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Concepts for Life Cycle Cost Control Required to Achieve Space Transportation Affordability and Sustainability

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Cost control must be implemented through the establishment of requirements and controlled continually by managing to these requirements. Cost control of the non-recurring side of life cycle cost has traditionally been implemented in both commercial and government programs. The government uses the budget process to implement this control. The commercial approach is to use a similar process of allocating the non-recurring cost to major elements of the program. This type of control generally manages through a work breakdown structure (WBS) by defining the major elements of the program.

If the cost control is to be applied across the entire program life cycle cost (LCC), the approach must be addressed very differently. A functional breakdown structure (FBS) is defined and recommended. Use of a FBS provides the visibility to allow the choice of an integrated solution reducing the cost of providing many different elements of like function. The different functional solutions that drive the hardware logistics, quantity of documentation, operational labor, reliability and maintainability balance, and total integration of the entire system from DDT&E through the life of the program must be fully defined, compared, and final decisions made among these competing solutions.

The major drivers of recurring cost have been identified and are presented and discussed. The LCC requirements must be established and flowed down to provide control of LCC. This LCC control will require a structured rigid process similar to the one traditionally used to control weight/performance for space transportation systems throughout the entire program.

It has been demonstrated over the last ~30 years that without a firm requirement and methodically structured cost control, it is unlikely that affordable and sustainable space transportation system LCC will be achieved.

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Nomenclature

ATK	= Alliant Techsystems
DDT&E	= Design, Development, Test and Evaluation
FBS	= Functional Breakdown Structure
FC	= Fuel Cell
GO_2	= Gaseous Oxygen
GSE	= Ground Support Equipment
H_2O	= Water
HP	= High Pressure
IVHM	= Integrated Vehicle Health Management
JSC	= Johnson Space Center
KSC	= Kennedy Space Center
LCC	= Life Cycle Cost
LH_2	= Liquid Hydrogen
Lox	= Liquid Oxygen
LP	= Low Pressure
MPS	= Main Propulsion System
MSFC	= Marshall Space Flight Center
NASA	= National Aeronautics and Space Administration
O&M	= Operations and Maintenance
OMS	= Orbital Maneuvering System
OPS	= Operations
Ox	= Oxidizer
QFD	= Quality Function Deployment
R&D	= Research and Development
RCS	= Reaction Control System
SPST	= Space Propulsion Synergy Team
SSME	= Space Shuttle Main Engine
STS	= Space Transportation System
TPM	= Technical Performance Metric
TQM	= Total Quality Management
TVC	= Thrust Vector Control
WBS	= Work Breakdown Structure

I. Introduction

The objective of this paper is to assure that the planning and implementation of the transportation systems required by a sustainable Space Exploration Program takes maximum advantage of the "lessons learned" from the major space programs of the past decades. The paper uses what has been learned about assessing and improving control of Life Cycle Costs (LCC) from these major space programs.

Civil and military applications of space transportation have been pursued for 50 years and there have been, and there is now, an even greater need for safe, dependable, affordable, and sustainable space transportation systems. Fully expendable and partially reusable space transportation systems have been developed and put in operation. Access to space is technically achievable, but presently very expensive.

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.

The basic approach developed by the SPST is to adapt the approach of the management process for weight control that NASA used on the Space Shuttle Program, but instead to also use it to control Life Cycle Cost for the new space transportation systems. This includes technology, advanced development, DDT&E, manufacture, operation, and recycle/disposal. This will require a major cultural adjustment to the way the US Government in general, and NASA and the aerospace industry specifically, do business, since Life Cycle Cost – womb to tomb cost, has not been included in the traditional program focus (we have never focused on trying to develop and control a sustainable space exploration program). Commercial enterprises all budget and control their projects/programs to Life Cycle Cost; otherwise they fail and go out of business.

The SPST proposes to address the global problem of budgeting and controlling Life Cycle Costs by assuring all requirements are in place from Level 0 to the unique element requirements level that address all the major objectives (performance, affordability, safety, and sustainability) of the space program's transportation system. The paper will address concepts for controlling LCC and will provide recommendations to achieve the best results for meeting the objective of an affordable and sustainable space transportation system.

II. Background

Because the recurring or operating costs, both fixed and those related to flight rate, are one of the largest portions of the LCC of a space transportation system, and because they flow from decisions made during the concept definition and design phases, it is useful to examine the current Shuttle Space Transportation System's (STS) costs.

The STS is an approximately 4 billion dollar a year operation. This operation is spread throughout the entire country. It is composed of: producing external tanks (MSFC and Lockheed-Martin); salvaging, recycling and re-filling solid rocket boosters and motors (MSFC, KSC and ATK); providing qualified engines for Shuttle Orbiters (JSC, SSC, Aerojet, and Pratt & Whitney Rocketdyne); providing mission and flight operations (JSC, Boeing, and United Space Alliance); providing ground operations (KSC and United Space Alliance); and providing for a host of assorted other functions from NASA Headquarters to Dryden Flight Research Center. And it includes coordination with the Air Force for use of the Eastern Test Range. The program represents a complex interaction of many entities. All these functions include work from the most direct (a technician, a flight controller, a line manufacturing employee, etc.) to the most indirect (a manager, a logistics provider, a scheduler, a procurement, finance or human resources officer, etc.).

The ground operations at Kennedy Space Center (KSC), as one of the most visible costs, serves as a representative example to examine in more detail.

