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The Need for Technology Maturity of Any Advanced Capability to Achieve Better Life Cycle Cost (LCC)

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Programs such as space transportation systems are developed and deployed only rarely, and they have long development schedules and large development and life cycle costs (LCC). They have not historically had their LCC predicted well and have only had an effort to control the DDT&E phase of the programs.

One of the factors driving the predictability, and thus control, of the LCC of a program is the maturity of the technologies incorporated in the program. If the technologies incorporated are less mature (as measured by their Technology Readiness Level – TRL), then the LCC not only increases but the degree of increase is difficult to predict. Consequently, new programs avoid incorporating technologies unless they are quite mature, generally TRL greater than or equal to 7 (system prototype demonstrated in a space environment) to allow better predictability of the DDT&E phase costs unless there is no alternative. On the other hand, technology development programs rarely develop technologies beyond TRL 6 (system/subsystem model or prototype demonstrated in a relevant environment). Currently the lack of development funds beyond TRL 6 and the major funding required for full scale development leave little or no funding available to prototype TRL 6 concepts so that hardware would be in the ready mode for safe, reliable and cost effective incorporation.

The net effect is that each new program either incorporates little new technology or has longer development schedules and costs, and higher LCC, than planned.

This paper presents methods to ensure that advanced technologies are incorporated into future programs while providing a greater accuracy of predicting their LCC.

One method is having a dedicated organization to develop X-series vehicles or separate prototypes carried on other vehicles. The question of whether such an organization should be independent of NASA and/or have an independent funding source is discussed. Other methods are also discussed.

How to make the choice of which technologies to pursue to the prototype level is also discussed since, to achieve better LCC, first the selection of the appropriate technologies

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must be determined and used for selection of a prioritized funding portfolio. This process must be followed to achieve the greatest efficiency in improved LCC reductions for any application being pursued.

Another factor driving the difficulty of controlling the LCC of programs is the uncertainty of the flight rate projections of the envisioned operational systems. Increasing the commonality of major subsystems in each operational program can reduce the impact of this uncertainty. By maturing subsystem technologies and by using them in multiple operational systems the LCC of the subsystems is reduced, thereby reducing the development risk and the LCC of each proposed operational system. Examples include key enabling propulsion, materials, and manufacturing technologies.

Nomenclature

ACS = Attitude Control System
AIM = Accelerated Insertion of Materials
AIM-C = Accelerated Insertion of Materials-Composites
DARPA = Defense Advanced Research Projects Agency
DDT&E = Design, Development, Test and Evaluation
FBS = Functional Breakdown Structure
IHPRPT = Integrated High Payoff Rocket Propulsion Technology
IHPTET = Integrated High Payoff Turbine Engine Technology
LCC = Life Cycle Cost
NASA = National Aeronautics and Space Administration
OMS = Orbital Maneuvering System
OPS = Operations
QFD = Quality Function Deployment
R&D = Research and Development
RCS = Reaction Control System
SPST = Space Propulsion Synergy Team
TPM = Technical Performance Metric
TQM = Total Quality Management
WBS = Work Breakdown Structure

I. Introduction

Non-military Government aerospace programs such as space transportation systems are developed and deployed only rarely, and they have long development schedules and large development and life cycle costs (LCC). Historically the only effort to control their costs has been in their DDT&E phase and they have not had their overall LCC predicted well. For such programs to be sustainable in the future both their non-recurring (DDT&E) phase costs and their recurring costs must be controlled and be lower than in the past – in other words, their LCC must be both lower and controlled. The non-recurring costs must be within their allocated budgets and their recurring costs must be low enough to not crowd out other programs. The primary cause of the lack of LCC control has been the lack of LCC being a requirement (it has only been a goal). The lack of LCC as a requirement has led to an overemphasis on mass and performance because without a LCC requirement there is no mechanism to trade mass and performance against non-recurring and recurring costs.

Assuming that LCC is a requirement in future programs, then the next major cause of both the lack of LCC control and LCC predictability is the maturity of the technologies incorporated in the program. If technologies used by a program are not mature at program initiation, then the non-recurring costs of the program will increase beyond that predicted because the technologies must be matured within the program. If older, mature, technologies are used instead, then the recurring costs will generally be the same as in the past, and past recurring cost have been too high. The high recurring costs will lead to high (although not necessarily obvious at the time) LCC.

The use of older, matured, technologies that affect operations (recurring) costs is not quite as simple as the previous two sentences would suggest. Besides using older technologies such as different (but proven) fluids for main propulsion, ACS/RCS, and orbital maneuvering thus resulting in high operation costs for the three different logistic trains, there are other mature technologies (such as proven umbilical designs) that would reduce operations costs if used, but that are often redesigned. Redesigning these technologies increases non-recurring costs and potentially increases recurring costs.

The ideal situation, from the point of view of a future program, would be to have the technologies useful to achieving mass, performance, and recurring cost requirements mature, available, and known at program initiation. This is not the case at present. This paper will discuss why and offer some recommendations to improve the situation.

II. Technology Readiness Levels

Technology development is not the same as engineering development. From Reference 1: "Technology development can best be distinguished from engineering development in that it requires venturing into the realm of unknowns – beyond the ability of individuals to make informed judgments based on their experience." New technologies potentially allow better performance, and/or lower costs in fielded programs provided they are fully developed. Various new technologies have different degrees of "unknown". The more "unknown" the less mature the technology and the more schedule and cost is likely needed to develop it to the level that it is no longer technology development, but instead is engineering development. Consequently, a measure of the degree of "unknown", i.e., the maturity level, of new technologies is desirable.

