentry demonstration, and atmospheric flight demonstration? Or add on one for every vehicle? And does this say anything about the cycle count required to develop some other technology? Probably not. (Also note that no detail was provided here concerning the number of paper studies and wind tunnel test series that preceded the flight tests.) The real answer has to be determined by a formal planning process that identifies the goals and the events that must take place to move from where you are to reach said goals, perhaps with division of the events into manageable step sizes.

However, to say "assess your current state of knowledge," "set some goals," and "establish a sequence of required events to get there" is probably not very satisfying for many potential readers of this document, so an outline of a normative, multi-cycle, science-based technology development program is provided in Appendix A. But note, by way of disclaimer, this is only a notional, descriptive, straw-man sequence of events or activities to provide a "jump start" to an actual planning exercise; in all likelihood, it does not represent an optimum technology development path for anything real! The events or activities described therein are cast in terms of the four basic elements of the scientific method as used in the discussions above, with each cycle portraying an orderly, consistent development of each element to maturity.[42]

When actually embarking on a technology development program, it is, of course, strongly recommended that a high-level maturation plan or approach be developed and documented in a formal Technology Development Strategy (TDS; cf. Appendix B), which should be duly reviewed and approved by appropriate (e.g., funding) authority before proceeding. Prior to initiating work in a cycle (or re-cycle), detailed technology maturation project plans (TMPs) would be derived from the strategy (cf. Appendix C). Generally speaking, it should be noted that the TDS and supporting TMPs are not standalone documents, but fit within a broader context of planning documents, as illustrated in Figure 18 below.

[42] Deliverables (e.g., test plans or technology development reports) are not listed to keep the outline simple. Nor are project (or quality) management activities shown for the same reason. Systems engineering activities that would further inform the technology development life cycle (and so add additional detail to this outline) are discussed elsewhere in this paper.

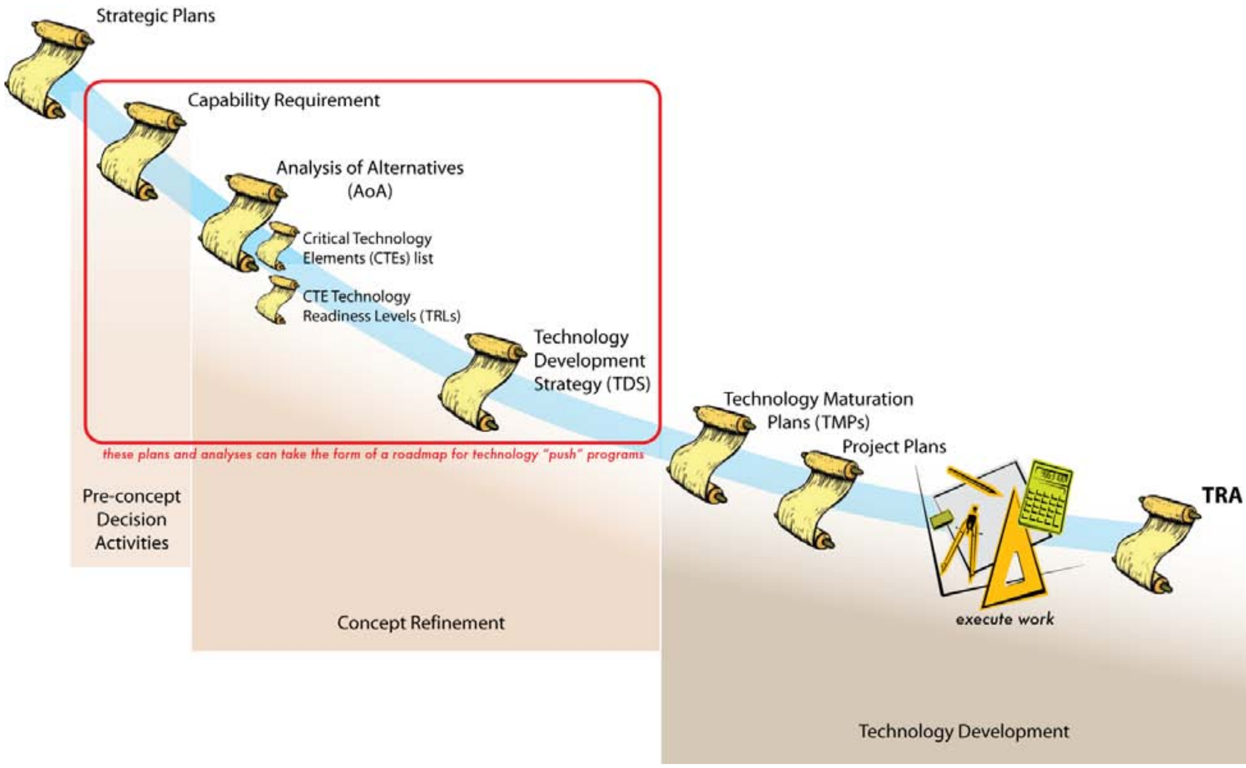


Figure 18. The family of planning documents for technology programs.

5.3 Applying Systems Engineering to Technology Development

There are many viewpoints of, or ways to think about, what systems engineering is. Given the science-based framework just presented, one of the ways to view systems engineering is as the recursive application of the scientific method to each basic element of the scientific method. Actually it goes one level beyond this. First it decomposes each basic element into several parts, and then it applies the scientific method to each part (or the PDSA cycle if you will). And, while there are variants, the systems engineering process can be applied in a formal way (and so satisfy quality management) since, unlike the scientific method, it is codified in several standards; for purposes herein, EIA-632 forms the normative reference. Adding an additional layer of decomposition to the scientific method is also necessary to support process definition at a level that would satisfy CMMI Level 3 criteria.

Systems engineering is a also a top-down methodology, and so looks to evaluate alternatives and drive toward system optimization; this tendency should be good for technology development, since it will help a maturation project keep a technology focus rather than quickly jump to a widget. In its formalized instantiation, systems engineering mandates treatment of risk, support for the entire life cycle, and integration of specialty engineering (safety, reliability, manufacturability, testability, …) into a project. Since there is no desire to turn this paper into a textbook on systems engineering, the focus of the discussion below will be on the decomposition of the scientific method and application of the PDSA cycle to each resulting part, while attempting to maintain the focus of the results on the technology development problem.

5.3.1 Decomposing the characterization element of the scientific method.[43]

Two sources for requirements are identified in the standard: *acquirer* and *other stakeholder*. Requirements collection activities are planned for and executed. Following collection, each set of requirements is validated (following a plan, of course); after variances, voids, and conflicts are resolved, the validated sets of requirements are captured in an established information database. Next, *system technical requirements* are defined and validated. Simply put, this means that the acquirer and other stakeholder requirements are integrated and transformed into a set of requirements that are unambiguous, complete, consistent, achievable, verifiable, necessary, and sufficient for a system design. Generally this means that requirements trade studies and risk analyses have to be performed even before design concepts are developed! Almost without exception it also means that analyses have to be performed to evaluate whether or not what will be asked of the designers makes sense or is achievable in any fashion at all (at least within the core competencies and processes they possess); questionable requirements are to be challenged. When all this has been accomplished, this element is capped off with a formal requirements review. Since each of the activities just mentioned begins with planning and ends with validation, resolution, and configuration management of the results, it should be an easy leap to see that the characterization element of the scientific method has been decomposed into multiple activities, each of which can is described as a PDSA cycle in its own right:

- Define acquirer requirements (EIA-632 Requirement 14)
- Validate acquirer requirements (EIA-632 Requirement 26)
- Define other stakeholder requirements (EIA-632 Requirement 15)
- Validate other stakeholder requirements (EIA-632 Requirement 27)

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[43] Covered by three primary elements in EIA-632, Requirements 14, 15, and 16, and eight supporting elements, Requirement 11 and Requirements 22 through 28.

- Define system technical requirements (EIA-632 Requirement 16)
- Validate system technical requirements (EIA-632 Requirement 28)
- Perform effectiveness analyses (EIA-632 Requirement 22)
- Perform tradeoff analyses (EIA-632 Requirement 23)
- Perform risk analyses (EIA-632 Requirement 24)
- Validate requirement statements (EIA-632 Requirement 25)
- Conduct a system requirements review (EIA-632 Requirement 11)

While this list of activities may look daunting—especially for a new technology maturation project—it should be recognized that it reflects a product development perspective. In technology development, requirements (particularly specifications) are often identified alongside the technology. Certainly some information—like the need for a technology or the capability gap it is to fill—must be defined prior to the start of development activities, but, on the other hand, much of the information identified by EIA-632 that is to be collected and vetted would only be needed mid- or late-term during a technology development phase. Early need for requirements not otherwise addressed until late in development may require the establishment of interim values through, e.g., application of models-based requirements techniques.

The idea of phased requirements development is illustrated in Table 2 for the acquirer requirements (cf. EIA-632 Requirement 14) against the normative development program cycles of Appendix A.[44] It should also be noted that frequently—**especially for a technology "push" activity**—just who the real acquirer (user) will be may not even be definable until such time that the technology is selected for insertion into a product. Therefore it may be necessary to deal with requirements development in a more pragmatic way: someone (even a virtual someone) may have to serve as an ersatz acquirer.

[44] Note also that End Products Validation plans (cf. EIA-632 Requirement 33) are developed as part of the Define Acquirer Requirements activity.

Table 2. Acquirer Requirements Phasing in a Technology Development Program

	Cycle					
Requirements Topical Area	1	2	3	4	5	6
Concept of operation	❍	●				
Functional requirements	❍	●				
Performance requirements	❍			●		
Natural and induced environments	❍				●	
Design constraints (e.g., supporting technology specifications)	❍				●	
Specialty engineering requirements (e.g., reliability)		❍			●	
Measures of Effectiveness		●				
Life cycle constraints (costs, schedules, facility use)		❍			●	

In a similar fashion, the other stakeholder requirements (cf. EIA-632 Requirement 15) can be evaluated in terms of when they are needed. A few items like technology base, standards, specifications, laws, and regulations are needed early. Some have a product focus that will not be needed until late (if at all). Most are clearly project management related and will drive the execution (and so rate of progress) of the development work, but will have little impact on the actual technical content.

