AIAA 2004-3534

APPLICATION OF RECOMMENDED DESIGN PRACTICES FOR CONCEPTUAL NUCLEAR FUSION SPACE PROPULSION SYSTEMS

Craig H. Williams*
NASA Glenn Research Center
Cleveland, OH 44135
(216) 977 – 7063

ABSTRACT

An AIAA Special Project Report was recently produced by AIAA's Nuclear and Future Flight Propulsion Technical Committee and is currently in peer review. The Report provides recommended design practices for conceptual engineering studies of nuclear fusion space propulsion systems. Discussion and recommendations are made on key topics including design reference missions, degree of technological extrapolation and concomitant risk, thoroughness in calculating mass properties (nominal mass properties, weight-growth contingency and propellant margins, and specific impulse), and thoroughness in calculating power generation and usage (power-flow, power contingencies, specific power). The Report represents a general consensus of the nuclear fusion space propulsion system conceptual design community and proposes 15 recommendations. This paper expands on the Report by providing specific examples illustrating how to apply each of the recommendations.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) modified its long-range Agency goal in the mid-1990's to include expanding human presence throughout the solar system. To guide NASA in accomplishing its long range goals, a rational approach for long term research and development must be clearly articulated. In 1998, after a 20 year hiatus, NASA re-established modest funding for very advanced space propulsion research, particularly nuclear fusion. Many conceptual vehicle designs emerged to guide technological research and development in this area. But comparing performance capabilities and assessing scientific/engineering credibility was difficult due to widely varying study assumptions. It soon became apparent that the figures of merit associated with these goals were not sufficiently established, inhibiting clarity in linking funding for experiments to credible vehicle conceptual designs. While the advent of human exploration of the solar system remains a long-term NASA goal, funding for advanced propulsion concepts wax and wane, though usually at extremely modest levels. It is therefore imperative that the meager funds be spent on well defined concepts, with realistic system and performance parameters that offer the best chances for success in the opinion of many in the NASA and U.S. Department of Energy (DOE) communities. In 2003, funding for very advanced space propulsion research, including nuclear fusion, was terminated. The future of this technical area remains unclear.

The impetus for authoring the AIAA Special Project Report titled, "Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems" [1] in 2003 was to establish a standardized set of design practices to be employed in conceptual engineering design studies of nuclear fusion space propulsion systems. A concerted effort was made to codify design practices that were balanced between being too detailed and all encompassing (thus an unwarranted burden to implement) and being too general and incomplete (thus not meaningfully improve fundamental aspects of a design). It included a generic mass properties template, power flow diagram, recommended design margins, design reference missions, recommended mass and power contingencies, and general guidelines for depth of engineering design detail and degree of extrapolation from existing scientific and engineering knowledge. The recommendations made in that document were intended to facilitate equitable comparisons between system concepts and to improve their overall technical quality. The Report represented a general consensus of the nuclear fusion space propulsion system conceptual design community. The intent was to provide technically experienced senior engineers (who may not be fully cognizant of all primary aspects of nuclear fusion space propulsion system design) useful guidance in the development of credible concepts. Much of the text in this paper emanates from that AIAA Report (currently in peer review) which was edited by an AIAA working group within a standing Technical Committee.

* M.E., P.E./Aerospace Engineering , Associate Fellow AIAA

EXAMPLE FUSION VEHICLE CONCEPT

Throughout this paper, a fusion vehicle concept will be utilized to illustrate how to implement the various recommendations put forward in the Report. The latest version of the conceptual nuclear fusion propulsion concept incorporated most (though not all) of the design philosophies proposed in the Report. A recent series of NASA Glenn Research Center papers detail the engineering parameters and related material for the magnetic fusion-based concept. [2, 3,4,5,6,7,8]

The example vehicle concept was originally referred to as the "*Discovery II*" and is illustrated in Figure 1. The rotating crew payload was forward of the propulsion system. It was linked to the central truss through a fixed central hub, which also attached to the avionics suite and truss booms supporting the communication antennas. The forward central truss supported the two, co-planar, low and high temperature heat rejecting radiators. Along the outside of the mid-central truss were four slush hydrogen propellant tanks. Within the mid-central truss was the D^3He fuel tank and refrigeration system for all propellant/fuel tankage. Throughout the central truss were also various data, power, coolant, and propellant lines. Within the aft central truss was the Brayton power conversion system. Also within the aft central truss were the power management and distribution system, the refrigeration system, the start/re-start reactor and battery bank. Running the entire length of the central truss was the fuel pellet injection system. Aft of the central truss were the spherical torus nuclear fusion reactor, fast wave heating, and the magnetic nozzle. The overall vehicle length was 240 m. The longest deployed system dimensions were the 203 m central truss and the 25 m heat rejection (radiator) systems. The maximum stowed diameter for any individual system, however, was limited to 10 m so as to fit within the envisioned payload fairing, facilitating launch and on-orbit assembly. The fully tanked initial mass in low Earth orbit (IMLEO) was 1,690 mt.

Table 1 illustrates the mass property summary for the fully loaded stack. The "payload mass" was 172 mt and consisted of useful payload only. The "fuel" was 11 mt of D^3He for the nuclear fusion reactor. The slush hydrogen "propellant mass" was 861 mt and was used for main impulse, reaction control, reserves, and losses. It did not include system or tankage mass. The total structure mass was 646 mt and referred to all mass required to operate the propulsion system, including weight growth contingency.

Table 1: Vehicle Mass Property Summary

Payload			172
	Structure	38	
	Shielding	69	
	Crew systems	25	
	Weight growth contingency	40	
Structure			646
	Central truss	6	
	Fusion reactor	310	
	Magnetic nozzle and divertor	6	
	Reaction control	16	
	Power conversion	30	
	Coolant system	11	
	Fast wave plasma heating	5	
	Propellant cryo-tankage	88	
	Refrigeration	2	
	Fuel tankage and injector	6	
	Startup/re-start fission reactor	10	
	Battery bank	5	
	Avionics and communication	2	
	Weight growth contingency	149	
D^3He fuel			11
Hydrogen	propellant		861
	Main impulse	807	
	Reaction control	20	
	Flight performance reserve	8	
	Residuals/losses	26	
------------	------		-------
IMLEO	(mt)		1,690

QUANTIFYING FIGURES OF MERIT

A top-down, requirements-driven design process had been proposed to quantify the ranges of mission-level figures of merit (FoM)[6, 7, 9, 10]. The most demanding requirements usually came from piloted, outer solar system missions expected within the 21st century. These generally had mission distances of 10's of AU, required adequate payload mass fractions (5% to 15%), multi-month trip times, and initial mass in low Earth orbit (IMLEO) of no more than a few 1,000's mt [6, 9]. Although several advanced propulsion concepts could, in theory, provide this caliber of performance, it is the judgment of many that some type of direct nuclear fusion space propulsion was the leading technology that could reasonably be expected to offer this capability.[1] Further, a consensus (though not unanimous) agreement was arrived at among the participants in a series of fusion community Technical Interchange Meetings (TIM) that mission-level FoM rather than engine / reactor-specific FoM, should be the primary focus of the designer's attention.[1] It was emphasized during the TIM, and is repeated here for clarity, that a considerable amount of analytic work exists in the

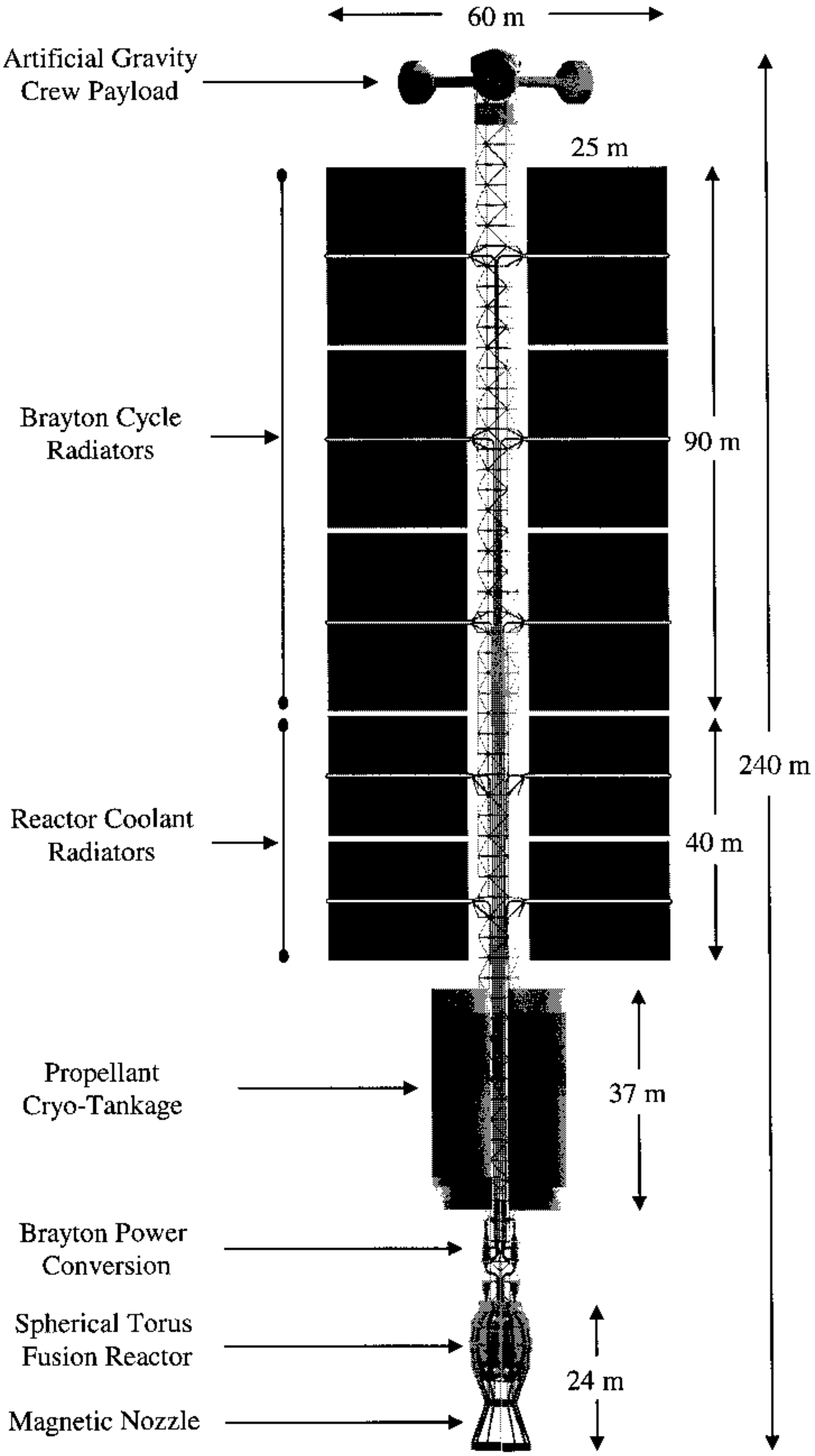

Figure 1: The Discovery II Vehicle

published literature pertaining to selection and evaluation of mission and propulsion system FoM for human interplanetary missions; the most recent of these were evolved during NASA's Space Exploration Initiative (SEI) of 1988-92.[11, 12] In this regard, care should be exercised and literature searches employed by vehicle designer and mission planner alike to take advantage of, and to be consistent with, the wealth of published information already in existence.

