Nuclear Fusion Space Propulsion Research, Experimentation, Theory Development, and Systems Analysis Efforts Led by the NASA Glenn Research Center (1994-2004)

Craig H. Williams[i]
NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, USA

This review paper summarizes work performed from 1994 to 2004 by a several interrelated government, academic, and industry teams led by the NASA Glenn Research Center. The nuclear fusion space propulsion system concept was predicated on a spherical torus reactor, which enabled manned missions to the outer planets in less than one year. Moderate thrust levels (1,000's lbf) from direct nuclear fusion exhaust plasma via a magnetic nozzle enabled high thrust-to-weight. An entire vehicle conceptual design, including an artificial gravity crew habitat, was created by the NASA Glenn Research Center. The proof of concept experiment test article and facility upgrade was performed at the Ohio State University which also included staff from the Ohio Aerospace Institute and Science Applications International Corporation. The governing equations for the plasma physics theory of magnetic nozzle operation were derived by the Los Alamos National Laboratory. A preliminary investigation of a proof of concept test utilizing Coaxial Helicity Ejection as a means to supply plasma for propulsion at the National Spherical Torus Experiment reactor was outlined by the Princeton Plasma Physics Laboratory. An industry standard on nuclear fusion propulsion conceptual design was created by two AIAA teams. Despite extremely modest funding levels, significant progress was made advancing the state of the art. The result was a coordinated conceptual, theoretical, and experimental design effort to guide fusion space propulsion development.

I. Nomenclature

a	=	thermal gyroradius
C	=	constant
c	=	speed of light in vacuum
L	=	length
M	=	mode number
m	=	mass
n	=	number density
R	=	local longitudinal radius of curvature of field line
r	=	radial coordinate (positive toward wall); origin at throat on nozzle centerline
T	=	temperature
t	=	time
V	=	magnitude of fluid velocity V
β	=	local ratio of thermal to magnetic pressure within the interface
Δ	=	penetration depth of ions into confining magnetic field in breech

[i] Aerospace engineer, NASA Glenn Research Center, Propulsion Division, and AIAA Associate Fellow.

δ	=	characteristic resistive diffusive width of plasma-field mixing layer
γ	=	wave growth rate
Λ	=	length from breech to throat L divided by ion gyroradius a_i
λ	=	mean free path
ρ	=	mass density of plasma
Ω	=	conventional Hall parameter
ω	=	frequency

Subscripts

b	=	breech
Brack	=	Brackbill
c	=	cyclotron
core	=	core
d	=	drift
e	=	electron
eq	=	equilibrium
ex	=	exit
i	=	ion
p	=	plasma
RT	=	Rayleigh-Taylor
t	=	throat
th	=	thermal
θ	=	azimuthal

II. Introduction

The demise of NASA's Space Exploration Initiative (SEI) program (a presidential initiative for planning manned missions to the Moon and Mars)[1, 2] after four years of effort came in 1993 through changes in appropriations and program definition following the change in presidential administrations. (Formal policy change did not occur until four years later)[3]. The new administration chartered a more modest direction for NASA's manned spaceflight program to nearer term activities: Space Station design/construction, lowering the cost to low Earth orbit (LEO), and dual-use terrestrial applications for space research and development (R&D). In spite of that down-scoping, in 1994 first-line management at Glenn Research Center (GRC) decided that an inspiring, forward-looking effort was needed to keep alive propulsion technology research for manned interplanetary travel, albeit at very modest (sometimes zero) funding levels. There had been an ample body of work performed by GRC under the leadership of Dr. Stanley Borowski on Nuclear Thermal Rocket (NTR) applications for manned Mars missions during SEI. In addition, work on Nuclear Electric Propulsion (NEP) for unmanned Mars cargo delivery, led by GRC's Dr. James Gilland and others, had made significant progress as well. After the demise of SEI, work on NTR continued at a low level, while some technology work on high power electric propulsion also proceeded. But NASA GRC management instigated a discussion to investigate what else could be done. It was eventually decided by management, Dr. Borowski, and this paper's author that focused, very limited propulsion research and analysis for manned outer solar system travel should also be pursued. A few tasks were identified which could be expected to produce meaningful progress and dual-use technology despite the anticipated meager funding (if any).

A foundation already existed based on the considerable analytical and experimental work by GRC leading the Agency's nuclear fusion propulsion program from 1958 to 1978 [4, 5]. The fusion program at GRC had been staffed by over a dozen people in two branches, fabricated and operated three on-site high power magnetic confinement facilities (including the Bumpy Torus fusion reactor), and over \$20M in then-year budget (~\$195M in current-year) over 20 years[4, 5]. By comparison, that program was dwarfed by the contemporary multi-agency/multi-NASA Center nuclear thermal propulsion program (Rover/NERVA) which was funded at approximately 70 times that of the NASA fusion budget over a similar time period [6, 7, 8]. Both of these programs (which GRC led in partnership with the U.S. Atomic Energy Commission) ended in the mid-1970s. Twenty years later in the mid-1990's, the only "advanced space propulsion research" NASA was pursuing was a ~\$1M/year budget line item composed of analytical studies and very modest (~\$10K to ~\$100K) experiments led by NASA Jet Propulsion Laboratory. [9] Despite a ~\$14B then-year total NASA agency annual budget in 1996 [10], less than ***one percent of one percent*** of the nation's space program budget was being used for what could only be charitably be called "advanced space propulsion research", a fact most taxpayers would find astonishing.

III. Preparatory Efforts

The author of this paper began performing a modest level of effort to start this initiative. The initiative had to be consistent with the new national space policy, make sense at low resource levels, and be technically sound. Concepts last pursued almost two decades earlier had to be reassessed and the most promising ones identified. Technical community resources (analytic tools, testing facilities, staff experience, etc.) had to be evaluated and their availability ascertained. Finally, dual use/near term terrestrial applications had to be found for the technologies, since their space applications were so far in the future. These preparatory efforts were pursued by a ~1 "full-time-equivalent (FTE) at GRC for four fiscal years (FY1994 through FY1997), supported initially by GRC, though NASA HQs later provided seed funding. [11, 12] These efforts formed the basis for eventual support by a new NASA HQ program for advanced propulsion research which began in FY1998. This paper's author served as the GRC project manager throughout the entire period from the initial preparatory efforts, through slightly beyond the end of the NASA HQ sponsored program.

A. Policy Rationale

Since the new presidential space policy was directed away from any near term manned lunar/Mars planning, the work emphasized consistency with achieving significant shortening of trip times due to detrimental effects on humans of prolonged exposure to weightless and ambient radiation environments (as Space Station on-orbit experience was showing). A deliberate tie into dual use terrestrial technologies was also emphasized. These points are discussed in Sections III-B and III-D.

B. Technical Rationale

One of the most fundamental obstacles to manned interplanetary travel is the lack of adequate propulsion system performance. While challenging enough for inner solar system travel, reasonable travel times and payload mass fractions for outer planet missions are prohibitive using any near-term available propulsion technology. Repeatedly, Agency studies have demonstrated that the nuclear thermal rocket is the most viable propulsion concept for manned trips to Mars and other inner solar system bodies. But the appropriate propulsion technology for the even more performance demanding outer solar system missions is far from clear. Further, to move beyond solely public sector-financed missions (or even feasibility from any funding source), propulsion technology with significantly improved performance will be mandatory. To delineate the required performance, two small GRC-internal analytic studies were performed in 1995.

One GRC study outlined the rationale for manned outer planetary missions [13], emphasizing only those which had a compelling need for human presence (as opposed to robotic): the flexibility in adjusting work due to unforeseen discoveries during pursuit of scientific research (such as staffed laboratories on the water ice/ocean moons in search of extraterrestrial life), and commercially-driven wealth acquisition (He^3 mining in planetary atmospheres for fusion power plant fuel supply). The study then referenced prior system studies which characterized various advanced propulsion technologies' specific impulses (Isp) and vehicle specific powers (Alpha or "α"). Only nuclear fusion was shown to be (theoretically) capable of producing Isp capabilities in the 10,000 to 100,000 lbf-sec/lbm range and α in the 10 to 100 kW/kg range. [13] Magnetic confinement concepts (where extreme fields confined plasma sufficiently to achieve ignition) generally had lower α's than inertial confinement concepts (where colliding energy beams imploded targets, relying on the substance's inertia to confine the reaction).

How those system parameters mapped into reasonable trip times (months) and adequate payload mass ratios (10% to 25%) were determined by another GRC analytic study. That study contained derivations of new analytic expressions (validated independently by a major trajectory design code) which produced simultaneously minimized travel time and maximized payload mass ratio for a given mission distance between planets (equivalent to delta-V), Isp, and α.[14] Implicit in the new analytic expressions was the necessity of the propulsion systems be capable of operating at high thrust-to-weight (~ one milli-'g' or 32.1739E-03 ft/sec**2), which resulted in nearly radial trajectories. Representative results are shown in Fig. 1, where a mission from Earth to Jupiter with an optimum Isp of 50,000 lbf-sec/lbm and α of 30 kW/Kg yield a maximum payload mass ratio of ~25% and a minimized trip time of three months.[14] When mapped onto advanced propulsion system characteristics, it was shown that only direct fusion propulsion was capable of producing systems with the necessary ability for reasonable manned outer solar system travel (Fig. 2).[15] Thus, a clear linkage was established between credible mission rationale, required system performance, and viable technology.

C. Assessment of Past Fusion Propulsion Concepts and Selection of Promising Baseline Design

Having established that direct nuclear fusion as the most appropriate propulsion technology for manned outer planetary missions, the next step was to survey past concepts in order to select and build on the most promising design.

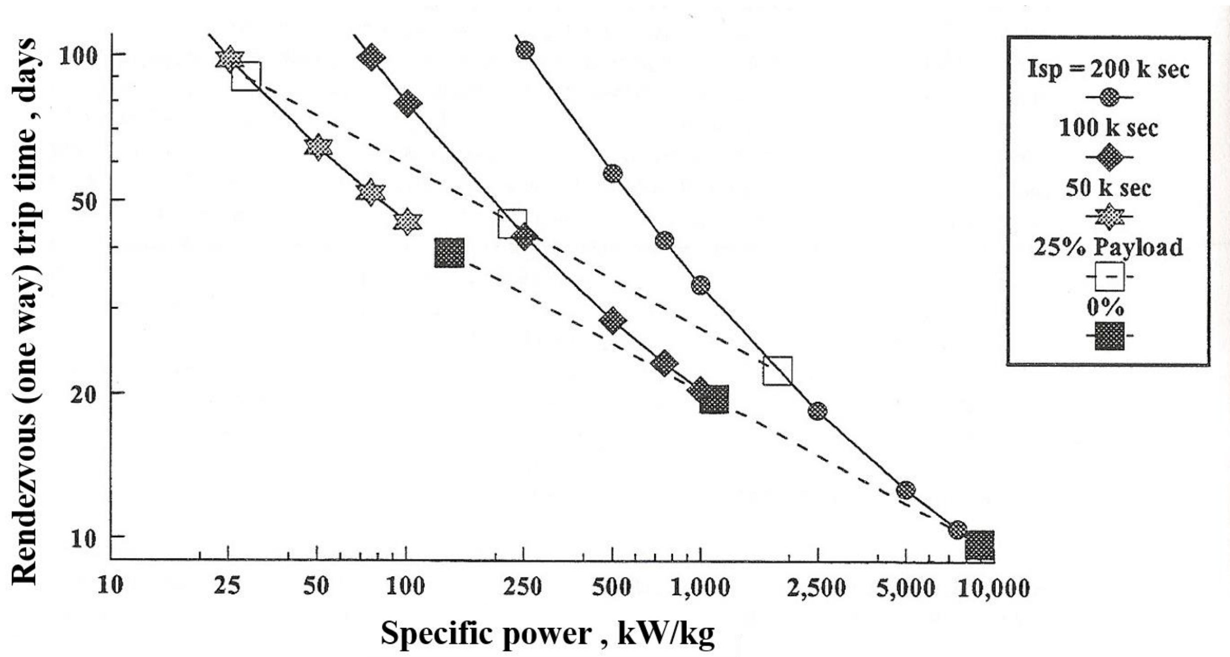

Figure 1: Earth to Jupiter mission (maximized payload ratio with minimized trip time)

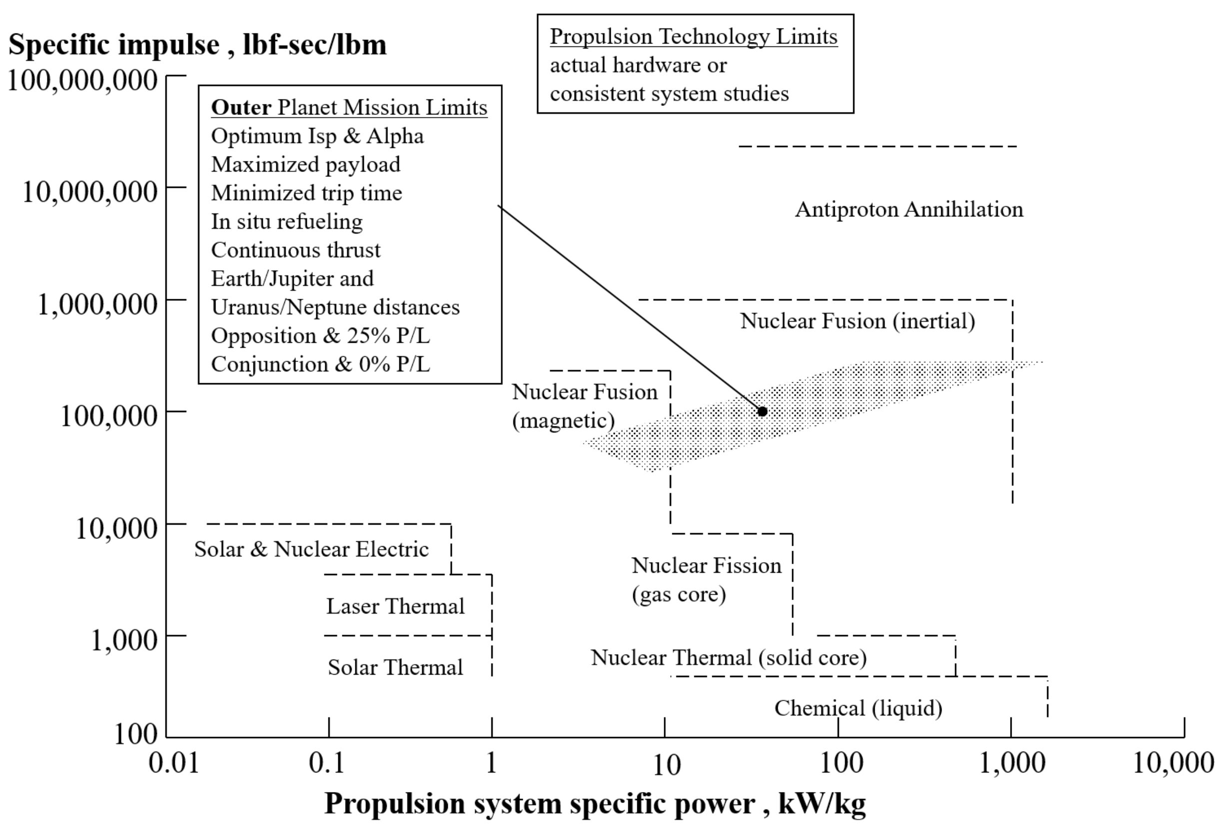

Figure 2: Projected space propulsion technologies vs. mission needs

In 1996, 13 fusion propulsion conceptual designs published over a span of 14 years were surveyed (eight magnetic confinement and the remainder being inertial concepts).[15] Various characteristics were compared: performance, design completeness, relative technological maturities, mass properties, power balance, and others) It became apparent that the concepts had varying degrees of incompleteness, focus, mission application, and subsystem maturities. Many required significant reevaluation (and on many cases, re-analysis by this paper's author) of their system and asserted performance characteristics (Isp & α) because of significant self-inconsistencies in the data.

