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Special Project

Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems

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Special Project Report

Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems

Sponsored by

American Institute of Aeronautics and Astronautics

Abstract

This document provides recommended design practices for conceptual engineering studies of nuclear fusion space propulsion systems. Discussion and recommendations are included 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).

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Foreword

To facilitate the improvement and standardization of conceptual designs of nuclear fusion space propulsion systems, Technical Interchange Meetings (TIM) took place in late 1999 and early 2000. The TIMs were broadly represented by the members of the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE) laboratories, academia, and industry professionals active in the field. The TIMs were led by NASA's Glenn Research Center (GRC). At their conclusion, it was suggested and all agreed that the results of the TIMs should be offered to the appropriate AIAA Technical Committee (TC) to review and codify the recommended design practices into an appropriate AIAA technical standard. The AIAA Nuclear and Future Flight Propulsion Technical Committee (NFFPTC) was identified as the most appropriate TC for this task. The NFFPTC's Chairman was approached and agreed to bring the TIMs product to the TC for their consideration. The NFFPTC subsequently formed an ad hoc working group for the expressed purpose of authoring an AIAA standards document to guide the development of higher quality conceptual designs for nuclear fusion space propulsion vehicles. Most of the recommendations stem from the work of the TIMs, with the balance contributed by the AIAA NFFPTC Fusion Design Working Group.

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The working group was created in 2002 and completed work in 2003.

The AIAA Standards Executive Council (Mr. Phil Cheney, Chairman) accepted the document for publication in October 2004.

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1 Introduction

1.1 Scope

This document provides recommended design practices for conceptual engineering studies of nuclear fusion space propulsion systems. Discussion and recommendations are included 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, propellant margins, and specific impulse), and thoroughness in calculating power generation and usage (power-flow, power contingencies, specific power). This report represents a general consensus of the nuclear fusion space propulsion system conceptual design community. It is intended for technically experienced senior engineers who may not be fully cognizant of all primary aspects of nuclear fusion space propulsion system design, and who desire a useful guide in the development of credible concepts.

1.2 Purpose

This document establishes 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 establish 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 is intended for technically experienced senior engineers who may not be fully cognizant of all primary aspects of nuclear fusion space propulsion system design, and who desire a useful guide in the development of credible concepts. The recommendations made in this document are intended to facilitate equitable comparisons between system concepts and to improve their overall technical quality.

1.3 Developments Focusing Attention on Nuclear Fusion Propulsion

NASA modified its long-range agency goals in the mid 1990's to include expanding human presence throughout the solar system. 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.^{1, 2} 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 the NASA and DOE communities. In 2003, funding for very advanced space propulsion research, including nuclear fusion, was terminated. The future of this technical area remains unclear.

2 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)^{1, 2, 3, 4}. 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 t^{1, 2}. 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. Further, a consensus (though not unanimous) agreement was arrived at among the TIM participants that mission-level FoM rather than engine / reactor-specific FoM, should be the primary focus of the designer's attention. It was emphasized during the TIM, and is repeated here for clarity, that a

considerable amount of analytic work exists in the 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.^{5, 6} 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).⁴ 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 $\text{lb}_f \cdot \text{sec}/\text{lb}_m$ and 5 to 50 kW/kg respectively.^{1,2} 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, defensible, 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 defensible 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 1.