Specifying the ranges of such mission-level FoM tended to bound the necessary propulsion system operating parameters such as specific impulse (I_{sp}), specific power (α), and nozzle jet efficiency (η_j) [10]. Such missions were found to be optimized (minimized trip time and maximized payload mass fraction) for vehicle system I_{sp} and α between 20,000 to 50,000 lbf•sec/lbm and 5 to 50 kW/kg respectively.[6, 9] Nozzle jet efficiency had to be carefully evaluated because in a great many instances, a minimum value existed below which a zero payload mass ratio resulted.

These operating parameters are a function of a set of primary vehicle system characteristics. Choosing a technically sound, defendable, and consistent set of these characteristics is a decision the concept designer must make. The decision should strive for clarifying the underlying reasoning behind the major technology choices embedded in the conceptual design. The primary vehicle system characteristics, whatever set they are chosen to be, are the focus of the engineering design effort and must be iterated until a self-consistent system design results that also satisfies mission requirements. Calculating these characteristics in a technically defendable manner is the focus of much of this document through its recommendations on ground rules and practices for mission and vehicle system characteristics. The relationships between these characteristics, their operating parameters, and the resultant FoM are illustrated in Figure 2.

RECOMMENDED GROUND RULES AND PRACTICES FOR CREDIBLE CONCEPTUAL DESIGNS

Differing ground rules and assumptions frequently lay at the crux of widely varying conclusions in past conceptual design studies of nuclear fusion propulsion. These studies sometimes also lack sufficient sub-system assessments, leading to overly optimistic reporting of vehicle performance and the inability to ascertain how well a concept satisfies given mission requirements or FoM. Use of a common set of ground rules on how mission and vehicle systems are characterized (similar to some past NASA vehicle studies), including a minimum set of FoM, would mitigate much of the most serious problems. For these reasons, the design standards herein include a set of generic design recommendations grounded in historic NASA and DOD space launch vehicle development data, and DOE scientific community experience in nuclear fusion research. Only then can concepts be judged on how well they satisfy requirements, and be fairly and meaningfully compared to competing concepts. These standards focus on aspects of fusion propulsion conceptual design having the greatest

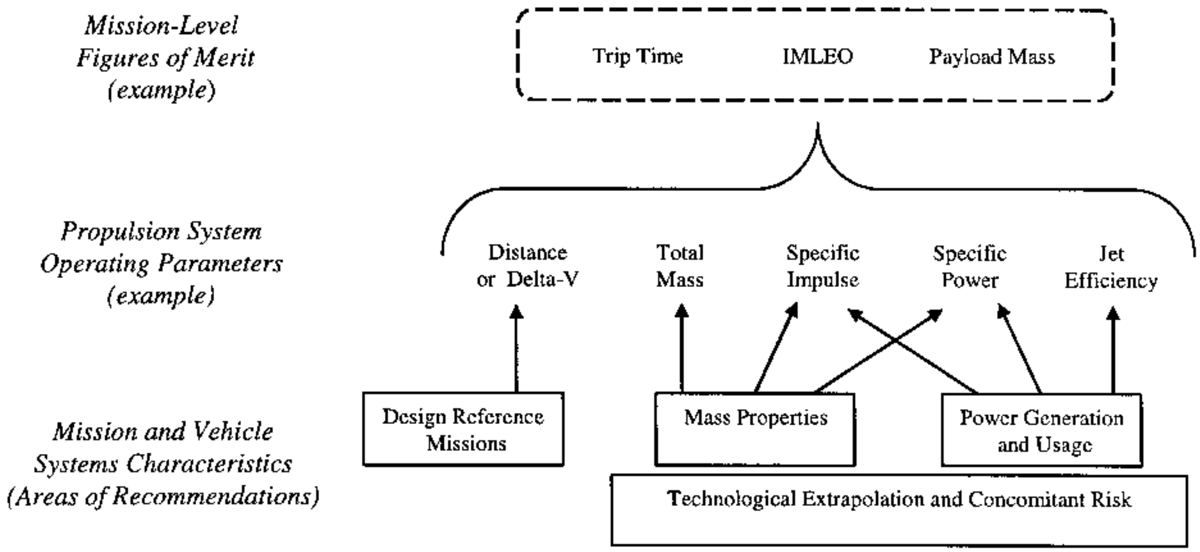

Figure 2: Relationships Between Example FOM's, Operating Parameters, and Recommendations on Mission/Vehicle Systems Characteristics

leverage: Design Reference Missions; Degree of Technological Extrapolation and Concomitant Risk; Mass Properties; and Power Generation and Usage. The overall quality and credibility of concepts can be improved by adopting a reasonable set of minimal ground rules in each of these areas. Further, they can serve to focus attention on key, technical issues that have a significant impact on propulsion system design and related laboratory experiments.

Design Reference Missions

The definition of a mutually agreed upon set of specific, design reference missions is needed to facilitate system design (notably propellant loading, tankage, and payload) and to enable the meaningful evaluation and comparison of FoM. A large amount of parametric mission data from several past studies of nuclear fusion propulsion concepts already exists in the literature.[13, 14, 15, 16, 17, 18] This historic data, and other related work [10], was used to guide TIM participant discussions on the appropriate ranges of missions best suited for fusion propulsion. Based on the potential capabilities of fusion propulsion systems, three design reference missions and operating scenarios of varying degrees of difficulty are provided in this design document. Arbitrary missions based on distance (e.g. 10,000 AU) were avoided and instead missions were selected predicated on scientific needs and on what might be valued by the public. Two of the reference missions proposed are piloted expeditions to locations where scientifically interesting worlds will eventually compel human in situ exploration. These missions could be a Martian search for life through a "south-pole-type, human outpost", and a follow-on to the discussed robotic "submarine" mission to the Jovian moon Europa. Outer solar system missions continue the logical progression of human space exploration planning from near-term, inner solar system destinations (i.e. the Moon and Mars) to further-term exploration. And because outer solar system destinations are ~ 1 to 2 orders of magnitude farther than those in the inner solar system, they will likely require the types of revolutionary improvements in propulsion encompassed by fusion-based systems.

Because no single design reference mission can adequately reveal the attributes and shortfalls of varying propulsion technologies, three missions are proposed that span ranges of mission objectives. The first mission is a piloted trip to Mars. Though it does not require fusion propulsion, it serves as a benchmark against which to compare fusion propulsion concepts with other more near-term propulsion technologies. The second reference mission is a piloted rendezvous to the Jupiter moon Europa, which is more typical of an outer solar system mission requiring an advanced propulsion technology such as fusion. A Jupiter / Europa mission would have demanding performance requirements, is scientifically interesting due to the possibility of life under its surface requiring human presence for investigation, is dominant in size among most moons, has an abundance of accessible hydrogen for propulsion application, and would be in proximity to an ample supply of fusion fuels D_2 and ^3He in the planet's atmosphere. The third reference mission constitutes a stretch goal: the rendezvous of a robotic observation platform to the Sun's gravitational lens focal plane, and providing cross-tracking maneuver capability.

The human payload masses recommended here are order-of-magnitude estimates scaled from existing piloted Mars and Jupiter mission studies. [2, 19, 20, 21] They provide for a six-person crew, partial (0.2 g) artificial gravity, adequate ambient radiation shielding, and sufficient provisions for trip times recommended below. Should the concept designer choose to incorporate vehicle / propulsion system-specific artificial gravity or ambient radiation shielding into the crew payload, separate payload mass relations are recommended below. Total round trip times are specified in order to ensure a mission design, which incorporates valid relative planetary orientations into the trajectory. The planetary stay time is left unspecified, is exclusive of the transit time requirements, and is considered to be mission peculiar. The piloted trip times are somewhat arbitrary, but representative of long duration human experience in low Earth orbit and consistent with some current Mars mission studies. The payload mass and cross-track requirements for the robotic mission were scaled up from one of the most ambitious current robotic missions. [22] Due to the implicit potential of many fusion propulsion systems to provide sufficiently large thrust-to-weight ratios, mission planners are allowed wide latitude in ΔV requirements, orbital parameters, and departure / arrival dates; hence these parameters are left unspecified. Designers are encouraged to include some discussion of launch manifesting, abort scenarios, vehicle system redundancy, vehicle re-use, fusion reactor lifetime, and ultimate reactor or vehicle disposal options; though such topics are generally thought of as being beyond the scope of the type of studies considered here.

Although the three-point design reference missions facilitate comparisons between fusion propulsion concepts, system designers should also consider including other missions that might represent the capabilities of their concepts more fully. A multi-mission design might lead to lower mass to Earth orbit

Table 2 : Performance Analysis Results

Destination	Jupiter	Saturn
Mission type	Rendezvous	Rendezvous
Travel distance (AU)	4.70	9.57
Specific power (kW/kg)	8.62	~ same
Specific impulse ($lb_f sec/lb_m$)	35,435	47,205
Payload mass (mt)	172	same
IMLEO (mt)	1,690	1,699
Trip time (days)	118	212
Jet power (MW)	4,830	same
Jet efficiency	0.8	same
Thrust (lb_f)	6,250	4,690
Total flow rate (kg/sec)	0.080	0.045
Exhaust velo/char velo	0.92	~ same
Initial thrust/mass (milli-g)	1.68	1.25

per mission than other concepts, optimizing a lifetime-mass-to-orbit FoM. A designer might also choose to depart from the presumption of piloted missions and instead consider payload mass fractions well in excess of 15%; as might be the case for unpiloted propellant tugs or robotic positioning of massive human assets prior to their arrival.

Recommendation #1

System designers should analyze the performance FoM (trip time, payload, IMLEO, etc.) of their fusion propulsion concepts against at least one of the design reference missions below.