Thus, many people and organizations have developed scales to measure the technical maturity of various technologies, materials, and processes. Each has its strengths and weaknesses and often one or another is more appropriate for a particular use. This paper will use the NASA Technology Readiness Level (TRL) scale because it is fairly general and used widely in the aerospace industry.

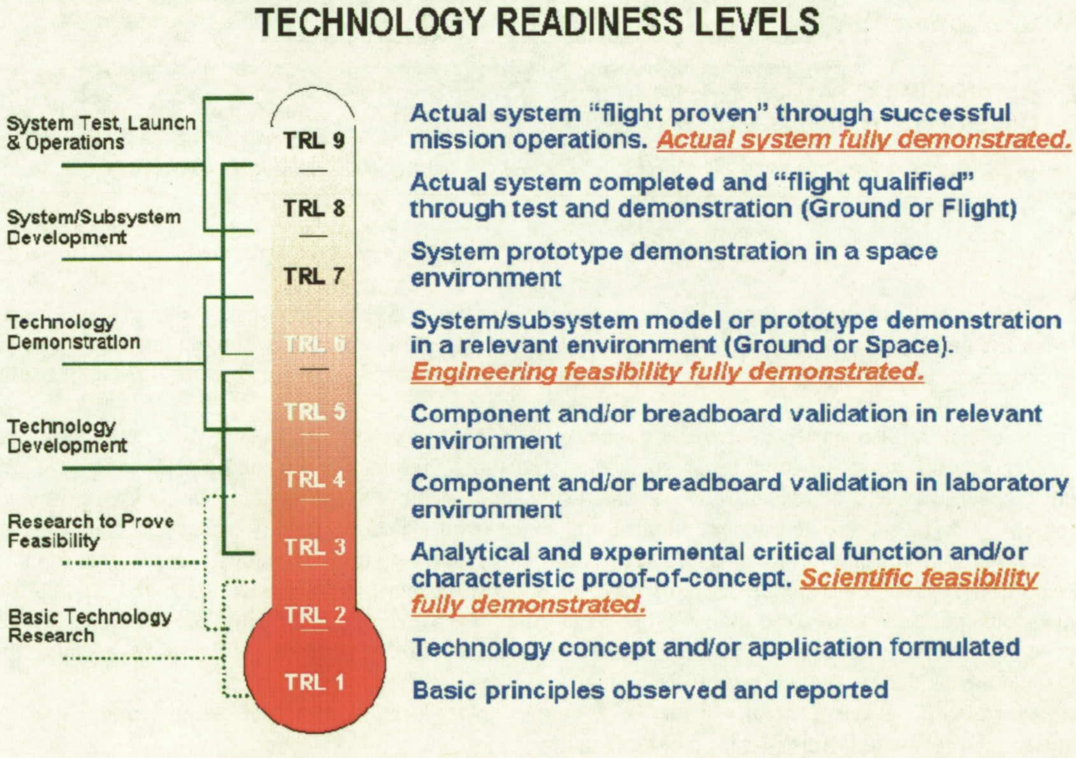


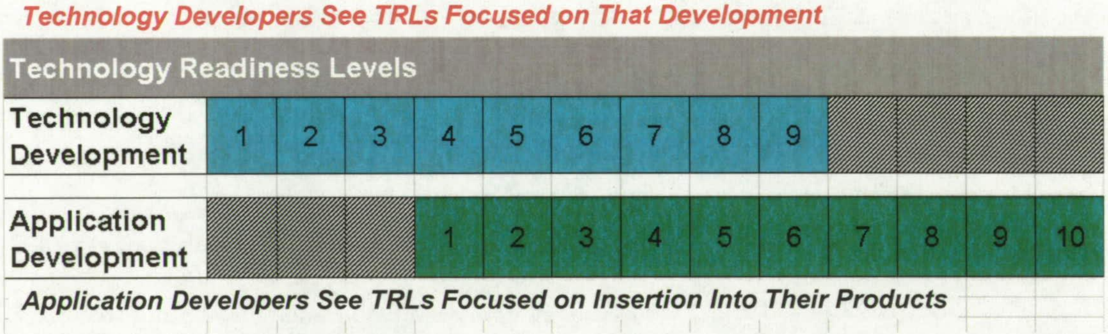
Figure 1 – Current NASA Technology Readiness Levels

A numeric scale to describe technology maturity was developed by Stanly R. Sadin at NASA and initially documented in a paper in 1988[2] as Technology Readiness Levels. The initial scale had seven levels. This was later expanded to nine as discussed in Reference 3. This scale (with some changes to the wording of examples) has also been adopted by the DoD. The current TRL states illustrated in Figure 1 relate to existing guidelines for NASA programs.

Technology Readiness Levels are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technologies. The TRL approach has been used in NASA space technology planning and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA. The technology maturation process for NASA space activities for which the TRLs were originally conceived includes: basic research in new technologies and concepts (targeting identified goals, but not necessary specific systems); focused technology development addressing specific technologies for one or more potential identified applications; technology development and demonstration for each specific application before the beginning of full system development of that application; system development (through first unit fabrication); and system launch and operations.

The actual determination of the TRL of a particular technology is actually difficult. Consequently efforts have been made to produce TRL calculators that ask a series of questions to help get an accurate determination. Reference 4 discusses the use of an Air Force TRL calculator.

The Accelerated Insertion of Materials program, AIM-C, found marked differences in perceived TRL among materials developers, technologists, and technology users even when presented with the same information. The TRL assigned could differ by up to three levels. The AIM-C program also found that this difference had been observed by previous programs as shown in Figure 2 from the C-17 aircraft program[5].