Several general conclusions were made. First: the concepts were designed for different applications: some for unmanned cargo applications while others were better suited for fast, piloted missions. This was evident from their propellant mass ratios which varied from 10% to 80%. [15] Second: with only one exception, all concepts were not designed for maximized payload fraction and minimized travel time. [15] Third: No concept had even a basic engineering design of the engine system. That is to say, how the plasma from the fusion reaction was specifically converted into propulsive thrust was lacking in all concepts. For these (and others) reasons it was concluded that all conceptual designs had significant shortfalls. However the spherical torus (ST) reactor concept appeared to have the most promising potential with the fewest intractable problems (Section V-C). Thus, an ST-based concept was chosen by the GRC team as its basis.

D. Assessment of Available Resources

There were several assets which proved to be invaluable to the success of this initiative. The most critical was the pre-existing conceptual design of a ST fusion reactor, choice of fuel, and operation characteristics conducive to space propulsion which had previously been designed by Dr. Stanley Borowski many years earlier. His participation on the GRC team was fundamental to the success, superior design, and focus on critical technical issues of the GRC-led initiative. Dr. Borowski also supplied the computer source code for a 1-D fusion power balance program, which was used as the analytic tool to further design and define the reactor's operation and performance parameters.[16] It eventually became the basis for designing and evaluating the primary support systems (such as the toroidal field coil structure, heat transfer analysis, first wall, inboard assembly, and many others).

The aerospace engineering department of Ohio State University had an underused bank of 2,100 capacitors of 43μf each capable of producing 1 GW of plasma power in a millisecond pulse. [17] This pulse width was determined to be sufficient to be considered "quasi-steady state" for the plasma physics processes of interest. Due to its immense size and capability, the cap bank was affectionately known as "Godzilla' and represented a unique facility in the space propulsion community. This facility became the hot fire, vacuum test site for the fabricated magnetic nozzle plasma source. Other hot fire facilities were available and were intended to eventually be brought into the project, such as GRC's "Vacuum Tank 7", a former magnetic nozzle test facility for electric propulsion concepts also utilizing hydrogen working fluid. This ~11 foot in diameter, ~16 foot long facility was planned to be the collocated facility for the new home of OSU's Godzilla bank after transfer to GRC to serve as the centerpiece of fusion propulsion research. [18, 19]

Finally, the US Department of Energy (DOE)'s new alternate concept flagship fusion reactor, the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory (PPPL), was just finishing construction. Its first plasma was achieved in February 1999. Its Program Manager, Dr. Martin Peng, by happenstance was Stan Borowski's PhD advisor. This acquaintance was invaluable to initiate the linkage between the GRC fusion initiative and this major DOE fusion research facility. Many of the proposed conceptual designs, critical subsystem guidance, and suggested modes of operation were provided by the NSTX's Program Manager to GRC.[ii]

E. Identifying Dual Use Applications

During that period of time, NASA HQ advocated a policy of "dual use" technology development, where terrestrial/non-aerospace applications of NASA technology were encouraged and viewed favorably by program management. Because manned missions to the outer planets were obviously in the far future, the dual use applications GRC and our partners were able to identify were essential to securing support for our initiative.

The civilian nuclear fusion power research program was an important part of the DOE's portfolio for decades. Magnetic Confinement Fusion (MCF) (as opposed to Inertial Confinement Fusion (ICF)) program was dominated by the Tokamak Fusion Test Reactor (TFTR) at PPPL, as well as planning for participation in the International Thermonuclear Experimental Reactor (ITER) program. However, there were several smaller programs representing "alternative reactor concepts" --- the largest of which was the National Spherical Torus Experiment (NSTX), also at

---

[ii] Peng, M., U.S. Department of Energy, Princeton Plasma Physics Laboratory, Princeton, NJ, personal communication, c. 2000.

PPPL. This reactor was nearing completion at the start of this NASA fusion propulsion initiative. As will be discussed in Section VIII-B one of the many technical issues at NSTX was Co-axial Helicity Injection (CHI), where magnetic helicity would be used to supply plasma current and provide an alternate means to control the reactor. Its inverse, Co-axial Helicity Ejection (CHE) was expected to occur at pulse shutdown, but was a little understood phenomena. Though not a critical topic for terrestrial power, CHE nevertheless was of interest to the NSTX program. But since extracting plasma power from a fusion reactor without adversely affecting the steady state fusion reaction would be fundamentally important to space propulsion, CHE became recognized as an essential phenomena for NASA to understand and master --- and a dual use technology.

Another dual use technology was the magnetic nozzle. The high Isp/high α propulsion required for these missions dictated that the plasma exhaust had to be of very high temperature and very high number density. A conventional convergent/divergent, solid-walled nozzle was out of the question due to the plasma state, and conventional high power electric propulsion methods (including MPD and other related NEP concepts) were ill-suited or inefficient. It was apparent a magnetic nozzle with its virtual convergent/divergent magnetic field geometry would be essential to take full advantage of direct fusion products. Magnetic nozzles were a poorly understood technology and remain so even to the present day. However, in the 1990's, the plasma spraying was a $10B industry.[20] It was thought that the use of magnetically nozzled plasma accelerators would be a superior means to perform plasma spraying for materials processing, application of various coatings/surface modifications, and advanced manufacturing. Since plasma spraying suffered from insufficient control and repeatable results, it was conjectured that a magnetically nozzled flow would improve performance as well as efficiency, while reducing electrode damage and uneven deposition of coatings.[20] Several non-dimensional numbers characterizing the plasma state were similar or reasonably close to those of fusion propulsion (although the power levels were dramatically lower for plasma spraying). This suggested that knowledge of certain physical phenomena at high power levels for fusion propulsion could also be applicable to lower power terrestrial plasma spraying industry. It was therefore believed that understanding the physics and technology of magnetic nozzle space propulsion operations could be a dual use technology directly transferable to the terrestrial plasma spraying industry.

A third dual use technology became apparent during the project. In order to provide extremely high temperature and number density plasma at stagnation conditions downstream of the reactor but upstream of the magnetic nozzle, a plasma source of some kind had to be prepared. The decision was to modify a very high power magnetoplasmadynamic (MPD) thruster. MPD is a form of electric propulsion frequently associated with large cargo (unmanned) missions with high delta V requirements, such as Mars cargo delivery to support manned bases. In order to generate large quantities of high power plasma (at high temperature and density), it was decided that an MPD thruster should be modified and used as a plasma source for the experiment (Section VI-C). The test firings were up to 100's MW of plasma power, the greatest power MPD operation ever demonstrated in unclassified experiments. This considerable hot fire experience contributed to the knowledge base of MPD thrusters.

IV. Space Transportation Research Project

A. Initiation, Scope, and Program Management

In fiscal year 1998, the $62M Advanced Space Transportation Program (ASTP) was fully initiated to support R&D of technologies to reduce the cost to accessing outer space.[21] The Marshall Spaceflight Center (MSFC) was designated by HQs to lead the ASTP based in part to its officially designated status as NASA's "Center of Excellence" in space propulsion R&D. One project within ASTP was the Space Transportation Research (STR) project. It had one of the smallest budgets (~$3M) in the program but was tasked to conduct research in the widest of all technical fields of propulsion, including advanced chemical, airbreathing, magnetic levitation, advanced nuclear thermal, beamed energy, nuclear fusion, electric, tether, sail, magnetohydrodynamics (MHD), aerobraking, antimatter, and even "faster than light". [22, 23] For five years, the STR project (initially in ASTP, then 3rd / 4th Generation Space Transportation Launch Technology (STLT) program) funded these concepts, typically at the ~ $25K to ~ $150K level per task.[24] The STR project was also managed by MSFC, which also chose to perform half of the entire STR portfolio at the Huntsville Center, the first time that Center had attempted to do propulsion research. It is important to note that NASA support of "advanced space propulsion" research continued a downward trend for decades: from the major GRC-led R&D Rover/NERVA and Fusion Energy for Space Power and Propulsion programs (which ended in the 1970's), to the GRC-led NTR and NEP work at its Nuclear Propulsion Office (1990-1993) for SEI, to finally the extremely small STR program led by MSFC.

B. Fusion projects Within STR

GRC was one of two NASA Centers that pursued fusion propulsion within the STR project. GRC had a rich history in fusion propulsion[4] and chose to build on that foundation while also leveraging a major ongoing DOE fusion reactor program (see Section VIII-A). GRC teamed with the considerably more capable PPPL which was about to commence operations with its full scale, world-class fusion reactor with significant staff (~100) conducting internationally-recognized physics research. All this was evaluated by a non-advocate review (NAR) conducted on the entire STR project (including the fusion reactor concepts) early in the ASTP. The findings and recommendations of the STR project are summarized in Fig. 3, where both of the GRC-led tasks received the highest ratings in the fusion category.[9]

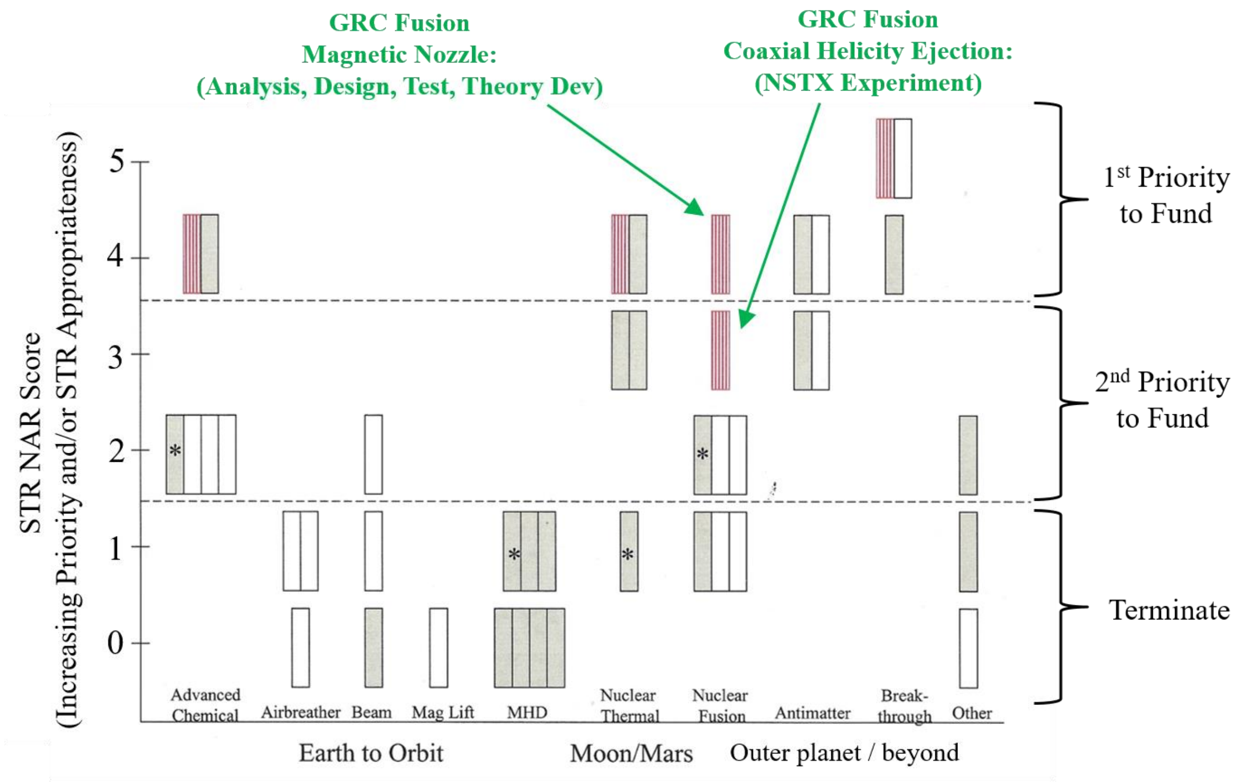

Figure 3: STR non-advocate review evaluation and recommendations

C. Composition and Leadership of GRC's Fusion Propulsion Teams

Five teams comprised GRC's fusion propulsion effort which were part of and funded by STR: design of the fusion vehicle conceptual, the magnetic nozzle experiment, development of magnetic nozzle plasma theory, planning the coaxial helicity ejection experiment, and creation of an AIAA industry standard. Each consisted of staff from one or more national labs, industry, and or academia. Figure 4 lists the individuals and their organizations for the first four teams. Figure 5 lists the organizations on the AIAA teams which produced the industry standard. The GRC initiative was by far the broadest-based national effort in fusion propulsion research in the STR (or any other) project since the fission and fusion space propulsion programs last led by GRC in the 1970's. In fact, three of the five teams (magnetic nozzle experiment, theory development, and coaxial helicity ejection experiment) were led by current or former high level DOE senior staff, who brought an impressive level of technical excellence and scientific gravity to the program.