Departure orbit: low Earth orbit (300 – 400 km altitude circular, 28.5° inclined or comparable stable orbit)

Reference Missions:

1. Piloted Mars round trip, 150 mt total useful payload to Mars orbit, total round trip transit time ≤ 6 months (not including planet stay time)

2. Piloted Jupiter/Europa round trip, 175 mt total useful payload to Europa orbit, total round trip transit time ≤ 2 years (not including planet stay time)

3. Robotic gravitational lens (550 AU) rendezvous only, 10 mt useful payload, ≤ 10 year one-way trip time, 2300 m/sec^2 cross-track

Example of Recommendation #1

Table 2 contains the overall performance analysis results for the *Discovery II* for half of Reference Mission #2. All vehicle mass properties were fixed, as were others such as: power out of the reactor, η_J, α, and velocity ratio. The I_{sp} , thrust, and propellant flow rate were thus mission peculiar, dependent variables. The Earth-to-Jupiter rendezvous mission thrust was 6,250 lb_f, I_{sp} of 35,435 $lb_f\,sec/lb_m$, and had a propellant flow rate of 0.079 kg/sec. Rendezvous missions were integrated for the optimal departure dates. The payload module for the Jupiter mission was 172 mt, 3 mt less than that specified in Recommendation #1. This could easily be increased with negligible increase in trip time. The 118 day (~4 month) trip time to Jupiter (significantly less than the <2 year round trip time) was rapid compared to those of representative alternate concepts, where similar rendezvous mission trip times using chemical or even nuclear thermal propulsion would be measured in years.

Recommendation #2

If an artificial gravity system and/or ambient radiation shielding for crew is designed, the useful payload mass should be set according to:

130% of [(X (mt) + artificial gravity system (or 25 mt) + ambient radiation shielding (or 70 mt)]

(where "X" is 20 mt and 40 mt for reference missions #1 and #2 respectively)

Identify/quantify required space infrastructure (LEO to HEO tugs, space bases, ISRU facilities, etc.)

Example of Recommendation #2

In recent years, NASA's Human Exploration and Development of Space organization has begun to focus on two of the most difficult obstacles to long duration human interplanetary travel: the detrimental effects of weightlessness and radiation on the human body. These two areas will have significant impacts on human payload design studies, and are the main reason for the *Discovery II's* new payload system. In addition, the nominal crew size of six (with sufficient accommodations and supplies for twelve) necessitated a crew payload larger than most current concepts.

The crew payload was comprised of three rotating Laboratory/Habitation (Lab/Hab) Modules attached to the fixed Central Hub via three connecting Tunnels (Figure 3). The Lab/Hab Modules were the primary laboratory and habitation facilities for the crew, and where most of the astronauts' time would be spent in a constant 0.2 g artificial gravity environment. The total mass attributable to the artificial gravity system was approximately 23 mt of the 38 shown in Table 3 (compared to the generic 25 mt specified in Recommendation #2.) The equation within Recommendation #2 for the example concept would be:

$$130\ \%\ [(25+15)+23+69]=172\ mt \qquad (1)$$

Table 3 : Payload Mass Properties

Structure			38
	Lab/Hab modules (3)	7	
	Central hub	4	
	Tunnels (3)	2	
	Airlocks (3)	1	
	Structural beef-up	3	
	Power management	2	
	Avionics	1	
	Life support	12	
	Thermal control	4	
	Rotation start/stop RCS	2	
	Payload adapter	~ 0	
Shielding			69
	Storm shelter	47	
	Nominal radiation	13	
	Thermal	1	
	Micrometeoroid	1	
	Containment hull	7	
Crew systems			25
	Accommodations	8	
	Consumables	10	
	Crew/suits	3	
	EVA equipment	2	
	Science	2	
Weight growth	contingency		40
------------------	--------------------------		-----
Total (mt)			172

Table 4 : Space Operation Characteristics

Mission type	rendezvous
Maximum range (AU)	~ 50
Maximum duration (months)	12
Departure/arrival planetary orbits (C3)	~ 0
Infrastructure required per planet	
Crew transport (low orbit to C3~0)	1
Propellant/deuterium ISRU plant	1
Propellant tankage (autonomous)	4
Atmospheric miner (^{3}He)	1
Number of propellant re-supply launches	4
Propellant/deuterium ISRU source	major moon
Vehicle staging or drop tanks	no
Vehicle life	reusable

The Central Hub was heavily shielded to serve as the storm shelter for ambient high radiation events. Multi-month trip times through interplanetary space have the concomitant danger of exposure to lethal doses of ambient radiation unless the crew payload is adequately shielded. The most serious concerns lie with galactic cosmic rays (GCR) and solar proton flares (both ordinary and large). The total mass attributable to the radiation/other shielding system was 69 mt (compared to the generic 70 mt suggested in Recommendation #2).

The *Discovery II* was designed for interplanetary cruise only. Table 4 illustrates selected space operation characteristics. A high altitude, sub-parabolic orbit (C3 ~ 0) space basing obviated the need for multi-week spiral escapes and captures at its origin and destination. These departure/arrival orbits could be low lunar, lunar-altitude, or Lagrange orbits at the Earth, and at high major moon or sub-parabolic orbit at the major planet destinations. It was envisioned that steady state operation (following initial assembly in LEO, pre-deployment of infrastructure) would consist of direct flights to the outer planets, with only refueling operations taking place prior to return (Figure 4).

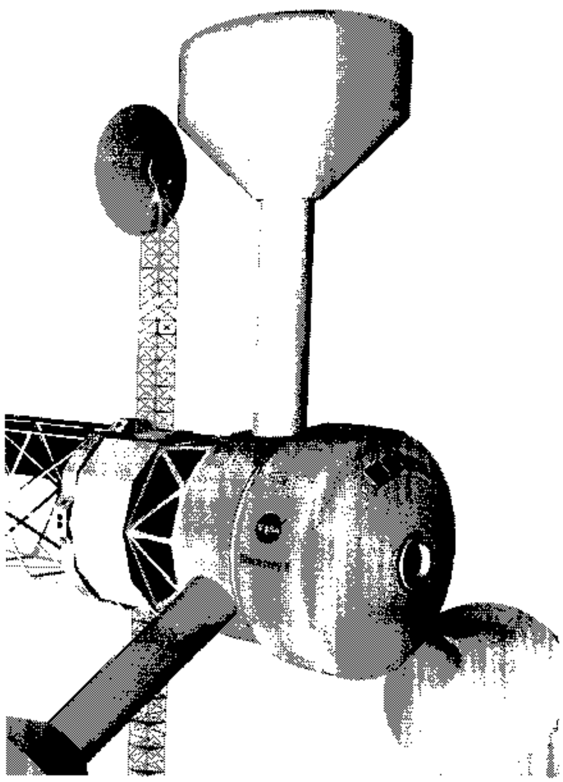

Figure 3: Artificial Gravity Crew Payload

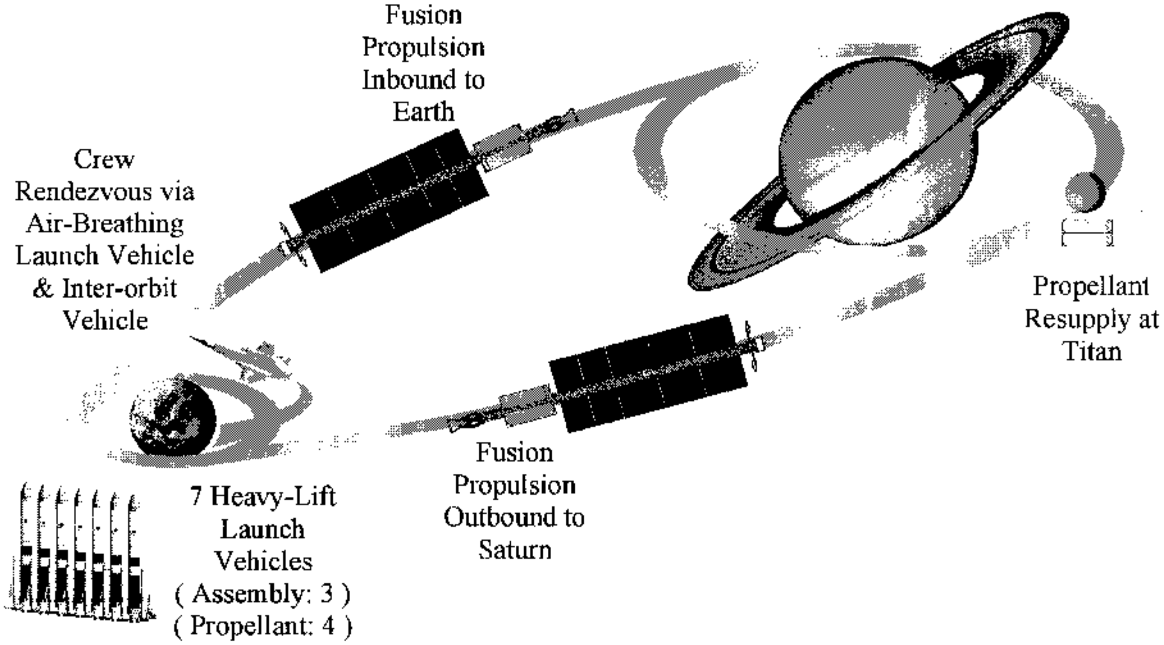

Figure 4: Space Operations Scenario (Alternate Mission)

Space basing necessitated pre-deploying considerable infrastructure at each destination. In-situ resource utilization (ISRU) plants on the water-ice rich major moons of the outer solar system would generate the slush hydrogen propellant and the deuterium needed for fuel. Autonomous propellant tankage, the same systems used by the *Discovery II*, would also transport the propellant from the ISRU plants to the *Discovery II*. These same vehicles would initially transport propellant via HLLV's from Earth. The crew would use a dedicated, air breathing propulsion vehicle for transport from Earth's surface to a space station in LEO, from which a small, high thrust inter-orbit shuttle would quickly transport them to the *Discovery II*.

The implied requirement of a planetary refueling capability is of great concern, but is consistent with a solar system-class transportation system regularly journeying to and between large outer planets with atmospheres and moons rich in H_2, D_2, and ^3He. Sources of available propellant near high departure/arrival orbits, such as water ice at the lunar poles, minor moons, outermost major moons, and even asteroids, would greatly facilitate refueling without entering into deep gravity wells, provided the facilities could be established and maintained at a sufficiently low cost. It is reasonable to assume that in the time frame of fusion propulsion systems, other technologies and infrastructure (such as semi-robotic mining encampments) would be available. ^3He would be acquired by either collecting solar wind deposited surface supplies or by scavenging in situ major planetary atmospheric deposits (if cost effective), to alleviate ^3He supply concerns.