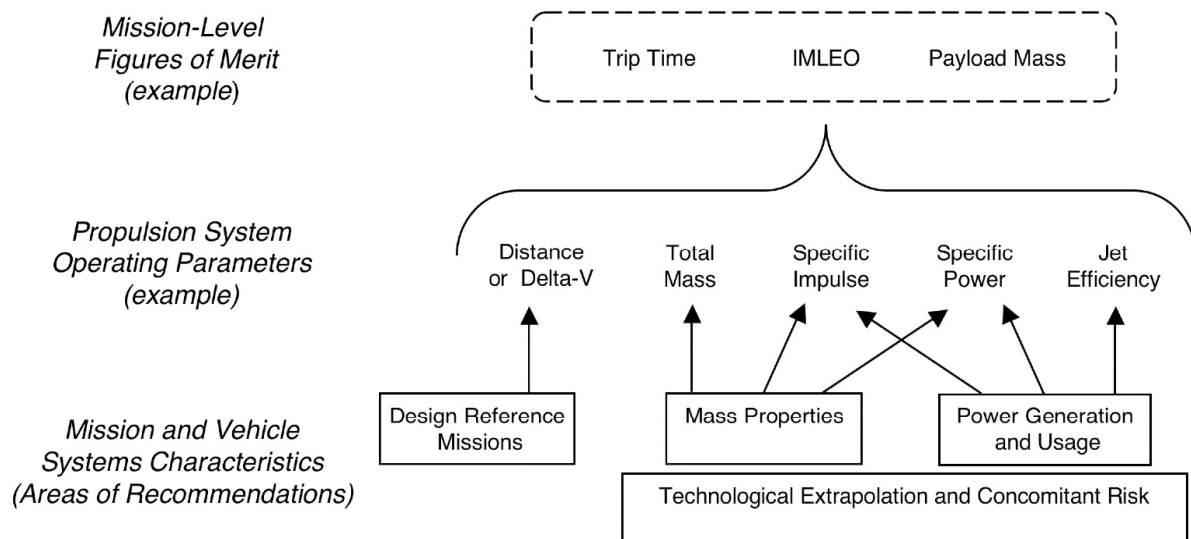


Figure 1 — Relationships Among Example FOM's, Operating Parameters, and Recommendations on Mission/Vehicle Systems Characteristics

3 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 Department of Defense (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 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.

3.1 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.^{7, 8, 9, 10, 11, 12} This historic data, and other related work⁴, 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 design reference mission constitutes a stretch goal: to send a robotic observation platform to rendezvous with the focal plane of the Sun's gravitational lens and provide cross-tracking maneuver capability.

The human payload masses recommended here are order-of-magnitude estimates scaled from existing piloted Mars mission studies.^{13, 14, 15, 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.¹⁶ 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 delta-V 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 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

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, $2300 \text{ m}\cdot\text{s}^{-2}$ cross-track

RECOMMENDATION

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 high Earth orbit (HEO) tugs, space bases, In-Situ Resource Utilization (ISRU) facilities, etc.)

3.2 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 the unwise disbursement of program funds, the 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 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 $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) superconductors have demonstrated critical current densities of $3,000 \text{ MA/m}^2$, even when exposed to external magnetic fields of 2 T and temperatures of 65° K .¹⁷ 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.^{18, 19} 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 helium 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.

RECOMMENDATIONS

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.

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.

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

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

3.3 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 ¹. 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 t or as much as 150 t ¹. 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 particle-to-magnetic field pressure ratio $\beta = 1$ 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.¹ 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 behind the mass properties, that concepts providing lengthy system definitions and tabulated mass breakdowns are of any higher fidelity than concepts in which only brief system summary of total mass values are 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.¹ 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.

3.3.1 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 vehicles²⁰, 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.^{21, 22} 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/desire to evaluate them.

RECOMMENDATION

A generic mass property spreadsheet, illustrated in Table 1, should be included in a system conceptual design.

Table 1 — Generic Mass Property Template for Nuclear Fusion Space Propulsion Systems

Shaded cells must be filled in with masses in metric tons					
Cells filled with "0" indicate embedded equations					
Adjust constants accordingly if needed					
Scaling Constants:					
Cryogenic tankage / insulation fraction (% total tankable propellant)	15				
Weight growth contingency (% vehicle dry mass)	30				
Flight performance reserve (% main impulse)	1				
Boil-off / residue losses (% total tankable)	3				
Reaction control propellant (% total tankable)	1.5				
	Enter all masses in metric tons				
Total Mass at Planetary Departure					0
Vehicle Dry Mass				0	
Fusion Propulsion System			0		
Input Power		0			
Input power generators					
Power transfer					
Radiators & thermal					
Fusion chamber wall		0			
Vessel wall					
Radiators & thermal					
Magnet		0			
Primary magnets					
Direct support structure					
Radiation shielding					
Thermal shielding					
Radiators & thermal					
Magnetic nozzle / propulsion		0			
Nozzle					
Expellant injection					
Divertor & other magnets					
Thrust vector control					
Radiators & thermal					
Fusion fueling		0			
Target assembly					
Injector / positioner					
Tritium breeding					
Radiators & thermal					
Concept – unique		0			
Other acceleration / grid					
Radiators & thermal					