Technology Developers See TRLs Focused on That Development

Technology Readiness Levels													
Technology Development	1	2	3	4	5	6	7	8	9	▨	▨	▨	▨
Application Development	▨	▨	▨	1	2	3	4	5	6	7	8	9	10

Application Developers See TRLs Focused on Insertion Into Their Products

Figure 2. C-17 Technology Readiness Metric Approach

This difference is partly due to perspective. To quote Reference 5: "Technology developers tended to start their TRLs with the discovery and documentation of a new capability. Application developers tended to start their TRLs at the stage when the technology was reproducible and when they could receive a specified product using an initial definition or specification".

The difference is also partly due to the concept of relevant environment having different interpretations. For space transportation, in-space, and lunar surface systems the "relevant" environment is expensive to simulate, especially for large scale systems and sub-systems. For a space transportation system it includes an intense vibratory environment; varying, severe aeroacoustic loads; and space itself (vacuum, radiation, hot and cold thermal). For in-space systems the environment includes less severe, but high, vibratory and aeroacoustic loads and, of course, space. For lunar surface systems the environment includes most of the space impacts – vacuum, radiation, and hot and cold thermals – plus the lunar dust. And many of these environments are experienced simultaneously. All in all these are very expensive environments to simulate and many users may not believe the simulations because they do not believe the analysis that predicted the environments.

Consequently, programs generally want the assurance that comes from actual use in launch, space, or on the lunar surface. Unfortunately this is even more expensive.

A good overview of the history of, and tools to assess, technology assessment was presented by James W. Bilbro in 2007[1].

Recommendations in the past have considered modifying the TRL definitions to accomplish a more complete technology development scale directed at operational maturity. For example, the recommendations proposed in Figure 3 modify and add an additional readiness level to achieve total system readiness.

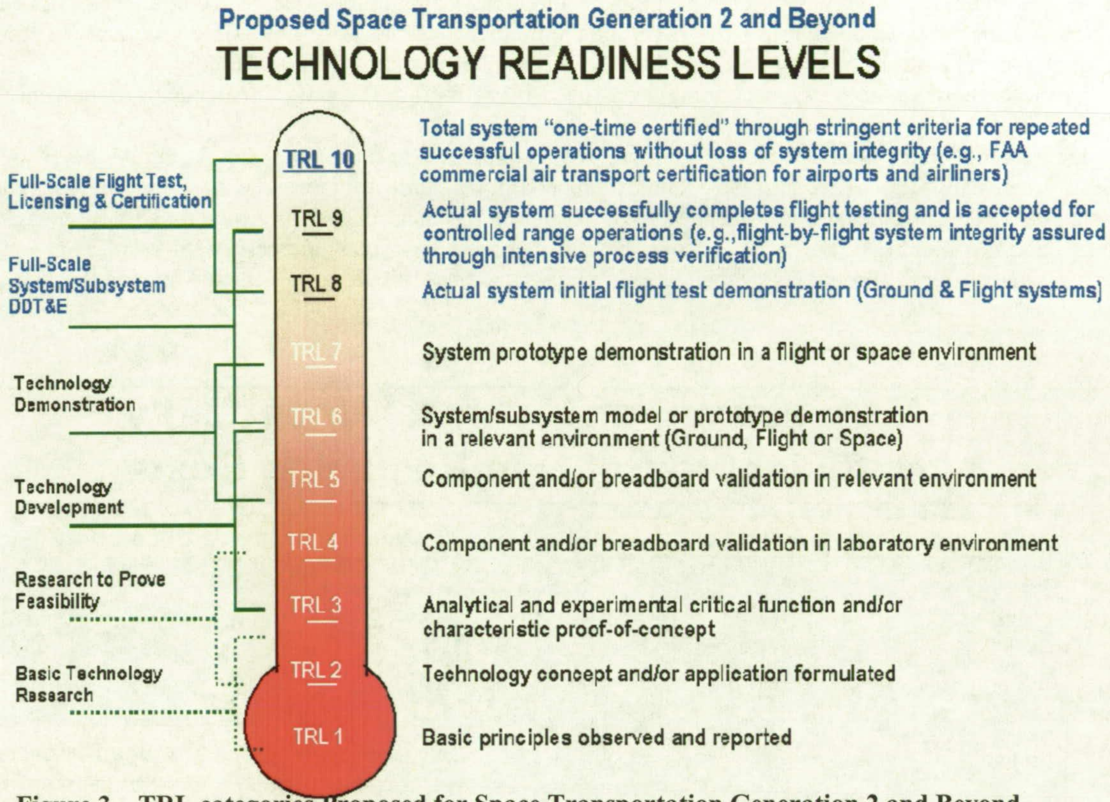


Figure 3 – TRL categories Proposed for Space Transportation Generation 2 and Beyond

The "without loss of system integrity" in the TRL 10 definition refers to the ability of a given space transportation vehicle to maintain functional integrity as the operator conducts ground processing, such that:

(a) operations that routinely take things apart are not encountered (for example, perhaps it was not anticipated that the launch site operator is required to access an interstage to remove engine caps and covers, which destroys the structural and functional integrity of the interstage previously closed-out at the stage manufacturer).

(b) routine assembly of the space vehicle is designed in such a way as to avoid a large amount of subsequent electrical, fluid, and structural functional integrity verification. These characteristics must be proven in environments where *all* elements interact in operationally realistic ground operations that actually lead to successful space flights.

(c) the design demonstrates avoidance of a large amount of unplanned troubleshooting and repair actions that accumulate to a routine burden.

Assuming these requirements are met, then demonstrated hardware/technology will be in the ready mode for safe, reliable, and more cost effective incorporation for operational platforms.