Degree of Technological Extrapolation and Concomitant Risk

Perhaps the most difficult task for the conscientious designer is the exercise of proper technical judgment in extrapolating from current to future technology. Almost any propulsion scheme can be made to appear feasible (and even attractive) if the engineering assumptions are sufficiently broad. This is often the case with new concepts where the physics or engineering definition required to perform a more thorough analysis may legitimately be unknown. In such instances it is always prudent to err on the conservative side when performing system assessments. Overly optimistic assumptions (while perhaps making the initial concept more attractive) are frequently not borne out in practice and inevitably foster significant technical and programmatic repercussions. Even with relative technological risks factored in, a concept that relies on liberal assumptions can be made to appear substantially more attractive than competing designs using more conservative assumptions, which can lead to unwise disbursement of program funds, stagnation of promising areas of research, or other unfortunate outcomes.

With regard to fusion-based space propulsion, several technological advances will have to occur to make this advanced concept a reality. The list is seemingly endless: satisfying the Lawson criterion by increasing confinement times, peak plasma temperatures, and number density profiles; understanding and controlling burning-plasma operations in steady-state devices; designing efficient tritium breeding systems; creating, transporting, and handling advanced reactor fuels; demonstrating disruption-free reactor operation or easy reactor restarts following anomalies; generating and controlling high bootstrap currents; developing and demonstrating high-temperature superconducting ceramics; demonstrating routine, high-repetitive-rate pellet fueling and high-gain burning in ICF reactors; and a host of other equally significant issues that must be solved to make fusion-based propulsion a reality. Although ground-based fusion reactor projects have been underway for several decades, their primary focus has been on sustained plasma confinement and power generation rather than high temperature plasma exhaust, the latter being quite undesirable for power generation but crucial for spacecraft propulsion. However, aspects of these research programs, together with other sub-scale tests and laboratory proof of concept experiments, have demonstrated the feasibility of several of the technologies required for space-based fusion propulsion systems. For example, thin-film / single-crystal YBCO superconductors have demonstrated critical current densities of 3,000 MA/m2, even when exposed to external magnetic fields of 2 T and temperatures of 65° K. [23] Extrapolating from these results, one might reasonably argue that 30 years from now (the anticipated time frame for the advent of a nuclear fusion vehicle), monolithic structures, such as magnet coils, made of these materials could be available. This would be a reasonable design extrapolation, based on the proven state of the art (as represented by peer-reviewed publications) and a reasonable, judicious, conservative projection of future capabilities.

Of course, many advanced concepts will of necessity contain technological extrapolations beyond what has been published on laboratory-level demonstrations. Attempting to establish a reasonable limit to projecting technological advancement to ensure credible system designs would admittedly be arbitrary. In these cases, the designer should reference the latest laboratory findings, quantify the extrapolation, and justify the action taken. If the designer is uncertain on how far to extrapolate, it is suggested that the proposed technology should not be extrapolated beyond an order of magnitude from known property limits. This of course presupposes that such extrapolations do not contradict known limitations. For example, it has been shown in laboratory experiments that fast neutron irradiation can enhance critical current density up to a factor of four for external magnetic fields at right angles to the c-axis of thin films of certain high temperature superconductors [24, 25]. It was not known to how high an irradiation level this phenomenon might still exist and when it might reverse itself. It would be reasonable to hypothesize that the enhanced critical current density could be maintained at least at a greater irradiation than documented in current literature. In this case, the design should identify the extrapolation and ensure the technological risk is accounted for by additional design margin should this not bear out (see 'Weight Growth Contingency' and 'Power Contingencies' sections). Exactly how additional margin is allocated is left to the engineer. How many and to what degree of extrapolation will require judgment by the designer, but they should be explicitly identified with consequences of unavailability discussed.

As a final admonition, it must be recognized by the vehicle designer or mission planner that technological assumptions and projections of capabilities should be consistent within a given time frame. For example, it would make little sense to presume the capability of ignited nuclear fusion reactor technology thirty years hence, but lack the capability to extract ^{3}He fuel from outer solar system planetary atmospheres or hydrogen propellant from the water-rich surfaces of the outer planetary moons that these very same fusion-based vehicles will be exploring. Similarly, it would make little sense to invoke liquid nitrogen-temperature superconducting materials, but not use equally advanced multidirectional, reinforced carbon-graphite matrix composites for load bearing structural support of the fusion reactor's first wall. While not every technology can be extrapolated with equal confidence, it is important to recognize that reasonable extrapolations can and should be made consistently in all critical technology systems. The designer should take a step back during the design process and consider whether their engineering judgment on the current and future availability of critical technologies and capabilities has been evenly applied throughout the vehicle concept and mission plan.

Recommendation #3

Technologies critical to the success of the concept should have at least been demonstrated at the sub-scale, proof-of-concept laboratory level. Such demonstrated technologies may be conservatively extrapolated and invoked in the design at a monolithic level. Peer-reviewed technical journal articles should be referenced to support each critical technology and to lend credence to design extrapolations.

Example of Recommendation #3

Table 5 contains examples of technologies critical to the success of the fusion vehicle concept (along with corollary conditions), the appropriate demonstrated technical data, and the corresponding values used in the example vehicle concept. References for each are contained in prior published documents.

Recommendation #4

For critical technologies lacking laboratory demonstrations, the designer should reference the latest laboratory findings, quantify the extrapolation, and justify the action taken. If the designer is uncertain on how far to extrapolate, it is suggested that the proposed technology should not be extrapolated beyond an order of magnitude from presently known property limits.

Example of Recommendation #4

Similar to Recommendation #3, Table 6 contains examples of technologies critical to the success of the fusion vehicle concept, but have not yet been demonstrated sufficiently close to the necessary operating conditions. The closest demonstrated values are given, along with the corresponding values used in the example vehicle concept. References/justifications for each are contained in prior published documents.

Recommendation #5

Due to the inherent risk in such large extrapolations, any significant impacts on vehicle design in the event of these technologies not being available should be explicitly addressed, and concomitant technological risks integrated into the weight growth and power contingencies.

Example of Recommendation #5

Table 7 contains qualitative statements on the implications of unavailability for each of the technologies listed in Table 6. Several of the technologies/systems are mandatory for the success of the vehicle concept (impact denoted by "concept lethal" if not available.) Although weight growth and power contingencies were incorporated into the vehicle concept, they would not be sufficient to account for the potential unavailability of any of the technologies specified in Table 7.

Table 5 : Critical Technologies and their Extrapolations from Demonstrated Values

System / Technologies	Demonstrated value	Value used in design
HLLV throw weight (260 nmi alt circ; 28.5 deg)	285,000 lbs	555,000 lbs
H_2 Cryo-tankage length to diameter	27.5 m (ET) to 10 m (S-II)	30+7 m to 10 m
YBCO critical current density (65 ºK; 2 T (external))	3,000 MA/m^2	12,000 MA/m^2
Fusion plasma confinement time (1992 ITER H mode)	0.565 seconds (pulsed)	0.552 seconds (ignition)
Bootstrap current fraction (β_{crit} = 32%; β_N= 5)	90+ %	116% (overdriven)
Synchrotron reflectivity (Be I-250; 50 keV; 7.5 10^{20}/m^3)	99%+ (actual)	99.5%(calculated)
YBCO magnet dimensions	thin film; single crystal	0.2 cm X 3.6 cm X 10 m
B_{max} at coil (9.2 MA/coil)	up to ~ 30 T	32 T
TF coil support max tensile stress (Ti-6Al-4V; 65 ºK)	19*10^8 N/m^2	19*10^8 N/m^2; W-36 shape
C-C radiator specific mass (He parallel duct heatpipe)	1 ½ kg/m^2	1 kg/m^2
Slush H_2 propellant (14 ºK) storage time	48 hours	indefinitely
Refrigeration power, mass scaling power range	0.1 - 10 Wth	13 - 133,000 Wth
D^{3}He pellet fuel injector final velocity	3.5 km/sec (single shot)	10 km/sec (at 1 Hz)

Table 6 : Critical Technologies/Systems Not Yet Demonstrated

System / Technologies	Closest demonstrated	Value used in design
Fusion reactor operation (ignited, magnetic confine)	Q = 30 - 40 % (single shot)	Q = 73; fueling = 1 g/sec
Advanced fusion reactor fuel	DD	D^3He (spin polarized)
High plasma temperature (with Te = Ti)	10 keV	50 keV; shape factor n = 2
Enhancement of I_{crit} (1-2 MeV neutron; B - c-axis)	4X (fluence = 6 $*10^{21}/m^2$)	4X (fluence = 2 $*10^{23}/m^2$)
Spin polarized D^3He fuel enhanced reactivity	50% in DT (measured)	50% in D^3He (theoretical)
Coaxial Helicity Ejection	CHI (plasma heating)	CHE (propulsion exhaust)
C-G matrix composite tensile strength (1,825 ºK)	1 GPa (unidirectional)	~1 GPa (multi-directional)
Be-induced depolarization of D^3He (1st wall)	theoretical indications only	assumed correctable
Divertor operation (single null)	"closed"	"open"
Divertor power transfer	20 MW/m^2 (pulsed)	10^3-10^4 MW/m^2 (steady)
Magnetic nozzle jet power, propellant	100 kW to 6 MW; various	~ 6 GW (steady state); H+
Propellant mass augmentation	no extrapolatable data	80 X
Propellant & fuel KE equilibration (20% enthalpy loss)	limited theory	100 % equilibration assumed
HHFW heating efficiency (start up; profile control)	limited experimental	0.1 A (driven)/W (injected)
^3He availability (ISRU at major planet atmospheres)	18 kg/yr (limited need)	~7 mt / flight (production)

Table 7 : Impact of Unavailability of Technologies/Systems in Table 6

System / Technologies	Impact if not available
Fusion reactor operation (ignited, magnetic confine)	concept lethal
Advanced fusion reactor fuel	increased radiation loss; sheilding/other increased mass
High plasma temperature (with Te = Ti)	reduced plasma power; decreased payload; longer trip time
Enhancement of I_{crit} (1-2 MeV neutron; B - c-axis)	decreased B field strength; reduced confinement
Spin polarized D^3He fuel enhanced reactivity	reduced plasma power; decreased payload; longer trip time
Coaxial Helicity Ejection	concept lethal (likely)
C-G matrix composite tensile strength (1,825 ºK)	increased reactor mass
Be-induced depolarization of D^3He (1st wall)	reduced plasma power; decreased payload; longer trip time
Divertor operation (single null)	concept lethal
Divertor power transfer	concept lethal
Magnetic nozzle jet power, propellant	concept lethal
Propellant mass augmentation	non-optimal Isp; increased trip time
Propellant & fuel KE equilibration (20% enthalpy loss)	non-optimal Isp; increased trip time
HHFW heating efficiency (start up; profile control)	increased mass if other technology used
^3He availability (ISRU at major planet atmospheres)	increased radiation loss; sheilding/other increased mass

Recommendation #6

Assumptions on critical technologies and their extrapolations should be self-consistent within a given time frame.