Shuttle ground operations at KSC is a roughly 1.4 billion dollar a year operation. It can be divided into eight categories: contractors (Categories 1 – 5); technicians hands-on labor (Category 1); Engineering, Safety & Quality (Category 2); Program Management and Internal Business Functions (Category 3); logistics, depot maintenance and interface to original equipment manufacturers (Category 4); sub-contractors to the primes (Category 5); NASA Program, Project and Institution (Categories 6 – 8); NASA Program and Project Management (Category 6); NASA and contractors center management and operations (Category 7); and, KSC infrastructure (Category 8).

The work ranges from Category 1, which is close-in, hands-on the flight hardware and support equipment at KSC, until, at Category 8, the work is on the base infrastructure, enabling, but farther removed from day-to day flight hardware processing. The indirect business category, often called overhead, lies for the contractor in Category 3, while for the government it lies in Category 7. The engineers and more technical support in Category 2 and 6 work together on a day-to-day basis. The largest workforce under one organization lies in Category 3, as this is the class of work which enables all else. Category 3 includes program management, requirements management, documentation control, configuration control, scheduling, work control including work document generation, interfaces to outside organizations such as other centers, suppliers, and the government as customer. Category 3 also includes internal facing business functions more readily defined as business costs.

The eight KSC detail Categories breakout as follows: Category 1 is $50M/year; Category 2 is $150M/year; Category 3 is $200M/year; Category 4 is $175M/year (all Orbiter); Category 5 is $115M/year; Category 6 is $75M/year; Category 7 is $300M/year; and Category 8 is $200M/year as shown in Figure 1.

Plus, there are additional costs of approximately $150M/year for other Reusable Solid Rocket Motor / Reusable Solid Rocket Booster (RSRM/RSRB) operations located at KSC but managed by the Marshall Space Flight Center (MSFC). This is over $1.4 billion dollars a year in funds with an approximate local Florida impact of 12,000 people to prepare, support or otherwise enable the Space Shuttle launches.

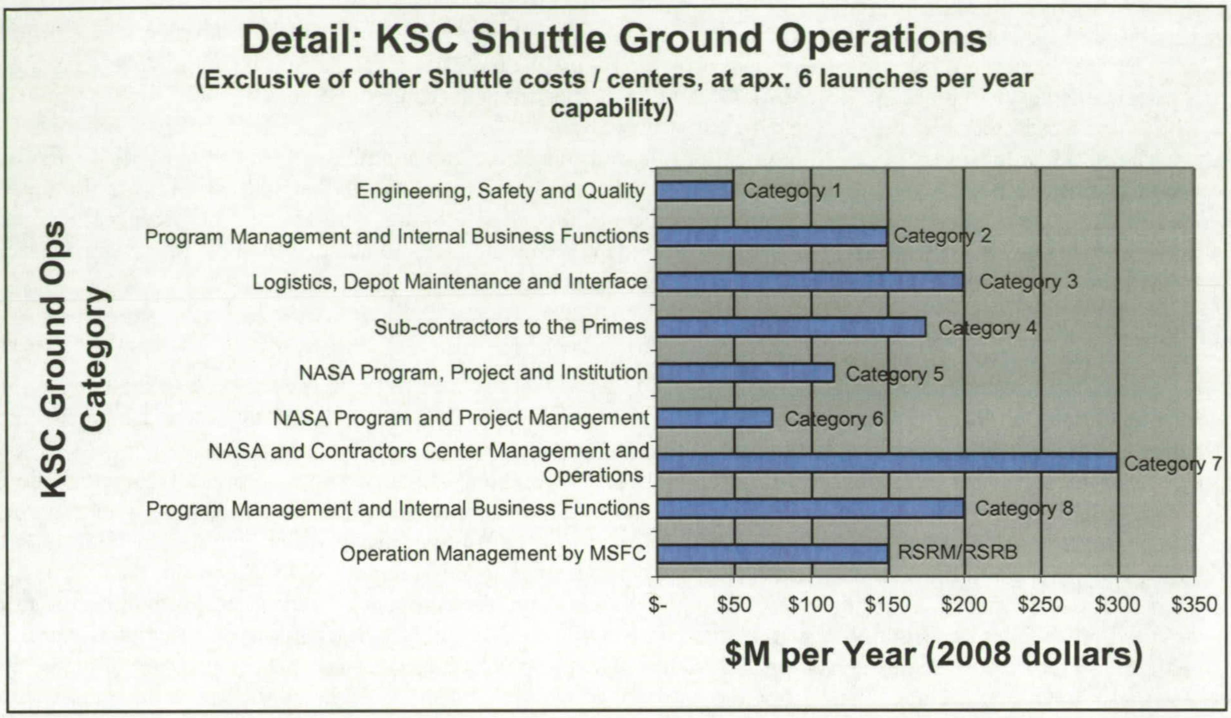

Figure 1. Shuttle Ground Operations Cost at KSC ($Millions/year)

It is tempting to assume that a reduction in technician's hands-on labor, by having simpler hardware or a smaller, less complex system, will cascade through all the other support functions. In practice some costs are fixed and relationships are more complex. For example, streamlining a process and eliminating half the hands-on work on a task does not necessarily eliminate half the programmatic and administrative support.