Another issue associated with TRLs is the measure of how difficult it is to mature a particular technology. Various techniques have been proposed to address this issue. One method is the determination of a Research & Development Degree of Difficulty (R&D^3) as proposed by John Mankins in Reference 6. An example of its usage in the Highly Reusable Space Transportation study is presented in Reference 7. Another method that produces more quantitative answers is the Advancement Degree of Difficulty (AD^2). AD^2 answers the question of what is required to advance the immature technologies from their current TRL to a level that permits infusion into a program within cost, schedule, and risk constraints. The AD^2 method is described in Reference 8.

III. Impact of Technical Maturity on LCC

If technology of lower technical maturity is used in a program, then the program will have higher costs and/or a longer schedule compared to using technology of higher technical maturity. This is because the lower maturity technology must be developed to a higher maturity within the program itself. Consequently, program managers will not use low TRL technology unless the program requirements cannot otherwise be accomplished. Since the job of a program manager is to accomplish the program requirements at the lowest possible cost and schedule risk, the program manager would be irresponsible to include any unnecessary low TRL technology

In the past, when low TRL technology was used in a program the program impact was not only adverse to schedule and cost but, more importantly, unpredictable.

Figure 4 illustrates the impact of using low TRL technologies in a program. On the right side of the figure is a rising green band that represents the technical uncertainty in the program. The band can be thought of as the aggregate TRL of the technologies in the program. As the technical uncertainty increases (moving right along the green band) the number of corrective actions (basically test-fail-fix cycles) increases. The increase is non-linear – as the TRL gets lower the band gets steeper. This steepness and the difficulty of precisely knowing the TRLs is the source of much of the unpredictability of the impact of low TRLs on the program's non-recurring cost. Moving down the green band (increasing the TRLs used in the program) greatly improves the program non-recurring cost.

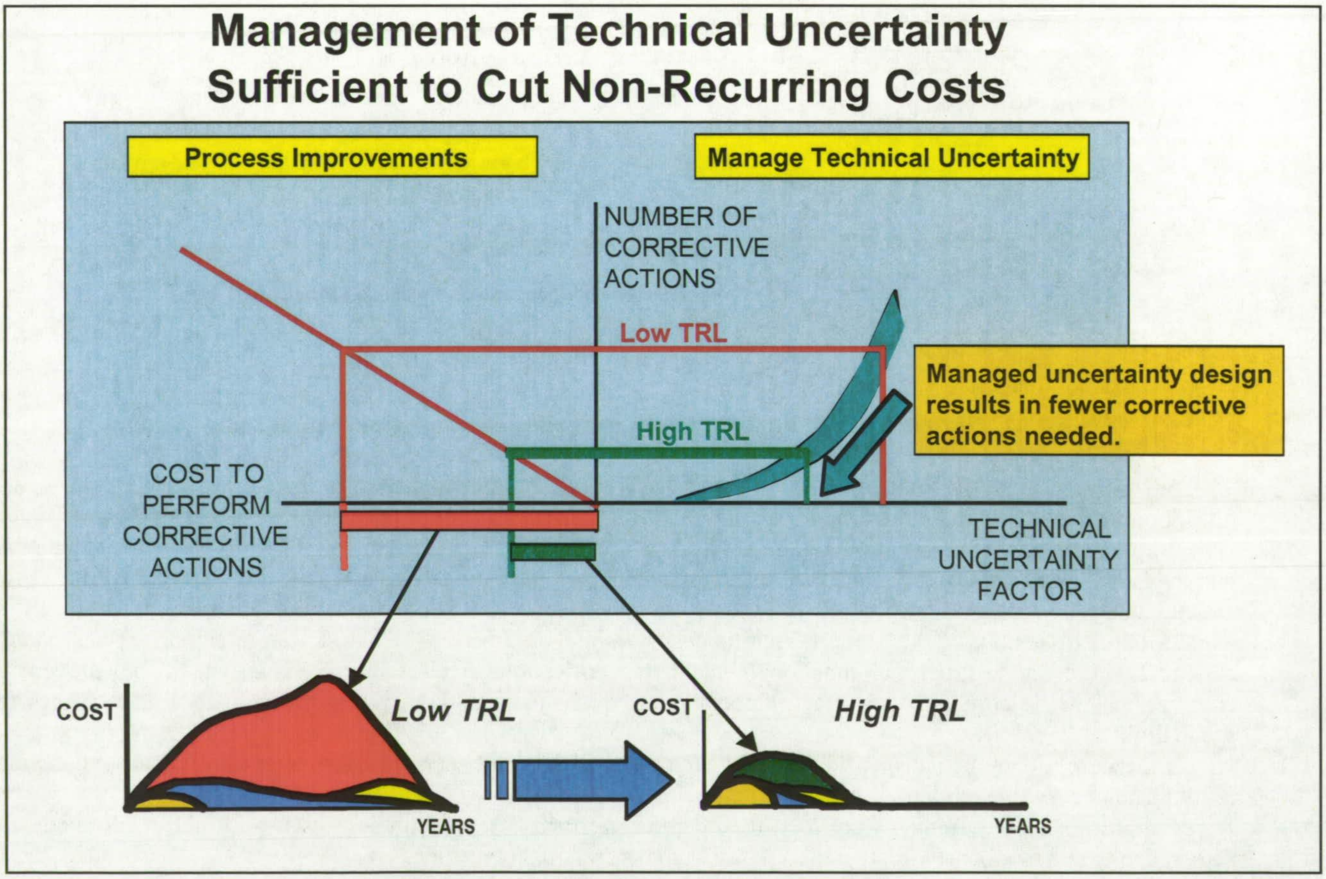


Figure 4. Program Impact of Technical Maturity

A critical need for improved communications between the user and the developer led to NASA's Code R and Code M chartering the Space Propulsion Synergy Team (SPST) in 1991. This SPST's first task was to use its member's diversified expertise toward developing new "Engineering Management Decision Making Tools": specifically developing innovative engineering processes in the architectural design, development, and operation of space transportation systems to satisfy the challenging requirements of both the transportation operators and the payload customers. The SPST established a dialogue between the personnel involved in all phases of the technology, design, development, and operation of space transportation systems.