Example of Recommendation #6

Table 8 contains a list of systems/technologies that can be plausibly argued to be comparable in technological difficulty and development timeframe.

Table 8: Likely Coexisting Technologies and Systems with Fusion Propulsion

In situ resource utilization	
	lunar, outer planet moons' H_2O, H_2, D_2, ^3He
	outer planet atmospheric H_2O, H_2, D_2, ^3He
	rendezvous (one way) vehicle design, operation
Higher temperature (LN_2) superconducting magnets	
Slush LH_2	
Load-bearing composite structures, tankage	
HLLV (130-225 mt class)	
Order-of-magnitude reduction in ETO launch costs	

Thoroughness in Calculating Mass Properties

A fundamental design goal is minimizing the total propulsion system mass in order to maximize vehicle performance. To correctly model performance, a reasonably thorough calculation of mass properties is necessary. The total propulsion system dry mass must include such systems as primary structure, fusion reactor (for magnetically confined fusion (MCF), driver (for inertially-confined fusion (ICF))), power conversion, heat rejection, plasma heating, thrust generation, fuel injection, refrigeration, start-up/auxiliary power, propellant / fuel tankage, reaction control, electrical/avionics, and interface adapter hardware. The dry mass associated with propellant and fuel tankage, as well as payload mass, is of course mission peculiar and therefore problematic unless integrated with design reference missions. Evaluating and comparing mass properties between fusion concepts can be difficult because of the varying degrees of thoroughness in design of systems and differences in taxonomy/grouping of subsystems. Standardized mass properties would facilitate one-to-one comparisons between concepts.

The problem of varying degrees of system definition is most evident when comparing systems that receive the preponderance of design effort, primarily the reactor/driver and power processing. The reactor / driver systems typically represent 30% to 80% of the total fusion propulsion system mass [6]. Given the nature and complexity of these systems, it is reasonable to expect design definition and mass estimates to dominate. However, the propulsion, propellant, and start-up systems have significant mass fractions in many concepts, but are sometimes overlooked.

Based on prior studies, several pertinent observations can be made: First, while it is reasonable to expect that significant effort is concentrated on the systems deemed likely to be the most massive or technically challenging, it is sometimes the case that a greater emphasis is placed on the areas in which the concept creators are expert, rendering the full design concept vague or incomplete. Second, significant sub-system masses that arise in current propulsion systems may turn out not to be significant for fusion systems, but they cannot be ruled out a priori. For example, interface hardware or avionics may constitute from 3% to 10% of present-day system's mass. If the same percent of interface hardware or avionics mass held true for fusion concepts, these percentages could translate into as little as 15 mt or as much as 150 mt [6]. Another example would be crew radiation shielding, a significantly massive system that is generally lacking or otherwise considered to be part of the useful payload. Third, although one should generally not dwell on small, low-mass systems, they can add up. For example: the startup battery bank and fuel tank / injector systems are typically small mass contributors, but the aggregate of their masses and concomitant weight growth contingencies can represent as much as 10% of the IMLEO. Fourth, it is frequently unclear to what extent system interactions were incorporated. For example, a $\beta = 1$ reactor with an applied 10 T magnetic field could have a pressure load of ~ 40 MPa (400 atm). The primary structure would somehow have to accommodate this load, presumably with significant structural mass. Yet primary structure is almost always a minor constituent in most fusion concepts. Fifth, although some concepts identify which system masses were optimized, calculated, or estimated, most do not. [6] The fidelity of mass property data is of course a strong function of the pedigree of the analysis. The sources and methods used to obtain the mass properties must be explicitly defined. Finally, although it is recognized that no conference or journal paper can capture all the detailed calculations of its authors, it is impossible to conclude, without an understanding of the analysis supporting the mass properties, that concepts providing lengthy system definitions and tabulated mass breakdowns are of any higher fidelity than concepts where only a brief system mass summary is provided.

Another issue that complicates comparisons is the differences in taxonomy and grouping of systems. For example, some concepts provide mass breakouts for radiators and power conversion equipment, items generally thought of as part of the power processing system. However other concepts apparently either commingle power processing systems with the fusion reactor system, or may not include significant sub-systems within the mass properties at all. [6] Unless a careful examination is done on a concept, perhaps involving the authors, comparisons of system masses between concepts can be problematic. The recommended practices outlined in the sections below are meant to alleviate these issues and provide a common framework against which all concepts can be evaluated on an equal footing.

Nominal Mass Property Template

A top-level mass property template has been developed as a spreadsheet to facilitate comprehensive and realistic mass property tabulation. The spreadsheet is sufficiently generic for MCF, ICF, and other innovative fusion concepts. Mass property data are also dependent on other primary system factors such as power level, technological immaturity, etc. and these data must be self-consistent with technological risk and weight growth contingency. The general format and system definition of the template is based on similar databases from existing upperstage expendable launch vehicles [26], augmented with data from current research fusion reactors, their supporting infrastructure (power supplies, auxiliary plasma heating systems, etc.), and other sources of comprehensive fusion propulsion mass property definition.[2, 27] It represents the "lowest common denominator" composite of approaches used from these data sources. The topics are grouped according to engineering systems, and arranged in a structured programming format. Certain items that were not fusion reactor power-dependent (such as reaction control propellant, cryogenic propellant tankage, etc.) carry suggested percentage values to guide the designer who may not have the ability to evaluate them.

Recommendation #7

A generic mass property spreadsheet should be included in a system conceptual design.

Example of Recommendation #7

Table 9 contains the detailed data summarized in Table 1. Some of the specific scaling factors in Table 9 differ from the generic values suggested in the Report, reflecting actual engineering data, analysis, or historical values. Some values were left unspecified because they were either included in other line-items, or did not apply to the vehicle concept, or were negligible.

Weight-Growth Contingency and Propellant Margins

Weight growth contingency is the mass margin allocated to compensate for the inevitable growth in mass experienced by aerospace systems as designs mature and fabrication proceeds. Underestimated mass properties become apparent and technical problems are solved by incorporating engineering solutions with concomitant additional mass. All new launch vehicle development programs carry such an allocation, though the percentage allowable varies as a function of components' technological maturity. Experience with the development of eighteen major aerospace vehicles has demonstrated that from the point of initial contract proposal through acquisition of first unit, the total average weight growth experienced by military aerospace vehicles has been 25.5%.[28] The leading reasons for this were better definition of original design, changes in scope, and overlooked components in original proposal. All these substantiated the need for adequate preliminary design and weight growth contingency. For more than two dozen major NASA manned and unmanned spacecraft (from Phase C/D to first flight vehicle), most programs experienced a similar 15% to 30% weight growth. [29, 30]

The necessity to add realism to design concepts, particularly when calculating specific power, is essential for credible evaluation of performance and other FoM. Unfortunately, the majority of recently published fusion concepts contained no explicit weight growth contingency allocation. Strictly speaking, weight growth contingencies should be evaluated on a system-by-system basis, but the lack of detailed definition of operational systems at early stages of design makes such an approach difficult. Unless the designer can provide a rationale for different weight growth contingencies for individual systems, it is recommended that a constant factor be assessed on the aggregate of all dry masses of the vehicle (i.e. the total vehicle stack, including payload, less total tankable propellant and fuel). The need to associate uncertainties: technology readiness, extrapolations of existing technology, complexity, etc., with subsystem technologies is considered fundamental to the appropriate assessment of advanced propulsion concepts, and to first order can be addressed using consistent weight growth contingencies.

Propellant margins and fluid losses typical of existing launch vehicles are another category of reserves that must be included. Propellant margins are

Table 9: Mass Properties for Example Fusion Vehicle

Scaling constants:

Cryo tankage/insulation fraction (~15% of total tankable propellant) = 0.1023 adjusted to design value
Weight Growth Contingency (30% of vehicle dry mass) = 30.0%
Flight performance reserve (~1% of Main impulse) = 1.0%
Boiloff/residuals/losses (~3% of total tankable) = 3.0%
Reaction control propellant (~1.5% of total tankable) = 0.0233 adjusted to design value

Enter all masses in metric tons

Total Mass at Planetary Departure (mt)					1,690
Vehicle Dry Mass				646	
Fusion Propulsion System			337		
Input power		5			
Input power generators	5				
Power transfer					
Radiators & thermal					
Fusion chamber wall		25			
Vessel wall	14				
Radiators & thermal	11				
Magnet		296			
Primary magnets	129				
Direct support structure	77				
Radiation shielding	90				
Thermal shielding					
Radiators & thermal					
Magnetic nozzle/propulsion		6			
Nozzle	3				
Expellant injection					
Diverter & other magnets	3				
Thrust vector control					
Radiators & thermal					
Fusion fueling		5			
Target assembly					
Injector/positioner	5				
Tritium breeding					
Radiators & thermal					
Concept-unique		0			
Other acceleration/grid					
Radiators & thermal					
Electrical Power System			30		
Power conversion		7			
Power conditioning/processing		3			
Energy storage		5			
Distribution		3			
Direct support structure		2			
Radiators & thermal		10			

Table 9: Mass Properties for Example Fusion Vehicle (cont.)

	Startup/Restart Power System				15
		Reactor	10		
		Electrical storage	5		
		Power conditioning/processing			
		Radiators & thermal			
	Shutdown and Disposal			0	
		Subsystem A			
		Subsystem B			
	Reaction Control Systems			16	
		Thrusters	16		
		Power processing			
		Radiators & thermal			
	Vehicle Structure			6	
		Primary structure (trusses, etc.)	6		
		Interface hardware/adapter			
		Micrometeoroid shielding			
	Tankage			91	
		Cryo propellant tanks	88		
		Insulation			
		Refrigeration (including radiators)	2		
		Fusion fuel tankage	1		
	Avionics & Communications			2	
	Weight Growth Contingency			149	
Fluids					872
	Total Tankable Main Impulse Propellants/Expellants			861	
		Main impulse	807		
		Flight performance reserve	8		
		Boiloff/residuals/losses	26		
		Reaction control propellant	20		
	Fusion fuels			11	
	Other fluids				
Payload System					172
	Primary structure			38	
	Radiation, solar flare, & thermal shielding			69	
	Crew accommodations/life support			25	
	Weight growth contingency			40	

typically established to accommodate such things as launch windows (daily and hourly) and system dispersions during flight. The propellant margin to mitigate dispersions while in-flight, typically referred to as Flight Performance Reserve (FPR), is of particular note since it represents the means to account for the statistically known uncertainties affecting the vehicle during its mission. Fluid losses can include propulsion system pre-chills, engine start-up and shut down transients, and various trapped, residual, and vented fluid losses. Frequently overlooked, these quantities can add up to significant values and are usually not included in conceptual studies. Absent actual values, it is typical to assign representative percentages to account for propellant margins and losses. Data from actual [26] and historic [31] expendable launch vehicle upper stages, as well as prior studies [20], formed the basis for the recommendations.