V. Fusion Vehicle Conceptual Design

Creating a conceptual design of the vehicle was fundamentally important to focus research efforts. The design effort and subsequent performance analysis enabled identification of major systems issues so that research could be targeted into high-leverage areas. Though initially published in 1998, the final technical paper version published in 2001 describing the entire fusion vehicle conceptual design was vastly improved in definition and comprehensiveness.[25] Although the entire spacecraft (including artificial gravity crew payload) was designed, the primary areas of focus were vehicle performance, fusion reactor and operation, power balance, and magnetic nozzle.

- NASA Glenn Research Center
  - Dr. Stan Borowski (fusion reactor design, operation, DOE PPPL interface)
  - Len Dudzinski (trajectory design, concept design)
  - Ian Dux (CAD of reactor, magnetic nozzle)
  - Albert J. Juhasz (power conversion)
  - Dr. Hani Kamhawi (OSU experiment setup)
  - Craig H. Williams (fusion propulsion project lead, mission design, reactor sub-system design)

- Ohio State University
  - Dr. Darin Marriott (OSU experiment execution)
  - Dr. Pavlos G. Mikellides (OSU experiment setup lead)
  - Dr. Peter Turchi (OSU experiment design, OSU experiment planning)
  - Dr. Thomas M. York (OSU experiment, OSU project management)

- DOE Los Alamos National Lab
  - Dr. Richard Gerwin (**magnetic nozzle and plasma theory**)

- Ohio Aerospace Institute
  - Dr. James Gilland (lead OSU experiment execution)

- SAIC
  - Dr. Ioannis G. Mikellides (OSU experiment execution)

- DOE Princeton Plasma Physics Lab
  - Dr. Martin Peng (NSTX reactor program manager, **lead CHE/reactor theory**)

- NASA Marshal Spaceflight Center
  - John Cole (NASA STR Program manager)

Figure 4: GRC Nuclear Fusion Space Propulsion Team Members

DOE LLNL	DOE LANL	DOE PPPL
NASA GRC	NASA JPL	University of Illinois
University of Wisconsin	United Technologies	University of Washington
Ohio Aerospace Institute	University of California	EDEn-Corp
Flight Unlimited	Andrews Space, Inc	

Figure 5: Organizations which participated in AIAA nuclear fusion propulsion teams

A. Overview

A conceptual vehicle design enabling fast, piloted outer solar system travel was created predicated on a small aspect ratio ST nuclear fusion reactor. Engineering conceptual design, analysis, and assessment was performed on all major systems including a rotating crew payload to provide partial Earth-g artificial gravity, central truss, nuclear fusion reactor, power conversion, magnetic nozzle, fast wave plasma heating, tankage, fuel pellet injector, startup/re-start fission reactor and battery bank, refrigeration, reaction control, communications, mission design, and space operations. Detailed fusion reactor design included analysis of plasma characteristics, power balance/utilization, first wall, toroidal field coils, heat transfer, and neutron/x-ray radiation.[25]

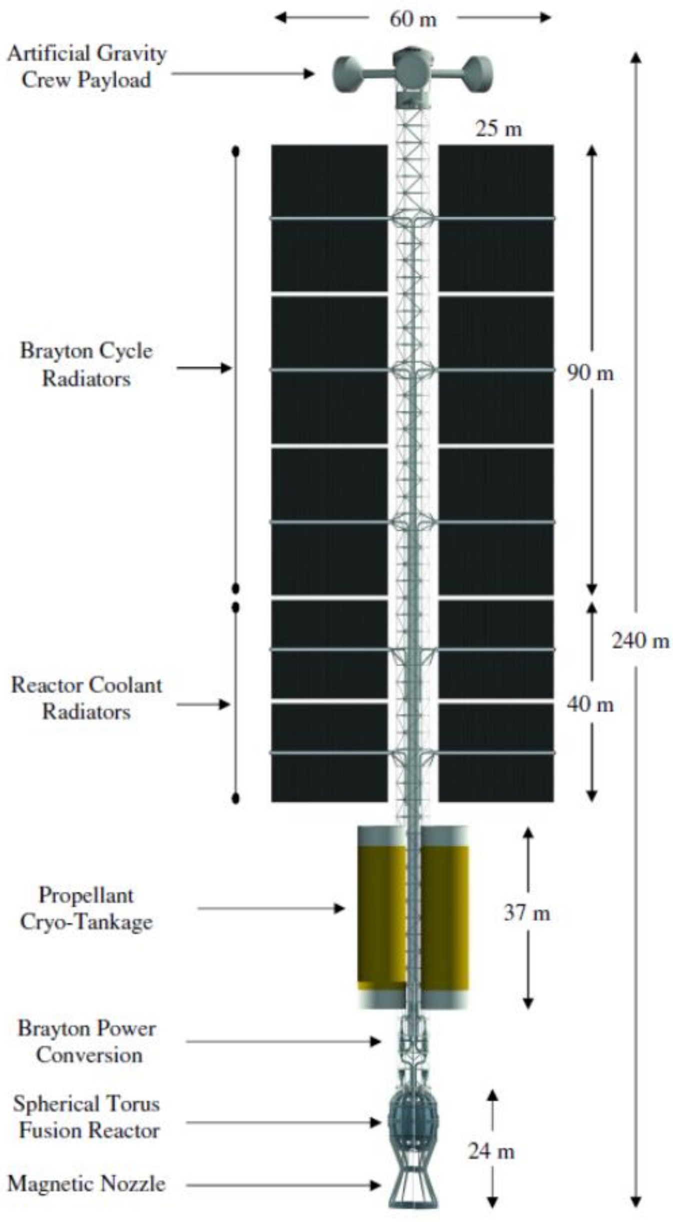

Figure 6: Nuclear fusion vehicle concept

Figure 6 illustrates the overall layout of the vehicle concept, where form was dictated by function.[25] The crew module was forward and far away from the radiation sources. The reactor was designed to minimize capture of waste radiation (which drove heavy/costly power rejection systems). Systems which required long structures (such as radiators and fusion fuel particle injector) were positioned on the central truss. 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 D3He 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 1A. [25]

Table 1: A) Vehicle and B) payload mass properties

Payload			172
	Structure	38	
	Shielding	69	
	Crew systems	25	
	Weight growth contingency	40	
Structure			646
	Central truss	6	
	Fusion reactor	310	
	Magnetic nozzle, divertor	6	
	Reaction control	16	
	Power conversion	30	
	Coolant system	11	
	Fast wave plasma heating	5	
	Propellant tankage	88	
	Refrigeration	2	
	Fuel tankage, injector	6	
	Startup/re-start fission reactor	10	
	Battery bank	5	
	Avionics, 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

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

B. Performance

Table 2 contains the overall performance analysis results for two missions. The Earth-to-Jupiter rendezvous mission thrust was 6,250 lbf, an Isp of 35,435 lbf sec/lbm with a resulting one way trip time of 118 days (~4 month).[25] The Earth-to-Saturn rendezvous mission thrust was 4,690 lbf, Isp of 47,205 lbf sec/lbm, with a resulting one way trip time of 212 days (~7 month) trip time. [25] The vehicle concept operated at the same specific power for both missions of 8.62 kW/kg, transported identical dozen-man crew payloads of 172 mt (representing a greater than 10% payload mass ratio), and initial mass in low Earth orbit of ~1,690 mt.[25] An in-house analysis was performed using the previously described method to compare a nuclear fusion system to nuclear thermal and liquid chemical (LOX/LH2) systems for a rendezvous mission from Earth to Saturn.[14] It was assumed that the NTR and liquid chemical systems had similar thrust to weight capabilities for a continuously burning fusion vehicle in order to simplify and remove a variable from the comparison. A 4% payload mass fraction was also held constant. The result were significantly different trip times: 7 months vs. 7 years vs. 14 years respectively.[26] Another analysis gave similar results, where a round trip manned mission to Jupiter relying on minimum delta-V transits (i.e. Hohmann transfers) using more conventional propulsion systems have been shown to take almost four years.[27] Trips to and/or between other outer planets would obviously take even longer. Analysis has led authors in the past to conclude that manned outer solar system travel relying on chemical or even nuclear thermal propulsion is not practical.[13, 27]

Table 2: Performance

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

C. Crew Payload

A literature search for an appropriate crew payload design for outer planet missions failed to produce any findings. This was to be expected given the almost total lack of investigation into manned outer planetary missions down through the years. Thus a crew payload was designed from scratch focused on three fundamental criteria: crew size and capabilities sufficient for the desired mission time, mitigation of effects of prolonged weightlessness, and protection from ambient radiation. The design was then compared to existing flight experience and hardware, primarily Apollo Lunar missions, International Space Station experience, and a couple of Mars studies.

For lengthy outer planetary missions, it was assumed that the crew size would be greater than Lunar or even Mars missions. A minimum of six crew members (but with provisions for up to twelve) was a design requirement. Further, a crew size-to-mission time length-to-habitation volume relationship used in past studies was adhered to in the design process. A rotating, three module configuration payload was adopted based on satisfying several rotation operation and launch vehicle payload fairing shroud criteria. Each module was two stories tall not counting the connecting tunnel. The payload housed the crew habitation areas, consumables, laboratory facilities, and vehicle controls. The mass properties for the crew payload are contained in Table 1B. [25]

The detrimental effects of prolonged exposure to zero gravity are well known: increased susceptibility to illness, bone de-calcification, deterioration of muscle strength, and possibly others. Exercise and dietary supplements have shown some mitigation success, but there was increasing belief that some degree of artificial gravity will be needed for manned interplanetary travel (though how much was still a matter of conjecture). It was for these reasons that the crew payload was designed to provide some degree of artificial gravity. Satisfying several sometimes conflicting requirements and findings from past studies, a design was created which produced 0.2-g gravitational acceleration (~Lunar surface). Table 3A contains some of the basic design characteristics of the crew payload. [25]

Prolonged trips to the outer planets will most certainly experience significant exposure to ambient radiation (galactic cosmic rays and solar proton flares). Protection will be essential, and while design solutions exist, they have substantial negative impacts in terms of increased system mass. Nevertheless, water jacketing was chosen to protect the crew: 2 cm depth throughout the entire payload for galactic cosmic ray protection and 20 cm depth for a limited volume “storm shelter” to be used for short duration solar proton flare activity. (Table 3A) [25]

Table 3: A) Payload and B) reactor characteristics

Nominal crew size	6 to 12
Consumables (months)	12
Number of habitable modules	7
Module structural material	GrEp
Lab/Hab, Central Hub diameter (m)	7.5
Lab/Hab height (2 story) (m)	5.6
Storm shelter height (m)	7.8
Total habitable volume (m^3)	872
Artificial gravity (g's)	0.2
Rotation rate (rpm)	3.25
Rotation arm (m)	17
Maximum walking-to-rim speed ratio	0.17
Radial gravity gradient (milli-g's/m)	12
Nominal GCR maximum dose (rem/yr)	~ 55
Storm shelter GCR maximum dose (rem/yr)	~ 30
Radiation shielding (nominal) (cm of H_2O)	2
Radiation shielding(storm shelter)(cm of H_2O)	20
MLI thermal shielding (in)	2
Micrometeoroid shielding (mm)	0.5
Power consumption (steady state) (kWe)	30
Mass (mt)	172

Major radius (m)	2.48
Minor radius (m)	1.24
Aspect ratio	2.0
Elongation	3.0
Plasma volume (m^3)	225.8
Safety factor (edge)	2.50
Safety factor (axis)	2.08
Fuel ion density ($10^{20}/m^3$)	5.0
Electron density ($10^{20}/m^3$)	7.5
Plasma temperature (keV)	50
Volume averaged beta	0.318
Confinement time (sec)	0.552
Average neutron wall load (MW/m^2)	1.03
Average radiation wall load (MW/m^2)	5.20
Ignition margin	1.235
Toroidal magnetic field (centerline) (T)	8.9
Maximum magnetic field (coil surface) (T)	32.3
Gain factor (Q)	73.1
Plasma current (MA)	66.22
Bootstrap current fraction (overdriven)	1.16
Wall reflectivity (effective)	0.98
Number density profile shape factor	1.0
Temperature profile shape factor	2.0

D. Fusion Reactor Concept and Fuel

A largely skeletal design was used for the ST nuclear fusion reactor. The design philosophy was to minimize reactor mass, maximize useful charged power out, and facilitate direct radiation of waste power to space without a containment vessel. An ignited plasma operating mode was chosen, as well as high bootstrap current, in order to minimize the re-circulating power fraction required and the concomitant conversion system mass for generating injection power. It was thought that a continuously thrusting propulsion system would be better served by this mode of reactor operation, where charged transport power was used exclusively for propulsion purposes. A small major radius and small aspect ratio reactor geometry was chosen to minimize size and mass. Table 3B contains primary characteristics of the reactor. [25]

Modeling of the plasma conditions pursued peaked temperature and number density profiles within the core of a plasma. This enabled a relatively small fusion-producing region to be established, satisfying Lawson and ignition criteria without necessitating large beta (the ratio of thermal pressure to magnetic pressure) throughout the plasma.[25] This approach was tremendously attractive for space propulsion applications where compact size, thus reduced mass, is of paramount importance.