Since 1991 the national Space Propulsion Synergy Team has reviewed and assessed the lessons learned from the major U.S. space programs of the past decades focusing on what has been learned from the assessment and control of Life Cycle Cost (LCC) from these systems.

From these extensive studies the SPST has identified the major drivers of recurring costs for space transportation systems. These results have been formulated as design guidelines and documented in a design guide[9] and are reported in another paper at this conference[10].

These guidelines are not technologies. They are items such as: minimize the number of tanks, minimize the number of different propulsion systems, minimize the number of fluids, minimize the number of umbilicals, maximize the amount of onboard automation, etc. But the accomplishment of any of these guidelines depends on new technology. For example, minimizing the number of propulsion systems would benefit from combining the main propulsion with the ACS/RCS and with the orbital maneuvering system (OMS). Such an integrated system itself would be a technology needing to be matured. In turn, component technologies would need to be matured. Examples are tank head operation of main propulsion for the OMS function and O_2/H_2 ACS/RCS thrusters accepting either gas or liquid propellants. These technologies actually exist but at maturities considered unacceptable by programs although often considered quite advanced by technology developers.

We have gone to the moon and we routinely access space. Obviously, the proven technologies (although not always the systems) currently exist to accomplish these tasks. However, we do not do these tasks at low recurring costs, i.e., sustainably. The proven (fielded) technologies to perform these tasks sustainably do not currently exist.

Most program managers and system architects would agree with the guidelines that the SPST has identified. However, in a future program they would probably not follow them. This is because the program would most likely be structured with mass and performance requirements and, possibly, a requirement on non-recurring costs. It is unlikely that recurring costs would be specified as anything higher than a "goal". Under such circumstances little new technology can be matured under the program. And, since older technologies exist to achieve the program requirements, even though they do not achieve the recurring cost "goal", then the older technologies will be used. The result will be a fielded system with somewhat better performance than previous systems, but without significant reduction in operating recurring costs. Such a system is not likely to be sustainable.

There are only two ways that recurring costs, and thus LCC, can be reduced in future programs. First, the technologies to accomplish the reduced recurring costs can be fully matured prior to their use in future programs. This will allow future programs to incorporate the technologies without high non-recurring costs (i.e., within budgets).

Second, a true requirement (not merely a goal) can be placed on LCC and thus on recurring costs for the future program. In this case the program will be forced to use the technologies necessary to accomplish the reduction in recurring costs. However, also in this case the non-recurring costs of the program will be increased because the technologies must be matured within the program itself.

IV. Approaches to Maturing Technologies

The purpose of maturing technologies prior to their need in programs is to burn down the risk so that future programs will have a high probability of meeting their non-recurring cost, their schedule predictions, and their recurring cost predictions, and thus their overall LCC.

One approach to addressing this problem is to develop tools that can *reliably* predict the impact of inclusion of low TRL technology on the program schedule and cost depending on the TRL values and the category of technology.

Such tools have not previously been available. Methods such as the use of the Research & Development Degree of Difficulty ($R\&D^3$) and the Advanced Degree of Difficulty (AD^2) have been used as partial answers but they do not produce schedule and cost quantitative answers. Three papers being presented at this conference[11,12,13] describe a tool that has been used at Pratt & Whitney Rocketdyne. This tool is quantitative and has been successful. However, it requires generation of data that is extensive and organization specific.

If in a future program using new technology, the cost of using the new technology is accurately predicted for cost and schedule, the funding source may still experience "sticker shock" even though the cost is the same as would have been paid with a lower initial estimate but with later increases. Partially this is because the funding source is used to expecting increases after the initial estimate and will assume that further increases will still occur.

Two other approaches are to develop the new technologies either as-needed in each new program or to develop the technologies separately and mature them before they are needed in specific programs.

The current practice is to develop most new technologies as-needed within funded programs, *but only if absolutely necessary*, due to the expense and unpredictability of the development.

NASA and industry currently *do* develop new technologies ahead of their need by programs. But the development is generally stopped at TRL 6 or below. Developing technologies for a space environment at large scale is expensive. Industry generally will not develop the technologies for government use because the government will pay for the development if a program is won and the technology is chosen for use, and NASA generally will not develop the technologies because NASA rarely has enough funds for all of its current programs. Consequently, many promising technologies are developed to about TRL 6 and left there. Many technologists consider TRL 6 to be sufficient for program use. But very few program managers consider TRL 6 to be mature enough for program use because the "relevant environment" is not the same as the complete expected program environment.

The major funding required for full scale development leaves little or no funding available to properly prototype TRL 6 concepts to place hardware in the ready mode for safe, reliable and cost effective incorporation on operational platforms.

