PRIMARY PROPULSION FOR PILOTED DEEP SPACE EXPLORATION

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MOTIVATION

Characteristic Velocity Increments for Planetary Transfer Missions*

Earth orbit to:

Mars orbit and return:	1.4×10^4 m/s
Venus orbit and return:	1.6×10^4 m/s
Jupiter orbit and return:	6.4×10^4 m/s
Saturn orbit and return:	1.1×10^5 m/s

*Impulsive, minimum propellant semiellipse trajectories

Rocket Equation: $\frac{M_f}{M_0} = e^{-\Delta V / U_e}$

Increase delivered payload:

- Match propellant exhaust velocity, U_e, to mission ΔV
- High Isp for planetary and deep space exploration missions
- Variable Isp to optimize mission profiles, reduce propellant mass

CURRENT PROPULSION SYSTEMS

CHEMICAL:

- HIGH THRUST
- REQUIRED FOR LAUNCH SYSTEMS
- LOW EXHAUST VELOCITY (< 5000 m/s)
- INEFFICIENT FOR DEEP-SPACE ($U_e \ll \Delta V$)

ELECTRIC:

- LOW THRUST (mN – N)
- HIGH EXHAUST VELOCITY
  - MPD: 5×10^4 m/s
  - ION: 10^5 m/s
- EFFICIENT IN-SPACE PROPULSION
- LOW ACCELERATION, LONG TRIP TIMES

NUCLEAR:

- HIGH THRUST
- MODERATE EXHAUST VELOCITY ($<10^4$ m/s)
- ENABLING FOR NEAR-TERM MISSIONS
- $U_e \ll \Delta V$ FOR DEEP SPACE MISSIONS

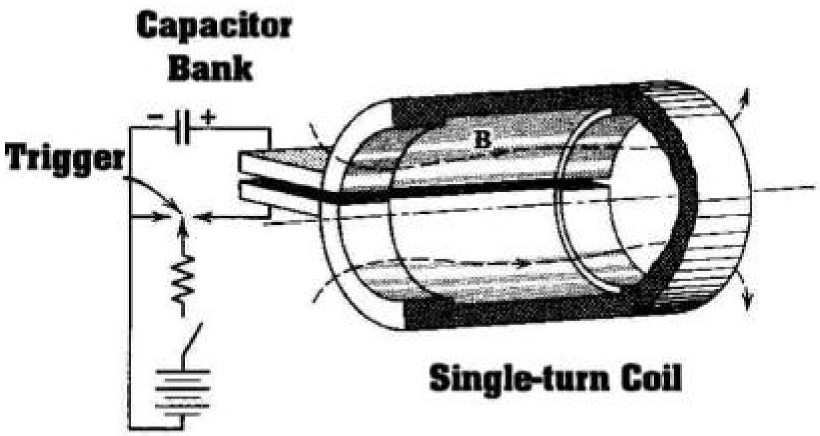
IDEAL DEEP-SPACE PROPULSION SYSTEM:

LONG LIFE, MODERATE THRUST, HIGH Isp

SYSTEM PROPERTY:	**REQUIREMENT:**
HIGH Isp	PLASMA PROPELLANT (HIGH KINETIC TEMPERATURE)
MODEST THRUST	100 N – 1000 N (REDUCED TRIP TIMES)
LONG LIFE	ELECTRODELESS (MITIGATE PLASMA EROSION)

CANDIDATE SYSTEM: COLLISIONAL THETA-PINCH

THETA-PINCH SYSTEM



PLASMAS AND CONTROLLED FUSION, ROSE AND CLARK, 1961

- EVALUATED DURING EARLY YEARS OF FUSION PROGRAM
- PULSED AXIAL MAGNETIC FIELD COMPRESSES AND RADIALLY CONFINES IONIZED PLASMA
- WITHOUT MIRRORS, PLASMA ESCAPES ALONG AXIAL FIELD LINES

