Report of the Nuclear Propulsion Mission Analysis Figures of Merit Subpanel

Quantifiable Figures of Merit for Nuclear Thermal Propulsion

Scope and Purpose

This is a report of the results of an inquiry by the Nuclear Propulsion Mission Analysis, Figures of Merit subpanel. The subpanel was tasked to consider the question of what are the appropriate and quantifiable parameters to be used in the definition of an overall figure of merit (FoM) for Mars transportation system (MTS) nuclear thermal rocket engines (NTR). Such a characterization is needed to resolve NTR engine design trades by a logical and orderly means, and to provide a meaningful method for comparison of the various NTR engine concepts.

The subpanel was specifically tasked to identify the quantifiable engine parameters which would be the most significant engine factors affecting an overall FoM for a MTS and was not tasked with determining "acceptable" or "recommended" values for the identified parameters. In addition, the subpanel was asked not to define an overall FoM for a MTS. Thus, the selection of a specific approach, applicable weighting factors, or any interrelationships, for establishing an overall numerical FoM were considered beyond the scope of the subpanel inquiry.

Background

The nuclear propulsion (NP) panels were formed to provide direction and guidance to NP studies as a result of the Space Exploration Initiative (SEI) program. While an implementation architecture has not yet been selected for the SEI, NP is utilized in many of the candidate architectures--most notably in those recommended by the Synthesis Group in the their report, *America at the Threshold*[1].

The definition, characterization, and evaluation of SEI architectures is an on-going activity. However, selection of a particular implementation may not occur for some period of time. Unfortunately, the perceived development time for a man-rated NP system is such that work must begin in the very near future to insure that it is operational by the earliest Mars mission dates. Therefore, it is desirable to determine what design criteria, or parameters, are the most important for a NP system. The NP FoM subpanel was formed to address this issue.

Groundrules and Assumptions

It was assumed that any later definition of an overall FoM for a MTS would be in accordance with the guidelines recommended by the Synthesis Group. Therefore, the overall program guidelines by which the parameters were selected and judged were those recommended in the Synthesis Group report. These guidelines are, in the order of importance recommended by the Synthesis Group: safety (which we refer to as risk), cost, performance, and schedule.

The parameters selected were considered on the basis of application to nuclear thermal propulsion (NTP) only. While many of these same parameters will undoubtedly be applicable to nuclear electric propulsion (NEP), selection of parameters for NEP will require a separate development due to the inherent differences between high- and low-thrust propulsion systems.

The parameters which are sought here are the NTP system-level metrics that have significant impact on the overall program guidelines. (However, to assess how the system-level parameters impact the guidelines, the linkage through the vehicle-level metrics must be identified.) In other words, we are interested in how the NTR engine system metrics impact program risk, cost, performance, and schedule.

Definitions

To minimize ambiguity it was found necessary to define some of the terms used in this activity so as to provide a common basis for discussion and evaluation. These definitions are provided here only to clarify the message of this report, and are not intended as NP program definitions.

Risk factors are defined as all those parameters which impact, either favorably or adversely, the possibility of catastrophic mission loss (vehicle and crew), mission loss (crew), mission failure (abort), reduced mission capability, or other losses external to the MTS [such as radiological hazards to people or the environment].

Cost factors are defined as all those parameters which impact, either favorably or adversely, the development cost, facilities cost, procurement cost, the operations and support cost. Thus, any factor which affects the total life-cycle cost of the MTS.

Performance factors are defined as all those parameters which impact, either favorably or adversely, the capabilities of the system. Since the performance of a MTS can be evaluated in several different ways, it is necessary to set the method of evaluation to ensure a consistent comparison. Thus, the *performance* is specifically defined as the IMLEO of the MTS for a fixed transit time and payload requirement.

Schedule factors are defined as all those parameters which impact, either favorably or adversely, the date of availability of a NTP, MTS system.

The definition of an *NTP* system, as used herein, is the combined components of the nuclear reactor, pressure vessel, expansion chamber and nozzle, and turbopumps, an all their directly related subsystems. In other words, the NTP [engine] system is defined as beginning at the turbopump inlets and ending at the nozzle exit.

Vehicle-level parameters are those items which are identified as parameters from an overall total vehicle standpoint. For example, IMLEO would be a vehicle-level performance parameter.

System-level parameters [NTP system] are those items which are identified as parameters from an engine standpoint. For example, engine thrust-to-weight ratio is a system-level parameter.