This view of a gradual unfolding of technology requirements—along with no or only weak linkage to a customer—points to another difference between technology and product development projects: it is very difficult to perform requirements validation (EIA-632 Requirement 26 and 27)! And with no validated acquirer or other stakeholder requirements, any system technical requirements (cf. EIA-632 Requirement 16)[45] that are developed are subject to a higher risk of change than might otherwise be desired, to say nothing of the fact that it makes no sense to validate (cf. EIA-632 Requirement 28), e.g., a derived requirement[46] against an un-validated "best guess" at what an acquirer requirement might be! While this picture of requirements engineering activities looks easier from the perspective that the bulk of the work does not have to be completed as early as it should be for product development, from a risk

[45] Note also that End Product Verification plans (cf. EIA-632 Requirement 31) are developed as part of the Define System Technical Requirements activity.
[46] This is in reference to system technical requirements, and not to derived requirements that may be identified as part of the solution definition process.

perspective, phased requirements development places a significant burden on risk management activities.

One straw-man approach (cf. Table 2 and Appendix A) is as follows. Conduct preliminary requirements development in Cycle 1 with validation—insofar as possible—of the basic technology need statement (cf. capabilities-based assessment review). Conduct interim technical reviews of any requirements developed prior to, or early in, Cycle 2 (cf. initial technical review); explicitly identify unknown or "soft" requirements in the project risk ledger by this point. Requirements development continues in parallel with Cycles 2, 3 and 4; opportunities to reduce the project risks being carried should be sought out, such as by conducting additional interim validation activities of key requirements as they are developed. Formal requirements validation takes place prior to, or early in, Cycle 5; results feed into a system requirements review and initial baseline review.

5.3.2 Decomposing the hypothesis element of the scientific method.[47]

The systems engineering approach in problem solving is an explicit avoidance of the typical: jumping to a point solution. On the basis of the established technical requirements, and with the support of tradeoff analyses, one or more logical (e.g., functional) representations and associated derived requirements are developed. The logical solution(s) and derived requirements are validated vis-à-vis the established system technical requirements. Alternative physical solutions are then generated, along with associated derived requirements, that satisfy the logical representation(s) and established requirements. On the basis of effectiveness, tradeoff, and risk analyses, a preferred physical solution is selected. The preferred solution is then fully characterized (e.g., (1) specifications for the system, end products, subsystems, and applicable interfaces; (2) interface control drawings or descriptions, detailed drawings, or sketches; and (3) parts lists, data dictionaries, or other planned physical configuration records). The decomposition of the hypothesis element of the scientific method can thus be described by the following set of activities (or PDSA cycles):

- Logical Solution Representations (EIA-632 Requirement 17)

[47] Covered by three primary elements in EIA-632, Requirements 17, 18, and 19, and six supporting elements, Requirements 22 through 25, 29 and 30.

- Physical Solution Representations (EIA-632 Requirement 18)
- Specified Requirements (EIA-632 Requirement 19)
- Perform effectiveness analyses (EIA-632 Requirement 22)
- Perform tradeoff analyses (EIA-632 Requirement 23)
- Perform risk analyses (EIA-632 Requirement 24)
- Validate requirement statements (EIA-632 Requirement 25)
- Logical Solution Representations Validation (EIA-632 Requirement 29)
- Design Solution Verification (EIA-632 Requirement 30)[48]

As for requirements development, this view of product-development-oriented activities requires adaptation when it comes to technology development. Following the straw-man development cycles of Appendix A, it should be noted that functional, proof-of-principle validation is expected to take place during Cycles 2 and 3, and validation of performance models during Cycles 3, 4 and 5. And if, as recommended above, formal requirements validation, review and base-lining takes place prior to, or early in, Cycle 5, it does not make sense to try to perform the Logical Solution Representations Validation prior to that. Yet fully characterized, preferred solutions are required in order to build the hardware of cycles 4, 5 and 6! On the other end of the technology development phase, some level of functional and physical understanding of the technology is needed in Cycle 1 in order to identify the underlying basic scientific or physical principles and supporting technologies. This suggests the following development sequencing:

- Logical Solution Representations—initial draft available in Cycle 1; validated against functional requirements in Cycle 2; validated against performance requirements in Cycle 4; formal and complete validation conducted just prior to, or early in, Cycle 5. It is suggested that system functional reviews, if only in part, take place at each of these points.

[48] Note that verification activities such as analysis or inspection of drawings take place within the design process itself, while those involving demonstration or test typically take place following product realization, as discussed further below.

- Physical Solution Representations—initial draft that identifies the underlying basic scientific or physical principles and supporting technologies available and subject to technical review in Cycle 1; preliminary identification of interfaces and critical parameters developed in Cycle 2; *functional* interface performance documented in Cycle 3 (note that functional interfaces may or may not align with physical interfaces, depending on architectural design); alternative system concepts evaluated and a *preferred physical solution* is identified by the end of Cycle 3 (an alternate system review is suggested at this point); key functional *components* are identified just prior to, or early in, Cycle 4; final update completed after the logical solution validation is completed just prior to, or early in, Cycle 5. Design Solution Verification plans (cf. EIA-632 Requirement 30) are also developed under this activity.
- Specified Requirements—early in Cycle 3, on the basis of the state of the logical and physical solution representations available at the end of Cycle 2, develop a design for a benchtop iconic (hardware) model of the system (technology); early in Cycle 4, on the basis of the state of the logical and physical solution representations available at the end of Cycle 3, design a breadboard system; early in Cycle 5, on the basis of the final (baselined) requirements and logical & physical solution representations, design a brassboard system; early in Cycle 6, update the brassboard design, as required, to support production of an advanced technology demonstrator. It is suggested that an appropriate adaptation of system requirements, initial baseline, preliminary design, critical design, and design readiness reviews take place as part of these hardware specification (design) activities (cf. EIA-632 Requirements 11 and 30).

5.3.3 Decomposing the predictions element of the scientific method.[49]

Systems engineering verification and validation (V&V) **planning** activities—particularly those associated with (functional) demonstrations and (performance) tests—serve the role of prediction in a science-based development sense. From an EIA-632 standpoint, V&V activities are of three basic types (EIA-632 definitions are included here for clarification purposes):

[49] Covered by EIA-632 Requirements 30, 31 and 33.

- Design Solution Verification (EIA-632 Requirement 30)—"The developer shall verify that each end product defined by the system design solution conforms to the requirements of the selected physical solution representation[50]."
- End Product Verification (EIA-632 Requirement 31)—"The developer shall verify that an end product to be delivered to an acquirer conforms to its specified requirements."[51]
- End Products Validation (EIA-632 Requirement 33)—"The developer shall ensure that an end product, or an aggregation of end products, conforms to its validated acquirer requirements."[52]

Strictly speaking, as each requirement is identified or derived, an appropriate method[53] for verification (or validation at the acquirer requirements level) should be identified; for the straw-man technology development activities, this means that an initial draft of a V&V plan should be issued in Cycle 1—concurrently with any requirements developed—and actively updated in every succeeding cycle. In a predictive sense, what is of interest here are V&V requirements related to (functional) demonstrations and (performance) tests; generalizing, "test" will be used herein for both functional demonstrations and performance tests (even though this is not strictly true as "test" requires one or more performance measurements to be made).

From a technology development perspective, the focus of V&V activities can be shifted somewhat by recognizing first that other stakeholder requirements rarely, if ever, impact acquirer requirements; they simply add to the "pile," placing constraints on what constitutes an acceptable solution. Second, this is doubly unlikely given that a technology, and not a product, is under development (i.e., defining acquirer requirements is a big challenge, while identifying, e.g., other stakeholder *product* constraints—particularly those from late in a product life cycle—may not be achievable, and, in fact, they may be of little importance—low risk—to the *technology* being developed). Therefore, it is reasonable for purposes herein to narrow the activities down from the three requirements of EIA-632 to two by associating validation with black-box testing and verification with white-box testing.

[50] Cf. EIA-632 Requirement 18.
[51] Cf. EIA-632 Requirement 16.
[52] Cf. EIA-632 Requirement 14.
[53] E.g., inspection, analysis, demonstration, test, or similarity.

It is important to note that, since the interest here is with science-based technology development—model-based development—V&V test plans must be tied to a predicted behavior that is linked with particular models at both a black- and white-box level. That is, in contrast, while typical product V&V only involves sufficient testing to show that a functional or performance requirement is at least minimally met by a particular design, technology V&V is interested in demonstrating that behavior is understood (and can be predictively modeled) over a sufficient range of conditions such that it is more likely to be useful for and successfully integrated into a variety of products. In principle this will involve stressing critical system characteristics beyond the anticipated operational limits in order to identify incipient weak spots. It also means that predicted behavior must be provided for all key elements (and be instrumented during testing). The level of understanding developed in this manner will also make it possible to understand technology design margins in any particular application.

5.3.4 Decomposing the experiments element of the scientific method.[54]

The first principal activity under *experiments* is Implementation (EIA-632 Requirement 20): the design solution developed under the hypothesis element is acquired, built, or coded according to specified requirements as appropriate. It should be noted that, dependent upon the life cycle phase of development, *experiments* may make use of anything appropriate, ranging from virtual-reality simulations to system hardware-in-the-loop simulations or operational use testing (including benchtop, breadboard and brassboard builds; by comparison, product development activities may also make use of prototypes or actual products). Subsystem products are validated against requirements (EIA-632 Requirement 33) and integrated into the technology test article.

The second principal activity under the *experiments* element is to conduct V&V testing (cf. EIA-632 Requirements 30, 31, and 33). V&V test procedures are defined following after the requirements set forth in the V&V plan (see *predictions* discussion above); procedures should include information such as purpose and objective, pre- and post-test actions, success (and failure) criteria, and the test environment. V&V tests are conducted using the defined procedures within the established verification environment. V&V test outcomes are complied, analyzed, and compared to the exit criteria; variations and anomalies are identified and corrected; results are documented.

[54] Covered by EIA-632 Requirements 20, 30, 31,and 33.