MODIFY THETA-PINCH GEOMETRY TO PROVIDE DIRECTED, HIGH ENERGY PLASMA EXHAUST

BASIC CONCEPT

- USE MAGNETIC MIRROR TO BLOCK UPSTREAM END OF THETA PINCH (MIRROR RATIO > 5)
- PULSE INJECT NEUTRAL PROPELLANT GAS
- PREIONIZE OUTER SURFACE AREA OF GAS FILL (PREIONIZATION PULSE IN DISCHARGE COIL)
- ADIABATICALLY COMPRESS AND HEAT PREIONIZED PROPELLANT TO REQUIRED DENSITY, TEMPERATURE
- ALLOW DOWNSTREAM EXHAUST TO PRODUCE THRUST
- FIX REPETITION-RATE TO PRODUCE DESIRED THRUST

APPROACH

PHASE I:

- SIMPLE THEORY TO DETERMINE VIABILITY
- ANALYTIC MODEL TO ESTIMATE POTENTIAL THRUSTER PERFORMANCE

PHASE II:

- 2-D CODE DEVELOPMENT FOR DETAILED PHYSICAL MODELING
- EXPERIMENTAL EVALUATION

SIMPLE THEORY

- IDEAL EXHAUST VELOCITY RELATED TO TEMPERATURE:

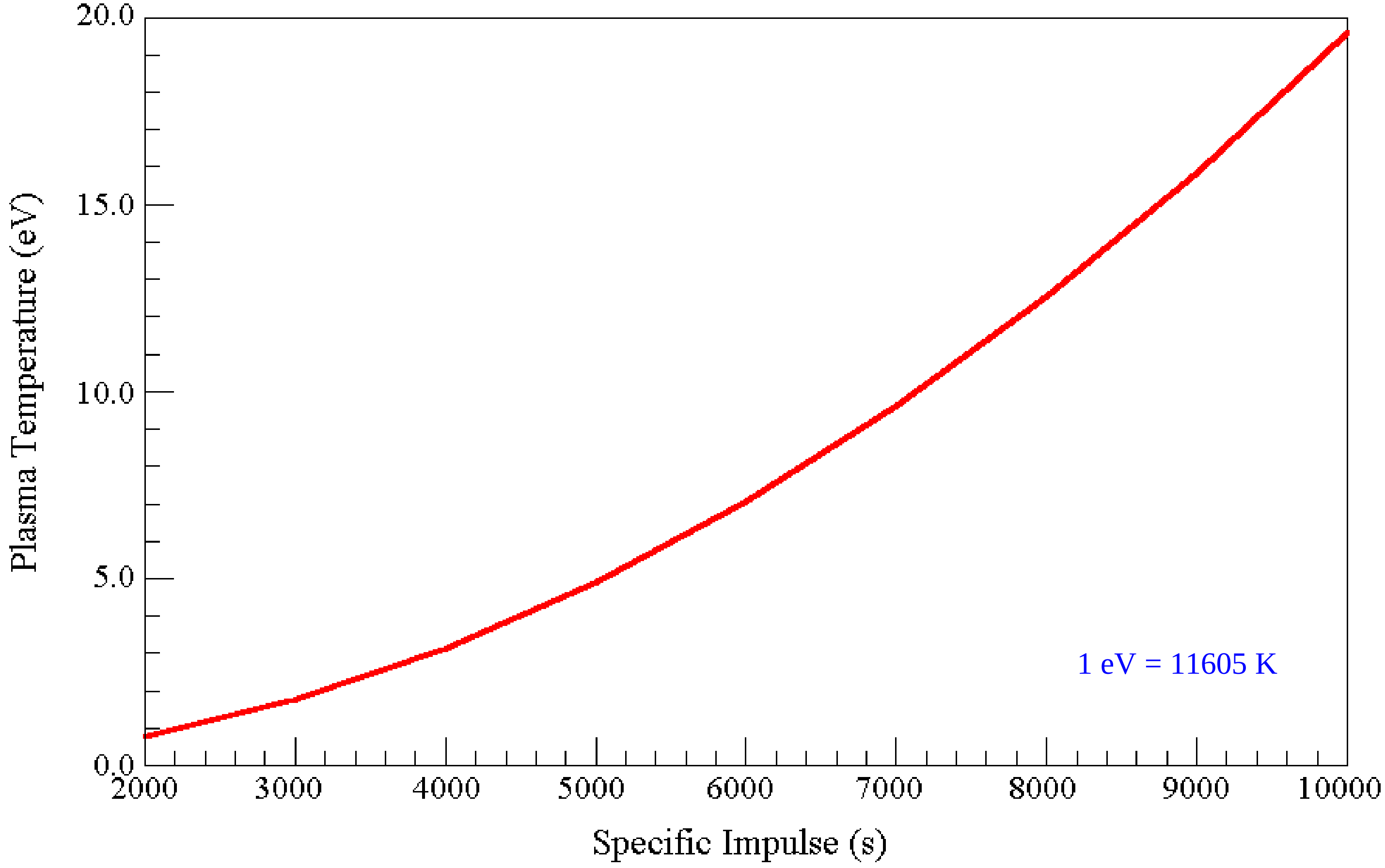
$$Ue = \sqrt{\frac{2g}{(g-1)}\frac{RT}{M}h_i} = gI_{SP}$$