Recommendation# 8

A 30% weight growth allowance should be assessed on the total dry mass of the propulsion system and the crew payload.

Example of Recommendation #8

Tables 1 and 3 both contain a 30% weight growth contingency based on the system dry mass.

Recommendation# 9

Flight performance reserve should be 1% of main impulse propellant & fuel

Recommendation# 10

Residuals & losses should be 3% of total tankable propellant & fuel

Example of Recommendations #9 and 10

Table 10 illustrates the mass summary for the fully loaded cryo-tankage in its ETO launch configuration (i.e., including adapter and associated contingency). Added to the useable, main impulse propellant was an FPR of 1% (of main impulse propellant), consistent with past mission experience to accommodate in-flight dispersions. Estimates of residuals and chill-down losses were also included and made up 3% (of the total tankable propellant). A 30% weight growth allowance was assessed on the tankage dry mass and adapter. The gross liftoff weight (GLOW) of a fully loaded cryo-tankage payload was 251 mt, of which 207 mt was slush hydrogen available for main impulse propulsion.

Similar values of FPR and residuals/losses were included in the D^3He fuel total in Table 1.

Table 10: Propellant Tankage Wet Mass Properties (single tank)

Propellant			215
	main impulse	207	
	flight perf. reserve	2	
	residuals/losses	6	
Stage Dry			22
Adapter			6
Contingency	(30% of dry mass)		8
----------------			------
GLOW (mt)			251

Specific Impulse

Specific Impulse (I_{sp}) is a fundamentally important quantity to the space propulsion system designer. It is a measure of how much thrust a system produces per unit mass flow rate of propellant. Unlike today's chemical systems, fusion systems have the potential for matching, and even exceeding, the optimum I_{sp} for a broad range of missions, where the payload mass ratio is maximized for a specific ΔV.

Due to the absence of prototype fusion propulsion systems, their propulsive characteristics must be analytically estimated, inferred from proof-of-concept experiments, or implied from overall mission & vehicle characteristics. More fundamentally, the designer must first identify whether the I_{sp} is a dependent or an independent quantity. If dependent, the system and mission characteristics on which it is based must be identified, such as the set: payload / structure / propellant masses, mission distance, specific power, and overall propulsion system efficiency. In this case, it is assumed that the propulsion system can in fact perform in such a way to produce such a set of system and mission characteristics. If independent, the method for calculating I_{sp} should be identified. For example, the I_{sp} upper bound might be estimated by merely setting the plasma's translational kinetic energy equal to the propellant's kinetic energy. Alternatively, a mission ΔV might be chosen from an integrated trajectory, thus establishing an I_{sp} based on the calculated vehicle mass properties. It may be possible to integrate a value of I_{sp} from an analytic model of thrust and propellant mass flow rate derived from a proof-of-concept pulsed experiment, provided the model is scalable.

In either case, designers should discuss issues governing their assumptions. For example, if I_{sp} is assumed to be a dependent variable (tailorable to a specific mission), the designer should explain the thrust producing process and identify critical technical issues to be addressed. For a continuous thrust, magnetic confinement concept, these could be direct exhaustion of scrape off layer plasma through an open divertor via co-axial helicity ejection, enthalpy exchange with tailorable thrust augmentation propellant flow, subsequent expansion through a magnetic nozzle, and estimation of enthalpy loss mechanisms. For an inertial confinement concept, discussion might include variable fueling repetition rate technology and fractional deflection of debris fragments by a magnetic coil to generate thrust.

Recommendation #11

An explanation of how I_{sp} is calculated and the technical issues pertaining to the approach should be provided.

Example of Recommendation #11

The conversion of the reactor's transport power into directed thrust was accomplished in two steps by the magnetic nozzle. In the first step, the nozzle mixed high enthalpy transport plasma from the divertor with the injected hydrogen propellant in order to reduce the excessive temperature and increase total charged propellant mass flow. In the second step, it converted the propellant enthalpy into directed thrust by accelerating the flow through converging/diverging magnetic field lines. In addition, its magnetic field prevented the high temperature plasma from coming in contact with the nozzle's coils and structural members that make up the thrust chamber. Thus for a fully ionized flow, the lines of magnetic flux also served as the containment device, minimizing heat transfer loses and the need for actively cooled structure.

The I_{sp}'s of 20,000 to 50,000 lb_f sec/lb_m and corresponding α's required for multi-month travel to the outer planets required ion reservoir temperatures of 100's eV. As was discussed, the too-great temperature and too-small number density plasma layers that entered the divertor from the reactor had to be adjusted prior to acceleration through the nozzle so as to produce the mission appropriate I_{sp}. This was accomplished by heating/ionizing slush hydrogen thrust augmentation propellant by the escaping reactor plasma, and then supplying the mixture to the magnetic nozzle at a constant flow rate. This then produced the desired values of bulk plasma temperature (thus I_{sp}) and mass flow rate (thus thrust-to-weight). Because of the assumed adjustable nature of I_{sp} through augmentation propellant flow rate, (rather than adjusting reactor power level), I_{sp} was a dependent variable. (The independent variables were: mission difficulty (distance or ΔV), α, payload mass ratio, η, and velocity ratio (since mass properties were fixed).)

The augmentation propellant mass flow rate of 0.079 kg/sec and was ~78 times that of the fuel, emphasizing that a significant portion of the magnetic nozzle system must be dedicated towards accommodating the injection of augmentation propellant. Even more importantly, equilibration of the reactor plasma's enthalpy with that of the augmentation propellant was assumed to be 100%. This represented a significant assumption on a heretofore undemonstrated technology. The potential for significant operational problems is commensurate and warrants focused future assessment (and was in fact planned to be part of the ongoing magnetic nozzle experiment supported by the concept team).

Thoroughness in Calculating Power Generation and Usage

Similar to the discussion surrounding the calculation of mass properties is that of calculating power generation and usage. An equally fundamental design goal is the maximizing of generation and efficient utilization of fusion power for thrust, while minimizing the creation (and thus necessary rejection) of waste heat and radiation. To correctly model performance, a reasonably thorough calculation and accounting of power flows is necessary. Characterizing the power generation and usage for various fusion concepts may differ greatly. Inertially confined fusion concepts may focus on fuel target design and gain, exhaust plasma-debris plume conductivity rates of change, driver energy–efficiency–repetition rates, induction power generation and processing. Magnetically confined fusion concepts may focus on Lawson and ignition criteria, plasma instabilities, confinement times, disruptions, temperature and number density peaking profiles, scrape-off layer interactions, and plasma transport loss. Evaluating and comparing power generation and usage is subject to problems similar to those pertaining to mass properties and will not be repeated here. No matter the concept, a reasonably thorough assessment of how fusion power is generated and used is required for the establishment of a credible concept.

Power-Flow

Accounting for all power flows is essential for the vehicle designer to fully evaluate and balance power producing and consuming systems (fusion reactor, radiation characteristics, tritium decay heat removal, cryo-tankage, refrigeration, radiator power, redundancy / contingency, etc.). A power flow diagram is a useful tool to ensure that all power sources are considered, that sinks balance, and that recirculation power, which can be appreciable for some concepts, is fully evaluated. A graphical depiction of the power flow, along with assignment of credible system efficiencies, facilitates design of realistic heat rejection systems (radiators), which are usually significant in terms of power processed, size, and mass.

Spreadsheets have been developed that contain thorough tabulation of power production, utilization, and losses that should be considered in fusion propulsion analyses. Some even have comprehensive, multivariable (~1,000) optimization routines for fusion propulsion concepts so as to adjust fusion reactor operating conditions (temperature, density, mixture ratio, etc.) and offer a truly systems engineering approach to vehicle design. [32, 33]

Recommendation #12

A power flow diagram should be included in a system conceptual design.

Example of Recommendation #12

Figure 5 illustrates the fusion power output and utilization. (The auxiliary fission reactor and its power flow were described separately.) Of the 7,895 MW of fusion power produced, 96% was in the form of charged particles with the remainder in (largely 2.45 MeV) neutrons. More than ¾ of the power out of the reactor (6,037 MW) was charged transport power, (D and He ions, protons, and electrons) used solely for direct propulsion via the magnetic nozzle system. Synchrotron power (535 MW) was either absorbed by the first wall or reflected out the divertor channel to space. Much of the Bremsstrahlung (1,016 MW) and neutron radiation (307 MW) was absorbed throughout the reactor. Most of the heat generated by absorbed radiation (1,119 MW) was transferred through a fan-circulated, gaseous helium (GHe) coolant system to a high temperature radiator. The remaining heat from absorbed radiation (96 MW) was converted to electrical power for onboard use (~29 MW). Electrical power requirements were largely for the motor/fan-circulated GHe coolant system