It is important to bear in mind that certain parameters have meaning for both vehicle and system levels. Reliability, for example, can be evaluated for the overall MTS (vehicle level), or for a NTP engine itself (system level). When considering these parameters, care must be taken to maintain a distinction between the vehicle and system levels.

Methodology

The approach to developing the FoM parameters was to build a hierarchy of system- and vehicle-level metrics under the overall program guidelines, similar to a hierarchical functional block diagram used in Systems Engineering. Initially, the subpanel identified a large group of candidate parameters. At this point, the candidate parameters were categorized as vehicle- or system-level parameters, with some falling into both categories.

Each of the candidates in the resulting set of vehicle-level parameters was then examined to determine whether or not it could have a significant impact on one or more of the program guidelines (risk, cost, performance, and safety). Those which did not appear to have a significant impact were discarded. The set of vehicle-level parameters was further categorized as to the perceived relationship to the guidelines: direct or indirect.

The candidate set of engine-level parameters was examined for traceability to the vehicle-level parameters; and NTP engine-level parameters not having such traceability were discarded. The remaining parameters were further distinguished by their relationships to their "parent" vehicle-level parameters. Again, as with the vehicle parameters, the NTP system parameters where characterized according to the perceived impact on the parent vehicle parameter. Finally, the engine parameters were examined and classified as quantifiable or subjective.

Results

The results are discussed from the standpoint of the hierarchy. The vehicle-level parameters are presented first; then, the [NTP] system-level parameters are given. It should be noted that the impact of the system parameters on the vehicle parameters (as well as the vehicle parameters on the overall guidelines) were subjectively distinquished. In many cases, it is plausible that a parameter may impact areas other than those identified. However, the identified impacts represent those items for which the subpanel felt the strongest relationships exist.

Vehicle-Level Parameters

The overall vehicle-level parameters are not all-inclusive but meant to be a representative set. The 7 vehicle-level parameters which were identified are objectively categorized according to their perceived relationship to the risk, cost, performance, and schedule guidelines. The relationships are further distinguished (subjectively) as being either direct or indirect. No ranking of these parameters is implied.

1. *Abort capability.* The heritage of the U.S. space program as well as current NASA policy dictate that all manned systems must possess abort capabilities to safeguard the lives of the crew. Obviously, abort capability has a direct relationship to risk. Abort capability has an indirect impact on performance since some abort options may require maneuvers which are not passive; that is, they require some level of propulsive capability.

2. *IMLEO.* The initial mass in low-earth orbit (IMLEO) [of a MTS] varies greatly with changes in transit time and payload. However, if the transit time and payload are compared on a consistent basis, IMLEO may be used as a primary indicator of performance. Therefore, by the definition of performance employed before, IMLEO has a direct impact on performance. In addition, IMLEO has a direct relationship to cost due to the cost of putting mass in LEO and due to the required assembly operations for large vehicle sizes.

3. *Number of critical systems.* The number of critical systems is directly related to cost. The number of critical systems will also have a direct effect on schedule, since all of the critical systems will be competing for [assumed] limited resources. The number of critical systems have an indirect effect on risk since the probability of a critical system failure is directly proportional to the number of critical systems.

4. *Operational flexibility.* The operational flexibility that exist for the various mission modes has a direct impact on the performance required of the vehicle. Therefore, it is assumed that some level of operational flexibility will be required in accord with the particular architecture that is selected. For example, an architecture that calls for

both opposition and conjunction class missions will require a great deal of operational flexibility. In addition, flexibility may indirectly affect risk and schedule, since flexibility may allow additional abort modes and may widen mission launch windows.

5. *Reusability*. If reusability of a MTS vehicle is required, this would have a direct impact on performance. In addition, reusability will have an indirect effect on cost and schedule due to the increased amount of testing that would be required to qualify the various systems for reuse.

6. *Vehicle cost*. The development and production costs of the vehicle will be a large fraction of the overall cost. Obviously, this is a direct cost impact. Vehicle cost will also have a direct impact on schedule due to [assumed] constrained funding.

7. *Vehicle redundancy, reliability, and simplicity*. The redundancy, reliability, and simplicity of the vehicle systems are inexplicably tied together. They have obvious, although indirect, impacts on risk and, if a high reliability philosophy is adopted, on schedule, as is the case for reusability. It may also affect performance in a second-order manner; i.e. redundant engines change the vehicle thrust to weight ratio, thus impacting g-losses.