5.3.5 Further thoughts.

It is perhaps instructive to compare the systems engineering activities explicitly referenced above to the normative reference—EIA-632—with the entire framework provided by said standard. In so doing it would be noted that the following topical areas have not been addressed (Requirements 1-10, 12-13, 21): Supply Process Requirements; Acquisition Process Requirements; Planning Process Requirements; Assessment Process Requirements (except for Technical Reviews); Control Process Requirements; and Transition to Use Process Requirements. All but one of these relates directly to project management, and so it should be understandable why they have not been referenced herein. Requirement 21—Transition to Use—refers explicitly, e.g., to the delivery, installation, and commissioning of a *product*, and so does not apply, although perhaps it is useful for program or project plans to explicitly note what technology transition entails.[55] There is one additional requirement not explicitly addressed: System Verification Process Requirement 32—Enabling Product Readiness; as noted for Requirement 21, technology maturation does not produce product designs, be it of a primary deliverable or of supporting products.[56] Thus, in conclusion, it would seem that the decomposition of the scientific method into a larger set of systems engineering activities, each of which are defined by a PDSA (or scientific method) cycle, is complete as set forth above—in a summary fashion—for the purpose of guiding *technology development* planning.

[55] As noted earlier, the information exchange from a technology development program to a product development program is generally in the form of a technology application manual and a supporting technical (or integrated) data package.

[56] If the new technology being developed requires the support of other new technologies, then they must be developed in their own right; cf. Appendix A, Cycle 1 note.

6. ASSESSING TECHNOLOGY DEVELOPMENT

6.1 Measuring Technology Maturity—An Introduction

The thrust of this paper has been to present a discussion of what technology development is and how to approach the technical side of technology maturation planning. This has included reference to formal planning activities (e.g., a Technology Development Strategy and supporting Technology Maturation Plans as outlined in Appendices B and C). But, more to the point, it has outlined the unfolding development of a new technology through the application of the scientific method as informed and detailed by the systems engineering discipline. A natural outcome of following such an approach will be a series of artifacts produced under the four basic elements of the scientific method that will clearly demonstrate the maturity of the technology being developed. However, there may be times when a "formal" assessment of technology maturity is appropriate (or even dictated)—generally referred to as a Technology Readiness Assessment (TRA)—such as when a prospective technology acquirer (product developer) is seriously inquiring about the state of maturation (more on this in §6.2 below).

From the previous discussions in this paper it should be recognized that the notion of technology maturity, or technology development progress, is a multi-dimensional problem, and it must be treated as such (particularly when knowledge and understanding are sought, and as generally opposed to the approach taken by "alchemists"). Technology development plans for a particular project should, a priori, explicitly identify the metrics and measures of interest, and valuation of these measures should be formally agreed to as part of a review process that is commonly called a Technology Readiness Assessment (TRA).

By way of illustration, consider the following example, where the technology development domain is characterized by four dimensions and associated metrics:

- Experience: theory → laboratory → field
- Environment: laboratory → relevant → operational
- Size: subscale → full scale
- Rendition: computer model → breadboard → brassboard → prototype → production

This dimensional set is not, however, unique, nor is it asserted that it is complete. To make the point, consider another example—which is used elsewhere in this paper (e.g., the extended TRL definitions of Appendix E)—that uses three dimensions: models, product, and process; however, note that, based on the metrics given, that these dimensions are not independent of the previous ones of experience, environment, and rendition (only sub- vs. full-scale is not addressed):

- Models: underlying physics → simple, integrated, first-order effects → detailed, integrated, first- and second-order effects → detailed, integrated, first- and second-order effects, validated to laboratory conditions → detailed, integrated, first- and second-order effects, validated to operational conditions → detailed, integrated, first- and second-order effects, validated to operational conditions, and benchmarked with hardware integrated at the subsystem level → detailed, integrated, first- and second-order effects, validated to operational conditions, and benchmarked with prototype hardware integrated to the system level
- Product: samples of supporting materials or technologies → singly-interfaced or interacting, paired samples of supporting materials or technologies → singly- and multiply-interfaced or interacting samples of supporting materials or technologies → breadboard representation of the key functional elements of the technology → brassboard representation of the technology integrated with realistic supporting elements → advanced brassboard representation of the technology integrated into the next-higher subsystem → prototype representation of the technology integrated to the system level
- Process: laboratory-scale → first producibility and cost estimates available → specific application producibility and cost estimates available → manufactured

While it may be possible to identify a definitive set of dimensions that describe the technology development domain independent of technology, the takeaway here is that a particular technology development activity should identify (e.g., in planning documents) those dimensions and metrics—and perhaps even measures—that are most appropriate.

A TRA can then be invoked to provide formal, independent, quantitative or qualitative measures for the defined metrics of interest. In turn, these measures indicate “growth” within the particular technology development domain. In practice, however, such an assessment is generally summarized for management and stakeholder consumption by casting the results into a one dimensional, ordinal number—a *technology readiness level* or TRL[57]—through the use of some scoring criteria. (Note that information is lost in such a transformation; i.e., it is not possible to reconstruct the original multi-dimensional measures from a TRL score. The only exception is when the technology-development domain has been characterized by a single dimension, such as what an "alchemist" might use.)

A warning concerning the use of TRL scores is warranted here because of abuses that are often observed (e.g., adding ordinal numbers or applying TRLs to products)—often, perhaps, because they are poorly understood. As explained above, a TRL score is a measure of technology maturity and, by analogy, is equivalent to using a person's age as a measure of maturity: it is a rough guide but, as anyone who has raised multiple children can attest, people mature at different rates and even to different levels (as some people never seem to grow up!). Under the law, age is used as a measure of maturity in the sense (or dimension) of a person's ability to make rational, responsible choices, and thus by reaching a certain age, people are allowed to, e.g., drive, vote and drink alcohol (although everyone should recognize that not all people who reach such an age actually demonstrate appropriate maturity when performing such activities). Likewise under the law (at least for major DoD acquisition programs; cf. Appendix D), a technology must have matured to a TRL of six before it can be used in a product. In both cases—elapsed time since birth for people and TRL for technologies—"age" is used in some sense as an indicator of risk; it is **not**, however, an actual measure of risk. Continuing the analogy, consider insurance for drivers: age is one, but only weak, factor (2nd order or higher, especially for younger drivers), while other "dimensions"—gender, training, experience, the car being driven, and other metrics—dominate risk calculation from the perspective of an insurance provider, as reflected in the cost of the insurance that must be borne by the driver; and note that such a risk calculation is based on a large, statistically significant, pool of drivers, and does not represent the actual risk of a particular driver. Likewise, in order to understand technology risks, details of the various development domain metrics must be evaluated. Without intending to belabor the point, one more analogous comparison will be made here. As a child matures, who would consider their age to be a measure of their potential to be successful as a doctor, lawyer, fighter pilot, president, or the like? In a similar way, TRLs do not indicate that the technology is right for a particular job,

[57] Although initially conceived of at NASA, further clarification of the TRL concept and its application was undertaken by DoD. See Appendices D and E.

or that application of the technology will result in successful development of a particular system; and the assessment of risks associated with technology *application* requires both an understanding of the development domain of said technology as well as the application domain of the intended product. *And note that TRLs were never intended to be used as a metric for measuring* ***product*** *development maturity*. Cf. Appendix D.

That being said, probably the best situation arises when project-specific TRL ratings (dimensional metrics-to-TRL mapping criteria) are defined that correspond to the planned development cycles (e.g., the normative cycles of Appendix A); that is, successful completion of one development cycle would correspond to an increase of one in the TRL score (e.g., completion of Cycle 1 would merit a TRL-1 rating). In this regard, a suggested, extended set of TRL definitions that is consistent with the three-dimensional technology development domain introduced above (models-product-process) can be found herein as Appendix E.

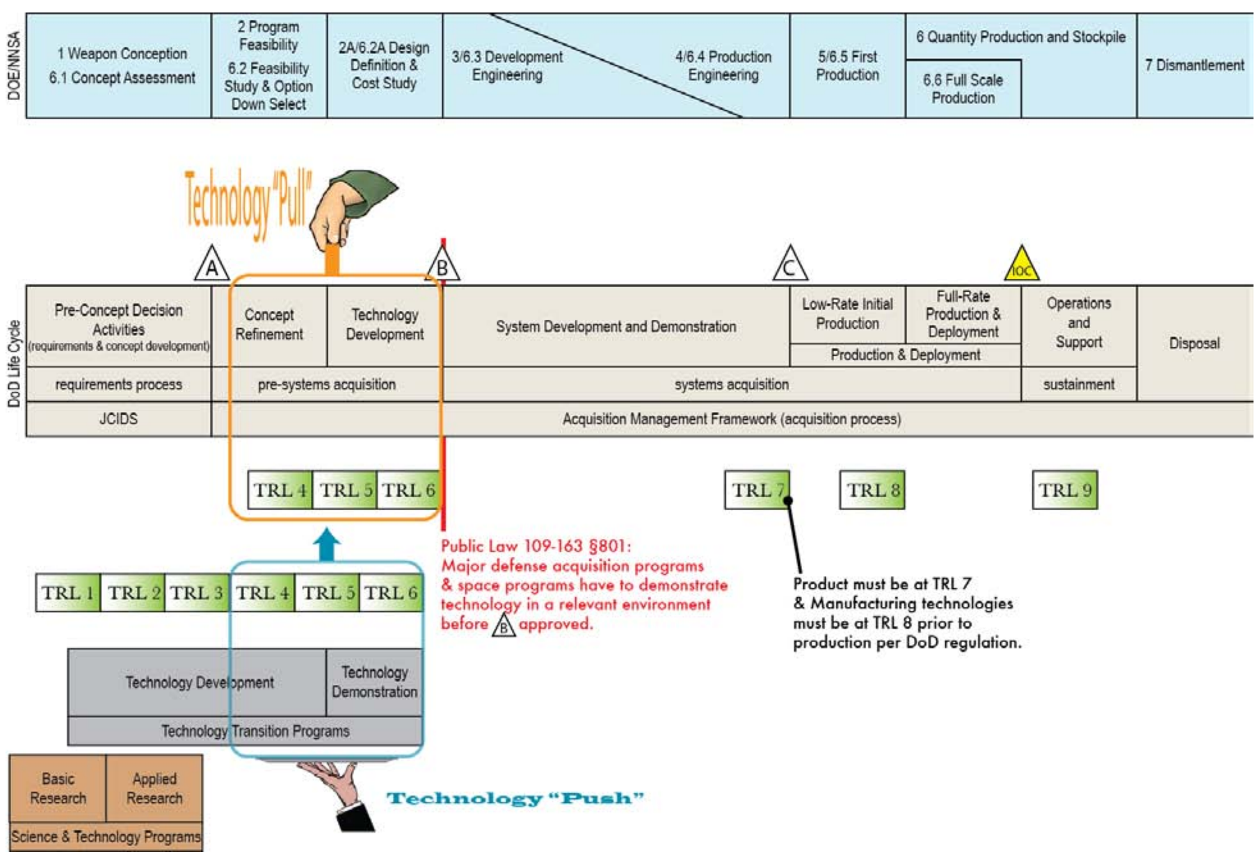

Figure 19. A rough mapping of TRL progression against various development life cycles.