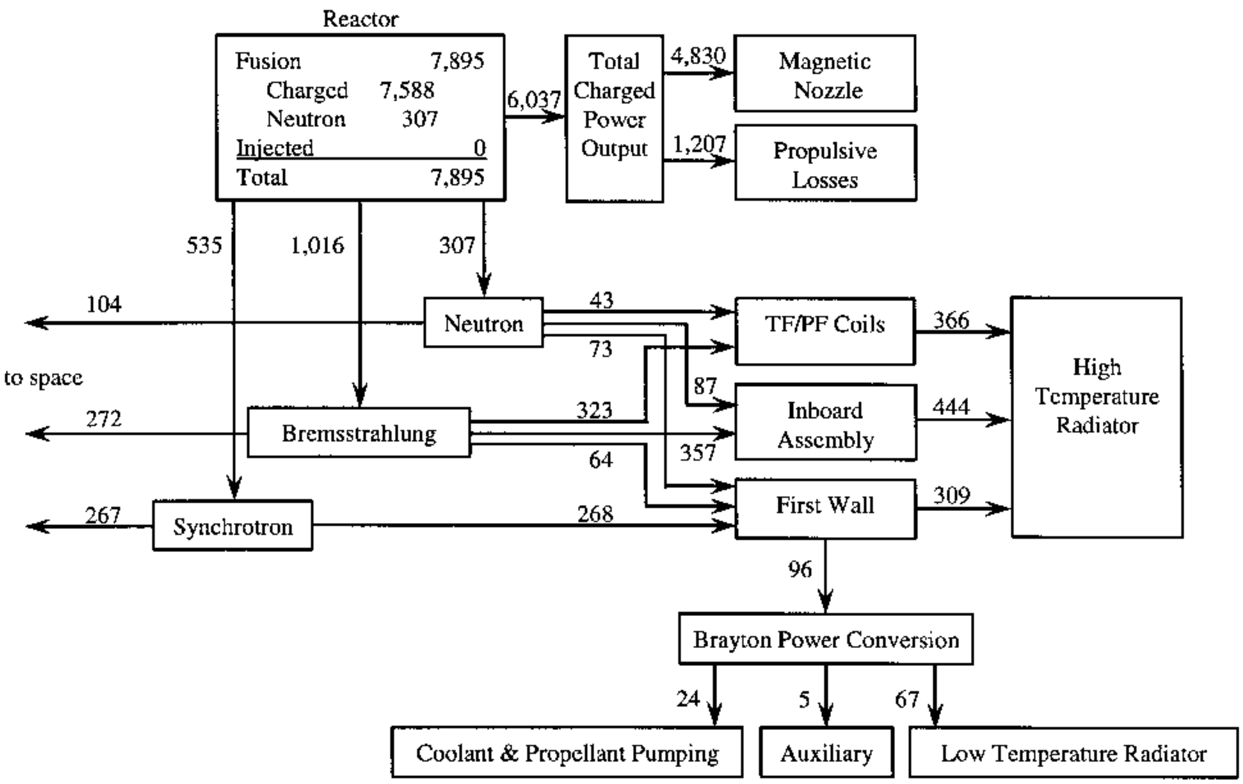

Figure 5: Fusion Power (MW) Output and Utilization

for the reactor (24 MW). The remaining power was consumed by propellant pumping and other auxiliary usage (superconducting coil and propellant tankage refrigeration, startup/re-start battery recharge, fuel injector, avionics, communications, and payload). No steady state injection power was necessary due to the ignited reactor, overdriven bootstrap current operation.

Jet Power-Loss and Auxiliary Power Contingencies

Uncertainties are usually present in the power levels calculated or assumed for all power-generating as well as power-consuming systems. The sources of these uncertainties in required power are analogous to those that occur with uncertainties in system mass properties, the latter of which are managed through the establishment of weight-growth contingencies. Power contingencies should therefore be quantified, especially because underestimates in certain power levels can have a direct effect on ascertaining vehicle performance. It is therefore recommended that: (1) power uncertainties (contingencies) should be assessed on the aggregate of systems that significantly contribute to the generation of jet power, as well as on the aggregate of all power consuming (auxiliary) systems, and (2) all significant effects of these contingencies should be discussed and reflected in their effects on credible trip times and other vehicle performance figures of merit.

Because there are no historical spaceflight data at the 10's kW to GW power levels representative of fusion systems, the concept designer is left to rely on power contingencies based on historical power requirement growth (or availability shortfall) with data from ~1 W to ~10 kW space systems (a considerable extrapolation). Prudent assessments of these systems [34] have lead to recommendations of 40% power contingencies, while other pre-Phase-A or Phase-A contract studies[35,36] of equally small or unspecified power levels have recommended 30% power contingencies. Knowing that power contingencies might be concept specific, it is suggested that a nominal contingency of 30% be applied to concepts if some other more appropriate contingency cannot be reasonably substantiated. It is recommended, however, that investigators avoid making power contingencies inadvertently drive nominal system design.

To report power contingencies, it is often helpful to separate onboard power systems into two categories: jet-power production and auxiliary usage. Due to differences in their technological maturities and absolute power levels, the recommended approaches to arriving at their values differ.

Jet-power producing power systems are directly coupled for main impulse propulsion and may include laser-driver systems, supplemental reactor plasma heating, fusion gain considerations, etc. There are also non-hardware related (fluid-mechanic and radiation) mechanisms that may be sources of enthalpy losses anticipated within the exhaust flow stream of directed thrust, (such as line radiation, charge exchange, non-axial flow, neutralization, non-thermalization for hybrid plumes, etc.) and other factors that might cause a loss in jet power, such as those arising from bimodal distributions in exhaust components, (such as speed or atomic weight). These jet power systems and jet power-loss mechanisms may be broadly referred to as propulsive losses. Because of the general lack of experimentally validated analytic models of these propulsive losses in the regime of interest of fusion propulsion, (and thus a concomitant lack of a basis to bound uncertainties), it is recommended that their contingency be approached differently. If the propulsive losses are sufficiently understood, then they should be quantified, their effects on jet power identified, and a power contingency of $\leq$ 30% above and beyond their aggregate should be levied. If however these propulsive losses are not understood, the sum of the propulsive losses and contingency should be set to 30% (i.e. actual jet thrust power divided by the total charged reactor-supplied, or inertial confinement reaction-supplied, power available for jet thrust = 70%). In addition, the designer should clearly identify the anticipated major contributors to jet power-loss and propose actions required to resolve these major unknowns. In no case should power contingencies include effects that are already included in weight-growth contingency factors.

Much of the potential jet power could have been lost unless the internal energy was efficiently converted into accelerated axial flow. Estimates of the relative importance of η_J on piloted interplanetary travel have been reported[6]. It has been shown that low η_J is particularly detrimental to payload mass fraction, since decreased η_J (at constant thrust) significantly increased propellant consumption. Figure 6 illustrates the profound effect of decreased η_J on payload mass fraction for the *Discovery II*. At η_j less than 55%, the payload mass ratio vanished, underscoring the necessity of an efficient propulsion system even for otherwise respectable power supplying reactor concepts.

Auxiliary power systems can include fusion reactor start-up, (including initial plasma heating), cryogenic refrigeration, crew systems, reactor coolant pumping, and other power-consuming systems prominent in the start-up or steady-state operation of the

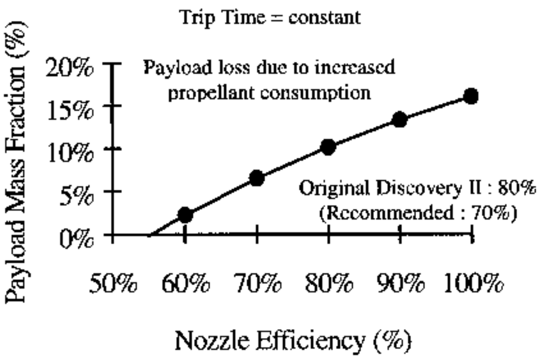

Figure 6: Magnetic Nozzle Efficiency vs. Payload Mass Fraction

vehicle. A power contingency of about 30% may indeed be appropriate for these systems, based on experience at much lower power levels, and is therefore recommended for inclusion in the conceptual design.

Recommendation #13

For jet-power-producing systems and loss mechanisms, a jet power reduction of 30% (i.e. actual jet thrust power divided by the total charged reactor-supplied (or inertial confinement reaction-supplied) power available for jet thrust = 70%) should be assessed unless the particular systems, loss mechanisms, and contingency can be shown to require a different (lower) value. If the propulsive loss mechanisms are not well understood, their presumed causes and presumed means to mitigate should be identified.

Example of Recommendation #13

Isentropic flow was assumed throughout, with an arbitrary nozzle efficiency set at 80% in the example fusion concept. For simplicity, it was assumed that the 20% nozzle loss took place at propellant-fuel enthalpy transfer, and that it exited the nozzle in the form of neutrals, ions with velocity vectors not strictly aligned with the thrust vector, collisions with support structure, line radiation, charge exchange, and other losses. If instead a 30% (rather than 20%) loss was assumed, the resulting jet power would only be 4,226 MW (vs. 4,830). The corresponding payload mass fraction would be reduced to ~6.5% (from ~10%), assuming fixed trip time and IMLEO, necessitating a ~55 mt increase in propellant consumption.

In an attempt to quantify the physics of some of these loss mechanisms, an experiment on magnetic nozzles had been initiated. After an initial series of test firings, NASA funding for all such advanced research was terminated, either ending or leaving all projects on indefinite hold.

Recommendation #14

For auxiliary systems, a power contingency of 30% should be allocated above and beyond the total, nominal power usage requirements.

Example of Recommendation #14

Table 11 summarizes the nominal auxiliary power usage provided by the fusion reactor (5 MW_e) and startup/emergency re-start power usage provided by the fission reactor (2 MW_e) in the example fusion propulsion concept. There was no power contingency specified in the original design of the auxiliary systems. If a 30% contingency were to have been included, the total power required to be provided would have been: 6.5 MW_e (for nominal usage via the fusion reactor) and 2.6 MW_e (for startup/emergency re-start power usage provided by the fission reactor). The ample waste heat from the fusion reactor could easily be tapped to supply the additional 1.5 MWe for nominal usage with little significant system impact. The additional 0.6 MWe for the startup/ emergency re-start power, however, would significantly impact the fission reactor power system.

Table 11: Auxiliary Power Usage
(Nominal (fusion) and Startup (fission))

	Nom	Startup
Electron cyclotron resonance heating	0.	1.
TF/PF/diver/mag noz coil refrigeration	3.95	0.39
Fuel injector	0.507	0.102
Battery recharge	0.16	0.125
Communications	0.2	same
Propellant/fuel tankage refrigeration	0.133	same
Payload	0.03	same
Avionics	0.02	same
Total (MWe)	5.	2.

Specific Power

Definitions of specific power and how it is calculated differ within the community. Much of the nomenclature has its heritage in the field of electric propulsion. To complicate matters, the same notation used for specific power, "alpha" or "α", is also used to denote its reciprocal: specific mass. Specific power is a very useful FoM, since it measures the amount of useful power out of a source and compares it to the dry mass needed for transforming it into thrust; a greater value being better. The difficulty arises when specific power is used for two different applications: an overall vehicle system value fed into a trajectory simulation or as a separate parameter used to evaluate and compare individual power systems.

The basis for the confusion lies in the manner in which the system masses are incorporated into the calculation of specific power. Calculating specific power using a system mass that excludes any mission dependent mass, notably propellant tankage, is a standard method used to calculate α for electric propulsion systems. The advantage of this approach is the divorcing of mission dependent hardware from power supply characteristics. Another approach to specifying specific power is to include mission dependent structure, particularly tankage, because specific power is most frequently used for mission performance assessment, where total structure mass must be included. While tankage masses are frequently small and thus of negligible impact to vehicle mass, that may not be the case for all fusion concepts. Yet another approach emphasizes that Specific Thrust Power (directed thrust beam, kW_{th}/kg_{engine}) (without tankage) is what matters most. Since considerable deliberations remain on how best to define specific power for fusion vehicle concepts, it is suggested that designers take advantage of the flexibility to calculate specific power in at least one of two ways clearly specifying which definition of specific power is being used.