The exploration program can immediately recognize that large sums go towards potentially architecture independent areas of program management (such as contractor Category 3 costs), as well as center functions that have nothing to do with an architecture (such as NASA and contractor Category 4 costs). The contractor business functions that include requirements generation, planning, document preparation, configuration control, scheduling, etc. are by nature connected to technical maturity as measured by demonstrated reliability. A part or sub-system that fails during any phase before launch is a reason for extensive support and/or business functions (Category 2 through 5) to exist, as well as driving as much as 25 to 50 percent of Category 1 dollars.

An unreliable system can never be affordable for human space flight because if the system is unreliable, then the support and business functions will be designed, or persist due to lack of investment, in forms that attempt to "process in" what was not designed into the system (such as by higher volumes of production, and/or higher numbers of test-fail-fix cycles in early design development).

Nonetheless, the indirect support activities, especially Categories 2, 3, 6, and 7, so dependent on information flow judging by their descriptive functions, represent immediate opportunities for affordability gains. Saving even 20% of categories 2, 3, 6, and 7 at KSC alone would save $150M/year. The extrapolation to the entire $4B would be on the order of $500M/year savings. Such an initiative is encouraged starting with an emphasis on business process, such as in engineering, and proceeding to program management, and eventually leading to the implementation of select additional investments in re-engineered processes such as via modern information technology.

Maturity, as manifest in demonstrated reliability, would be an item for generational advance and investment. Initial investments here would include an initiative to quantify where design technology maturity would best ripple through the entire system composed of all Categories, but at the NASA and program level.

III. Concepts for Life Cycle Cost Control

This Nation's ability to provide the development and operation of safe, dependable, affordable, and sustainable space transportation systems is still not being achieved.

The Saturn/Apollo lunar exploration program was terminated early because the recurring transportation cost was not sustainable while supporting the exploration efforts. The reusable Shuttle transportation system was developed to replace the Saturn launch vehicle in an effort to greatly reduce the recurring cost of transportation. Even though the recurring cost of space transportation systems operation was reduced approximately 50 to 60 percent, the reduction was not sufficient and did not approach the target goal.

During conceptual definition and DDT&E phases, the only major objective (system attribute) controlled in past and present programs by a structured engineering management process is performance closure by managing flight systems weight. The development is controlled using a systems breakdown structure (SBS) where major elements of the total system can be estimated, budgeted, and controlled throughout the development phase. The present cost estimating process bases cost on flight system dry weight and performs all trade studies optimizing each single flight system function, with no effort to address integrating the total systems considering all desired attributes. As an example, objectives were set for LCC for the Shuttle, but no engineering management processes were exercised to provide control (only the DDT&E cost was tracked). Because the objective was not treated as a requirement, it was not achieved. This traditional technique of controlling cost has not proven to work well in accomplishing the desired LCC control.

Therefore, to take maximum advantage of the "lessons learned" from the major space programs of the past decades, this paper has reviewed top-level results of a selected number of studies and analyses that have been conducted by the SPST. These directly address the "lessons learned" from previous transportation systems.

The major lesson identified from the Saturn/Apollo and Shuttle experience is that much improved, innovative processes must be developed and rigorously applied to effectively control LCC. Any future space transportation system LCC must be controlled throughout the entire architectural design concept phase, DDT&E phase, and its operations phase to provide a sustainable space exploration program. Since a major part of LCC for a space transportation system is the recurring or operational phase cost, this cost must be defined in the design concept phase and rigorously controlled throughout that and subsequent phases.

A major source of knowledge utilized by the SPST was a study conducted of the "shortfalls" of current space transportation systems (Space Shuttle) to determine and document the shortfalls that developed between initial requirements/objectives and the actual results achieved[1]. A major "lesson learned" from these activities is the importance of first clearly defining, flowing down, and controlling the systems requirements and maintaining control throughout the R&D Program. The SPST has emphasized the need to clearly define the requirements up front: that is the "what's" required of the desired space transportation system. To sum up this lesson learned, the way we do business must be changed to avoid "doing what we always do and achieving what we always got". Therefore, our engineering management processes must be changed to include a structured process to control those major operational functions that are major cost influences to provide the LCC controls required for a sustainable Space Exploration Program.

Insight gained from performing the shortfalls assessment stresses the need to perform optimization at the total systems level and not at the subsystem level (stove-piping).

These extensive studies by the SPST have shown the need of LCC control, but introduction has been a continuing problem as new programs have been implemented without such effective control. The SPST is recommending that the aerospace industry adopt the proven methods of controlling weight and performance and apply them to controlling cost.

A. Structured Process for Recurring Cost Control

Once the performance and LCC requirements have been flowed down, an addition to the engineering management processes must be made to add a new structured engineering management process modeled on the processes used in the past to successfully manage, track, and control weight. This process must be enforced by the program managers throughout the design, development, production, and operation of the program. The process should include contractual rewards and penalties for LCC compliance where contracting methods are exercised just as they are used for performance and weight. The objective is to establish LCC as a true requirement and to not let it become merely a "goal".