6.2 Measuring Technology Maturity—Planning An Assessment

The preceding section suggested that a TRA be used as the means to measure technology maturity. The actual TRA-related processes to follow for a particular project can be tailored, depending more or less upon three factors: the reasons it is being conducted, the technology development path being followed, and who is going to use the results for what purpose. These factors are further discussed below.

6.2.1 TRA Planning Factors

6.2.1.1 Reasons to conduct a TRA

1. Your customer has requested a development status, but you haven't got a clue.

2. You have no technology development plans and little in the way of management controls, but you would like to know the development status of the technology in support of budget requests, budget allocations, …

3. It is a scheduled, programmatic verification activity ("program design review") intended to provide confirmation that development efforts have been completed as planned. (Analogy: what a system verification review or functional configuration audit is to a system design activity.)

6.2.1.2 Technology development paths

1. "Push" from an R&D activity: e.g., someone came up with a way to do it "cheaper, faster, better"—or even with something novel; they are now looking to find a user for the technology.

2. "Pull" from the product level: an advanced performance level is required from a particular technology in order for the product to meet its requirements. Such development requests typically come out of system concept studies, and generally include both minimum performance requirements and targets (goals).

3. "Query" from the product level: it is believed that product system performance can be met with existing technology ("state-of-the-art" or less); i.e., only developed or mature technologies need apply.

6.2.1.3 Users of TRA results

1. Management (and funding agency). Use TRA results as a program or project progress metric (e.g., earned value).

2. Technology developers. Use TRA results to advertise and sell their product.

3. Product designers. Use TRA results as one criterion (among others) to judge feasible alternatives. Can also be viewed as a type of risk metric.

6.2.2 Brief TRA Process Approach (Needs) Analysis

While recognizing that most people probably operate in various shades of grey, the following is presented in a "black and white" sense (with a third possibility thrown in) in order to contrast the possible TRA process approaches as a function of the three potential customers for the results.

6.2.2.1 Management need

Low road. TRA needed for reason № 1 or 2 (see §6.1.1). Only invest sufficient resources to produce an acceptable "rock". Minimal (or no) guidance is needed.

High road. TRA needed for reason № 3. A formal TRA process is needed, but it cannot standalone; it needs to be "married" to an appropriate level of technology development planning and related management activities.

Climbing the hill (lo-to-hi): For a program or project that is trying to transition from a little or no oversight management mode into one that represents best practices, application of a "high-road" type process—although painful—would be a way to generate much of the information needed in *properly* restructuring said program or project.

6.2.2.2 Technology developer need

Low road. Operate like a "used car" salesman. Guidance is only needed to provide a sufficient and consistent TRL "veneer" to the product (i.e., similar in rigor and level of effort as a management "low road" mode of operation).

High road. Operate as if an oath had been taken before a judge. Process requirements are very similar (if not the same) as for managers operating on the "high road."

No road. Operate without making any readiness assessment—i.e., clueless but very excited over their "creation;" buyer beware!

6.2.2.3 Product Designer

Low road. Believe the seller. Pay for it in cost and schedule overruns. Make sure to use a factor of 2 or 10 on the budget estimate, and agree to anything schedule wise (otherwise known to be meaningless)!

High road. Regardless of whether it was a "push" or "pull" technology need, only rely on well-documented management-high-road-type assessments (i.e., place little or no value on what are believed to be reason № 1 or 2 motivated responses). Do it right the first time!

Mid road. There is no middle road. Just a slippery slope down to failure to meet cost, schedule, or performance requirements!

6.2.3 TRA Process—Further Observations

1. There is little need to develop TRA processes for reason № 1 or 2 motivated responses.

2. Conceptually it should be expected that within properly crafted "high-road" processes further graded applications exist. However, it is not clear that appropriate grading can be developed without at least first outlining a complete TRA schema.

3. It should be understood that TRA process development and implementation requires investment in defining what a technology development program or project should look like in a management and engineering sense.

6.2.4 Formal TRA Requirements

6.2.4.1 Technology Perspective

If it is determined that a formal TRA is in order, the technology development team assembles an evaluation data package that should include: (1) relevant technology development strategy and maturation plans, including—possibly technology domain specific—dimensions, metrics, and measures that were determined *a priori* to project start as providing the means by which maturity (i.e., successful development cycle completion) would be evaluated; (2) the technical data package that represents all technology development artifacts that correspond to the four basic elements of the scientific method as described elsewhere in this report. A best practice review process[58,59,60] is then followed to perform a *technical* evaluation of the evidence provided.

6.2.4.2 Product Designer Perspective

Although this paper has been focused on presenting technology development as a process to which the scientific method and the systems engineering process can be applied, it has been recognized that a product designer as a customer for a technology has their own maturity evaluation viewpoint that will be considered in brief here for the sake of completeness. First, however, it must again be pointed out, as earlier, that: (1) technology maturity is **not** application or product design maturity; (2) a TRL is an ordinal number that is derived by transforming the measures that describe a multi-dimensional space through some scoring criteria in order to indicate some qualitative measure of readiness (not usefulness) of a technology to be used; and (3), TRLs of independent technologies are independent (implied by domain considerations).

The mathematical implication is that TRLs cannot be added, averaged, or even directly compared (in an absolute, cardinal number sense). Following Appendix D, a product designer should, instead, focus consideration of TRLs to those elements deemed to be *critical*. Toward this end, Appendix F is provided to assist in the identification of Critical Technology Elements (CTEs). Appendix G then provides a succinct outline of a procedure for reviewing and approving the list of CTEs so generated, followed by a TRA of the same (i.e., **not** of all piece parts). It

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[58] *Transition from Development to Production.* Department of Defense (DoD 4245.7-M), September, 1985
[59] *Best Practices: How to Avoid Surprises in the Worlds Most Complicated Technical Process.* Department of the Navy **(**NAVSO P-6071). March 1986.
[60] *Design Reviews Reference Guide: Transition from Development to Production.* AT&T Bell Laboratories, Holmdel, NJ, July, 1989.

should be emphasized here that a product should not contain more than a few CTEs; to make the point, consider, for example, that an entire Marine Corps helicopter currently in the system development phase—the CH-53K Heavy Lift Replacement (HLR)—had only ten CTEs identified in the initial readiness assessment conducted for the program, with the count being reduced to three CTEs in a subsequent assessment:[61] the main rotor blade, the main gearbox, and the main rotor viscoelastic lag damper (noting that the seven technology elements eliminated from treatment as a CTE may still present engineering challenges, but the management attention given to technologies deemed *critical* was not considered to be warranted).

In an attempt to relate and tie together the relationship that exists between technology and product development, including the concepts of development cycles, TRLs and risk, consider Figure 20. Here the technology development spirals and associated maturity levels are as defined in Appendices A and E. As illustrated, it can be seen that if a product designer representing a product line chooses to insert a low TRL technology for a critical function, they *may* be assuming considerable risk (i.e., TRL provides an indicator of risk, but is **not** a measure thereof).

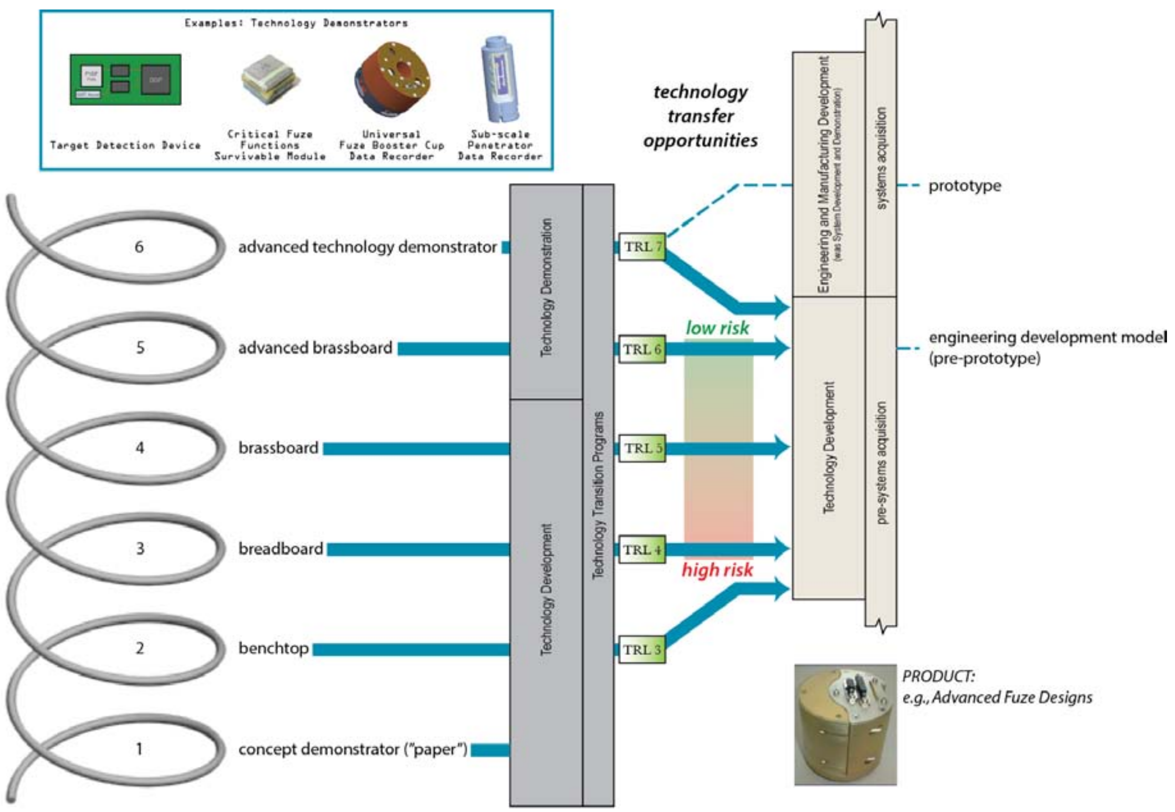

Figure 20. Relationship details between technology & product development lifecycles.