Ue = exhaust velocity
T = propellant temperature
M = propellant molecular weight
R = gas constant

η_i = ideal cycle efficiency
γ = adiabatic index
g = 9.8 m/s^2
Isp = specific impulse (s)

HIGH TEMPERATURES, LOW MOLECULAR WEIGHTS

SPECIFIC IMPULSE vs. PLASMA TEMPERATURE



SIMPLE THEORY

- PLASMA HEATED BY ADIABATIC COMPRESSION:

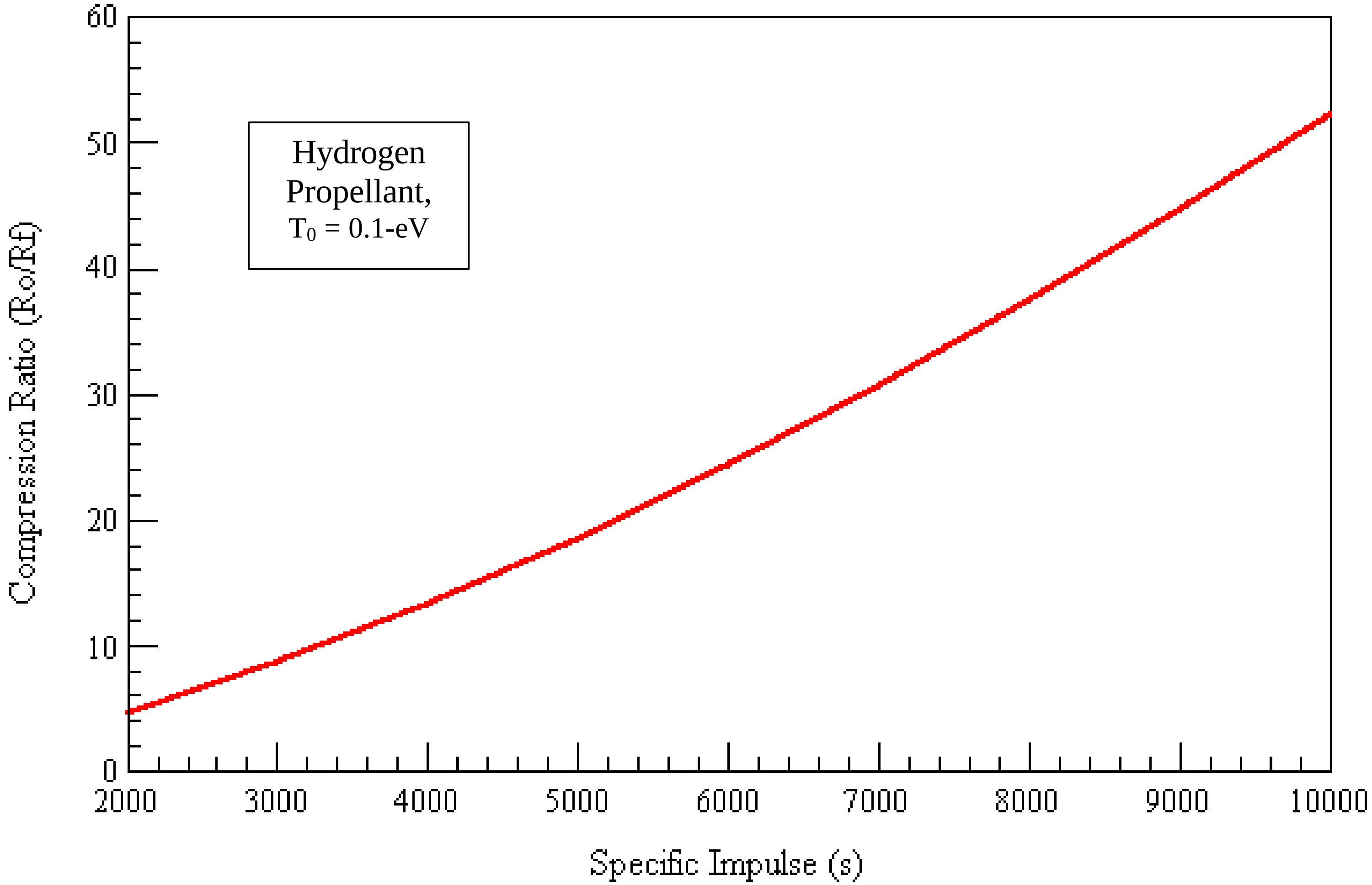
$$\frac{T_f}{T_0} = \left(\frac{r_0}{r_f}\right)^{4/3}$$