Recommendation #15

System designers should calculate the specific power of fusion propulsion concepts using at least one of the following definitions and provide substantiating data:

α vehicle : total directed jet power divided by total vehicle dry mass (does not include useful payload)

α power : total directed jet power divided by vehicle dry masses that scale with power only (do not include useful payload, tankage, primary structure, reaction control, or avionics)

Example of Recommendation #15

α in the example fusion concept was calculated to be 8.62 kW/kg based on a definition from the literature. [37] That definition was based on power out of the reactor (or power source) supplied to the propulsion system (not the jet power out of the propulsion system).

Using Recommendations #15 and #13, as well as the data in Table 1, it follows that the values for $\alpha_{vehicle}$ and α_{power} are:

$$\alpha_{vehicle} = \frac{(1-30\%)(6{,}037)\,MW}{[646+(20+8+26)]\,mt} = 6.04\,kW/kg \tag{2}$$

$$\alpha_{power} = \frac{(1-30\%)(6{,}037)\,MW}{130\%\,[646-(6+16+88+2+149)]\,mt}$$

$$= 8.44\,kW/kg \tag{3}$$

SUMMARY

Renewed interest in conceptual designs of nuclear fusion space propulsion systems has highlighted the need to establish certain basic study groundrules to ensure development of credible vehicle concepts. The recommendations assembled herein were the result of a series of meetings within the fusion propulsion community responding to the generally acknowledged need to improve the overall quality and comprehensiveness of conceptual designs. Specific recommendations made on design reference missions, degree of technological extrapolation and concomitant risk, and thoroughness in calculating mass properties and power generation/usage should provide guidance to senior engineers who may not be fully cognizant of all primary aspects of nuclear fusion space propulsion system design. While deliberating on the recommendations, a concerted effort was made to establish a balance between being too detailed and all encompassing (thus an unwarranted burden to implement) and being too general and incomplete (thus not meaningfully improve fundamental aspects of a design). Although adoption of such design practices is voluntary, their intrinsic value in advancing credible space propulsion system design should be evident. As illustrated by the numeric examples in this paper, the recommendations can have a significant impact on the entire vehicle conceptual design.

ACKNOWLEDGMENTS

The author wishes to thank the following leaders in the Nuclear Fusion Propulsion Technical Interchange Meetings: Dr. Charles D. Orth (DOE LLNL), Dr. Peter J. Turchi (DOE LANL), Mr. Scott A. Carpenter (EDEn-Corp), Dr. John F. Santarius (University of Wisconsin (Madison)), Dr. Robert H. Frisbee (NASA JPL) and also the many who contributed. The author also extends his appreciation to the members of the AIAA NFFPTC Fusion Design Working Group who were instrumental in providing concepts and text that contributed to the AIAA Report, most of which is echoed in this conference paper: Dr. Michael R. LaPointe, Dr. Charles D. Orth, Dr. Brice N. Cassenti, Mr. Scott A. Carpenter, and Dr. Dana G. Andrews. Finally, I am deeply indebted to the many who have been so helpful in providing guidance and expertise towards the creation of the original fusion propulsion vehicle concept (used as the example in this paper), the details of which have been published in earlier conference papers and journal articles.

REFERENCES

[1] "Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems", AIAA Special Project Report, SP-108-2004, pre-print in peer review, 2004.

[2] Williams, C.H., Dudzinski, L.A., Borowski, S.K., Juhasz, A.J., "Realizing '2001: A Space Odyssey': Piloted Spherical Torus Nuclear Fusion Propulsion," AIAA paper 2001-3805, July 2001.

[3] Williams, C.H., "Trajectory Design and Mission Analysis of Fast, Outer Solar System Travel", AAS paper 01-161, February 2001.

[4] Williams, C.H. Borowski, S.K., Dudzinski, L.A., Juhasz, A.J., "A Spherical Torus Nuclear Fusion Reactor Space Propulsion Vehicle Concept for Fast Interplanetary Piloted and Robotic Missions", AIAA paper 99-2704, June 1999.

[5] Williams, C.H. Borowski, S.K., Dudzinski, L.A., Juhasz, A.J., "A Spherical Torus Nuclear Fusion Reactor Space Propulsion Vehicle Concept for Fast Interplanetary Travel", NASA TM 208831, NASA Lewis Research Center, Cleveland, OH, Dec. 1998.

[6] Williams, C.H. and Borowski, S.K., "An Assessment of Space Propulsion Fusion Concepts and Desired Operating Parameters for Fast Solar System Travel", AIAA paper 97-3074, July 1997.

[7] Williams, C.H. and Borowski, S.K., "Commercially-Driven Human Interplanetary Propulsion Systems: Rationale, Concept, Technology, and Performance Requirements", paper # 58, 13th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, January 1996.

[8] Williams, C.H., "An Analytic Approximation to Very High Specific Impulse and Specific Power Interplanetary Space Mission Analysis", NASA TM 107058, NASA Lewis Research Center, Cleveland, OH, September 1995.

[9] "Fusion Propulsion Workshop Technical Interchange Meeting," NASA MSFC meeting proceedings, March 1997.

[10] Orth, C.D., "Goal-Oriented Down-Selection Criteria for Fusion Space Propulsion Based on a Concept's Physical Limitations", Report to the NASA Advanced Propulsion Workshop in Fusion Propulsion, DOE Lawrence Livermore National Laboratory contract W-7405-Eng-48, November 2000.

[11] Palac, D., Spurlock, F., "Figures of Merit Discussion Topics," NASA Lewis Research Center Space Exploration Initiative Review presentation, November 1990.

[12] Borowski, S.K., et al., "Evaluation of Advanced Propulsion / Power Concepts," NASA Lewis Research Center presentation to SSTAC ad hoc Committee on Planetary Propulsion, March 1988.

[13] Schultze, N.R., "Fusion Energy for Space Missions in the 21st Century," NASA TM 4298, August 1991.

[14] Moeckel, W.E., "Comparison of Advanced Propulsion Concepts for Deep Space Exploration," **AIAA Journal of Spacecraft**, Vol. 9, No. 12, December 1972.

[15] Frisbee, R.H., Leifer S.D., "Evaluation of Propulsion Options for Interstellar Missions," AIAA paper 98-3403, July 1998.

[16] Frisbee, R.H., "Introduction to Fusion Propulsion Missions and Systems Studies," NASA JPL presentation to the NASA Advanced Propulsion Workshop in Fusion Propulsion, November 2000.

[17] Williams, C.H., "An Analytic Approximation to Very High Specific Impulse and Specific Power Interplanetary Space Mission Analysis," Advances in the Astronautical Sciences, Vol 93, Part 1, 1996, pp.801-818.

[18] Williams, C.H., "Trajectory Design and Mission Analysis of Fast, Outer Solar System Travel," Advances in the Astronautical Sciences, Vol 108, Part 1, 2002, pp.823-832.

[19] Drake, B.G., Editor, "Reference Mission Version 3.0 Addendum to the Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team," NASA JSC Exploration Office, Document EX13-98036, June 1998.

[20] Borowski, S.K., Dudzinski, L.A., McGuire, M.L., "Vehicle and Mission Design Options for the Human Exploration of Mars/Phobos Using 'Bimodal' NTR and LANTR Propulsion," NASA Technical Memorandum 1998-208834, December 1998.

[21] Borowski, S.K., Dudzinski, L.A., McGuire, M.L., "Artificial Gravity Vehicle Design Option for NASA's Human Mars Mission Using 'Bimodal' NTR Propulsion," conference paper AIAA-99-2545, June 1999.

[22] "Cassini Launch Press Kit", NASA Headquarters publication, October 1997.

[23] Awaji, S., et al., "Crossover from Intrinsic to Extrinsic Pinning for YBa2Cu3O7 Films," **Cryogenics**, vol. 39, 1999.

[24] Puzniak, R., et al., "Enhancement of Critical Current Density in Fast Neutron Irradiated Melt-Textured YBa2Cu3O7-x", **Cryogenics,** vol. 33, No. 3, 1993.

[25] Wacenovsky, M., et al., "Influence of Fast Neutron Irradiation on Critical Currents and Irreversibility Lines in MPMG-Processed YBa2Cu3O7 Superconductors," **Cryogenics**, vol. 33, No. 1, 1993.

[26] "Shuttle/Centaur G-Prime Configuration, Performance, and Weight Status Report," General Dynamics Space Systems Division report GDC-SP-83-001-13, NASA contract NAS3-23322, March 1986.

[27] Orth, C., "VISTA: A Vehicle for Interplanetary Space Transport Application Powered by Inertial Confinement Fusion (Systems Analysis Final Report)," University of California, Lawrence Livermore National Laboratory, Report UCRL-LR-110500, May 2003.

[28] Hawkins, K., "Space Vehicle and Associated Subsystem Weight Growth," SAWE paper 1816, May 1988.

[29] Shelton, W., "MSFC Programs Weight Growth History," NASA MSFC presentation, April 1979.

[30] Smith R. E. et al., "Weight Control and Weight Histories of Marshall Space Flight Center Projects," NASA MSFC-RPT-1553 A, July 1991.

[31] "Shuttle/Centaur G Configuration, Performance, and Weight Status Report," General Dynamics Space Systems Division report GDSS-SSC-85-006-4, NASA contract NAS3-23322, April 1986.

[32] Carpenter, S. A.; Deveny, M. E.; Brennan, K. M.; and DeBoskey, D. A.; "IDEAs: Integrated Design Environment Algorithms - A Precursor to Systems Engineering in Virtual Reality," 11th Symposium of Space Nuclear Power and Propulsion, AIP Conference Proceedings No. 301, Part Two (575-580), Albuquerque, NM, 1994.

[33] Carpenter, S. A. and Brennan, K. M.; "Overview and Status of a Mirror Fusion Propulsion System Design Study," Published in the Proceedings of the 49th Congress of the IAF, Melbourne, Australia, paper IAF-98-S.6.07 (1998) and in Acta Astronautica, Special Edition, Vol. 44, Issue 7-12 (471-506), Sept. 1999.

[34] "Recommended Practice for Mass Properties Control for Satellites, Missiles, and Launch Vehicles", ANSI/AIAA R-020A-1999, American National Standards Institute, May 2000.

[35] Landano, M.R. and Rose, J.R., "Design, Verification/Validation and Operations Principles for Flight Systems," NASA JPL document JPL D-17868, June 1999.

[36] Chew, G., Pelaccio, D., Jacobs, M., Stancati, M., Cataldo, R., "Development of a Robust Space Power System Decision Model," Space Technology and Applications Forum (STAIF-2001), 18th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, February 11-14, 2001.

[37] Shepherd, D.G., **Aerospace Propulsion**, American Elsevier Publishing Co., New York, 1972.