[61] http://www.gpo.gov/fdsys/pkg/GAOREPORTS-GAO-07-406SP/html/GAOREPORTS-GAO-07-406SP.htm

APPENDIX A. OUTLINE OF A NORMATIVE, MULTI-CYCLE, SCIENCE-BASED TECHNOLOGY DEVELOPMENT PROGRAM

A.1 Technology Development Phase

A.1.1 Cycle 1

Objective

- Describe the new technology in terms of validated models for the underlying basic scientific or physical principles and supporting technologies.

Characterization

- Develop a statement of need.

Hypothesis

- Develop an initial description (symbolic, word model) of the technology—that may take the form of an analogy with another technology—and identify the underlying basic scientific or physical principles and supporting technologies.

Predictions

- Develop a preliminary, contextual assessment of the underlying basic scientific or physical principles and supporting technologies that characterizes the expected functional and performance requirements they will have to meet.

Experiments

- Develop the references (e.g., appropriate, validated, peer-reviewed, published, mathematical models) that provide objective evidence that the supporting science and technologies are understood within the context of the new technology by validated models.

  NOTE: If the underlying basic scientific or physical principles and supporting technologies are not adequately understood in the context of the new technology, basic research and development must be undertaken prior to further development of the new technology[62]—unless program management determines they want to accept the risks involved and pursue concurrent development.

[62] These would be referred to as Critical Technology Elements (CTEs) in DoD parlance, and would merit their own development strategies and plans.

A.1.2 Cycle 2

Objective

- Develop a symbolic (mathematical) model that demonstrates functional proof-of-principle by describing how the underlying basic scientific or physical principles and supporting technologies interact to produce the output or effect claimed for the new technology.

Characterization

- Identify potential technology application(s).

Hypothesis

- Develop analogue models, including functional and physical architectures.
- Develop initial symbolic model(s) that are suitable for analytically demonstrating the output or effect (functionality) claimed for the new technology (plausibility or proof of principle) on the basis of interactions of supporting science and technologies.

Predictions

- On the basis of the Cycle-1 hypotheses, describe the expected functional behavior of the system and its key constituent elements (underlying basic scientific or physical principles and supporting technologies).

Experiments

- Conduct “paper” experiments that evaluate the functionality demonstrated by the symbolic model(s) vis-à-vis the expected functional behavior of the technology.

A.1.3 Cycle 3

Objective

- Develop and validate the technology symbolic *model(s)* by proof-of-principle (functional) demonstrations at the system level and by measuring performance at the key constituent element level using an iconic (hardware) model assembled from discrete laboratory research and test equipment.

Characterization

- On the basis of the Cycle-2 hypotheses, develop model-based technology requirements.

Hypothesis

- On the basis of the Cycle-2 symbolic model(s), develop design tool(s) suitable for generating the specification of a *benchtop* iconic (hardware) model.
- Design and assemble an *benchtop* iconic (hardware) model that provides a physical simulacrum of the initial symbolic model(s) of the technology suitable for both physically demonstrating the output or effect (black-box functionality) claimed for the new technology (plausibility or proof of principle demonstration), as well as for measuring the interactions of the key constituent elements (internal, white-box functional performance of the supporting science and technologies). Note that, in general, this benchtop test bed will be built up of discrete laboratory research and test equipment.

Predictions

- On the basis of the Cycle-2 hypotheses (symbolic model(s)), describe the expected system functional behavior and the performance of its key constituent elements.

Experiments

- Develop and execute test plan(s) and evaluate the results to validate that the model(s) correctly predict the observed system functional behavior and measured interactions of the key constituent elements.

A.1.4 Cycle 4

Objective

- Develop and validate the technology symbolic *model(s)* by measuring performance at the system and key-constituent-element levels using an iconic (hardware) model that integrates representative key components.

Characterization

- Update the model-based technology requirements set.

Hypothesis

- Update design tool(s) on the basis of the latest revision of the technology models.
- Design and assemble a *breadboard* iconic model of the technology that integrates representative key components in an assemblage suitable for physically demonstrating the black-box functional performance claimed, as well as for measuring the white-box interactions of the key constituent elements.
- Develop an initial technology cost estimate and producibility assessment (update during succeeding phases).

Predictions

- On the basis of the latest revision of the technology symbolic model(s), describe the expected functional performance of the system and its key constituent elements.

Experiments

- Develop and execute test plan(s) and evaluate the results to validate that the model(s) correctly predict the measured performance of the system and the interactions of the key constituent elements.

A.1.5 Cycle 5

Objective

- Develop and validate the technology symbolic *model(s)* by measuring performance at the system and key-constituent-element levels while operating under simulated operational environments using an iconic (hardware) model satisfying "form, fit, and function".

Characterization

- Develop an initial baseline of an applications-specific requirements set for the technology (although this may be for an advanced technology demonstrator; e.g., one of the flight demonstration vehicles of Figure 2), including interfaces and environments. Update during succeeding phases.

Hypothesis

- Update design tool(s) on the basis of the latest revision of the technology models.

  NOTE: If the underlying basic scientific or physical principles and supporting technologies were not, at Cycle 1, adequately understood in the context of the new technology (i.e., environmental effects)—but a concurrent development path was pursued—such work must be completed by this point and integrated into the system models if it is to be of any use in the technology development effort. This also begs the question of how to re-validate the models given such changes.

- Design and assemble a *brassboard* iconic model (EDM) of the technology that satisfies form, fit, and function while supporting both black-box and white-box testing. Integrate with realistic (in an interface sense) supporting elements.

Predictions

- On the basis of the latest revision of the technology symbolic model(s), describe the expected functional performance of the system and its key constituent elements under operational environmental conditions.

Experiments

- Develop and execute test plan(s) and evaluate the results to demonstrate the functionality and performance claimed for the new technology under operational environments.

  NOTE: Cycle-5 testing is generally conducted in a laboratory setting using appropriate equipment (e.g., ovens, vibration tables) intended to <u>*simulate*</u> *operational environments. To determine how extensive the test regimen must be requires a technical assessment of the state of the models used to describe the technology vis-à-vis the breadth of the operational environments for which functionality must be maintained. That is, given:*

  - ***confidence*** *in the modeling techniques employed and the robustness of understanding the underlying physics, testing is conducted to verify functional performance under selected, important operational conditions. The results serve to benchmark and further validate the models. The models themselves are then used to show functionality of the technology over the full spectrum of operational environments.*
  - ***uncertainty*** *in the models used to describe the technology, testing is conducted to verify functional performance across the full spectrum of operational employments. The results then serve to validate the models to operational conditions.*

A.2 Technology Demonstration Phase

A.2.1 Cycle 6

Objective

- Validate the *technology* in terms of its envisioned application.

  *NOTE: Further technology **model** development and validation activities are not expected to be required in the demonstration phase (i.e., model validation should be complete at the end of Cycle 5).*

Characterization

- Baseline an applications-specific requirements set for the technology (although this may be for an advanced technology demonstrator).

Hypothesis

- Update design tool(s) on the basis of the latest revision of the technology models.
- Design, assemble, and “deliver” an *advanced brassboard* iconic model (ATD) of the technology suitable for integration into and operational testing at the next higher assembly level.

Predictions

- On the basis of the latest revision of the technology symbolic model(s), describe the expected behavior of the ATD.

Experiments

- Support development and execution of a validation test plan at the next higher assembly level.

APPENDIX B. TECHNOLOGY DEVELOPMENT STRATEGY (A DoD PRODUCT LIFE CYCLE VIEW)

A Technology Development Strategy (TDS) focuses specifically on the activities of the Technology Development Phase. Where feasible, the TDS should also discuss activities associated with the post-program initiation phases of the planned acquisition.

While there is no mandatory format for the Technology Development Strategy, Public Law 107-314, Section 803, requires the following minimum content:

- A discussion of the planned acquisition approach, including a summary of the considerations and rationale supporting the chosen approach.

  DoD Instruction 5000.2 requires the following details:

  - A preliminary description of how the program will be divided into technology spirals and development increments;
  - The limitation on the number of prototype units that may be produced and deployed during technology development;
  - How prototype units will be supported; and
  - Specific performance goals and exit criteria that must be met before exceeding the number of prototypes that may be produced under the research and development program.

- A discussion of the planned strategy to manage research and development. This discussion must include and briefly describe the overall cost, schedule, and performance goals for the total research and development program. To the extent practicable, the total research and development program should include all planned technology spirals or increments.

- A complete description of the first technology demonstration. The description must contain specific cost, schedule, and performance goals, including exit criteria, for the first technology spiral demonstration.

- A test plan which must describe how the first technology spiral demonstration will be evaluated to determine whether the goals and exit criteria for the Technology Development phase have been achieved. The test plan is focused on the evaluation of the technologies being matured during the Technology Development phase. (This plan is distinct from the separately developed and approved Test and Evaluation Strategy (TES). The TES takes a broader view and is the tool used to begin developing the entire program test and evaluation strategy, including the initial test and evaluation concepts for Technology Development, System Development & Demonstration, and beyond.)

Multiple technology development demonstrations may be necessary before the user and developer agree that a proposed technology solution is affordable, militarily useful, and based on mature technology. The Technology Development Strategy should be reviewed and updated upon completion of each technology spiral and development increment, and approved updates should be available to support follow-on increments.

APPENDIX C. TECHNOLOGY MATURATION PLAN (FOR A SINGLE DEVELOPMENT CYCLE): SIMPLE STRAWMAN TEMPLATE[63]

General

Each technology below the minimum TRL required must be addressed by a Technology Maturation Plan (TMP).

Plan Contents

Front Matter

Technology Title

Program Management Office

Program Name / System Title

Introductory Material

Describe the technology.

Describe how the technology is used in a higher-level system.

Describe the intended benefits of the technology.

Maturation Status

Summarize achievements to date.
Provide an assessment of current technology maturity status.