It is important to establish a structured process to control recurring costs across multiple levels and elements of a program

Figure 2 shows that at any particular level in the program there are elements being designed for that level. Each of the elements has requirements for mass, performance, and, assume, on non-recurring and recurring cost. Note carefully the flow of impacts shown in the figure. Level X can impose requirements on Suppliers A, B C, and D and on the Operations. And they can all give information on requirement compliance back to Level X. However, Operations and each of the suppliers have no ability to modify requirements to each other. Nonetheless, many of the

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decisions made by Suppliers A, B, C, and D directly impact and change the requirements on Operations. For example, each of the suppliers may require a heat exchanger of some sort. That heat exchanger will require a working fluid. Each of the suppliers will optimize its heat exchanger to best meet its own mass, performance, non-recurring, and recurring cost requirements (allocations). Unfortunately, since the internal environments of each supplier are probably different, the optimum working fluid choice will probably be different. If four working fluids are chosen (or even very different conditions of the same fluid, e.g., different types of purified water), then both the non-recurring and the recurring costs incurred by Operations will increase by about a factor of four in the area of building and maintaining the facilities and supplying the heat exchanger fluids.

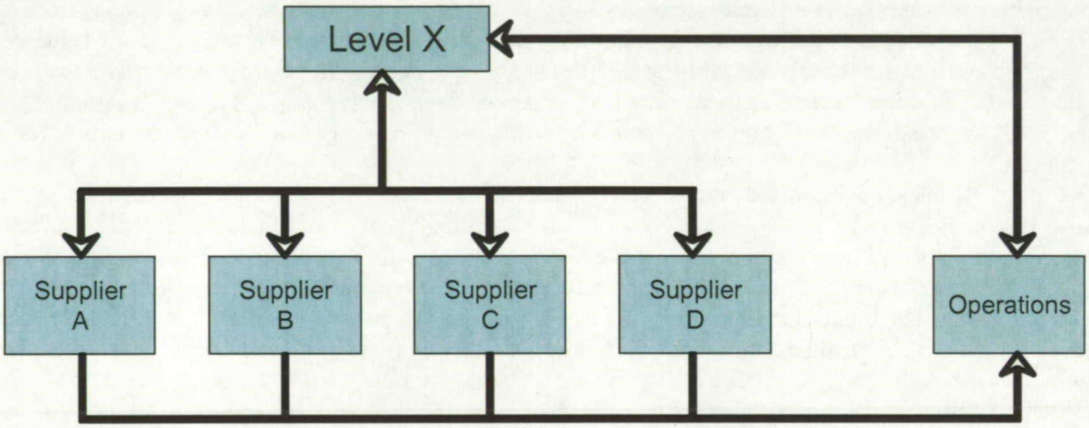

Figure 2. Requirements and Information Flow.

The point is that unless Level X uses its information flow from all the suppliers and operations to modify the choices of the suppliers, the resulting system may be far from meeting its recurring, and maybe even non-recurring, cost requirements, even though the system does meet its mass and performance requirements and each of the suppliers met their non-recurring and recurring cost requirements. If costs are requirements and not goals, and thus enforceable and tradable amongst the other requirements, then Level X can seek the optimum system choice regarding number of heat exchanger working fluids. The answer may be one or more depending on the degree of sub-optimal design needed to use specific fluids and the relative impact on the mass, performance, and cost of the choices.

To make this approach work, Level X must have the ability and will to modify the requirements to each supplier and operations in an expeditious manner to quickly reflect the system level trades. Thus, Level X must have the analytic tools, such as utility analysis, to trade between dissimilar requirements; the contract mechanisms to quickly modify requirements; and the budget to flow-down for re-design as necessary.

The SPST suggested improvement is to develop and implement a very active process of reallocating requirements to lower levels to achieve overall system requirements throughout the DDT&E program. This should be done across multiple dissimilar requirements, e.g., increase mass to lower recurring cost.

The LCC of the entire exploration architecture consists of the development and acquisition costs and the operations and disposal costs. For space transportation systems that will be in place for a long time, typical for U. S. space systems, the operations and disposal costs will dominate the LCC. New programs must be "sustainable", e.g., they must be within their specific budget and within their yearly budget caps both during procurement and throughout their long operating life. For this to be achievable, operability must be designed into the architectures and elements from the very beginning. Failure to achieve the budgeted transportation costs will squeeze the exploration budget and has the potential to severely impact the sustainability of the entire program.

The operations and disposal costs are determined, often without specific planning, during the system architecture definition and the individual element developments. It has been estimated that 80 percent of the design decisions are irreversibly made in the system architecture definition and the individual element development design phases.

It is very difficult during architecture definition to balance and minimize, or even compare, the overall LCC, including both development and acquisition costs and operations costs. This is primarily due to the lack of full definition of all the necessary functions of the potential architecture options. Different options have different levels of definition but still must be compared. And often not all of the supporting elements necessary for each architecture are identified at all. It is also very difficult during element developments, primarily due to schedule and budget pressures, to maintain the design discipline to ensure that operations costs will not escalate due to design decisions addressing immediate design, weight, performance, or development problems. The emphasis in design is to get the job done (i.e., achieve weight and performance) within the schedule and hopefully within the budget. When problems must be solved there is seldom the budget or schedule available to properly consider the operations cost impacts of the design options examined. Consequently, the future operations and disposal costs escalate to improve the currently incurred development costs.

Only if overall LCC, including operations, is a required metric, co-equal with weight and performance, can the LCC have any real chance of being controlled. In the past, goals for LCC were not a contractual requirement that was flowed down to the individual element developments with rewards and penalties equal to those for weight and performance. Consequently, LCC goals simply have not been met.

Requirements not flowed down, become "goals" and are rarely met.