The relationship of these vehicle-level items is summarized in Table 1. The table shows that each parameter affects two or three of the guidelines; however, none impact all four. The table also shows that the impacts are fairly well distributed among each of the four guidelines: risk, cost, performance, and schedule. Thus, it appears that the seven vehicle-level parameters chosen are a good representative set.

Table 1. Relationship of vehicle-level parameters to the overall guidelines.

	Risk	Cost	Performance	Schedule
Abort Capability	direct		indirect	
IMLEO		direct	direct	
No. Critical Systems	indirect	direct		direct
Operational Flexibility	indirect		direct	indirect
Reusability		indirect	direct	indirect
Cost		direct		indirect
Redundancy, Reliability, and Simplicity	indirect	direct		indirect

All of these seven parameters are quantifiable or qualifiable, at least to some extent, with the exception of item 4, operational flexibility, which is subjective. Items 1 and 5, abort capability and reusability, are simply yes/no qualifications. While the remaining items are quantifiable, it should be noted that items 6 and 7, vehicle cost and redundancy/reliability/simplicity, are traditionally difficult to quantify a priori.

System-Level Parameters

A large list of NTP system-, or engine-level parameters was identified and examined with respect to the above list of seven vehicle-level parameters. Those not having a demonstrable impact on any of the vehicle-level items were eliminated. The 13 remaining NTP engine-level parameters are identified below with a discussion of their traceability. Again, their relationships to the higher (vehicle) level parameters are characterized (subjectively) as direct or indirect.

1. *Damage tolerance.* The ability of the system to operate at full or reduced capacity subsequent to sustaining damage directly impacts the vehicle's abort options. The damage tolerance may indirectly affect the vehicle operational flexibility and reliability items.

2. *Development cost.* The development cost, including the facilities cost, directly impacts the vehicle cost.

3. *Ease of startup/shutdown.* The ease with which the engine maybe operated in the transient mode directly impacts the vehicle simplicity item and may indirectly impact the vehicle's abort and operational flexibility items.

4. *Fuel erosion rate.* The fuel erosion rate directly impacts reusability and may indirectly impact the operational flexibility considerations.

5. *Neutronic interaction.* This item is only important if multiple (clustered) engines are to be used. In that case, neutronic interaction directly impacts the vehicle simplicity and indirectly affects operational flexibility and redundancy considerations.

6. *Number of engine components.* The number of critical engine components directly impacts the simplicity, reliability, and redundancy considerations. The number of engine components also indirectly impacts the cost.

7. *Operational lifetime.* The operational lifetime directly impacts the vehicle reusability and reliability considerations. It also may indirectly affect the operational flexibility and abort options.

8. *Production cost.* The cost of production (this is clearly closely related to item 6, the *number of engine components*) directly impacts the vehicle cost.

9. *Redundancy, reliability, and simplicity of engine.* The redundancy, reliability, and simplicity are closely related characteristics. Taken as a whole they directly impact the vehicle redundancy, reliability, simplicity, and may indirectly affect abort considerations.

10. *Restart capability (number of restarts).* The restart capability directly impacts vehicle reusability and indirectly affects the operation flexibility.

11. *Effective specific impulse.* The effective specific impulse (effective means that the degradation due to startup/shutdown transients and cool-down is included) of the engine is a direct driver of vehicle IMLEO. The specific impulse may also impact the operational flexibility in an indirect manner.

12. *Technology readiness level.* The technology readiness level (this is will obviously have a large impact on item 2, *development cost*) is indirectly related to vehicle cost.

13. *Thrust/weight ratio.* The thrust to weight ratio has a direct relationship to the vehicle's IMLEO due to gravity losses during the earth departure burn (this may be greatly minimized by multi-burn departure schemes and may become a much less significant factor).

Of these 13 NTP engine-level parameters, all are quantifiable to some degree except for item 3 (*ease of startup/shutdown*). Although it maybe possible to define a quantification for this item, it would be difficult to remove all subjectiveness. In addition, it should be noted that items 1 (*damage tolerance*), and 2 (*development cost*) may be difficult to accurately quantify a priori.

To determine which of the guidelines (risk, cost, performance, and schedule) are impacted by an individual NTP engine-level parameters, the traceability must be examined from the engine system level up through the vehicle level. For example, item 3 (*ease of startup/shutdown*) impacts the vehicle-level parameters of simplicity, operational flexibility, and abort considerations. These vehicle-level parameters in turn impact, at least to some degree, all of the overall guidelines.