Maturation Plan

Describe the planned activities (including schedule), including:

- Definition of what TRL will be achieved and when
- Maturation events (verification criteria)
- Key decision points (e.g., relationship to a decision point to switch to an alternate technology in an acquisition program)

Summarize specific actions to be taken (what will be done and by whom):

- Construction of breadboard, brassboard, prototype, or demonstration units
- Tests to be run
- Performance levels to be met
- Test environments to be employed (and their relationship to the operational environments)

Discuss Funding Status

[63] This template is only intended to capture technology maturation unique information that should be presented in a project plan. Consult a project management guide to identify other types of information that should also be included in the plan.

APPENDIX D. AN INTRODUCTION TO DoD TRLS[64]

For at least four decades engineering efforts for DoD have been required to have plans and controls in place to manage program risks:[65]

> *5.3.1 Program risk analysis. The contractor's program definition and redefinition effort shall include analysis of system functional requirements and possible solutions. This analysis should identify critical areas and design, development, or technical performance measurement tasks which will reduce the known risks, and effect early identification of other risks as the work progresses.*

However, it must be concluded that either through a failure to identify technology development risks (i.e., insufficient systems engineering resources), or to properly manage said risks (e.g., insufficient risk management resource allocation, or poor, schedule-driven management decisions), many major DoD acquisition programs of the late 20th Century experienced significant cost and schedule overruns.[66] Such problems were exacerbated by the fact that: (1) these programs often called for use of very immature technologies in order to meet performance expectations or requirements—i.e., system development activities were launched on the gamble that technology maturation would be successful—and (2), that DoD Science and Technology funding was generally insufficient to anticipate and develop the needed technologies to an appropriate level of maturity prior to their use. The magnitude and frequency of DoD acquisition program overruns eventually led the U.S. Congress to pass Public Law 109-163:[67]

> (a) CERTIFICATION REQUIREMENT.—Chapter 139 of title 10, United States Code, is amended by inserting after section 2366 the following new section:
>
> **"§ 2366a. Major defense acquisition programs: certification required before Milestone B or Key Decision Point B approval**
>
> "(a) CERTIFICATION.—A major defense acquisition program may not receive Milestone B approval, or Key Decision Point B approval in the case of a space program, until the milestone decision authority certifies that—
>
> "(1) the technology in the program has been demonstrated in a relevant environment;
>
> "(2) the program demonstrates a high likelihood of accomplishing its intended mission;

[64] For a simple NASA view, see Mankins, John C., "Technology Readiness Levels: A White Paper," Advanced Concepts Office, Office of Space Access and Technology, NASA, April 6, 1995.
[65] *System Engineering Management*, MIL-STD-499, 17 July 1969.
[66] GAO/NSIAD-99-162, p. 17.
[67] Title VIII, Subtitle A, Section 801, January 6, 2006

"(3) the program is affordable when considering the per unit cost and the total acquisition cost in the context of the total resources available during the period covered by the future-years defense program submitted during the fiscal year in which the certification is made;

"(4) the Department of Defense has completed an analysis of alternatives with respect to the program;

"(5) the program is affordable when considering the ability of the Department of Defense to accomplish the program's mission using alternative systems; …

In other words, Congress felt it had to step in and "help" DoD manage risk in major acquisition programs. The DoD regulatory framework that supports issuance of the now legally mandated certification in regards to technology maturation (certification requirement (1)) begins with DODD 5000.1 (note as well the implicit systems engineering requirements in both the congressional language and in this directive!):[68]

E1.1.14. Knowledge-Based Acquisition. PMs shall provide knowledge about key aspects of a system at key points in the acquisition process. PMs shall reduce technology risk, demonstrate technologies in a relevant environment, and identify technology alternatives, prior to program initiation. They shall reduce integration risk and demonstrate product design prior to the design readiness review. They shall reduce manufacturing risk and demonstrate producibility prior to full-rate production.

In turn, this directive invokes DODI 5000.2,[69] which provides further clarification and implementation requirements. In particular, in regards to technology risk:

3.7.2.2. The management and mitigation of technology risk, which allows less costly and less time-consuming systems development, is a crucial part of overall program management and is especially relevant to meeting cost and schedule goals. Objective assessment of technology maturity and risk shall be a routine aspect of DoD acquisition. Technology developed in S&T or procured from industry or other sources shall have been demonstrated in a relevant environment or, preferably, in an operational environment to be considered mature enough to use for product development in systems integration. Technology readiness assessments, and where necessary, independent assessments, shall be conducted. If technology is not mature, the DoD Component shall use alternative technology that is mature and that can meet the user's needs.

[68] DoD Directive No. 5000.1, *The Defense Acquisition System*, May 12, 2003.
[69] DoD Instruction No. 5000.2, *Operation of the Defense Acquisition System*, May 12, 2003.

As invoked by reference,[70] Interim Defense Acquisition Guidebook (IDAG)[71] §4.3.2.4.3 provides further guidance on what constitutes a technology readiness assessment (TRA):

> *Per DoD Instruction 5000.2, the TRA is a regulatory information requirement for all acquisition programs. The TRA is a systematic, metrics-based process that assesses the maturity of Critical Technology Elements. The TRA should be conducted concurrently with other Technical Reviews, specifically the Alternative Systems Review, System Requirements Review, or the Production Readiness Review. If a platform or system depends on specific technologies to meet system operational threshold requirements in development, production, and operation, and if the technology or its application is either new or novel, then that technology is considered a Critical Technology Element. The TRA should not be considered a risk assessment, but it should be viewed as a tool for assessing program risk and the adequacy of technology maturation planning. The TRA scores the current readiness level of selected system elements, using defined Technology Readiness Levels. The TRA highlights critical technologies and other potential technology risk areas that require program manager attention. The TRA essentially "draws a line in the sand" on the day of the event for making an assessment of technology readiness for critical technologies integrated at some elemental level. If the system does not meet pre-defined Technology Readiness Level scores, then a Critical Technology Element maturation plan is identified. This plan explains in detail how the Technology Readiness Level will be reached prior to the next milestone decision date or relevant decision point. Completion of the TRA should provide:*
>
> > *(1) A comprehensive review, using an established program Work Breakdown Structure as an outline, of the entire platform or system. This review, using a conceptual or established baseline design configuration, identifies program Critical Technology Elements;*
> >
> > *(2) An objective scoring of the level of technological maturity for each Critical Technology Element by subject matter experts;*
> >
> > *(3) Maturation plans for achieving an acceptable maturity roadmap for Critical Technology Elements prior to critical milestone decision dates; and*
> >
> > *(4) A final report documenting the findings of the assessment panel.*
>
> *After the final report is written, the chairman submits the report to the appropriate Service officials and the program manager. Once approved, the report and cover letter are forwarded to the service acquisition official. For Acquisition Category ID or IAM programs, the service acquisition official provides a recommendation to DDR&E for DUSD(S&T) final approval. If deemed necessary, the DDR&E can conduct an Independent Technical Assessment (ITA) in addition to, and totally separate from, the program TRA.*

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[70] DODI 5000.2, Reference (bi).

[71] The version referenced in the Instruction is dated October 30, 2002. The current guidebook in use is dated November 2004.

IDAG §10.5.2 assigns additional TRA responsibilities, provides a summary table of Technology Readiness Level (TRL) descriptions, and, for additional information, points the reader to the *TRA Handbook*. While the table is not reproduced here, it should be noted that it is at TRL-5 and -6 (on a nine-point scale) that technologies undergo "validation in relevant environment," which is the tie point back to the technology demonstration requirement of Public Law 109-163 presented above.

Also of interest is the TRA scope defined by the IDAG: Critical Technology Elements (CTE); i.e., not all technologies employed in a design are evaluated in terms of their TRL, but only those deemed critical. On the other hand, this limitation in scope is offset by the breadth of the product to be considered: "technologies…in development, production, and operation;" e.g., a new manufacturing technology identified for use to meet unit production cost requirements should be identified and managed as a CTE. That is, any and all products used in, by, or for the system at any point in its lifecycle—and not just the end product—have to be evaluated vis-à-vis the maturity of the technologies employed therein.

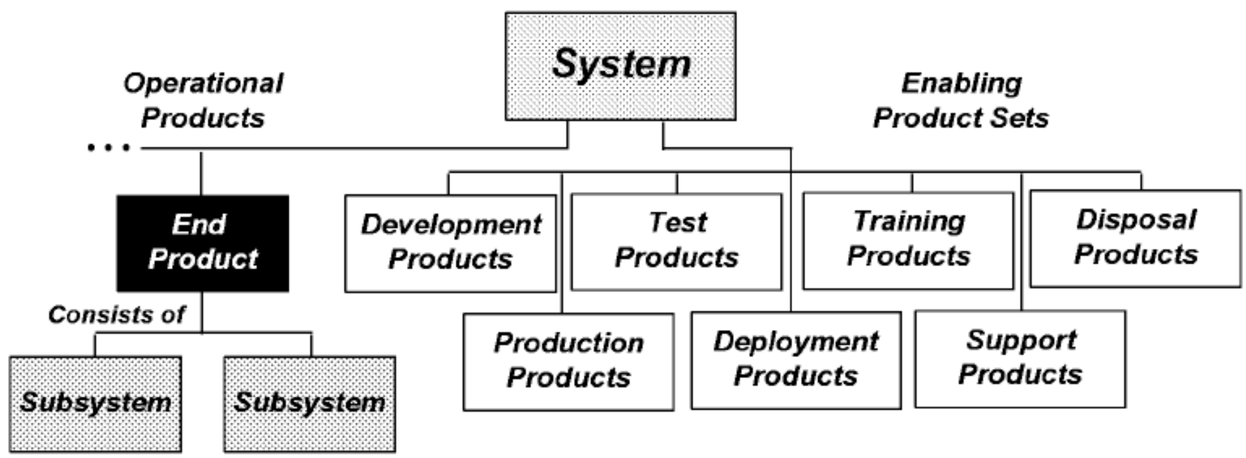

Figure 21. A system block diagram (from EIA-632) that illustrates the types of system products that should be considered when identifying CTEs.

The "working" definition of a CTE as given by the Handbook (aka Deskbook) is as follows:[72]

> *A technology element is "critical" if the system being acquired depends on this technology element to meet operational requirements (with acceptable development, cost, and schedule and with acceptable production and operation costs) and if the technology element or its application is either new or novel. Said*

[72] Deputy Under Secretary of Defense for Science and Technology (DUSD(S&T)), *Technology Readiness Assessment (TRA) Deskbook*, May 2005, §3.2.2.

another way, an element that is new or novel or is being used in a new or novel way is critical if it is necessary to achieve the successful development of a system, its acquisition, or its operational utility.