B. Use of Functional Breakdown Structure

The SPST has also developed a new approach for formulating requirements that will provide full accountability of all functions required to perform the planned missions. The approach is to develop a top-level functional breakdown structure (FBS) with modular subsets that may be utilized as a basis for defining the desired "functional requirements" in any system.

The FBS is a structured, modular breakdown of every function that must be addressed to perform a 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 functional breakdown structure should be used to ensure that architecture options are compared fully and validly. Once the architecture is chosen that can meet the performance and LCC requirements, then the LCC and performance requirements must be allocated and flowed down to all lower tiers. The FBS should be used for this. LCC, or an LCC allocation, must be a requirement at each of the lower tiers.

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 developed Functional Breakdown Structure should be used to accomplish this difficult task.

The SPST has developed a preliminary space transportation system FBS including supporting elements for a manned exploration mission[2].

C. Design Cost Drivers

To control space transportation system LCC it is necessary to identify the major cost drivers. Design decisions drive the operations costs which then dominate the LCC.

The proposed Exploration Vision must be "sustainable" (i.e., it must be within budget and within yearly budget caps both during procurement and throughout its long operating life). For this to be achievable, operability must be designed into the architectures and elements from the very beginning. Indeed, NASA is attempting to implement this as shown by NASA NPR: 7120.5C dated February 2005. NASA Program and Project Management Processes and Requirements, Paragraph 6.2.3 Systems Engineering Requirements: The Project Manager and project team shall:

(a.) With the Program Manager, customers, and stakeholders, define a validated set of Level 1 requirements and success criteria for the project in Phase A.

(b.) Develop operations scenarios and concepts, mission profiles, and mission operational modes for the purpose of fostering a better understanding of operational requirements, including LCC drivers for logistics and maintenance.

To further this effort the Space Propulsion Synergy Team has developed, over a number of years and a number of separate tasks, a series of Technical Performance Metrics (TPMs) that would help assure sustainable, operational space transportation system architectures.

The shuttle shortfalls assessment provided insight into the major areas that needed improvement as well as to the kind of operational criteria that needed to be addressed. This assessment along with the operational areas identified by a "bottom-up" task allowed the formulation of the proposed operability design requirements technical performance metrics (TPMs). The "bottom-up task also provided the insight that a structured engineering management process would be required to budget and control the TPMs throughout the entire concept to DDT&E completion phases.

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.

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.

Target values, a reference value from the Shuttle for comparison, and a discussion of the impact of the metric is presented for each TPM. Further information is available in a Design Guide generated from the original study[3].

1. Total number of separate identified vehicle propulsion systems and/or separate stages

Metric Nominal Target Value: 2, e.g., Integrate MPS, OMS, and TVC and integrate RCS, Fuel Cell (FC) power and Thermal Management, i.e., low pressure storage vs. supper critical storage.

Shuttle Reference Value: Many systems in MPS, OMS, RCS, TVC, Thermal Management Systems and Life Support Systems (12 of these in orbiter).

Discussion: Traditional practice of designing separate standalone propulsion systems for ascent (MPS), reaction control (RCS), de-orbit and space maneuvering (OMS), and thrust vector control (TVC) could be provided by a single integrated system. This would result in a reduction in tanks, pressurization, and interface systems that will result in a very large reduction in flight hardware and ground support infrastructure. Traditional lack of integration adds un-necessary hardware that adds weight, many ground servicing interfaces at several ground stations and a very large logistics support infrastructure for replacement parts for both the flight and ground systems. It also reduces the reliability while decreasing the safety of the vehicle resulting in a very large added maintenance burden to the operations. These servicing interfaces may also become applicable in-space or at ground-node sites on the moon or mars. These separate flight systems also require additional turnaround time for servicing. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. This places a very large increase on the LCC of the program. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.
The number of separate stages: This impact will be exasperated and multiplied when considering the support infrastructure from all the added separate systems, plus stage interface systems, and their logistics supply chain. This places a very large increase on the LCC of the program.

2. Total number of flight tanks in the architecture.
Metric Nominal Target Value: 12, Low Pressure (LP) fuel, LP Lox, 2 gas pressurant tanks, 2 H_2O tanks, 2 GO_2 tanks, 2 supper critical storage fuel and 2 supper critical Lox tanks.
Shuttle Reference Value: In excess of 95.
Discussion: Every tank on the vehicle will require pressurization and down-stream feed distribution systems. This adds unnecessary hardware and flight weight, a very large logistics support infrastructure for replacement parts and a large ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces for servicing. It also requires logistics support for procurement, quality control verification, special cleaning processes etc. for replacement hardware. These impacts add very large cost (LCC) to the program and decrease the safety of the operation.