A. Approaches to Developing and Maturing New Technologies

Developing technologies beyond TRL 6 outside of new programs can be done, and is done by the DoD. Among the approaches used by the DoD are government/industry initiatives where the DoD pays for some development while also requiring that industry align its own R&D with the needs expressed in the initiative (and sometimes requiring cost-share). Examples of these are the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Initiative, the Integrated High Performance Turbine Engine Technology (IHPTET) Initiative, and the Accelerated Insertion of Materials (AIM) Program. Another approach used by the DoD is the use of an agency specifically tasked to develop technologies and future capabilities. This is the Defense Advanced Research Projects Agency (DARPA). DARPA is able to develop technologies from very basic research through prototypes and testbeds.

Whatever methods are used, the technology needs for commercial space launch and in-space technologies may be different than those for the civil space programs of NASA. Civil space missions are more likely to be mass and performance driven. Therefore optimizing each subsystem in order to accomplish system performance may be key.

Commercial space, on the other hand, focuses on lowering the program's LCC by lowering initial non-recurring cost as well as lowering the recurring operational cost. This includes avoiding technology barriers, focus on system robustness and the use of common subsystem technologies. Therefore commercial space launch may not focus on the maximum payload to orbit, for example, but rather the overall robustness of the operational system that can result in a lower LCC. As such, the technology development may place more emphasis on manufacturing and production technologies, common hardware functional and interface requirements, as well as enabling technologies that will have multiple platform and mission applications.

The technologies needed will depend on the details of the future mission requirements, but all of the future programs must have low recurring costs if there are to be any resources left to perform missions. Therefore both civil and commercial space will benefit from the technologies matured. Because both civil and commercial space will benefit, they should both have input into the development of the portfolio of technologies to be developed.

Some options to address maturing technologies for future use are discussed below.

1. NASA Initiatives

The use of multi-year, long-term funded initiatives has been successful for the DoD in the rocket engine, gas turbine, and materials development areas to develop and mature technologies. It could just as easily be successful in the civil and commercial space arena. To actually get industry to align their own R&D with the government, the initiatives must be believable. That generally implies multi-year funding not subject to extreme changes.

2. Industry Consortia

Industry consortia can increase the efficiency of maturing technologies by leveraging government and industry resources, and/or by defining specific companies to only work on specific technologies within a technology area (defined work-split). Consortia have been used successfully by NASA previously. They are often difficult to set-up due to industry reluctance to accept only part of a program where they believe they could win all of it, due to intellectual property concerns, and due to government desire for competition. Nonetheless, when such an approach is possible, it could both produce matured technologies and, perhaps more importantly, the common use of specific technologies across the industry.

3. Component and Design Certification Programs

There are many individual technologies that have been developed that have proven to be very dependable and have had low maintenance needs. Their use, wherever possible, will reduce LCC.

NASA and the industry should harvest and develop a catalog of these previously successful components and designs, and then encourage the use of these components and designs to the maximum extent consistent with trades among mass, performance, non-recurring costs, recurring costs, and safety in order to minimize non-recurring and recurring costs and, maximize reliability and safety.

Use of these components or, if far enough from the needed requirement, designs will have a small impact on mass and/or performance due to being somewhat sub-optimal for the new program, but will significantly improve reliability, maintainability, safety and both non-recurring and recurring costs.

This catalog of previous components and/or designs should be taken further to allow certification of these components and/or designs so that future programs do not need to justify their use, even for man-rated programs. And as new technologies are matured, they too should be certified where possible. An industry standard certification process could be developed to support the TRL 10 level shown in Figure 3.

In turn the certification process could also help to provide standardization for future civil and commercial space transportation and in-space programs. This approach will also encourage commonality of components in multiple operational programs and thereby reduce the development risk and the LCC of each proposed new operational system.

4. Specific Technology Maturing Organization

The simplest, but probably most controversial, option is to establish an organization to develop and mature new technologies. It is simplest because, besides being funded to develop technologies (in-house and by contract), it could employ most of the previously discussed options.

An immediate question is whether the organization tasked with maturing the new technologies should be an independent organization or should be part of the agency that will perform the future programs.

One positive aspect of being in the same agency is focus. The technologies chosen for development should be easily identified. The drawback is that same focus. The technology maturing organization could easily become mostly an "off-book" developer of technologies for current programs. It might be very difficult to produce the kind of broad portfolio of new technologies needed for future programs.

If the agency that will perform the future programs is also an agency that has operational responsibilities, then the problem becomes more severe.

If the organization tasked with developing advanced technologies is also an organization that has operational responsibility, then it is unlikely that the funding set aside for developing technologies will be consistent and predictable, even if it starts out as a separate line item. Operational responsibility brings with it the obligation to maintain the operational capability even when problems develop.

A rather simple example may illustrate this point. If you are putting aside money every month for your children's college, you have no excess money available, and you have no borrowing ability, and then your car requires major work to continue to run, what will you do? There is really no choice, you must use at least this month's set aside money to fix the car. It does not matter how serious you are about setting aside the college money or how strong your will is, you must address the problem with the car. This is the same situation an organization with operational responsibility is in. Unless its funding source will bail it out, it *must* address any difficulties that arise from its operational responsibility.

A second problem is that the technologies chosen for development will likely be biased to maintaining and improving the operational capability to the detriment of technologies for future programs.

Although these problems can be addressed and perhaps solved, it would be much simpler to have the organization tasked with developing new technologies have its funding isolated from any agencies with operational responsibility.

This organization should try to use any lessons learned from studying DARPA which is a DoD attempt to achieve the same function. Indeed one option is to use the DARPA model to perform this function for civil and commercial space. It is possible that this new organization could be part of NASA using major existing or accessed assets, but it would be a challenge to keep it from becoming a financial feeder of existing programs and to keep its funding fenced when funding needs became severe in operational areas.