When comparing this definition to that of the IDAG, it is of some importance to note the phrase “with acceptable development, cost, and schedule and with acceptable production and operation costs.” Put another way, a technology that does the job but is not affordable is an **unacceptable** technology, and so would never be identified as a CTE because it will never “make the cut” during the analysis of alternatives that leads to concept definition. This harks back to the language in Public Law 109-163, certification requirement (3); why the cost consideration is not found in DODD 5000.1, DODI 5000.2, or the IDAG CTE definition is not clear at this point. In addition to providing this working definition of a CTE, the Handbook also provides definitions, descriptions, and supporting information for both Software and Manufacturing Technology TRLs (as well as clarifying information for the Hardware TRLs defined in the IDAG). While consideration of Figure 21 suggests additional TRL definitions will have to be developed, the existing set—Hardware, Software, and Manufacturing Technology—probably provides a sufficient framework to conduct such development with reasonable assurance that consistency can be maintained.

APPENDIX E. EXTENDED TRL DEFINITIONS[73]

E.1 Technology Readiness Level 1 (TRL-1)

TRL	DoD		
	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
	SNL		
	Basic principles observed and reported.	This is the first level of technology readiness and includes fundamental scientific research. At this level, basic scientific principles are being studied analytically and/or experimentally. Examples might include paper studies of a technology's basic pro	None provided.

TRL-1 is unusual in that it is the only level where the supporting maturity artifacts generally antecede invention of the technology being evaluated. That is, although one or both of the descriptions given above contain the statements "Scientific research begins to be translated into applied research and development" and "studies of a technology's basic properties," the *technology* concept or application itself is not even thought of—invented, if you will—until activities leading to TRL-2. Only when a technological invention has been formulated on the basis of one or more physical principles and properties—including other technologies—is it possible to assess the maturity of the same (i.e., in hindsight as they relate to said emerging technology, and so a technology concept that has not reached TRL-2 may be ranked at TRL-1, given supporting evidence). Said another way, a technology can be said to be at TRL-1 if the physics and technologies inherent in the supporting elements (building blocks) on which it is based are adequately understood in the context of their application.

Evaluating the maturity of technology vis-à-vis TRL-1 has to begin with identification of the key scientific principles (which includes technologies in the current context) that underlie the invention. The expectation should be that one or more peer-reviewed technical reports or publications exist which describe the emerging technology and the foundation on which it is based. References within said materials should point to the body of evidence (published research) that provides objective evidence that the supporting principles and technologies are understood. That is, to be considered to have matured to TRL-1, this research must be more than mere observation: the underlying physical principles (1) have to have been identified, and (2), have to be characterized by appropriate, validated mathematical models. The latter requirement means that the supporting evidence may include experimentation (e.g., in materials development, this could involve laboratory synthesis and testing of materials to establish chemical and physical properties).

Dimensional Analysis:

Models: Underlying physics

Product: Samples of supporting materials or technologies

Process: Laboratory-scale

[73] Note that these definitions are consistent with the technology development cycle description of Appendix A.

E.2 Technology Readiness Level 2 (TRL-2)

TRL	DoD		
	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
	SNL		
	Concept and/or application formulated	Practical applications are beginning to be invented or identified. Applications are still speculative and there is no proof or detailed analysis to support assumptions. Examples might include applied research in a field of potential interest.	None provided.

TRL-2 follows the initial invention of a new technology. To reach a maturity level of TRL-2, sufficient concept development and analysis must take place to demonstrate proof of principle—plausibility—of the invention (i.e., demonstrate plausibility to a sufficient degree to support requests for concept development funds[74]). Evaluating the maturity of technology vis-à-vis TRL-2 is on the basis of published report(s) that describe not only the constituent elements of said technology (which only supports TRL-1), but on how they interact to produce the output or effect claimed by the invention. That is, analysis efforts have to progress from TRL-1-level models of individual, underlying physical principles (including technologies) to integrated models of the invention—albeit of a preliminary or coarse nature (e.g., first-order effects). Conceptually such activities could include experiments as necessary to develop a preliminary understanding of key interactions of underlying elements in support of initial model development.

Dimensional Analysis:

Models: Simple, integrated, first-order effects

Product: Singly-interfaced or interacting, paired samples of supporting materials or technologies

Process: Laboratory-scale

[74] Details concerning what actually constitutes sufficiency in this context are, in general, determined by the organization controlling the science and technology program funds being used.

E.3 Technology Readiness Level 3 (TRL-3)

TRL	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
	DoD		
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
	SNL		
3	Concepts demonstrated analytically or experimentally	Active research and development is initiated. This includes analytical and laboratory-based studies to physically validate analytical predictions of key elements of the technology. These studies and experiments should constitute “proof-of-concept” validation of the applications concepts formulated at TRL 2. Examples include the study of separate elements of the technology that are not yet integrated or representative.	None provided.

Activities leading to a maturity level of TRL-3 follow analytical demonstrations of the plausibility of an invention (i.e., a technology looks sufficiently promising that significant funds are made available to further develop the concept following attainment of TRL-2). Evaluating the maturity of technology vis-à-vis TRL-3 is on the basis of published report(s) that in detail describe the interactions of the constituent elements and confirm the **functionality** claimed by the invention. That is, analysis efforts have to show progress from the basic TRL-2-level integrated model(s) to a detailed level that, e.g., captures first and second order effects; the level of detail to be attained is that deemed sufficient to support the design, operation, and evaluation of a laboratory-scale breadboard technology validation unit. Activities leading to TRL-3 are likely to include experiments for model development and proof-of-concept purposes.

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects

Product: Singly- and multiply-interfaced or interacting samples of supporting materials or technologies

Process: Laboratory-scale

E.4 Technology Readiness Level 4 (TRL-4)

TRL	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
	DoD		
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
	SNL		
	Key elements demonstrated in laboratory environment	The key elements must be integrated to establish that the pieces will work together. The validation should be consistent with the requirements of potential applications but is relatively low-fidelity when compared to a final product. Examples include integration of ad-hoc hardware or software in the laboratory such as breadboards, low fidelity development components, and rapid prototypes.	None provided.

Simply put, TRL-4 represents a technology maturity level where the detailed models available at TRL-3 have been validated. Model validation is on the basis of a breadboard operated in a laboratory setting, and does not require definition of a specific application.[75] The breadboard design itself is founded on the models developed in attaining TRL-3 (i.e., the models are used as design tools), while the units so produced are evaluated under test plans developed with the intent to validate said models in a laboratory setting. In cases where demonstrated functional performance does not meet expectations, further model development (including experimental support) is required. Evaluating the maturity of technology vis-à-vis TRL-4 is on the basis of published report(s) that, in detail, document the breadboard design, describe the tests, and provide the data and supporting analysis that demonstrates the predictive capabilities of the models used to describe the technology (**functions and performance**).

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects, validated to laboratory conditions

Product: Breadboard representation of the key functional elements of the technology

Process: Laboratory-scale; first producibility and cost estimates available

[75] This does not preclude such knowledge. For example, technology "pull" programs may sponsor technology breadboarding during analysis-of-alternatives activities conducted during the concept refinement phase of a system lifecyle. Technology development and demonstration ("push") programs sponsor similar efforts.

E.5 Technology Readiness Level 5 (TRL-5)

TRL	DoD		
	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "highfidelity" laboratory integra	Results from testing a 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
	SNL		
	Key elements demonstrated in relevant environments	Fidelity of the key elements increases significantly. Key elements are integrated with realistic supporting elements so that the technology can be tested and demonstrated in simulated or actual environments.	None provided.

Developing technology to reach TRL-5 from a TRL-4 requires that a **specific** application be defined. This may either be a conceptual design (technology "pull") or a design created for technology demonstration purposes (technology "push"). However, in either case it is incumbent upon the supporting systems engineering activity to define two aspects of the problem against which the technology is to be successfully evaluated in support of achieving TRL-5: (1) interfaces; and (2), operational environments. (It must be presumed that the technology was selected for further application development on the basis of the functionality and performance levels demonstrated in reaching TRL-4.) It should be recognized that these system requirements are likely to change, but they form the initial baseline interface and environmental definitions that will be used to guide further technology development.

Generally speaking, brassboard hardware is developed during technology maturation efforts to reach TRL-5 that is intended to fulfill form, fit, and functional requirements (fidelity of non-essential aspects of the design—e.g., packaging—is not required). This hardware is tested while integrated with realistic (in an interface sense) supporting elements. Testing is generally conducted in a laboratory setting using appropriate equipment (e.g., ovens, vibration tables) intended to simulate operational environments. To determine how extensive the test regimen must be requires a technical assessment of the state of the models used to describe the technology vis-à-vis the breadth of the operational environments for which functionality must be maintained. That is, given:

- <u>**confidence**</u> in the modeling techniques employed and the robustness of understanding the underlying physics, testing is conducted to verify functional performance under selected, important operational conditions. The results serve to benchmark and further validate the models. The models themselves are then used to show functionality of the technology over the full spectrum of operational environments.
- <u>**uncertainty**</u> in the models used to describe the technology, testing is conducted to verify functional performance across the full spectrum of operational employments. The results then serve to validate the models to operational conditions.

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects, validated to operational conditions

Product: Brassboard representation of the technology integrated with realistic supporting elements

Process: Laboratory-scale; specific application producibility and cost estimates available

E.6 Technology Readiness Level 6 (TRL-6)

TRL	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
	DoD		
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of 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 a simulated operational environment.	Results from laboratory testing of a prototype 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?
	SNL		
6	Representative of the deliverable demonstrated in relevant environments	Represents a major step in a technology's demonstrated readiness. Examples include testing a prototype or representative of a deliverable in a high fidelity laboratory environment or in a simulated operational environment.	None provided.

For the purposes of discussion here, the hardware produced to mature a product to TRL-6 will be referred to as an *advanced brassboard*. For a normal product development cycle, TRL-6 precedes system development engineering, and thus, by definition, the hardware used cannot be a prototype. However, for a technology demonstration system, or for late introduction of technology into a system (e.g., to correct a problem arising during system development), this advanced brassboard could be equivalent to a prototype. The design of advanced brassboard hardware will generally reflect changes based on lessons learned in reaching TRL-5 (e.g., clean up PWB layouts to remove "blue wires"), as well as to incorporate changes driven by revision to interface and operational-environment requirements.