3. Number of safety driven functional requirements to maintain safe control of systems during flight and ground operations.
Metric Nominal Target Value: 7, 2 He bubbling of cryo for thermal conditioning, Lox turbopump seal purge, 2 cryo umbilical purges, 2 engine shutdown purges.
Shuttle Reference Value: In excess of 70.
Discussion: Critical functional systems like the Lox anti-geysering He purge, the Lox turbopump seal He purge, pogo suppression, hazardous gas detection systems, and compartment purges are examples of these functions. These functions are required to prevent loss of vehicle both on the ground and in flight. Reducing these functions by selecting an architecture that deletes its need will increase the safety and reduce hardware (weight savings) required providing a very large life cycle cost savings. These functions all increase the turnaround time and manpower to perform the O&M of these added systems as well as an increased flight hardware logistics support system. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

4. Number of maintenance actions unplanned before or between missions.
Metric Nominal Target Value: ≤ 1, Balancing the reliability, maintainability, and safety requirements should drive this result.
Shuttle Reference Value: ~ 800.
Discussion: The total number of active components either drives the needed component reliability level (increasing the DDT&E cost) or the use of redundancy needed to reach the desired system reliability to enable overall system safety. The traditional practice of using multiple string components and systems places a very large maintenance burden on the operations which drives the unplanned work content and time during turnaround on the ground, on the moon or mars and at ground nodes like lunar or earth orbit stations. This practice destroys the system integrity during turnaround and the need to recertify the system

for every flight. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

5. Number of maintenance actions planned before or between missions.
Metric Nominal Target Value: 0, Requirement for IVHM/Full automation should produce this result.
Shuttle Reference Value: ~ 2200.
Discussion: Limited life or expendable hardware along with required inspections or checkouts require access equipment, disrupt system integrity, and lengthen the turnaround time. The requirement for these functions will drive the need for every flight re-certification which is very costly. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

6. Total number of traditional ground interface functions required.
Metric Nominal Target Value: 4, Fuel, Ox, electrical and High Pressure (HP) gas.
Shuttle Reference Value: Hundreds.
Discussion: Every additional function adds ground support systems (GSE), facilities, direct labor and considerable indirect infrastructure and support. These added functions increase LCC and decrease safety. Some examples of these functions are mating operations, inspections, adding temporary environmental protection, planned maintenance, unplanned maintenance and replacing expendable items. These additional ground interface functions require added turnaround time for servicing. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. This places a very large increase on the LCC of the program. This impact will be multiplied when considering "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

7. Percent of all systems not automated.
Metric Nominal Target Value: 0% - IVHM, This is achievable if effort is made to make traditional mechanical hardware smart.
Shuttle Reference Value: (Inspections and checkout mostly manual).
Discussion: Many manual intrusive inspections and functional verifications are required before every launch. Also the many redundant subsystems and components that perform critical functions that could cause loss of life or vehicle must be verified before flight in order to establish there really are redundant capabilities. These manual functions require much labor and schedule time to perform. To effectively utilize the redundant hardware there needs to be an automated management capability to avoid a large ground monitoring capability needed to timely respond to failed critical hardware or subsystems. These traditional manual checkouts add large cost (LCC) to the program and decrease the safety of the operation.

8. Number of different fluids required.
Metric Nominal Target Value: 4, Fuel, Ox, HP gas, and water.
Shuttle Reference Value: 24 every flight.
Discussion: Each additional fluid requires a costly ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces. It also requires logistics support for procurement, quality control verification, special cleaning processes etc. Each fluid dictates at least one additional vehicle interface that must be serviced. Some of these fluids being toxic require a medical support operation to maintain reference information on each of the personnel being subjected to the possible exposure along with special training. Several of these toxic fluids also require the personnel to wear self-contained garments which also require a support group to maintain the garments. These impacts add very large cost (LCC) to the program and decrease the safety of the operation. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

9. Total number of vehicle element-to-element support systems (Major element interfaces such as Orbiter to SSME or ET).
Metric Nominal Target Value: 12, Fuel feedline, Ox feedline, Fuel repress line, Ox repress line, 2 electrical power, 2 data, 3 structural attachments (gimble and 2 TVC).
Shuttle Reference Value: Example is the SSME with 26 support systems from the Orbiter for each SSME.
Discussion: This adds unnecessary hardware that increases vehicle weight, a very large logistics support infrastructure for replacement parts and reduces the reliability while decreasing the safety of the vehicle and resulting in a very large added maintenance burden to the operations. This places a very large increase on the LCC of the program. Example of this practice on the Shuttle is the SSME requiring both hydraulics and pneumatics for valve control and both sub-systems use electromechanical components to effect the controls. The basic valve could be controlled by an electromechanical device eliminating the other support systems in their entirety.

10. Number of flight vehicle servicing interfaces.
Metric Nominal Target Value: 14, LH_2, Lox, HP He, 2 electric power, fuel cell reactant LH_2 and Lox, H_2O, 2 data, Cabin air, Waste removal, HP O_2 and HP N_2.
Shuttle Reference Value: ~102.
Discussion: Each additional interface requires a large ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces. This impact is repeated for every facility the vehicle occupies during the ground operation. It also requires logistics support for procurement, quality control verification, special cleaning processes etc. These interface systems require time and personnel to provide this connection and disconnection for each facility being used by the vehicle element. This adds considerable time and labor to the turnaround flow decreasing the vehicle's operational effectiveness. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add very large cost (LCC) to the program and decrease the safety of the operation. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

11. Number of confined/closed compartments.
Metric Nominal Target Value: 1, Crew Cabin.
Shuttle Reference Value: 13 or more.
Discussion: Closed compartments that provide possible entrapment of combustible gases/fluids require addition of purge systems, hazardous gas detection systems, and corrective actions when required to provide safe control of system. These compartments require an inert purge during hazardous operations, but require a conversion to a life supportable environment before personnel can enter to perform corrective action when required. All the above functions drive the need for added ground infrastructure/systems resulting in a large increase in cost and added turnaround time. Confined spaces limit access for planned operations and unplanned maintenance adding to the turnaround time and decreasing the safety of the operations. Added turnaround time drives the need for added vehicles and ground facilities/GSE adding even more cost. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and lunar, mars, and earth orbit stations.