D^3He (1:1 ratio) was chosen as the reactor fuel in order to maximize the charged transport power output and minimize neutron output power fraction. It was decided that in the time frame of this concept, reactor operation at a plasma temperature of 50 keV would represent only an incremental technological challenge over that of a DT-based concept operating at 10 keV (and a fuel significantly more conducive to space propulsion application). Also, solar system-class operation presupposed propellant and fuel supply availability in the hydrogen and helium-rich outer planet atmospheres and satellites, mitigating supply issues surrounding ^3He. D^3He fuel with a spin vector polarized parallel to the magnetic field was used to capitalize on the up-to 50% enhancement in fusion reactivity cross section, tremendously improving the charged output power. [25]

E. Power Balance

Figure 7 illustrates the fusion power output and utilization. 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.[25] 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), over 80% of which was used to drive heat transfer/rejection systems. No steady state injection power was necessary due to the ignited, overdriven bootstrap current reactor operation. The Q of >73 (fusion power out/input power) was based on 108 MW of High Harmonic Fast Wave start-up heating.[25]

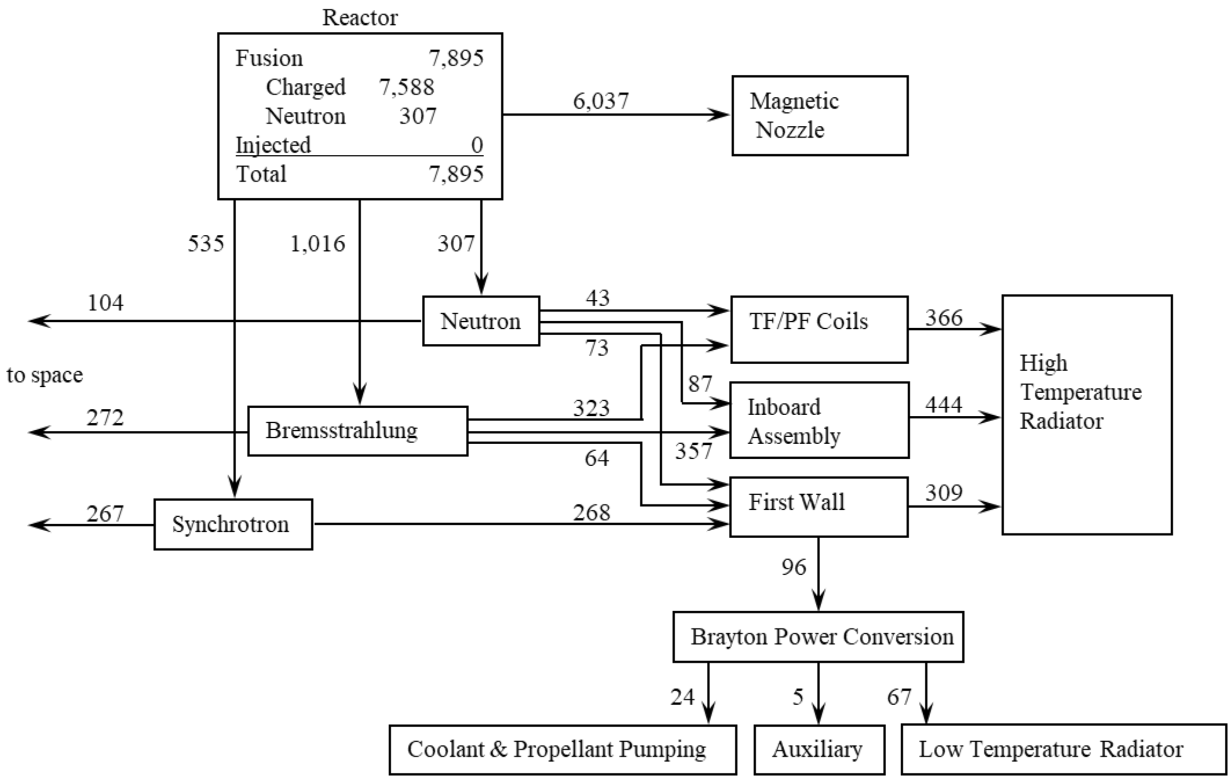

Figure 7: Power balance (input, output, and utilization all in MW)

F. Magnetic Nozzle

The conversion of the reactor's transport power into directed thrust was accomplished in two steps by the magnetic nozzle. First, high enthalpy transport plasma from the divertor was mixed with injected hydrogen propellant in order to reduce the excessive temperature and increase total charged propellant mass flow. Then the propellant enthalpy was converted 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 physical contact with the nozzle's coils and structural members which create 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 Isp's of 20,000 to 75,000 lbf-sec/lbm and corresponding α's of 10 to 100 kW/kg required for multi-month travel to and between the outer planets necessitate ion reservoir temperatures of 100's eV and number densities $\sim 10^{22}$/m**3. [25] Scrape off layer plasma from the reactor has temperatures still too great (~1,000 ev) and number density too low ($\sim 10^{20}$/m**3) exiting through the divertor. So these plasma reservoir values must be adjusted prior to acceleration through the nozzle in order to produce the mission appropriate Isp and α. This was accomplished by supplying slush hydrogen thrust augmentation propellant which is first heated/ionized by the escaping reactor plasma. This produced the desired reservoir conditions to enable bulk plasma temperature (thus Isp) and mass flow rate (thus thrust-to-weight) optimized for the mission.

A magnetic nozzle concept is illustrated in Fig. 8. [25] The "reservoir" of the magnetic nozzle was somewhat analogous to a conventional liquid chemical rocket engine's combustion chamber. Adjacent to the reactor's divertor, it consisted of two small radius superconducting coils of the same design and materials as the TF coils. Forming an "effective" 10 cm radius solenoid, they provided the meridional magnetic field to confine the converging propellant and reactor plasma streams until their temperatures equilibrated. The reservoir was in large part a "virtual" chamber due to its mostly skeletal design where magnetic field lines defined the flow boundary for charged particles passing through. This design minimized mass and heating concerns but also placed a premium on rapid, effective ionization and enthalpy equilibration (i.e. neutrals were lost through the sides). The second small radius coil also constituted the "throat" for the nozzle, where choked flow (sonic) conditions existed. An arbitrarily larger radius third coil formed the downstream, diverging section and provided additional curvature to the magnetic field. [25]

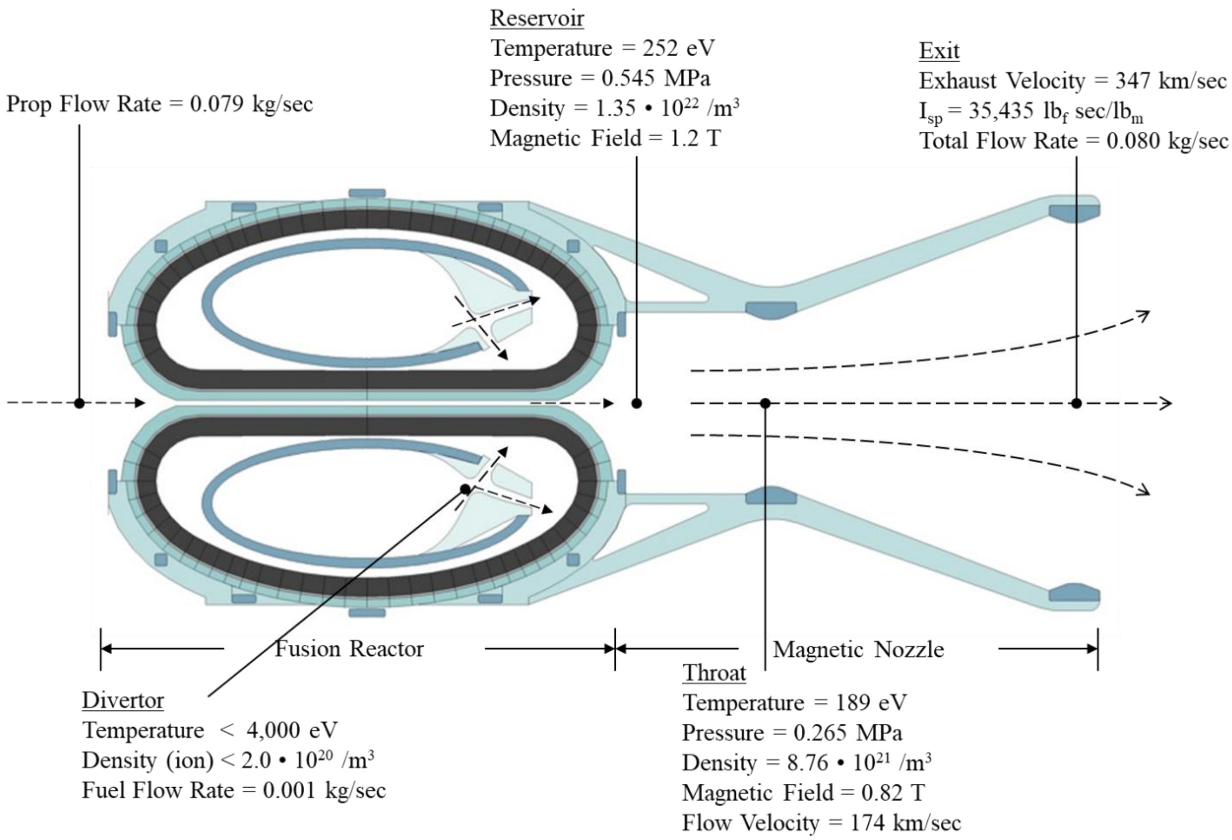

Figure 8: Cross section of nuclear fusion reactor and magnetic nozzle

VI. Magnetic Nozzle Experiment at OSU

Validating the theoretical model through hot fire testing in vacuum of a representative magnetic nozzle test article would bolster the credibility of the concept. This work was done at the aerospace engineering department at Ohio State University (OSU) by professors, graduate students, and staff from NASA GRC, Ohio Aerospace Institute (OAI), and Science Applications International Corporation (SAIC).

A. Introduction

It was vitally important that the magnetic nozzle experiment parameters be representative of those of the conceptual fusion space propulsion system in order for the results to be applicable. Obviously, an ignited, steady state fusion reactor did not exist (and will not for the foreseeable future). But there are ways to mimic the extremely high power level in a transient (pulsed) way. If the pulse length can be shown to be sufficiently "long" for the physics of interest, then the test can be considered "steady state". Figures 9 and 10 illustrate various space propulsion test facility capabilities in terms of plasma temperature vs. number density, and total power. Of the still operational facilities, the capacitor bank and vacuum chamber at Ohio State University (OSU) (affectionately known as "Godzilla" and the "Blue Tube" respectively) were the closest match available to the desired operating parameters for outer solar system missions. While the facility could not accommodate the precise stagnation temperature, density, or power characteristics needed, it was decided to proceed due to the meager program funding and the lack of a superior facility.

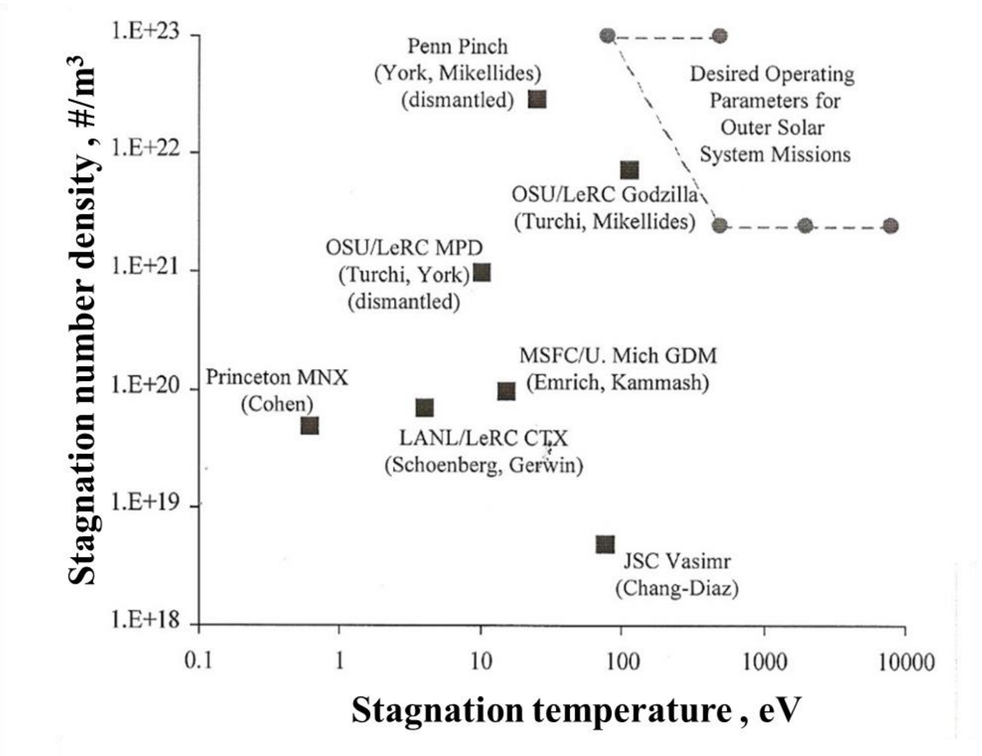

Figure 9: Characteristics of facilities (temperature and density) vs. fusion mission requirements

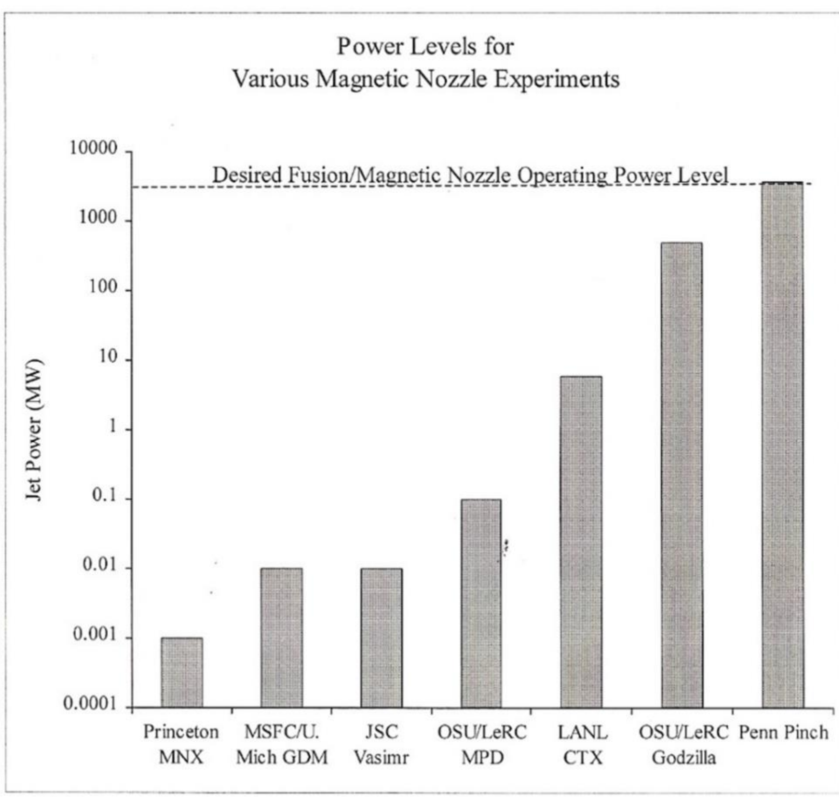

Figure 10: Characteristic of facilities (power) vs. fusion mission requirements

Figure 11 illustrates various non-dimensional number boundaries such as the ratio of the ion gyro radius (r_{gi}) to resistive skin depth (δ^*), the ratio of the ion gyro radius to the choked throat diameter (D^*), and ratio of the resistive skin depth to choked throat diameter. These dimensionless ratios served as proxies for various plasma behaviors. Godzilla's attainable plasma characteristics satisfied these boundaries. Thus it was thought that testing performed at the facility could produce conditions close enough to the desired values for outer solar system travel so that the plasma physics phenomena observed could arguably be applicable.