Consequently, it is proposed that an organization with a single objective to develop space launch and in-space technology be established and that it be independent from having operational responsibilities.

B. Prioritizing the Technologies to be Matured

The selection of the appropriate technologies must be determined and used for generating a prioritized technology portfolio. By strategically selecting critical subsystem technologies for development, the future development risk and LCC of operational systems for many applications can be reduced. The technologies needed will depend on the future mission requirements, but all of the future programs must have low recurring costs if there are to be any resources left to perform missions. Consequently, among the most important technologies needing maturation are those that will lower operation recurring costs. To identify the LCC driving technologies the SPST recommends using a Functional Breakdown Structure (FBS) and concentrating on the LCC drivers previously discussed.

1. Functional Breakdown Structure

It is necessary to identify all the requirements and elements of an architecture at the beginning of a program if the LCC is to be controlled. The SPST has developed a methodology utilizing a Functional Breakdown Structure (FBS) to accomplish this difficult task.

The FBS is a structured, modular breakdown of every function that must be addressed to perform a generic mission and is also usable for any subset of the mission. It is not tied to any particular architectural implementation because it is a listing of the needed functions (not elements of the architecture). The FBS provides a universal hierarchy of required functions, which include ground and space operations as well as infrastructure – it provides total visibility of the entire mission. This is a new approach that will provide full accountability of all functions required to perform the planned mission. It serves as a giant check list to be sure that no functions are omitted, especially in the early architectural design phase.

A significant characteristic of a FBS is that if architecture options are compared using this approach, then any missing or redundant elements of each option will be identified. Consequently valid LCC comparisons can be made. For example, one architecture option might not need a particular function while another option does. One option may have individual elements to perform each of three functions while another option needs only one element to perform the three functions.

Once an architecture has been selected, the FBS will serve as a guide in development of the work breakdown structure (WBS), provide visibility of those technologies that need to be further developed to perform required functions, and help identify the personnel skills required to develop and operate the architecture. It also will allow the systems engineering activities to totally integrate each discipline to the maximum extent possible and optimize at the total system level, thus avoiding optimizing at the element level (stove-piping). In addition, it furnishes a framework which will help prevent over or under specifying requirements because all functions are identified and all elements are aligned to functions.

The SPST has developed a preliminary space transportation system FBS including supporting elements for a manned exploration mission[14]. Further discussion about using a FBS is presented in Reference 15.

2. LCC Cost Drivers

To control space transportation system costs it is necessary to identify the major cost drivers. Design decisions drive the operations costs which then dominate the LCC. As discussed above the SPST conducted a study that identified the major operations cost drivers.

The study reformatted the major lessons learned from previous programs as Technical Performance Metrics (TPMs). To the degree that these are implemented, both the design and the operations aspects of LCC will decrease.

Performance and weight can be adversely impacted by the pursuit of these TPM's in some missions and some architectures. Consequently, a balance must be struck between these TPMs and the performance and weight to achieve an acceptable LCC. This balancing should guide the architecture development.

Of the sixty-four TPMs identified in the study, the following eighteen have been determined to be the major cost drivers. The design and operations aspects of LCC are decreased by establishing minimum values of these TPMs consistent with the mission objectives and then flowing down the values of the TPMs as actual requirements. The SPST sought a method to compare many different variables and understand their interrelationship with each other. The tool chosen was a specific Total Quality Management (TQM) tool - Quality Functional Deployment (QFD). These results were supplemented by the Shuttle Shortfall Analysis study. The procedure is to minimize each of these factors. The factors to be minimized (in order of importance) are:

1. Total number of separate identified vehicle propulsion systems and/or separate stages;
2. Total number of flight tanks in the architecture;
3. Number of safety driven functional requirements to maintain safe control of systems during flight and ground operations;
4. Number of maintenance actions unplanned before or between missions;
5. Number of maintenance actions planned before or between missions;
6. Total number of traditional ground interface functions required;
7. Percent of all systems not automated;
8. Number of different fluids required;
9. Total number of vehicle element-to-element support systems;
10. Number of flight vehicle servicing interfaces;
11. Number of confined/closed compartments;
12. Number of commodities used that require medical support operations and routine training;
13. Number of safety driven limited access control operations;
14. Number of safing operations at landing (for reusable elements);
15. Number of mechanical element mating operations;
16. Number of separate electrical supply interfaces;
17. Number of intrusive data gathering devices;
18. Number of Criticality 1 system and failure analysis modes.

After defining an architecture using these TPMs, a structured engineering management process would then be needed to budget and control the TPMs throughout the design and development phases of any future program.

As previously stated, these guidelines are not technologies. But the accomplishment of any of these guidelines depends on new technology. For example, minimizing the number of propulsion systems would benefit from combining the main propulsion with the ACS/RCS and with the orbital maneuvering system (OMS). Such an integrated system itself would be a technology needing to be matured. In turn, component technologies would need to be matured. Examples are tank head operation of main propulsion for the OMS function and O_2/H_2 ACS/RCS thrusters accepting either gas or liquid propellants.

The more these guidelines are implemented, the greater the improvement in LCC for any application being pursued. These guidelines are presented in more detail in Reference 16.

V. Conclusions

The SPST's first conclusion is that if the industry always does what it has done before, then the industry will always get the same result. Therefore, achievement of major reductions in LCC will not be accomplished using the same existing processes and organizational establishment. The SPST has concluded that future programs would benefit from the availability of matured new technology. This availability could lower the LCC of future programs and increase the probability of the programs meeting their other requirements (mass, performance) within cost and schedule by buying down the program risk prior to the program initiation, which would, in turn, increase the sustainability of the future programs.