Electrical Power System			0		
Power conversion					
Power conditioning / processing					
Energy storage					
Distribution					
Direct support structure					
Radiators & thermal					
Startup / Restart Power System			0		
Reactor					
Electrical storage					
Power conditioning / processing					
Radiators & thermal					
Shutdown and Disposal			0		
Subsystem A					
Subsystem B					
Reaction Control Systems			0		
Thrusters					
Power processing					
Radiators & thermal					
Vehicle Structure			0		
Primary structure (trusses, etc.)					
Interface hardware / adapter					
Micrometeoroid shielding					
Tankage			0		
Cryogenic-propellant tanks			0		
Insulation					
Refrigeration (including radiators)					
Fusion fuel tankage			0		
Avionics and Communications					
Weight Growth Contingency			0		
Fluids				0	
Total Tankable Main Impulse Propellant / Expellants					
Main impulse			0		
Flight performance reserve			0		
Boil-off / residuals / losses			0		
Reaction control propellant			0		
Fusion Fuels					
Other Fluids					
Payload System				0	
Primary structure					
Radiation, solar flare, and thermal shielding					
Crew accommodations/life support					
Other					

3.3.2 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%.²³ 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 vehicles and spacecraft, from the point of development Phase C/D to first flight vehicle, most programs experienced a similar 15% to 30% weight growth.^{24, 25}

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 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, 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 actual²⁰ and historic²⁶ expendable launch vehicle upper stages, as well as prior studies¹⁴, formed the basis for the recommendations.

RECOMMENDATIONS

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

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

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

3.3.3 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 delta-V.

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 delta-V 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

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

3.4 Thoroughness in Calculating Power Generation and Usage

Similar to the discussion surrounding the calculation of mass properties (Section 3.3) 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. Inertia-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.

3.4.1 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.^{27, 28}

RECOMMENDATION

A power flow diagram as illustrated in Figure 2 should be included in a system conceptual design.

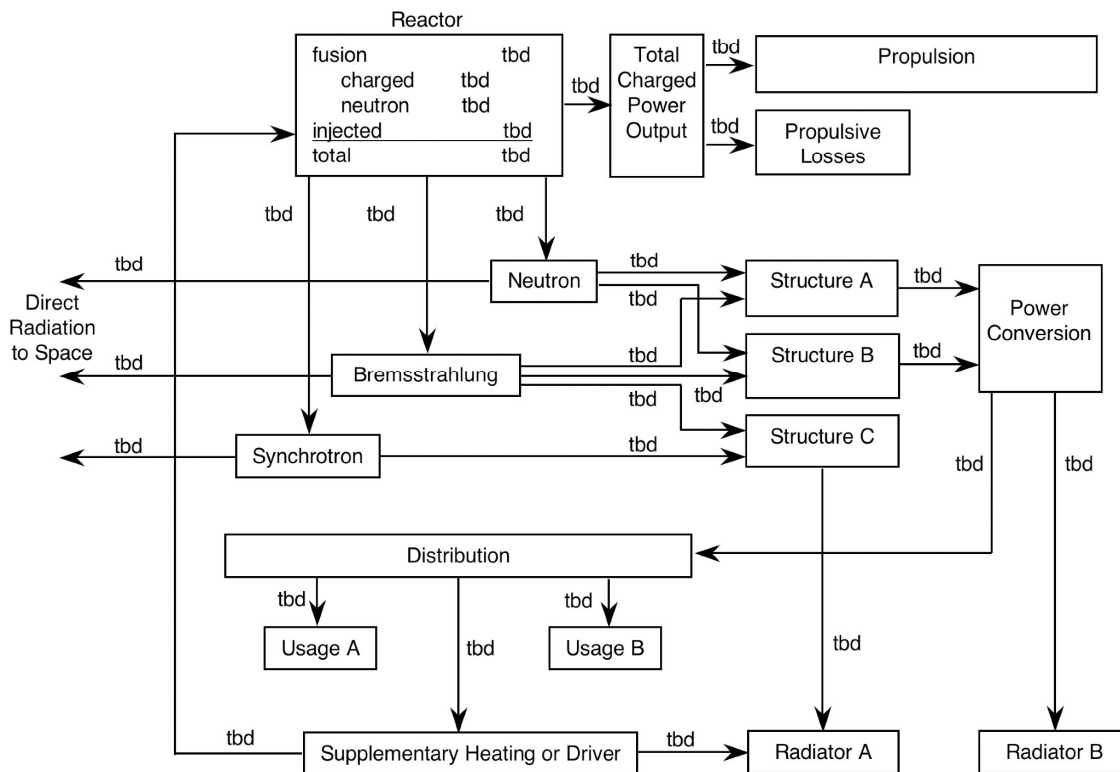


Figure 2 — Sample Generic Power Flow Diagram (all power values in MW – “tbd”)

3.4.2 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 systems²⁹ have lead to recommendations of

40% power contingencies, while other pre-Phase-A or Phase-A contract studies^{30, 31} 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.