A summary of the relationships of the NTP system-level parameters to the MTS vehicle-level parameters is presented in Table 2. This table shows some interesting results. Notice that none of the system parameters appear to impact the vehicle parameter *number of critical systems*. While this may not be true for NEP systems, apparently we can ignore this vehicle parameter for the NTP systems. The table also indicates that the vehicle parameters *operational flexibility* and *redundancy, reliability, and simplicity* are impacted by more of the engine parameters than any of the other vehicle-level parameters. Interestingly, most the engine parameters that affect vehicle *redundancy, reliability, and simplicity* do so in a direct manner; while those that affect *operational flexibility* do so in an indirect manner.

Table 2. Relationship of system- to vehicle-level parameters.

	Abort	IMLEO	Systems	Flexibility	Reuse	Cost	R/R/S
Damage Tolerance	direct			indirect			indirect
Development Cost						direct	
Startup/Shutdown	indirect			indirect			direct
Fuel Erosion				indirect	direct		
Neutronic Interaction				indirect			direct
No. of Components						indirect	direct
Operational Lifetime					direct		direct
Production Cost						direct	
Redun/Relia/Simplicit	indirect						direct
Restart Capability				indirect	direct		
Effective Specific Imp.		direct		indirect			
Tech. Readiness Lvl.						indirect	
T/W Ratio		direct					

The preceding discussion demonstrates that a comprehensive FoM for a MTS is a function of many of the NTP system-level parameters. Therefore, we must not only consider such things as specific impulse and thrust-to-weight ratio in the analysis of candidate NTP systems. In other words, a meaningful analysis of such NTP systems cannot be conducted by a simple comparison of one or two parameters.

Conclusions and Recommendations

The NTP engine parameters presented herein are submitted and recommended for use as parameters in the NP program. It was found that the relative "goodness" of any particular NTP concept cannot be ascertained by using only one or two engine metrics.

Moral: Let's not make specific impulse and thrust/weight ratio our gods.

Thus, a group of 13 engine-level parameters are suggested, of which 12 are quantifiable. In addition, the hierarchy by which these parameters were developed is suggested as an initial model for the relationships of these parameters to the overall vehicle factors.

Recommendation 1: Adopt all 12 of the quantifiable engine parameters as metrics for the evaluation of competing NTR concepts.

A prioritization, or weighting of these parameters is not suggested at this time. This is due to a lack of information on how all of the NTR system parameters impact the vehicle parameters. While the relationships of some of the parameters are well understood, this is not true for all of them. In addition, some of the relationships between the parameters may vary for differing concepts--such as for high-pressure solid core and low-pressure solid core NTRs.

It is also important that methods be defined for how each of these 12 items are to be quantified in order to ensure similar comparison of the competing NTP systems. One way to do this would be to form an evaluation panel which would be tasked with determining the values of each of the quantifiable FoM for all of the competing concepts.

Recommendation 2: Adopt standard definitions for how each of the 12 NTR parameters (metrics) are to be quantified.

Obviously, a study is needed to examine the relative sensitivities of the vehicle-level parameters to the underlying NTP engine-level parameters. These sensitivities will provide a method of determining the appropriate ranking, or weighting, of the system parameters as to how they affect the vehicle parameters. Determining as well as understanding these sensitivities will be crucial to the development of an overall, comprehensive FoM.

Recommendation 3: Commission a study to define the relative sensitives of the 7 vehicle (MTS) parameters to the 12 quantifiable NTR parameters. From these sensitivites weighting factors can be developed.

It is important to distinguish that what the subpanel has identified herein is not a sea of many FoMs, but rather a set of applicable NTR engine risk, cost, performance, and schedule parameters that must be included in the subsequent development of any overall, comprehensive FoM.

Recommendation 4: Whenever an overall, comprehensive FoM is defined for the SEI program, adopt the 12 NTR parameters into that framework for evaluation of candidate NTP systems.

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References

1. Synthesis Group Report: *America at the Threshold--America's Space Exploration Initiative*. Available from the Superintendent of Documents, U.S. Government Printing Office, Washington D.C. 20402.

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6. AUTHOR(S)

Davy A. Haynes

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NASA Langley Research Center
Hampton, VA 23665-5225

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