12. Number of commodities used that require medical support operations and routine training.
Metric Nominal Target Value: 0 Toxics and 3 Special Training, Cryogenics, HP Gases, and Solid Propellants.
Shuttle Reference Value: 3 major and 3 minor toxic fluids.
Discussion: The use of toxic substances and fluids require the operating personnel to provide current reference data on their health and body functions so that in the event of exposure the medical personnel can provide the proper corrective action deemed necessary if accidentally exposed. Also working with cryogenics, high pressure gases, toxics, ordnance and confined environments require special training of operations personnel. This added support function adds life cycle cost to the ground operation. This impact will be exasperated and multiplied when considering servicing at "ground nodes" like the moon, mars, and

lunar, mars, and earth orbit stations as it will require handling and transport of these commodities to these other locations.

13. Number of safety driven limited access control operations.
Metric Nominal Target Value: 9, Pressurizing 3 fluids HP gas tanks to flight level, Servicing 2 super critical cryo fluids, Servicing 2 low pressure cryo fluids, and 2 heavy lift operations.
Shuttle Reference Value: In excess of 266 functions.
Discussion: This addresses confined compartments, hazardous operations like lifting large loads, working with ordnance/explosives, toxic substances/fluids, lasers or microwave energy devices, high voltage power, high pressure gases, cryogenics and x-rays. Limited access is required to limit the exposure to only those directly involved in that operation; therefore limiting the number of personnel required to take corrective action in the event of an unplanned event. Workings with these hazardous operations requires special training for personnel involved. These limited access operations have a very large impact on the turnaround time and support operations functions. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

14. Number of safing operations at landing (for reusable elements).
Metric Nominal Target Value: 1, Vent high pressure gas tanks to 50% level.
Shuttle Reference Value: 6.
Discussion: These added safing operations subject ground personnel to hazardous conditions, and adds considerable turnaround time. This safing operation requires dedicated ground support equipment for access and servicing, which adds considerable time and labor to perform the required maintenance and provide logistic support. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation. To provide both ground and water landing/recovery compounds this impact.

15. Number of mechanical element mating operations (element-to-element and element-to-ground).
Metric Nominal Target Value: Example 9 for each rocket engine, 2 low pressure feed lines, 2 HP repress lines, 2 electrical power/data connectors, 2 TVC attachments, gimble block support.
Shuttle Reference Value: Example there are 24 components mating between the one SSME and the Orbiter (A total of 72 total SSME mechanical connections to the Orbiter).
Discussion: Many mechanical mating operations requires lifting of large loads subjecting ground personnel to hazardous conditions, and adds considerable turnaround time. This mating operation generally requires a dedicated ground station for integration which adds considerable facility and ground support systems that again require maintenance and logistic support. Element to element mating functions require labor for connection and functional verification. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

16. Number of separate electrical supply interfaces.
Metric Nominal Target Value: Example 2 for each rocket engine to vehicle, 2 electrical power/data connectors.
Shuttle Reference Value: Example: there are 12 electrical components mating needed for each SSME to the Orbiter (A total of 36 total SSME electrical connections to the Orbiter).
Discussion: Each additional interface requires a large ground infrastructure for storage, distribution, and transfer operations to the vehicle interfaces. This impact is repeated for every facility the vehicle occupies during the ground operations. It also requires logistics support for procurement, quality control verification processes, etc. Element-to-element mating functions require labor for connection and functional verification. These impacts add large cost (LCC) to the program and decrease the safety of the operation. Distribution of unique electrical needs can be provided more efficiently on board without the added impact of driving this function to the ground side of the interface. This total system (flight and ground) improvement should even result in decreased vehicle weight.

17. Number of intrusive data gathering devices.
Metric Nominal Target Value: 0.
Shuttle Reference Value: Example is there are 45 intrusive sensors on each SSME.
Discussion: Intrusive instrumentation requires those systems being monitored to be drained and conditioned prior to replacement along with re-establishment of the supported system's integrity verification when replacement has been accomplished. This replacement operation is very costly in time and labor for fluid systems with emphasis on toxic and cryogenic systems. Even accessibility is a form of intrusiveness and can cause an operation of less than one hour to become four or five days (example: SSME engine controller replacement from an on-pad abort). These operations always drive additional turnaround time. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.

18. Number of Criticality – 1 (Crit-1) system and failure analysis modes.
Metric Nominal Target Value: TBD.
Shuttle Reference Value: Example is that there are 550 Crit 1 & 1R failure modes on each SSME.
Discussion: These Crit-1 failure modes require functional verification between flights and their backup redundant modes verified as well because of their criticality to the vehicle operation. More Crit-1 failure modes cause higher probability of failure (less safe operation and higher probability of loss of vehicle). The verification tasks, inspection, and checkout extend turnaround time and increase labor resulting in increased cost. Operations that add turnaround time drive the need for fleet support to meet the mission needs of the operation which require both additional flight elements and dedicated ground support facilities and equipment. These impacts add large cost (LCC) to the program and decrease the safety of the operation.
Integrated system fail-safe assurance: All designs from the total integrated system, sub-systems, down to the individual component should exhibit fail-safe assurance passively (inherent fail-safe feature within the design).