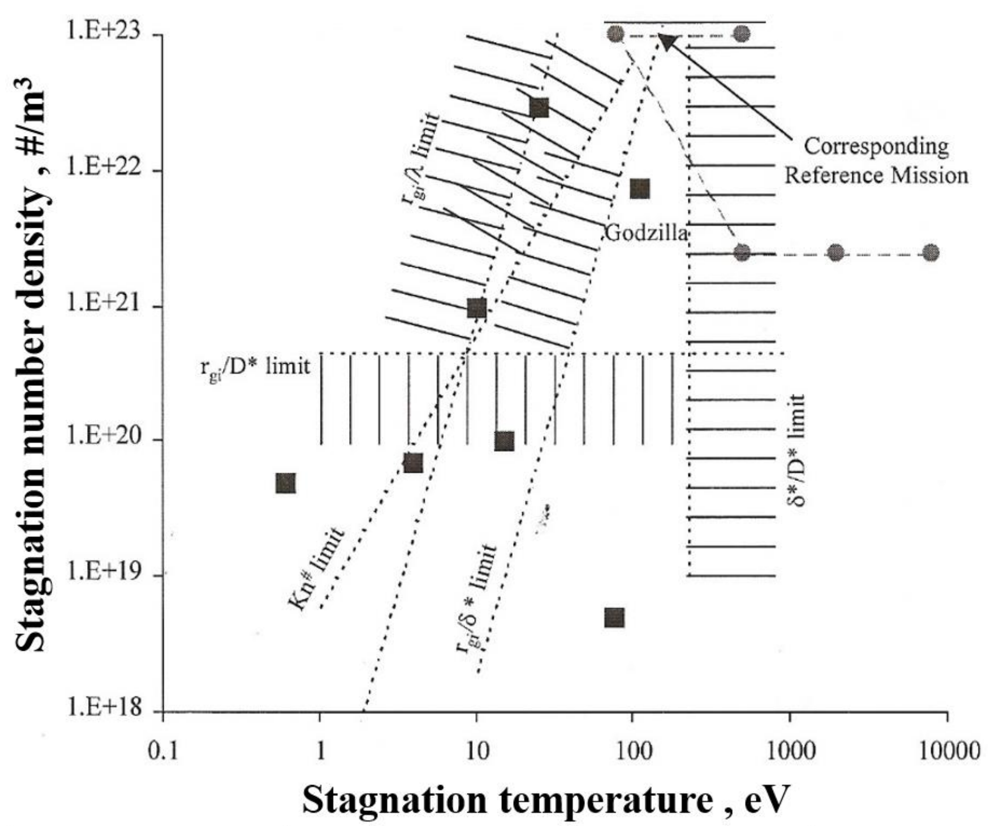

Figure 11: Characteristics of facilities (dimensionless parameters) vs. fusion mission requirements

B. Godzilla Facility

The "Godzilla" capacitor bank was a pulse forming network consisting of 2,100 capacitors of 43μf each producing a maximum potential voltage of 12 kV and maximum current of 300 kA. It provided up to 200 MW_e of power (and theoretically capable of up to 1,000 MW) for 1.6 milliseconds.[17, 28, 29] This immense mega-joule level facility was the centerpiece for the magnetic nozzle experiment for the GRC-led effort. Figure 12 is a photograph of OSU's Godzilla capacitor bank (with its guardian Professor Peter Turchi on the right to present a sense of scale)[17]. Originally designed and built to develop and test MPD space thrusters for the U.S. Air Force Office of Scientific Research (AFOSR), this facility offered the outstanding capability to approach the conditions representative of nuclear fusion propulsion without having to resort to accessing a DOE fusion reactor directly. Initial experimental data from Godzilla demonstrated quasi-steady state voltage and current durations between ¼ to ½ milliseconds and specific impulses between 15,000 to 30,000 lbf sec/lbm. [28].

Godzilla was mated with a 5 m long, 0.6 m diameter "Blue Tube" vacuum chamber which had a diffusion pump capable of producing a vacuum of 10^{-5} Torr. [29] This proved to be ample for accommodating the plasma source test article which operated in short pulses. The entire facility was housed in its own building with ample safety precautions due to the nature of facility.

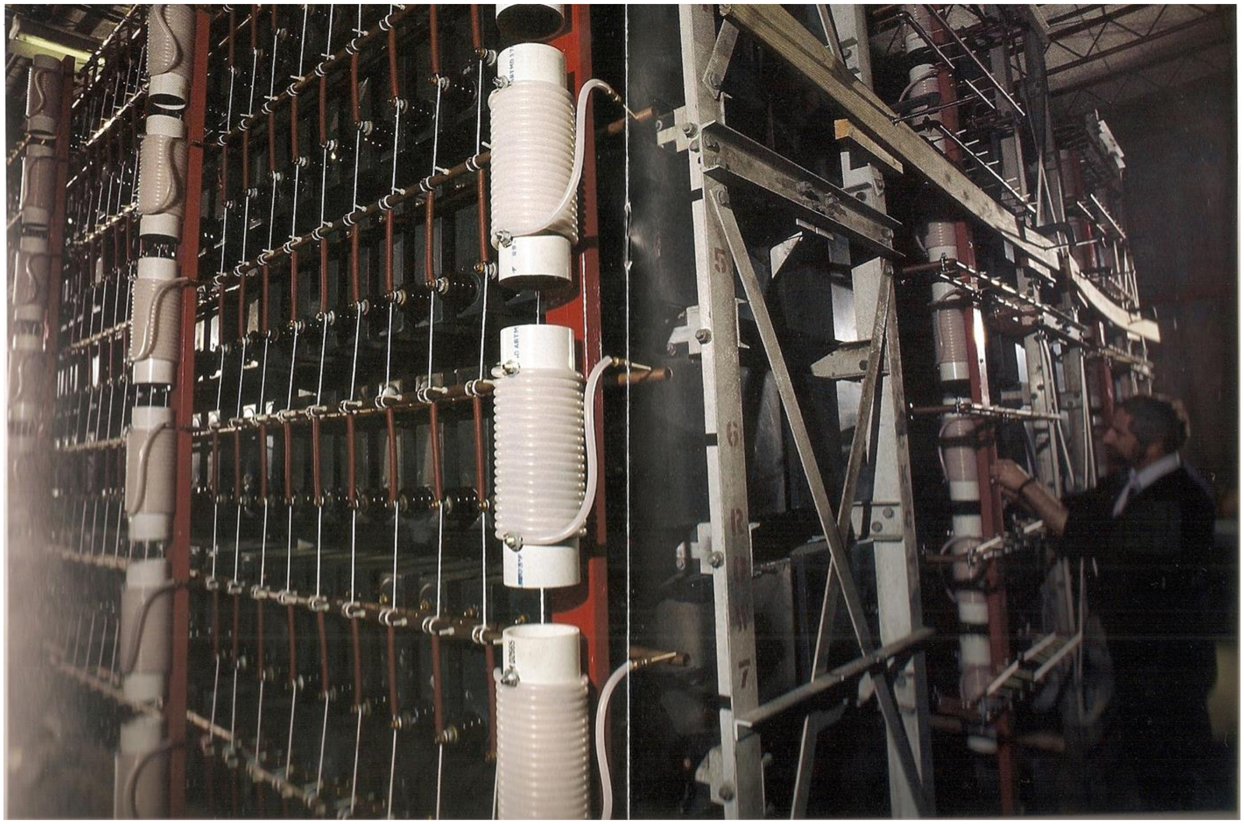

Figure 12: Godzilla capacitor bank (photo courtesy of Ohio State University)

C. Plasma Source Test Article

Before a magnetic nozzle could be designed, fabricated and tested, a plasma source for high temperature stagnated working fluid (helium) was needed. An MPD inverse pinch switch was available, so the decision was made to modify and install it into the Blue Tube to serve as the plasma source. The flow of helium working gas was initiated by breaking a diaphragm at the exit of the reservoir, initiated by Paschen breakdown across the electrodes. [29] Given the very high power, the plasma source served as the switch to discharge the capacitor bank. The source also enabled the redirection of plasma axially towards the centerline to increase stagnation conditions (plasma temperature). [30] Figure 13A and B are upstream and downstream view photographs of the plasma source. [31] Understanding the characteristics of the plasma source was essential before incorporating a magnetic nozzle into the experiment. Since the range of flow rates and power levels were expected to be considerable, it was deemed prudent to verify that the reconfigured inverse pinch switch was actually supplying the plasma with desired characteristics (speed, velocity vectors toward centerline, and degree of ionization, others). This verification of source's performance characteristics consumed considerably more resources than anticipated, preventing fabrication of the magnetic nozzle itself within the project's time frame.

Figure 13: A) Plasma source upstream view and B) downstream view

D. Theoretical Model and Analysis of the Magnetic Nozzle

An analytic model was developed and analyzed using the MACH2 code (an unsteady, 2D axisymmetric code which solves dynamic, single-fluid, MHD equations). [31] These numerical simulations were performed to gain insight into the operation of the magnetic nozzle, as well as to calibrate the mass flow system using pressure measurements for several diaphragms and chokes. [32] They also were used to guide minimization of the source's electrode gap to reduce waste heat, enabling maximizing enthalpy of the fluid to enable the greatest specific impulse[32] . The analysis calculated mass flow rate and pressure as a function of time. Classical resistivity was assumed, where modeling did not include gradient-driven microinstability caused anomalous resistivity, nor effects due to Hall Effect, plasma rotation, or electron pressure in Ohm's law (which will prove to be an important consideration in Section VII).

The MACH2 simulations predicted the resultant performance of the combined source and magnetic nozzle: the velocity vectors, pressure, and temperature profiles for the resulting flow (Fig. 14A, B, and C) [31]. The results showed that, "the timing of the downstream stagnation field" was "critical in allowing a smooth transition between the source and the field, with no shocks". [31]

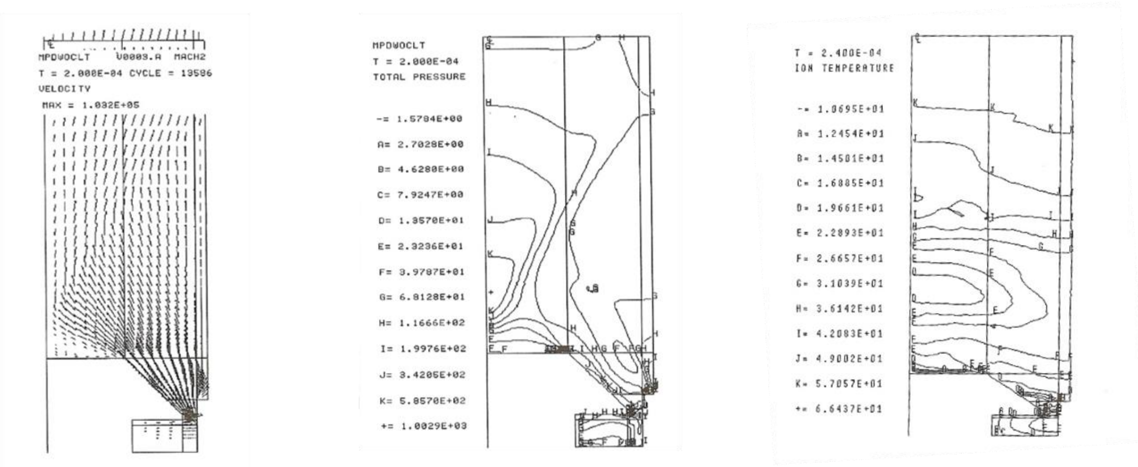

Figure 14: MACH2 computed A) velocity, B) pressure, and C) temperature

It was found that the plenum exhaust time was more than two orders of magnitude greater than the capacitor bank discharge time, thus validating the assumption of infinite quantity of working fluid, thus a constant pressure boundary condition could be invoked. [32] Plasma and field conditions were found to reach a steady state conditions after approximately 0.1 milliseconds (for a stagnation temperature of 100 eV), which was well within the Godzilla pulse width of a half millisecond (Fig. 15A).[32] Total thrust was estimated to be in excess of 1,000 lbf (with a corresponding Isp of approximately 17,000 lbf-sec/lbm), while analysis was extended into greater stagnation temperatures (up to 250 eV) predicting Isp of up to approximately 25,000 lbf-sec/lbm (Fig. 15B).[32]

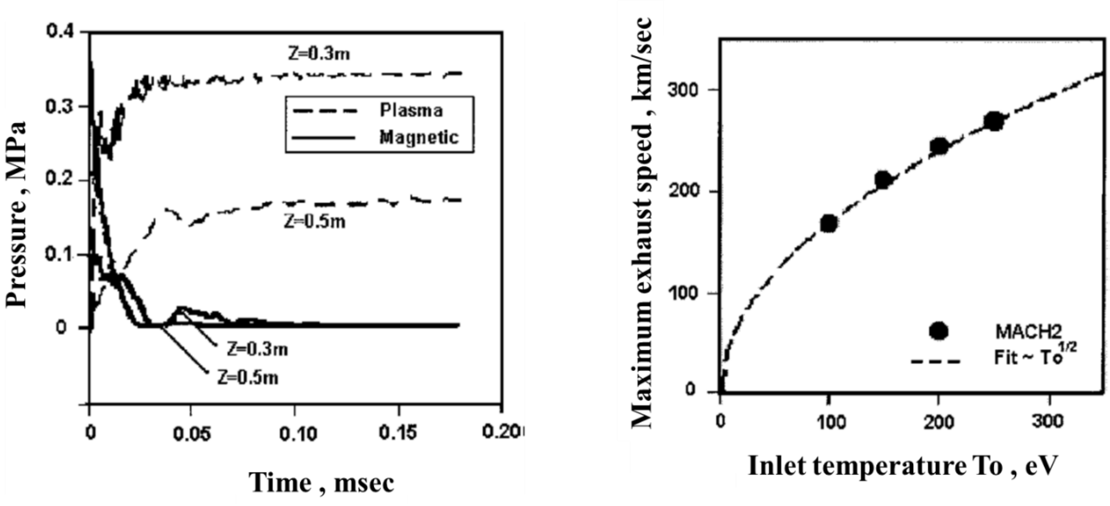

Figure 15: MHD simulations A) pressure pulse and B) exhaust speed (proportional to Isp)