However, it has been difficult to get new technologies incorporated into new space transportation and in-space programs because of the need to reduce programmatic risk during development. New programs are very expensive and infrequent, thus limiting the opportunity to introduce new technologies into these new transportation and in-space programs. Since maturing technology within a program development has produced adverse, and unpredictable, effects on the program costs and schedule, the programs are very risk adverse in relation to new technology.

Consequently, there is a need to develop some mechanism to develop new technologies beyond TRL 6 prior to their need by future programs.

It would also be useful to expand the TRL scale to add a level 10 that emphasizes operationally mature technologies.

VI. Recommendations

The SPST is making two recommendations. The first recommendation is:

1. Establish an organization with a single objective to develop space launch and in-space technology that:
    a. will not be directly connected to specific funded programs;
    b. will leverage industry R&D through initiatives (e.g., the DoD's IHPRPT/IHPTET);
    c. will conduct and fund technology development
        i. from basic research projects,
        ii. to advanced development,
        iii. to prototypes;
    d. will develop selected technologies through demonstrations of the major objectives by using
        i. prototypes,
        ii. ground based testbeds,
        iii. payloads on other vehicles as launch demonstrators or released as in-space experiments,
        iv. full size and/or sub-scale flight technology testbeds;
    e. will have isolated funding from any agency with operational responsibilities.

The second recommendation is:

2. Harvest and develop a catalog of previously successful components and designs, and then
    a. encourage the use of these component and designs to the maximum extent consistent with trades among mass, performance, non-recurring costs, recurring costs, and safety in order to
        i. minimize non-recurring and recurring costs and,
        ii. maximize availability and responsiveness through reliability, maintainability, and safety.

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National Aeronautics and Space Administration

John F. Kennedy Space Center's Activated Metal Treatment System (AMTS) for Paints

The National Aeronautics and Space Administration (NASA) seeks partners interested in the commercial application of the Activated Metal Treatment System (AMTS) for treating polychlorinated biphenyls (PCBs) in paints. NASA's Kennedy Space Center is offering companies licensing or partnering opportunities in the development of this innovative remediation technology.

Current physical removal methods are able to strip off PCB-containing paint from surfaces (e.g., media blasting); however, these methods typically create a new waste stream that must be treated according to Toxic Substances Control Act (TSCA) regulation. In contrast, AMTS extracts PCBs and breaks them down into benign by-products while on the structure. Therefore,

BENEFITS

- No impact to structure—does not affect the material beneath the paint and allows for the surface to be repainted/reused following application.
- In situ—treats PCBs in place, versus traditional abatement methods that generate a secondary Toxic Substances Control Act (TSCA) waste stream.
- Cost-competitive—requires none of the costs associated with placing a building under vacuum or transporting, treating, and/or disposing of a secondary waste stream. Preliminary estimates indicate that AMTS could cost less than $15 per square foot for materials (not including labor). In addition, total costs (materials plus labor) are anticipated to be less than comparable costs for media-blasting.
- Effective—has been shown in lab-scale and field-scale tests to remove approximately 80% of PCBs from paint (three layers in thickness with initial PCB concentration as high as 700 parts per million [ppm]) within 4 hours, and approximately 100% of PCBs within 48 hours.
- Safe—produces benign by-products.
- Versatile—can be used as a "paint-on/wipe-off" method for in-situ applications or as an immersion method (e.g., for dismantled parts awaiting disposal).

technology ■ opportunity

APPLICATIONS

- Painted structures such as buildings and ships
- Concrete surfaces contaminated by PCB-laden transformer oil
- Caulks and other adhesives
- Electrical equipment
- Soils (ex situ)
- Other PCB-contaminated debris

TECHNOLOGY STATUS

☑ Patent pending

☑ U.S. patent No. U.S. patent 7,271,199

☐ Copyrighted

☑ Available to license

☐ Available for no-cost transfer

☐ Seeking industry partner for further codevelopment

no additional treatment for PCBs is required. Also, because the treated surface can be reused following application, AMTS has advantages over other methods and often opens up recycling opportunities that would not have been possible prior to AMTS' application.

Technology Details

PCBs have been shown to cause cancer in animals and to have other adverse effects on immune, reproductive, nervous, and endocrine systems. Although the production of PCBs in the United States has been banned since the late 1970s, many surfaces are still coated with PCB-laden paints. The presence of PCBs in paints adds complexity and expense for disposal. Some treatment methods (e.g., use of solvents, physical removal via scraping) are capable of removing PCBs from surfaces, but these technologies create a new waste stream that must be treated. Other methods, like incineration, can destroy the PCBs but destroy the painted structure as well, preventing reuse.

To address limitations with traditional abatement methods for PCBs in paints, researchers at NASA's Kennedy Space Center (KSC) and the University of Central Florida have developed the Activated Metal Treatment System (AMTS) for Paints. This innovative technology consists of a solvent solution (e.g., ethanol, d-limonene) that contains an activated zero-valent metal.

AMTS is first applied to the painted surface either using spray-on techniques or wipe-on techniques. The solution then extracts the PCBs from the paint. The extracted PCBs react with the microscale activated metal and are degraded into benign by-products. This technology can be applied without removing the paint or dismantling the painted structure. In addition, the surface can be reused following treatment.

Partnership Opportunities

All NASA licenses are individually negotiated with the prospective licensee, and each license contains terms concerning commercialization (practical application), license duration, royalties, and periodic reporting. NASA patent licenses may be exclusive, partially exclusive, or nonexclusive. If your company is interested in the new Activated Metal Treatment System for Paints technology, or if you desire additional information, please reference Case Number KSC-12878 and contact:

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