To implement item 4 above, it is important to balance the reliability, maintainability, and safety requirements. This is discussed in detail in a separate paper[4].

It is very difficult for every element and contractor within a program to know the impact of every decision it makes on the overall system. It is also very difficult for the upper levels of the program to be aware of every decision that might impact other elements and contractors and the overall system. This is true both during architecture trades and during DDT&E. Therefore the SPST suggests establishing and maintaining a registry of high recurring cost impact items. The extensive list of prioritized items that are the major recurring cost drivers just discussed above should be the categories in the registry. For example, if the number of different fluids, or number of toxic fluids, is increasing, a red flag should go up and questions of the necessity of the new fluids should be raised.

D. Use of Structured Mechanism for Design to Life Cycle Cost

Controlling life cycle costs also requires the use of a structured mechanism to implement a Design to Life Cycle Cost process. Design to life cycle cost should be a rigorous process. The foundation must be implemented and demonstrated during the early part of the vehicle design program and refined during its duration. It is a process where trades-offs among development, operational, performance, schedule, risk, DDT&E costs, and life cycle costs must be addressed on a continuing basis. An ability to control costs within stringent total program and fiscal constraints must be demonstrated early in the design development phase and must be carried through until the last day of operation of the vehicles developed under the program. Key features of a Design to Life Cycle Cost Management process include:

1. Cost credibility through the use of extensive cost databases to develop initial values and operation cost models to assure the credibility of initial, early estimates;
2. The ability to assess annual funding constraints while exploring alternative system concepts;
3. Use of a Design to Life Cycle Cost Management manager reporting directly to the program manager, thereby providing a high level, single point of contract;
4. A Design to Life Cycle Cost Management process which is an integral part of a performance management system, thereby assuring an integrated cost management system which is coupled with the technical performance measurement system to enhance the early detection of unfavorable trends;

5. Cost effective design solutions through system engineering control of the technical performance and operation cost assessments;
6. Early establishment of realistic but rigorous cost objectives and an emplaced, highly visible management processes and the discipline to achieve them.

The Design to Life Cycle Cost Management process should define and implement cost effective design improvements early in the design phase to assure visibility into production and life cycle cost trends; ensure prompt creditable cost, schedule and technical performance feedback on current status; and coordinate with responsible design engineers and functional managers to assist them in making effective and timely cost reduction decisions.

System engineering and the Design to Life Cycle Cost Management process should be jointly responsible for allocating system resource allocations and performance requirements; for identification of high risk or high cost components which are the major life cycle cost drivers that provide the greatest opportunity for design tradeoff; for technical management of system level cost/capability/risk tradeoffs; for analysis of technology selection impacts on program costs; and for monitoring design engineering technical performance against identified system capability goals. There should be a focus on both development and operational cost containment. If system cost projections exceed target values, design trades should be initiated to redefine system design characteristics to a level that supports system costs requirements.

As the design phase progresses the emphasis should shift to producibility and maintainability improvements that will benefit production and life cycle costs. An operations cost model should be used during the design process to provide operations cost impact data for design option selections. Operational life cycle costs must be continuously and rigorously evaluated as an integral component of overall system design.

IV. Conclusion And Recommendations

Based on study and analysis of several space programs, including the Space Shuttle, by the SPST, it is clear that past and current efforts to control life cycle costs have been inadequate and ineffective.

The "lesson learned" from these studies is that much improved, innovative processes must be developed and rigorously applied to adequately control life cycle costs. These improved/innovative process need to be enforced by the Program Managers throughout the design development, production and operation of the space systems that will be required for the Space Exploration Initiative missions.

It is believed that the improved life cycle control processes developed by the SPST and presented in this report will provide the necessary cost controls when properly applied in the future advanced systems.

In summary the SPST recommendations are:

1. Make both non-recurring and recurring costs a required metric, co-equal with weight and performance, and flow it down to the individual element developments with rewards and penalties in the same manner as used for weight and performance control.
2. Fully and clearly define competing architectures and alternate implementations of architectural elements.
   a. Use a functional breakdown structure (FBS) as a tool to accomplish this full definition.
   b. A preliminary FBS for Space Exploration has been developed and is available from the SPST.
3. Fully and clearly define the requirements at the program beginning.
   a. Use a functional breakdown structure (FBS) as a tool to accomplish this full definition.
4. Establish and maintain a registry of high recurring cost impact items.
   a. Use A Guide for the Design of Highly Reusable Space Transportation – Final Report, Space Propulsion Synergy Team (SPST), August 29, 1997.
5. Develop and implement a very active process of reallocating requirements to lower levels to achieve overall system requirements throughout the DDT&E program. This should be done across multiple requirements, e.g., increase mass to lower recurring cost.
6. Balance the safety, reliability, and maintainability requirements to provide controls on recurring maintenance burden to provide operational effectiveness and LCC control:
   a. Develop a thorough understanding of the cost dependence on reliability and maintainability tradeoffs;
   b. Develop a thorough appreciation of the coupling of maintainability and reliability;
   c. Use a methodology or process for developing and balancing quantitative safety, reliability and maintainability requirements.
7. Minimize the eighteen recurring cost drivers identified by the SPST.
8. Develop and use a structured mechanism for Design to Life Cycle Cost.

References

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[4] Rhodes, R. E., Donahue, B. B., Chen, T. T., "Space Transportation System Availability and Its Relationship to Life Cycle Cost", 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2009-5343, August 2009.