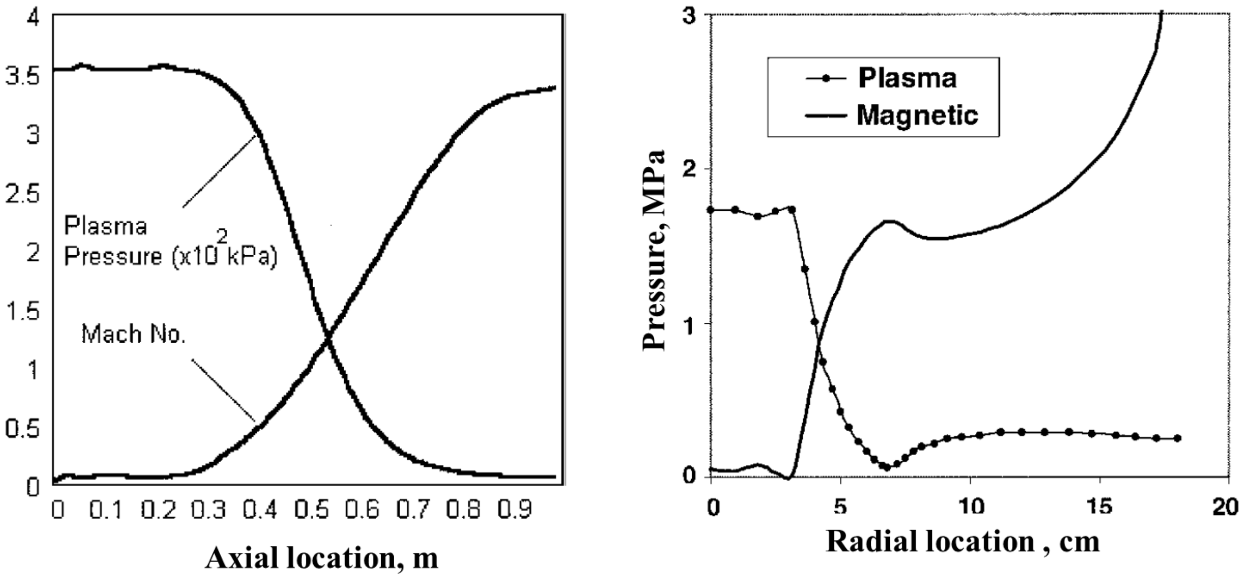

Figure 16: A) Axial characteristics and B) radial characteristics (boundary layer thickness)

The flow accelerated nearly isentropically through the nozzle (where stagnation temperature was 100 eV and time was at 0.24 milliseconds), reaching a Mach number in excess of 3 at the exit plane (Fig. 16A). [32] While these results appeared promising, the boundary layer composed of a mixture of plasma and magnetic field was found to be significant (~ 4 cm thickness; Fig. 16B)[32], which exposed serious implications for efficient magnetic nozzle operation (see Section VII). [32] Significant losses in axial velocity (up to 60%) were found due to resistive drag forces as the plasma separated off of the field lines.[32] The estimated total thermal power converted to thrust power was approximately 70%, which earlier analysis suggested a payload mass fraction would be significantly compromised to a value of only ~6%.[32, 25] However, a thorough analysis of the implications of anomalous resistivity and related physics associated with the plasma-field boundary layer and other losses would be needed to adequately quantify these losses, but which was outside of the capability of the MACH2 code.

E. Hot Fire Testing and Results

Hot fire testing of the source was performed over a range of power levels and mass flow rates. The experimental results were measured in terms of current and voltage. Additional instrumentation was used for a small subset of test firings to measure density and electron temperature directly in order to give early indications as to whether appropriate simulated fusion for space propulsion conditions were to be expected.

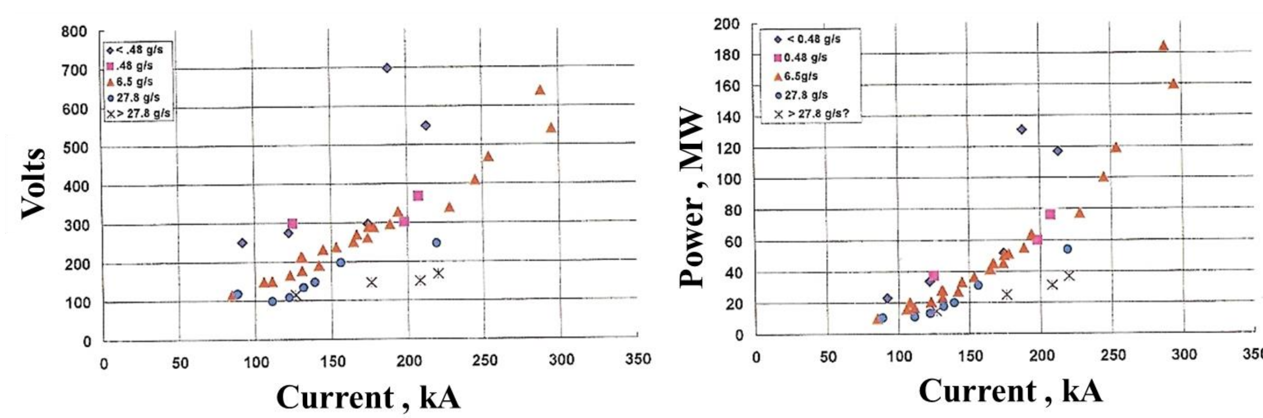

Figure 17: Hot fire testing results A) voltage and B) power

Satisfactory results included main exhaust speeds ranging from 70 to 90 km/sec, majority of the flow towards the centerline to reduce the chance for instabilities downstream, and fully ionized (even doubly ionized) plasma. [30] The results illustrated well behaved relationships between these variables, enabling confidence that predictions could be made when a magnetic nozzle is added to the experimental setup. Mass flow rates from 5 to 27 g/sec were well behaved and followed MPD–like behavior predictions. [33] Ranges were measured for powers between 10 to 200 MW_e, voltages from 100 to 700 V, and currents from 100 to 300 kA. [31, 33] The range of voltage and power measured for given currents are shown in Fig. 17A and B. [31]

Measuring the number density of the plasma exhaust was attempted during a single hot fire, with a flow rate of 6.45 g/sec, though the high power levels made that difficult using a triple probe diagnostic. The plasma density approached 10^{20} m^{-3}, near the value predicted by MACH2 (Fig. 18A)[31], but still two orders of magnitude too low for representative stagnation conditions for fusion propulsion (Fig. 9). Electron temperatures were measured for several mass flow rates and current levels, with representative data (again with flow rate of 6.45 g/sec), results are shown in Fig. 18B.[31, 33] As with number density, a temperature value of ~200 eV (an order of magnitude greater than what was measured) would be needed for representative fusion propulsion (at stagnation conditions) (Fig. 9). Nevertheless, these results demonstrated that the Godzilla facility was capable of supplying plasma in the form necessary to produce relevant experimental results using a magnetic nozzle.

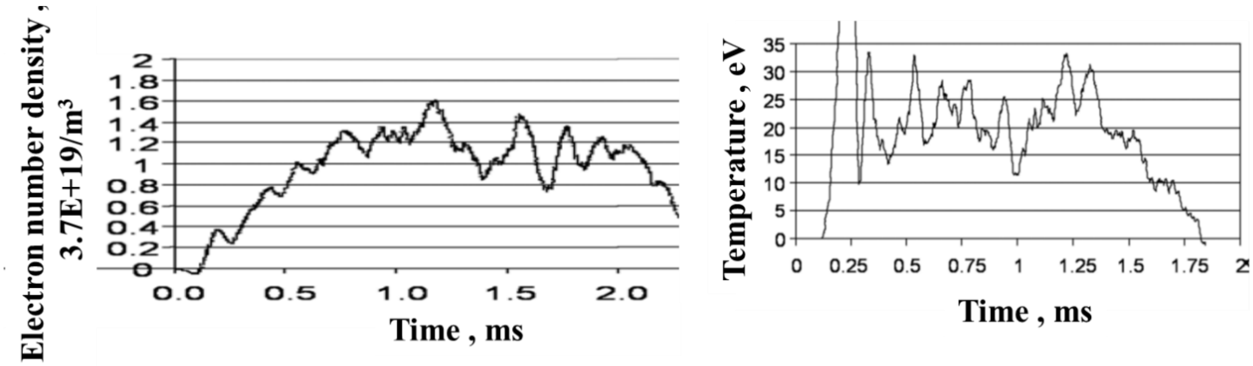

Figure 18: Pulse length vs. A) number density and B) temperature

VII. Magnetic Nozzle Plasma Theory

A. Introduction

A necessary complement to the OSU experimental campaign was the validation of theoretical assumptions embedded within the MACH2 MHD code used to guide key aspects of that experiment. At issue were the importance of correctly representing and controlling the diffusive intermixing occurring within the plasma ─ magnetic field boundary layer, the validity of classical (as opposed to anomalous) resistivity theory invoked by the MACH2 code, and the nature of the instabilities in regions of bad magnetic curvature. Those issues directly affected the ability of the code to accurately predict a magnetic nozzle's ability to accelerate the plasma flow, its efficiency in doing so, and the successful detachment of plasma from the magnetic field lines.

Thus a comprehensive academic study was initiated at DOE Los Alamos National Laboratory (LANL) on the theoretical physics governing critical unknowns of a fusion-grade plasma flow through a magnetic nozzle.[34] These unknowns focused on the nature and integrity of the boundary layer interface between the plasma and the nozzle's magnetic field. The nature of this boundary layer and how to control it became widely recognized as one of the most critical aspects of successfully performing direct nuclear fusion propulsion. While the theoretical study ran concurrently with the other GRC-led fusion propulsion efforts, the difficulty and complexity of the endeavor was initially vastly underestimated. The LANL researcher, despite being impressively credentialed in this particular field over his lengthy career, soon realized that several profound problems had to be addressed and would not yield solutions easily. As a result, while his initial five month study produced preliminary results to guide the OSU experiment, his analytic work was recognized to be of such great import that the effort was extended three more years. At that point, the decision was made to convert the already considerable volume of work into a NASA "Technical Publication" (the most prestigious level of official publication). LANL agreed to continue the work (including a considerable amount of technical editing with NASA GRC) on a non-cost extension basis. The work was not completed and published until 2009, fully a decade after it was started and seven years after the termination of the STR program. This work was the only “team” within the GRC-led fusion effort which was comprised of a single individual --- Dr. Richard Gerwin. Dr. Gerwin did not sacrifice quality for timeliness. The resultant 100+ page tome remains to this day arguably the most thorough and critical scholarly work on this topic.[35] The only tragedy was that Dr. Gerwin did not live to see the publication of his work, passing away only three weeks before his work came off the printing press.

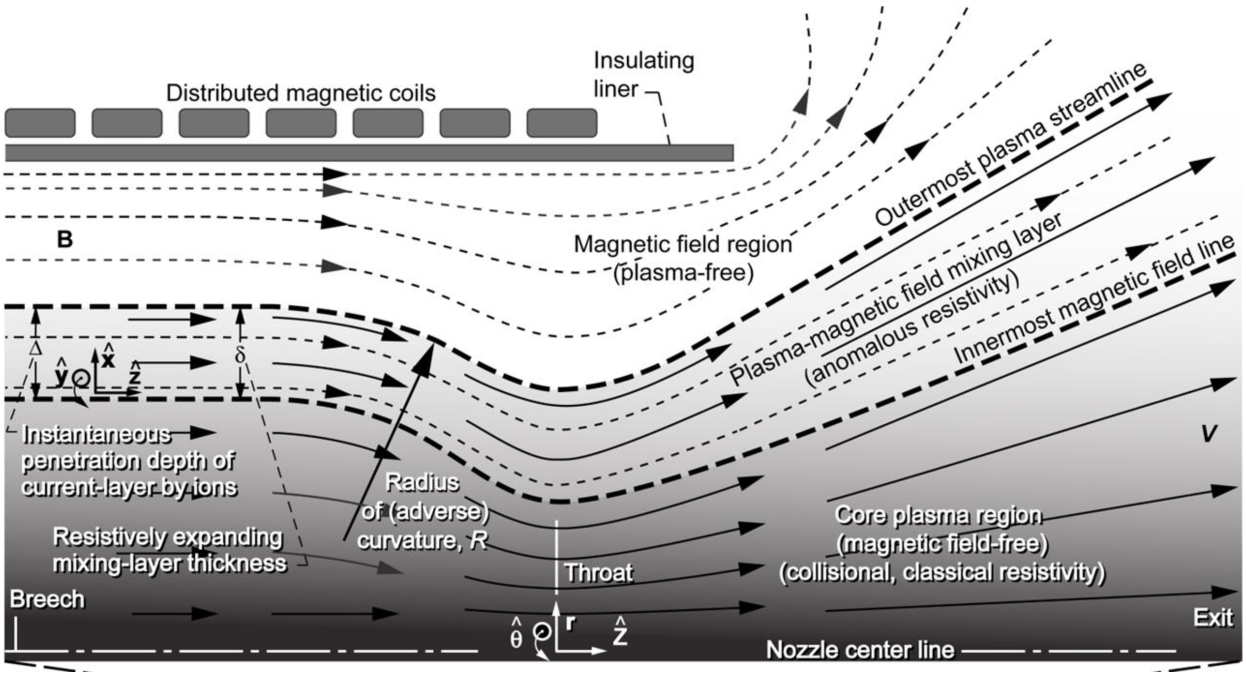

Figure 19: Plasma physics within the magnetic nozzle

B. Boundary Layer Effects: Diffusive Intermixing in Plasma-Field Interface

Diffusive intermixing of plasma into magnetic field and also resistive diffusion of magnetic field into plasma both occur simultaneously, and are difficult to characterize and control.[35] (Fig. 19) The degree to which they occur and under what circumstances were studied and analytic expressions were derived. Applying simple resistive form of Ohm’s law, cross B-field momentum, and equal species temperatures, yielded an expression for resistive MHD boundary layer of width (δ) (Eq. (1))[35]:

Assuming beta ~ 1 and classical resistive diffusivity, for parameters representative of the OSU experiment (except for substituting hydrogen as the working fluid rather than helium) the boundary layer thickness was of order ~0.6 cm (compared to breech-to-throat length of ~ 1 m) assuming zero initial thickness[35] (appropriate in order to compare with the resistive simulations performed by MACH2 code). Further, given the greater time the plasma spends upstream of the throat (increasing the opportunity for the layer to grow), it was believed that the value given by Eq. (1) might be only one-half of the actual thickness. It was also shown that the derivation for thickness was the same whether the problem solved was field-into-plasma or plasma-into-field. Finally, if there was an initial thickness (see results of anomalous resistivity, Section VII-D) the boundary layer could be a few centimeters thick.[35] Either way, thickness of the plasma-field boundary layer was found to be significantly large compared to the nozzle dimensions (and by implication, large when assessing losses and difficulty of control).

$$\delta^2 \approx 2a_i^2\left(\frac{L_{bt}}{\lambda_e}\right)\sqrt{\frac{m_e}{m_i}} = \beta\left(\frac{c}{\omega_{pi}}\right)^2\left(\frac{L_{bt}}{\lambda_e}\right)\sqrt{\frac{m_e}{m_i}} \tag{1}$$

C. Boundary Layer Effects: Hall Effect, Plasma Rotation, and Electron Pressure in Ohm's Law

The necessity of incorporating the Hall effect into Ohm's law was discussed, where the full Hall current was able to flow and concomitant plasma rotation and electron pressure allowed. By including these other effects, the derivation for boundary layer thickness resulted in a much different analytic expression. That expression yielded a thickness of the order of only a few ion-gyro radii (and was independent of electron collision frequency) (Eq. (2)). [35] This result illustrated a favorably small interface thickness if a more detailed consideration of boundary layer effects are considered and if the quotient of the length from breech-to-throat divided by ion gyroradius is less than the conventional Hall parameter. It was shown that this expression did degenerate into the more simple resistive diffusion expression (Eq. (1)) if the nozzle length was long enough to satisfy a critical length expression linking Hall current and a counteracting electric field established by the sufficiently rotating plasma.

$$\delta^2 \approx \left[1+2\left(\frac{\Lambda}{\Omega}\right)\right]\frac{V_{\mathrm{th}i}^2}{\omega_{ci}^2} = \left[1+2\left(\frac{\Lambda}{\Omega}\right)\right]a_i^2 \tag{2}$$

D. Initial Plasma-Field Boundary Layer Width and Gradient-driven Lower Hybrid Drift Microturbulent (Anomalous) Resistivity

Upon initial plasma-to-magnetic field contact, a boundary layer was found to instantaneously establish and was significant. This initial boundary layer was due to Hall and kinetic particle phenomena which could not be understood through resistive MHD simulations (such as MACH2). The range of the boundary layer thickness was shown to be a function of ion plasma frequency only (of the order of a few ion inertia lengths (c/ω_{pi})) (Eq. (3))[35]. "For example, if the initial interface were 2 cm thick and the nozzle breech of injected plasma were 30 cm in radius, then 15 percent of the injected plasma propellant would be immediately affected. This would occur before the onset of additional adverse effects along the flow." [35]

$$2.6\left(\frac{c}{\omega_{pi}}\right) \tilde{<} \ \Delta \ \tilde{<} \ 3.6\left(\frac{c}{\omega_{pi}}\right) \tag{3}$$

Gradient-driven Lower Hybrid Drift (LHD) microturbulent (anomalous) resistivity significantly affected the spatial rate of resistive broadening of the plasma-magnetic field interface. The recognition that anomalous resistivity was likely to be a major influencer of boundary layer physics upstream of the throat was a major finding of this study. Anomalous resistivity dominated classical resistivity at sufficiently high temperatures and was most pronounced between the breech and throat. Incorporating anomalous resistivity, removing other simplifications, and taking into account the initial width of the layer, the ratio of ion gyro radius to initial boundary layer thickness was found to be (Eq. (4)). Since the transit time between breach to throat was short, the ratio was largely constant. From this, it can be seen that "the emphasis should be placed on small-ion-gyroradius regime". [35]

$$\frac{a_i}{\delta} = \frac{1}{2}\beta_i^{1/2}\sqrt{\frac{n_b/n}{1+\left(\frac{n_b}{n}\right)^{1/6}\frac{(a_i/\delta)^2}{\beta_i/4}\left(\frac{t}{t_b}\right)}} \tag{4}$$

A comparison was made between classical and anomalous resistivity to discover under what conditions (primarily temperature and number density) each would dominate. The two were of comparable impact when the temperatures satisfied the derived relation (Eq. (5)):

$$T = \frac{1}{1.22\sqrt{C_{\mathrm{Brack}}}}(10^{-2})\frac{n_{\mathrm{core}}^{1/4}}{V_d/V_{\mathrm{th}\,i}} \tag{5}$$

For the number density of interest to space propulsion (and the OSU experiment), ~ 10^{15}/cc, and a velocity ratio of interest ~1/3, both anomalous and classical resistivity were found to be comparable impact, since stagnation plasma temperatures were of the order of 220 eV. [35] This suggested both anomalous and classical resistivities had to be evaluated to gain a proper understanding of magnetic nozzle physics.

E. Rayleigh-Taylor Type (Macroscopic) Instabilities

Rayleigh-Taylor (RT) (macroscopic) MHD instabilities of the "Flute mode" type were expected. If the product of RT growth rate and dwell time of plasma in that region was sufficiently large, the number of e-folds available for the RT instability could enable loss of control of plasma flow if RT instability is not mitigated. Various regions of "bad" (adverse) magnetic curvature within the magnetic nozzle are susceptible to RT instabilities, namely initial interaction of plasma with magnetic field lines in the breech, the converging approach to the throat, and at the exit plane where the field lines diverge and return to close the loop.

At the breech entrance, inserting propellant nearly parallel to magnetic field lines could mitigate RT instability, where plasma would impact at a shallow angle almost instantaneously. For the parameters of interest, results indicated that RT instability here should not be a problem (at the entrance). However, the single fluid MHD analysis used was felt to be less than appropriate and that a more sophisticated model was needed.

For the regions approaching throat and exit plane, a fluid-based ideal MHD model was deemed appropriate. The use of finite Larmor radius (FLR) stabilization produced a relation which applied throughout the nozzle, eliminated plasma profiles that are RT-unstable, but should be conditioned as provisional since Hall effect was not included. (Eq. (6)) Preliminary results of the derived relation for parameters of interest show RT instability should not be a concern (at the throat or exit plane).

As for centripetal acceleration generated forces, it was determined that generally throughout the flow, the bulk fluid and ion thermal velocities were similar, thus "….gravitational acceleration due to adverse curvature generally should constitute only a minor modification to the edge layer gradient that drives the short-wavelength LHD flute instabilities."[35]

$$\gamma_{\mathrm{RT}} \approx \frac{V_{\mathrm{ex}}}{R_{\mathrm{eq}}^{2/3}\left(c/\omega_{pi}\right)_b^{1/3}} \tag{6}$$

F. Concluding thoughts

This body of work clearly identified major areas which were severe impediments to the understanding and designing of viable magnetic nozzles. While this work was being carried out, comments were occasionally made by others in the fusion community (but not the GRC team) that magnetic nozzles were relatively straight forward to design, fabricate, and operate --- by inference, this theoretical work was unnecessary. Gerwin's authoritative work definitively proved those opinions wrong. When combined with other analytic work which illustrated the necessity of highly efficient magnetic nozzles, it was clear that this field faces a tremendous amount of theoretical (as well as experimental) work before direct fusion propulsion becomes a reality.

VIII. Coaxial Helicity Ejection Experiment Planning

A. National Spherical Torus Experiment (NSTX) at DOE Princeton Plasma Physics Laboratory (PPPL)

Spherical torus fusion reactors are low aspect ratio machines with cross sections which are more "donut" shaped than conventional toroidal fusion machines (such as the International Thermonuclear Experimental Reactor (ITER), which are generally considerably larger and heavier)[36]. Because fusion power produced is proportional to the square of the plasma's pressure, small aspect ratio toroids are thought to be capable of producing greater power at lower magnetic field strength, and smaller/lighter/less expensive systems than other reactor/confinement concepts. It is for those reasons the National Spherical Torus Experiment (NSTX) was attractive for both terrestrial power production as well as a predecessor concept for space propulsion. A "proof of principle" experiment, NSTX reached first plasma in February 1999, initiating a dozen year research period. [37] At that time, NSTX was the flagship alternative confinement concept reactor for fusion research in DOE's portfolio (Fig. 20A). Having the leadership of such an internationally recognized research facility supporting a NASA project was a tremendous advantage and motivator to the GRC-led effort. NSTX has been in operation for over twenty years, and while recently undergoing upgrades (2016), remains an active DOE research facility. (Fig. 20B)

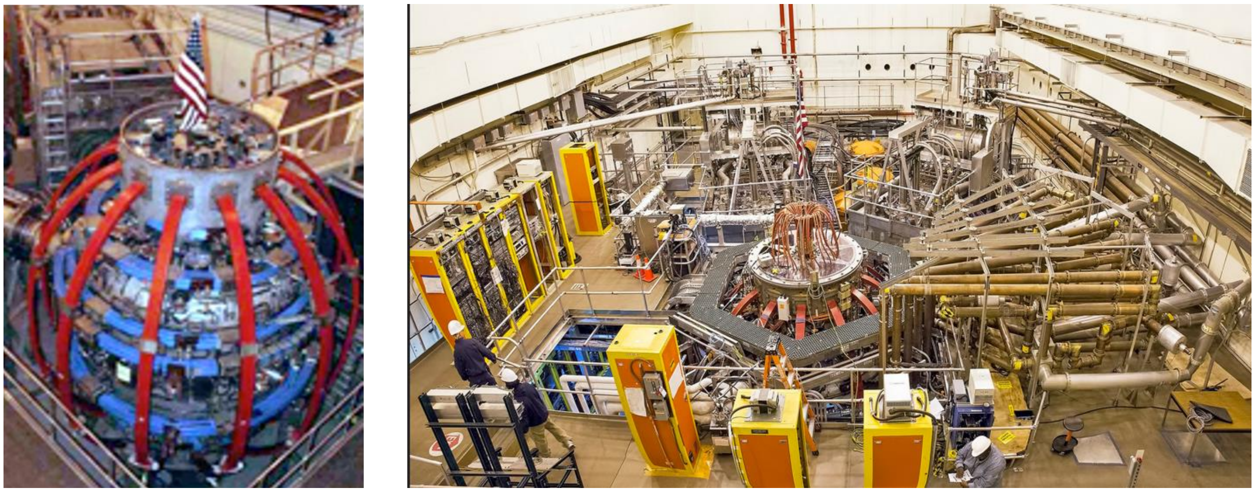

Figure 20: National Spherical Torus Experiment A) originally in 1999 and B) NSTX-Upgrade in 2016

B. Proof of Concept Experiment Using NSTX: Coaxial Helicity Ejection (CHE)

Magnetic helicity is essentially the product of the toroidal and poloidal field fluxes within a magnetized plasma[38]. It is an important quantity when discussing toroidal plasmas. Coaxial Helicity Injection (CHI) has already been observed in other experiments (such as HIT-II reactor at University of Washington) as well as the NSTX reactor at PPPL.[38, 38, 39] Helicity can be injected (CHI) into these plasmas by applying direct current electricity through divertor flux tubes[38] (Fig. 21A) [40]. Thus, it is another means for controlling the nature of the plasma. The existing proof of concept experiment for CHI at NSTX was proposed to be modified to study the physics of its inverse --- Coaxial Helicity Ejection (CHE) which was anticipated to take place upon shutdown (Fig. 21B) [40]. CHE had the potential to exhaust kinetic energy of the scrape of layer (SOL) plasma and would have been fundamental to enable direct fusion propulsion. The proposed experiment on NSTX was to permit reversal of the applied voltage and current at the divertor to eject helicity faster than resistive dissipation.[38, 40] It was extremely fortuitous that interest existed in both phenomena (CHI and CHE) by two research communities concurrently. Experimentally verifying the feasibility of CHE would for the first time establish the scientific basis and engineering concept of extracting reactor plasma energy for space propulsion --- an area which to this day has received little more than hand waving by the space propulsion community. The needed resources for the CHE experiment were modest augmented diagnostic instrumentation, plasma physics modeling, and staff time. Unfortunately, after the initial NASA funding for the preliminary research assessment[38], the STR program could not support the PPPL-proposed full initiative[40], and indeed the entire NASA STR project was terminated soon afterwards.