Integration requirements to mature a product to TRL-6 also change from TRL-5. Instead of integrating with realistic supporting elements, the technology being matured must be integrated into the next higher assembly of the specific application, and whose other elements should likewise represent a similar state of design (i.e., advanced brassboard). For purposes herein, the next higher assembly will be referred to as the *subsystem* (even though it may be, in actuality, a subassembly, component, assembly, product, system, or system of systems).

Testing, as for TRL-5 is generally conducted in a laboratory setting using appropriate equipment intended to simulate operational environments, although it is allowable under the definitions to conduct the tests in a real (non-laboratory) environment provided all operational environmental requirements can be simulated. Since a TRL-5 maturity level indicates the technology models have been validated to operational conditions, generally speaking, subsystem testing of an advanced brassboard need only to verify continued functional performance under selected, important operational conditions.

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects, validated to operational conditions, and benchmarked with hardware integrated at the subsystem level

Product: Advanced brassboard representation of the technology integrated into the subsystem

Process: Laboratory-scale

E.7 Technology Readiness Level 7 (TRL-7)

TRL	DoD		
	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). Examples include testing the prototype in a test bed aircraft.	Results from testing a prototype system in an 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?
	SNL		
	Final development version of the deliverable demonstrated in operational environment	Development version of the deliverable is near or at the planned operational system. This represents a significant step beyond TRL 6 and requires the demonstration of an actual development version of the deliverable in the operational environment. Examples include integration and demonstration within the next assembly, and advanced concept technology demonstrations of integrated systems such as flight testing.	None provided.

Reaching TRL-7 requires prototype hardware, with integration to and operational testing at the system level.

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects, validated to operational conditions, and benchmarked with prototype hardware integrated to the system level

Product: Prototype representation of the technology integrated to the system level

Process: Manufactured

E.8 Technology Readiness Level 8 (TRL-8)

TRL	DoD		
	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
8	Actual system completed and 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	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered
	SNL		
	Actual deliverable qualified through test and demonstration	The technology has been proven to work in its final form under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the actual deliverable in its intended a	None provided.

Reaching TRL-8 requires early production hardware, with integration to and qualification at the system level.

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects, validated to operational conditions, and benchmarked with production hardware integrated to the system level

Product: Production representation of the technology integrated to the system level

Process: Manufactured

E.9 Technology Readiness Level 9 (TRL-9)

TRL	DEFINITION	DESCRIPTION	SUPPORTING INFORMATION
	DoD		
9	Actual system 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 (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.
	SNL		
9	Operational use of deliverable	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 deliverable under operational mission conditions. This TRL does not include ongoing or planned product improvement of reusable systems.	None provided.

Reaching TRL-9 requires production hardware integrated into a fielded (operational) system that has completed operational test and evaluation.

Dimensional Analysis:

Models: Detailed, integrated, first- and second-order effects, validated to operational conditions, and benchmarked with production hardware integrated into a fielded system

Product: Production representation of the technology integrated to a fielded system

Process: Manufactured

E.10 Graphical Portrayal of TRL vs. Model Development and Hardware Integration Level

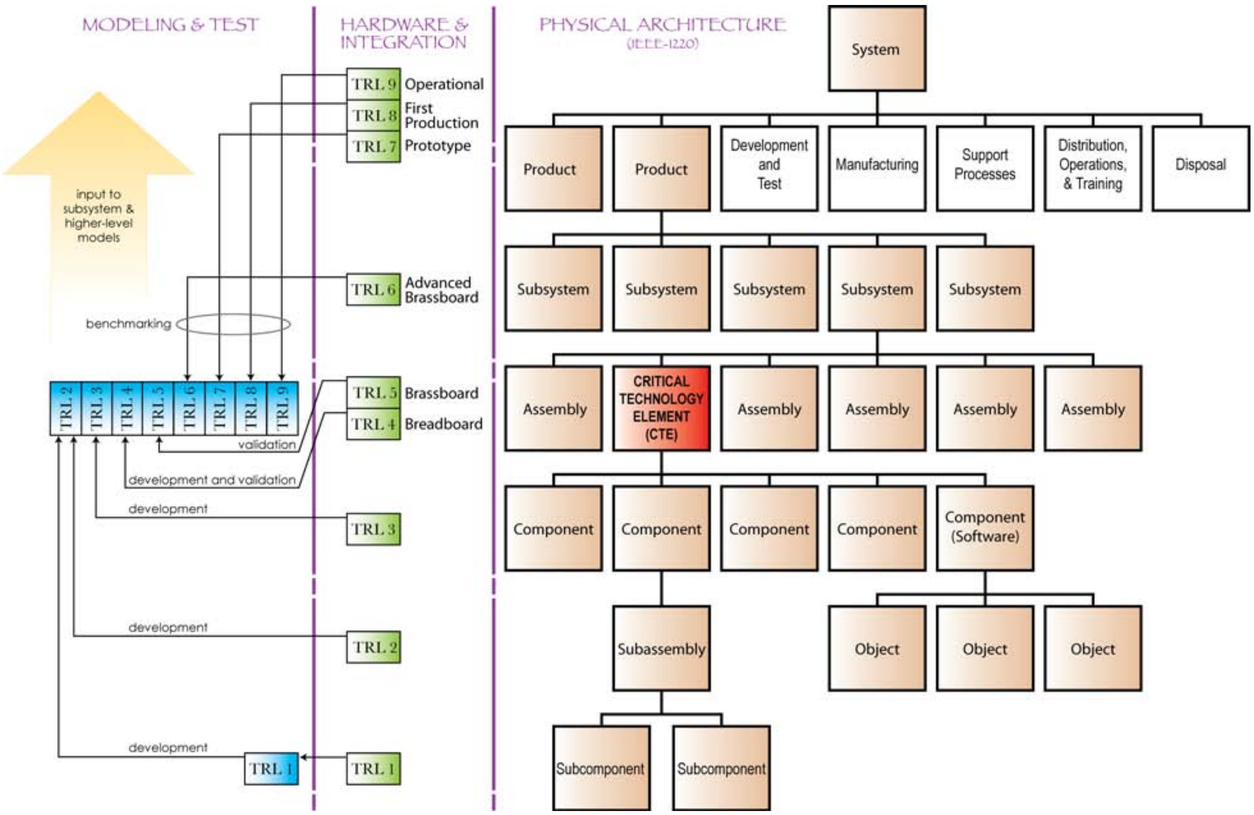

Figure 22. Hardware-centric view of TRL progression in technology development.

APPENDIX F. IDENTIFYING CRITICAL TECHNOLOGY ELEMENTS

F.1 Purpose

The ultimate objective of critical technology element (CTE) identification (and TRAs thereof)—from a technology development activity perspective—is to focus resources to bring the technologies to the requisite maturity level so that they can be "exploited" by a system design and development (SDD) activity (e.g., detailed design for a specific application). Screening out elements that are actually critical can impact SDD schedule and cost. Not screening out non-critical elements will dilute available development resources, which could result in a technology not being mature enough to be selected for use at SDD (i.e., system trade studies will reject use of said technology).

F.2 Method

F.2.1 Develop product technology element list

A product technology element (PTE) list is generated that should include **all** lower level elements that form part of a product by reviewing applicable source documents such as:

- Requirements (e.g., functional, performance, environmental) used as basis for development effort (i.e., technology development generally precedes system requirements review (SRR) [in this context, "system" is what the product is integrated into]
- Functional and physical architectures
- Interface definition
- Work Breakdown Structure (WBS)
- Drawing tree
- …

F.2.2 Develop candidate CTE list

Screen technology elements on the basis of the definition of a CTE:

A technology element is "critical" if [it meets both of the following conditions]

1. *the system being acquired* [the product] *depends on this technology element to meet operational requirements (with acceptable development, cost, and schedule and with acceptable production and operation costs)*

AND…

2. *the technology element or its application is either new or novel.*

Said another way, an element that is new or novel or is being used in a new or novel way is critical if it is necessary to achieve the successful development of a system [the product]*, its acquisition* [e.g., manufacturing technologies]*, or its operational utility.*

Example of what does not meet CTE criteria #1: chrome plating on a car rearview mirror.
Example of what does not meet CTE criteria #2: SAE bolt used to hold mirror on car.

Appendix G, Succinct CTE R&A Procedure with TRA

AT—Technology Readiness Assessment Team
CTE—Critical Technology Element
IP—Independent Critical Technology Element Review Panel
IT—Independent Technology Readiness Assessment Evaluation Team
LM—Product Line Manager
PM—Program Manager (product customer; who the development is ultimately for)
SM—Product Senior Manager
TL—Product Development Project Technical Lead
TRA—Technology Readiness Assessment
TRL—Technology Readiness Level

1. SM (or PM) mandates product TRA
2. LM, with TL, develops TRA schedule
3. SM (or PM) approves TRA schedule
4. TL conducts CTE identification process
    a. Prepares candidate CTE list
    b. Proposes final CTE list
5. TL develops CTE TRL evaluation data package (generally conducted concurrently with CTE identification process)
    a. Performs CTE TRL evaluation data collection
    b. Assembles CTE TRL evaluation data package
    c. Submits CTE TRL evaluation data package (may be online)

optional

6. LM appoints member(s) to IP
7. IP evaluates CTEs
    a. Reviews TL candidate and proposed CTE lists
        i. Reviews identification process artifacts (e.g., documentation)
        ii. Considers additional supporting information (e.g., interviews)
    b. Recommends final CTE list
8. LM reviews CTE recommendations
    a. resolves any issues concerning CTE identification
    b. approves final CTE list
9. LM submits final, approved CTE list to the SM (or PM)
10. SM (or PM) formally acknowledges acceptance of the CTE list; may involve additional evaluation
11. LM appoints member(s) to AT
12. AT conducts TRA Process
    a. Reviews CTE identification rationale
    b. Reviews data package submitted by TL
    c. Requests and reviews additional information from TL as required
    d. Prepares TRA for submission (includes TRL for each CTE and rationale)
13. LM approves TRA and forwards to SM (or PM)

optional

14. SM (or PM) appoints member(s) to IT
15. IT evaluates the TRA
16. SM (or PM) formally acknowledges acceptance of the TRA (may first involve resolution of issues arising from the TRA evaluation)

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