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 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.

RECOMMENDATIONS

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 anticipated major causes and proposed actions required to resolve these unknowns should be identified.

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

3.4.3 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, $\text{kW}_{\text{th}}/\text{kg}_{\text{engine}}$) (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

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)

4 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. Lastly, most of the design practices discussed can (with some adjustments) be applied to other advanced space propulsion technology concepts.

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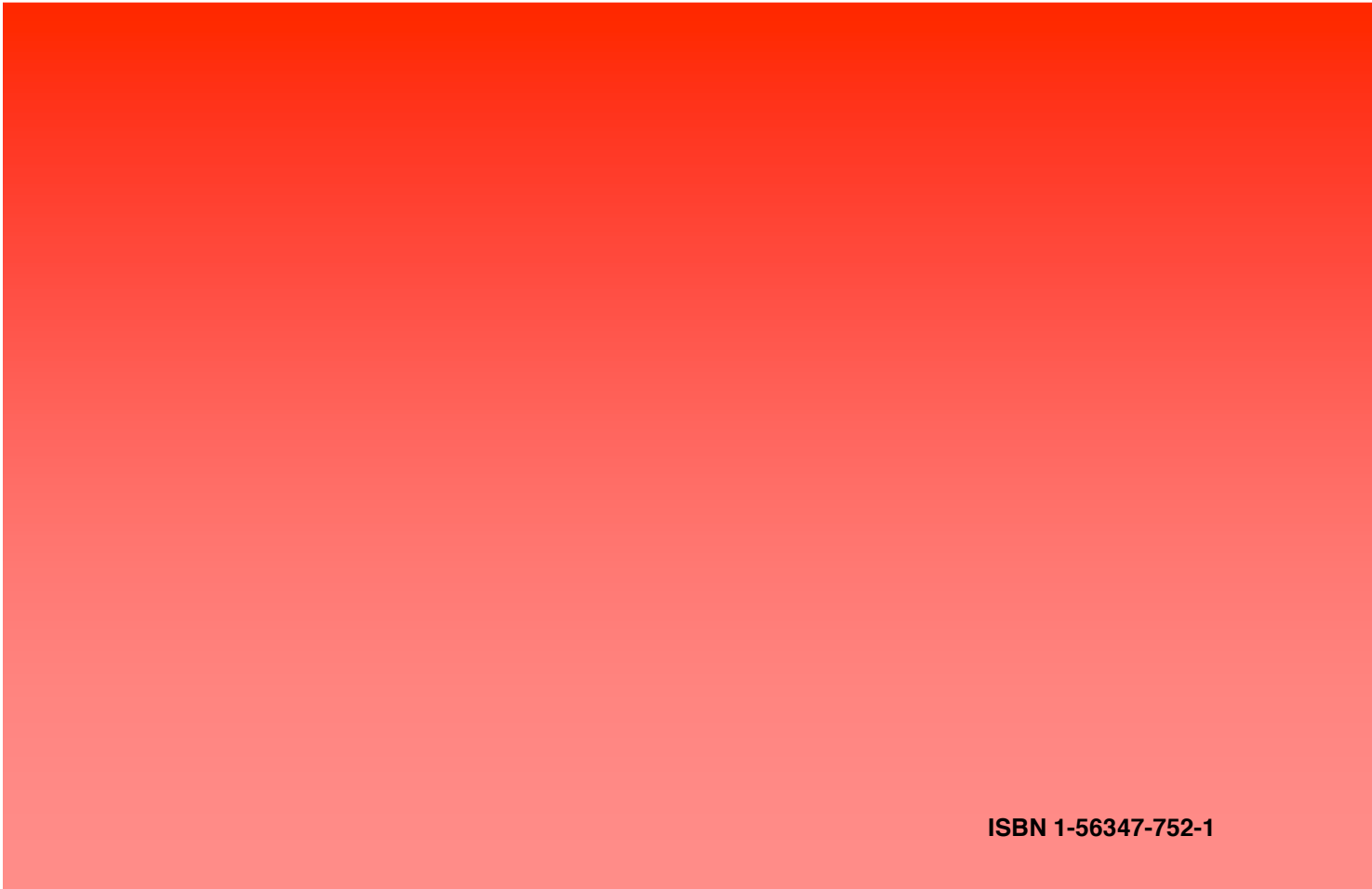
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