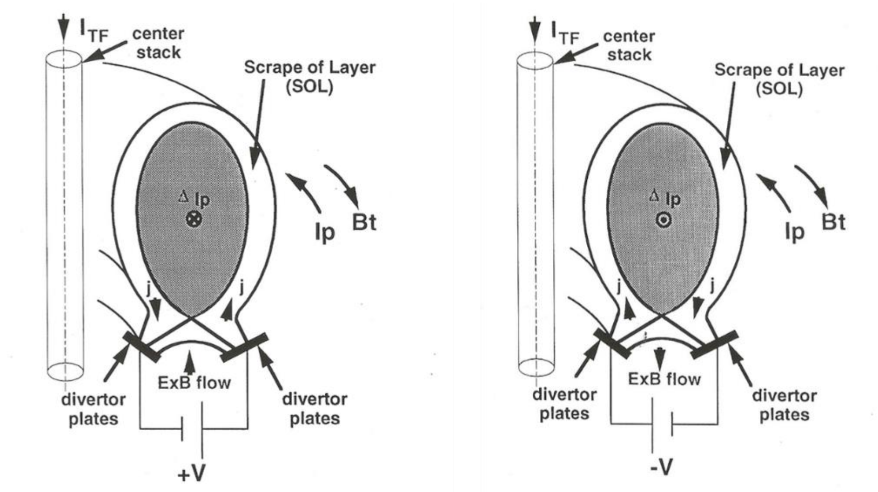

Figure 21: Coaxial Helicity A) Injection vs. B) Ejection

C. Proposed Bootstrap Current Overdrive, High Plasma Beta, and Other Propulsion-Oriented Operations

Another advantage of small aspect ratio toroids is the ability to produce a high "bootstrap" current, thereby reducing the recirculation power required to externally drive currents (for heating and ensure proper confinement).The potential for greater than 100% pressure gradient driven plasma currents (bootstrap current "overdrive") would have obviated the need for external systems to supply current altogether.[iii] As a result, no "injected power" was required to be diverted from propulsion utilization, which also avoided the need for heavy systems to provide that power. This was a huge advantage over other concepts which had small "Q" (the ratio of power out to power in), some as low as slightly greater than 1.0 (compared to that of the GRC concept (where Q = 73). [25]

High beta operation reduced the need for immense magnetic pressure and its supporting structures (essential for attractive space propulsion application). Nevertheless, a toroidal magnetic field of ~9 T at the core centerline and ~32 T at the coil surface were still required. But these fields generated immense overturning forces and stresses which had to be counteracted by the reactor structure (~10^9 N/m^2). [25] High local beta at the plasma core reduced what would have been even greater magnetic fields with their concomitant loads.

There were other proposed operations conducive to space propulsion (such as usage of advanced fuels (spin polarized D^3He fuel; NSTX uses DD fuel), but NSTX was not intended to operate in these modes initially. However the NSTX program manager proposed some of these advanced methods as appropriate for space propulsion in the future. [iv] The eventual demonstration of these capabilities, together with CHE, were critical to showcase the advantages of spherical torus-based reactor system.

IX. AIAA Industry Standard

During the initial years of the newly established STR program, a number of conceptual fusion propulsion designs emerged, each based on different reactor/confinement methods. Organizations showcased their concept's abilities to accomplish varying missions in the hope of fostering programmatic interest. But comparing the concepts, their performance capabilities, and assessing scientific/engineering credibility proved difficult due to widely varying study assumptions.[15] A consensus quickly arose within the fledgling community that some type of design standard was necessary so that scientific and engineering assumptions and technology projections invoked in studies would substantiate credible vehicle conceptual designs.

A broad team from NASA, DOE, academia, and industry was led by NASA GRC beginning in late 1999. The results of our efforts were proposed to the AIAA Nuclear and Future Flight Propulsion Technical Committee (TC), as the most appropriate TC for this task. An ad hoc working group of the NFFPTC was formed and used the material to author an AIAA standards document to guide the development of higher quality conceptual designs of nuclear fusion space propulsion vehicles. The results from the ad hoc NFFPTC working group were accepted by the AIAA Standards Executive Council and an industry standard was published in October 2004. [41]

This standard represents a 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 physics, space propulsion systems, and vehicle design. It is a useful guide for them to develop credible concepts by applying a standardized set of design practices. A balance was struck between advocating sufficiently detailed engineering to establish credibility without becoming overly burdensome (since so little work in this field is funded). 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). The first known application of these standards were on the GRC vehicle concept. [42]

X. Post STR Project Termination Activity

Limited project close-out analysis was performed by the GRC project manager for another year. Two conference papers were then authored (one was 'invited') in 2004 to document these efforts. Since that time, no nuclear fusion propulsion work has been done by NASA GRC.

It is encouraging to note that part of this body of work has transcended the technical community and into the popular culture. Years following the last publications (and not coordinated with GRC), a graphic video artist in Australia created an inspiring thirty second video of the nuclear fusion vehicle traveling through outer space.[43]

[iii] Peng, M., U.S. Department of Energy, Princeton Plasma Physics Laboratory, Princeton, NJ, personal email, May 1999.

[iv] Ibid, Peng, M.

XI. Conclusion

The nuclear fusion space propulsion research led by the NASA Glenn Research Center from 1994 through 2004 produced arguably the most significant results in the field since the end of a much more comprehensive agency fusion program from 1958-78. The multi –Center, –Agency, academia, and industry teams advanced the state of the art significantly despite the extremely modest financial support provided by NASA. The results of this initiative included a well-defined pre-Phase A conceptual design, experimental results supporting an eventual vacuum subscale test, a significant theoretical basis for the underlying plasma physics, a detailed scientifically-sound concept linking an actual fusion reactor to a propulsion device (possibly for the first time), and a broadly accepted industry standard on which to base future design concepts. The importance of each of these major areas of work cannot be understated, since past work of comparable breadth and depth could not be found documented in any published sources. The conclusion that can be drawn and substantiated is that nuclear fusion propulsion is the primary credible propulsive concept for manned outer planetary missions of reasonable trip times (months) and payload mass ratios (10 to 25%) if the results from this initiative are embraced and adopted.

Acknowledgments

The author wishes to thank all of the nuclear fusion space propulsion team members and organizations listed in Fig. 4 and 5 for their work from 1994 through 2004. They made substantive contributions to this emergent technical field, each doing his part to significantly advance the state of the art and bring manned exploration of the outer planets closer to fruition. I am indebted to Dr. Stanley Borowski who was the originator of this initiative in the mid-1990's, an authoritative source to turn to for nuclear fusion science/engineering, and a provider of project development guidance throughout. Because of the successes, his invitation to prepare this historical review paper was gladly accepted.

References

[1] Bush, G. H. W., "Remarks on the 20th Anniversary of the Apollo 11 Moon Landing", presidential speech, Washington DC, July 1989.

[2] Stafford, T.P., et al., "America at the Threshold: America's Space Exploration Initiative", U. S. Government Printing Office, Washington DC, May 1991, pp. 2-9.

[3] anonymous, "National Space Policy, Appendix F-2", fact sheet, National Science and Technology Council (White House), Washington DC, September 19, 1996.

[4] Schulze, N. R., Roth, J.R., "The NASA-Lewis Program on Fusion Energy for Space Power ad Propulsion, 1958-1978." Fusion Technology 19(1), Journal of the American Nuclear Society, La Grange Park, IL, January 1991, pp.11-28.

[5] Schulze, N. R., "Fusion Energy for Space Missions in the 21st Century", NASA TM-4298, 1991.

[6] Robbins, W.H., Finger, H.B., "An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program", NASA Contractor Report 187154, AIAA-91-3451, July 1991.

[7] Haslett, R.A., "Space Nuclear Thermal Propulsion Program Final Report", USAF Phillips Laboratory, PL-TR-95-1064, Kirtland Air Force Base, NM, May 1995.

[8] Dewar, J., "To the End of the Solar System: The Story of the Nuclear Rocket", 2ed ed., Apogee Books, Burlington Ontario, Canada, ISBN 978-1-894959-68-1. OCLC 1061809723, 2007.

[9] Merkle, C.L. (chairman), et al., "Ad Astra per Aspera: Reaching for the Stars", Report of the Independent Review Panel of the NASA Space Transportation Research Program", NASA Marshall Spaceflight Center, Huntsville, AL, January 1999.

[10] anonymous, "NASA Budget Estimates 1996", federal government report, NASA Headquarters, Washington DC, 1996.

[11] Williams, C.H., Borowski, S. K., Graham, S.R., "Thoughts on POP-94 Line Item: Advanced Propulsion Concepts", NASA internal presentation, Advanced Space Analysis Office, NASA Lewis Research Center, Cleveland, OH, May 1994.

[12] Campbell, D. J., "Office of Space Systems Development (OSSD) POP 94", official letter and attachments from NASA LeRC Center Director to NASA HQ/Code D Associate Administrator, NASA Lewis Research Center, Cleveland, OH, June 28, 1994.

[13] Williams, C.H., Borowski, S.K., "Commercially-Driven Human Interplanetary Propulsion Systems: Rationale, Concept, Technology, and Performance Requirements", *13th Symposium on Space Nuclear Power and Propulsion*, Space Technology and Applications International Forum (STAIF), edited by M.S. El-Genk, American Institute of Physics conference proceedings #361 Part 3, Albuquerque, NM, January 1996, pp. 1057-1064.

[14] Williams, C. H., "An Analytic Approximation to Very High Specific Impulse and Specific Power Interplanetary Space Mission Analysis", NASA TM-107058, 1996.

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

[16] Borowski, S.K., Strickler, D, 'sys0712', one dimensional nuclear fusion power balance FORTRAN computer code, undocumented, U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN, April 1986.

[17] anonymous, "Aeronautical and Astronautical Engineering at the Ohio State University", brochure, Ohio State University, Columbus, OH, c.1998.

[18] anonymous, NASA GRC official photo, C-94-03094, 1994.

[19] Hooper, E.B., Ferguson, S.W., Makowski, M.A., Stallard, B.W., Power, J.L., "Analysis and Experiments of a Whistler-Wave Plasma Thruster", preprint, IEPC-93-038, UCRL-JC-114643, U.S. Department of Energy, Lawrence Livermore National Laboratory, Livermore, CA, August 1993.

[20] Schoenberg, K.F., Moses, R.W., Wagner, H.P., "Magnetically Nozzled Plasma Accelerators for Advanced Manufacturing", American Institute of Physics conference proceedings #392, edited by Duggan, J.L., Morgan, I.L., Applications of Accelerators in Research and Industry, New York, 1997, pp. 1155-1158.

[21] anonymous, "NASA Budget Estimates 2000", federal government report, NASA Headquarters, Washington DC, 2000.

[22] Littles, J.W., "Advanced Space Transportation Program (ASTP) POP 96-1 Guidelines; Development of the FY 1998 Budget", official letter from NASA MSFC Director to NASA HQ Code M Associate Administrator, April 1, 1996.

[23] Leifer, S., "Overview of NASA's Advanced Propulsion Concepts Activities", AIAA paper 98-3183, 1998.

[24] Wheeler, J.A., "FY 99 Initial Operating Plan (GL's by Center)", official MSFC email with attached table, November 4, 1998.

[25] Williams, C.H., Dudzinski, L.A., Borowski, S.K., Juhasz, A.J., "Realizing "2001: A Space Odyssey": Piloted Spherical Torus Nuclear Fusion Propulsion", NASA TM-2005-213559, March 2005.

[26] Williams, C.H., unpublished analysis, NASA Glenn Research Center, September 9, 1999.

[27] Williams, R., Lea R., "Transportation Requirements for Manned Interplanetary Missions", AIAA Technology for Manned Planetary Missions Meeting, New Orleans, LA, March 4-6, 1968.

[28] Turchi, P.J., "Magnetic Nozzle Studies for Advanced Rocket Propulsion", proposal, OSURF Ref. No. 59726-55-00, Ohio State University, Columbus, OH, September 1998.

[29] Turchi, P.J., Gessini, P., Mikellides, P.G., Kamhawi, H., Umeki, T., "Gigawatt, Quasi-Steady Plasma Flow Facility for Fusion Rocket Simulations", AIAA 98-3592, July 1998.

[30] Mikellides, P.G., Turchi, P.J., Mikellides, I.G., "Design of a Fusion Propulsion System—Part 1: Gigawatt-Level Magnetoplasmadynamic Source", AIAA Journal of Propulsion and Power, Vol. 18, No. 1, January-February 2002, pp. 146-151.

[31] Gilland, J.H., Mikellides, I.G., Mikellides, P.G., Gregorek, G., Marriott, D., "Magnetic-Nozzle Studies for Fusion Propulsion Applications: Gigawatt Plasma Source Operation and Magnetic Nozzle Analysis", close out and final report, Ohio Aerospace Institute, grant no. NAG3-2601, June 30, 2003.

[32] Mikellides, I.G., Mikellides, P.G., Turchi, P.J., York, T.M., "Design of a Fusion Propulsion System—Part 2: Numerical Simulation of Magnetic-Nozzle Flows" AIAA Journal of Propulsion and Power, Vol. 18, No. 1, January-February 2002, pp. 152-158.

[33] Gilland, J.H., Mikellides, P.G., Marriott, D. "Energy Deposition Via Magnetoplasmadynamic Acceleration: I. Experiment", Plasma Sources Science and Technology, 18 (2009) 015001, pp. 1-12.

[34] Schoenberg, K.F., "Los Alamos Theoretical Modeling Support", proposal, U.S. Department of Energy, Los Alamos National Laboratory, Los Alamos, NM, No. R-2020-98-0, May 22, 1998.

[35] Gerwin, R., "The Integrity of the Plasma Magnetic Nozzle", NASA TP–2009-213439, December 2009.

[36] Parker, R.R., et al. (ITER Joint Central Team), "Overview of the Design of In-Vessel Components for ITER", Fusion Technology, Vol. 26, November 1994, pp. 273-283.

[37] Ono, M., Peng, M., et al. (NSTX team), "Making of the NSTX Facility", 18th IEEE/NPSS Symposium on Fusion Engineering Proceedings, Cat. No.99CH37050, Albuquerque, NM, October 25-29, 1999, pp. 53-58.

[38] Peng, M., Ono, M., "Spherical Torus (ST) Propulsion by Means of Coaxial Helicity Ejection (CHE): an Innovative Approach to Enable Direct Propulsion from a Compact Fusion Device", proposal, U.S. Department of Energy, Princeton Plasma Physics Laboratory, Princeton, NJ, September 3, 1998.

[39] Moses, R.W., Gerwin, R.A., Schoenberg, K.F., "Transport Implications of Current Drive by Magnetic Helicity Injection", Physics of Plasmas, Vol. 8, Number 11, American Institute of Physics, November 2001, pp. 4839-4848.

[40] Peng, M., Ji, H., Kugel, H.W., Ramakrishnan, R., "Proposal to Study Coaxial Helicity Ejection (CHE) for Direct Fusion Propulsion", proposal including briefing charts, U.S. Department of Energy, Princeton Plasma Physics Laboratory, Princeton, NJ, August 20, 1999.

[41] Williams, C.H., et al., "Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems", AIAA special project report, SP-108-2004.

[42] Williams, C. H., "Application of Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems", AIAA 2004-3534, July 2004.

[43] Papadopoulos, P., "Discovery II", online video from Fragomatik, https://www.youtube.com/watch?v=Y5zYqwEKnDA, 2014.