where:

T_0 = initial plasma temperature		r_0 = initial plasma radius
T_f = final plasma temperature		r_f = final plasma radius

- NO IRREVERSIBLE SHOCK HEATING OF THE PLASMA

PLASMA COMPRESSION RATIO vs. SPECIFIC IMPULSE



SIMPLE THEORY

- IDEAL GAS EQUATION OF STATE:

$$P = rRT = \sum nkT$$

where ρ = mass density, n = number density, k = Boltzmann's constant

- ADIABATIC COMPRESSION LAW:

$$\frac{P_f}{P_0} = \left(\frac{r_0}{r_f} \right)^{5/3} = \left(\frac{r_0}{r_f} \right)^{10/3}$$

provides compressed plasma pressure in terms of compression ratio

SIMPLE THEORY

- PLASMA PRESSURE BALANCED BY MAGNETIC FIELD:

$$P = \frac{B_0^2}{2\,m_0} = r\,R\,T$$

- NEGLECT RADIAL DIFFUSION ACROSS MAGNETIC FIELD
- MIRROR RATIO $R_M \geq 5$ AT UPSTREAM END OF CHAMBER

$$P_{LOST} = 1 - \left(\frac{R_M - 1}{R_M} \right)^{1/2} \leq 10\%$$

- PLASMA FREELY ESCAPES FROM OPEN END OF CHAMBER

SIMPLE THEORY

- TIME FOR PLASMA TO ESCAPE FROM CHAMBER LENGTH L:

$$t_P \approx \frac{L}{U_e}$$

- MASS OF PLASMA LOST FROM SYSTEM IN TIME τ_P:

$$\Delta m = r_0 (p r_0^2) L$$

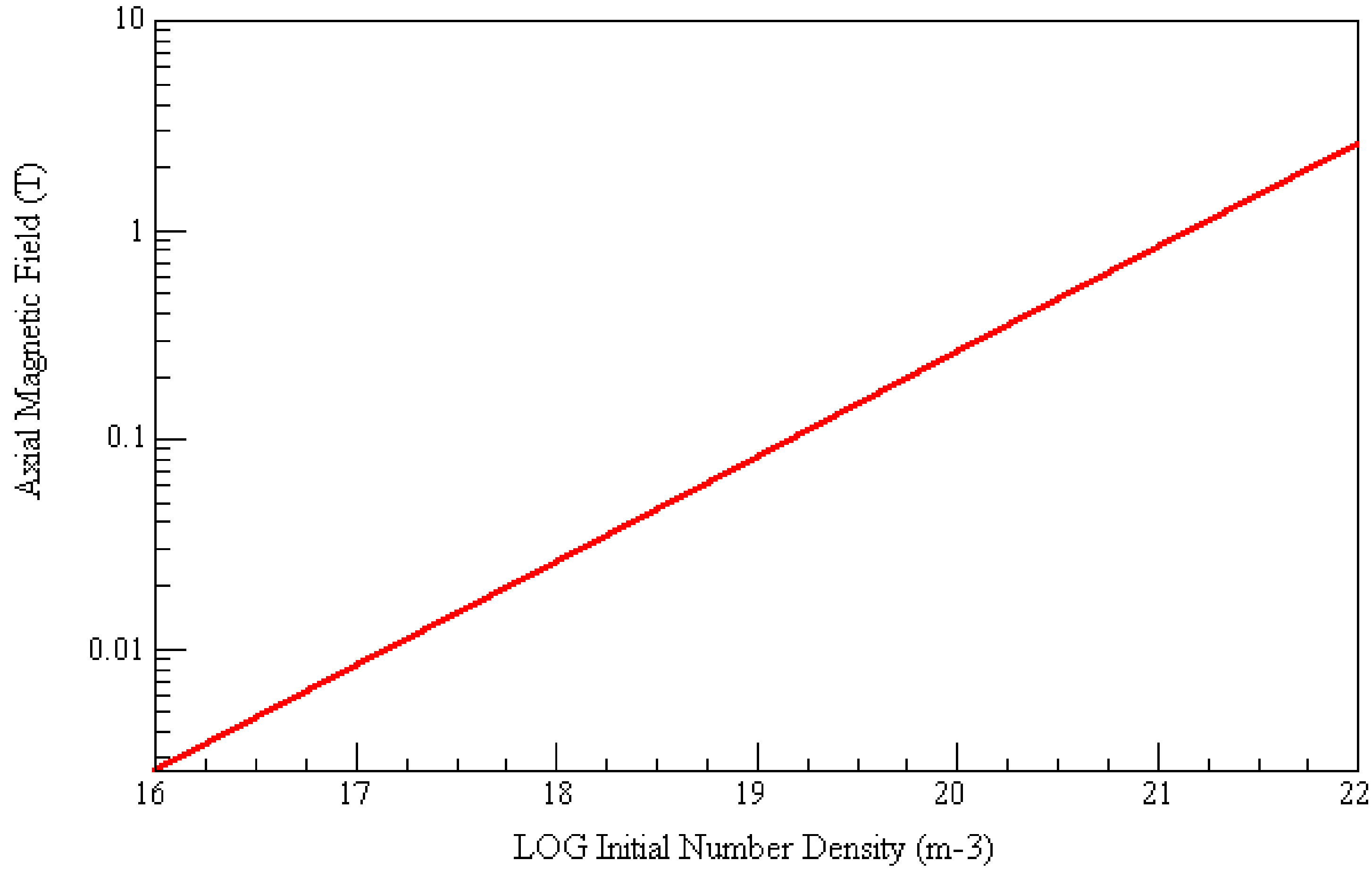
- IMPULSE-BIT PROVIDED BY PULSED PLASMA EXHAUST:

$$I_{BIT}(N-s) = \Delta m \times U_E$$

- AVERAGE THRUST = $I_{BIT} \times$ f (Hz) $\leq$ I_{BIT}/τ_P

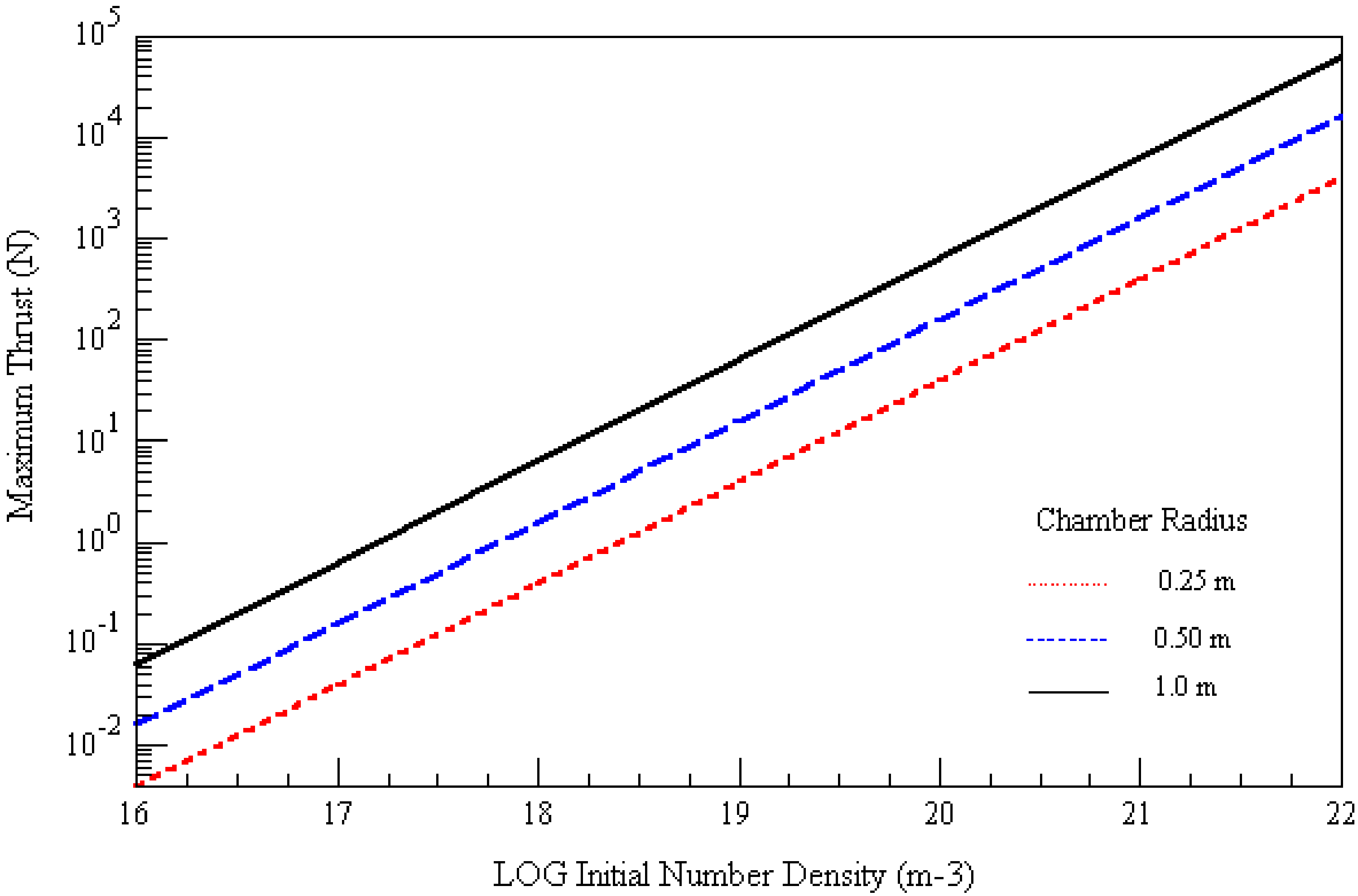
MAGNETIC FIELD STRENGTH vs. INITIAL NUMBER DENSITY

HYDROGEN PROPELLANT, Isp = 5000 s



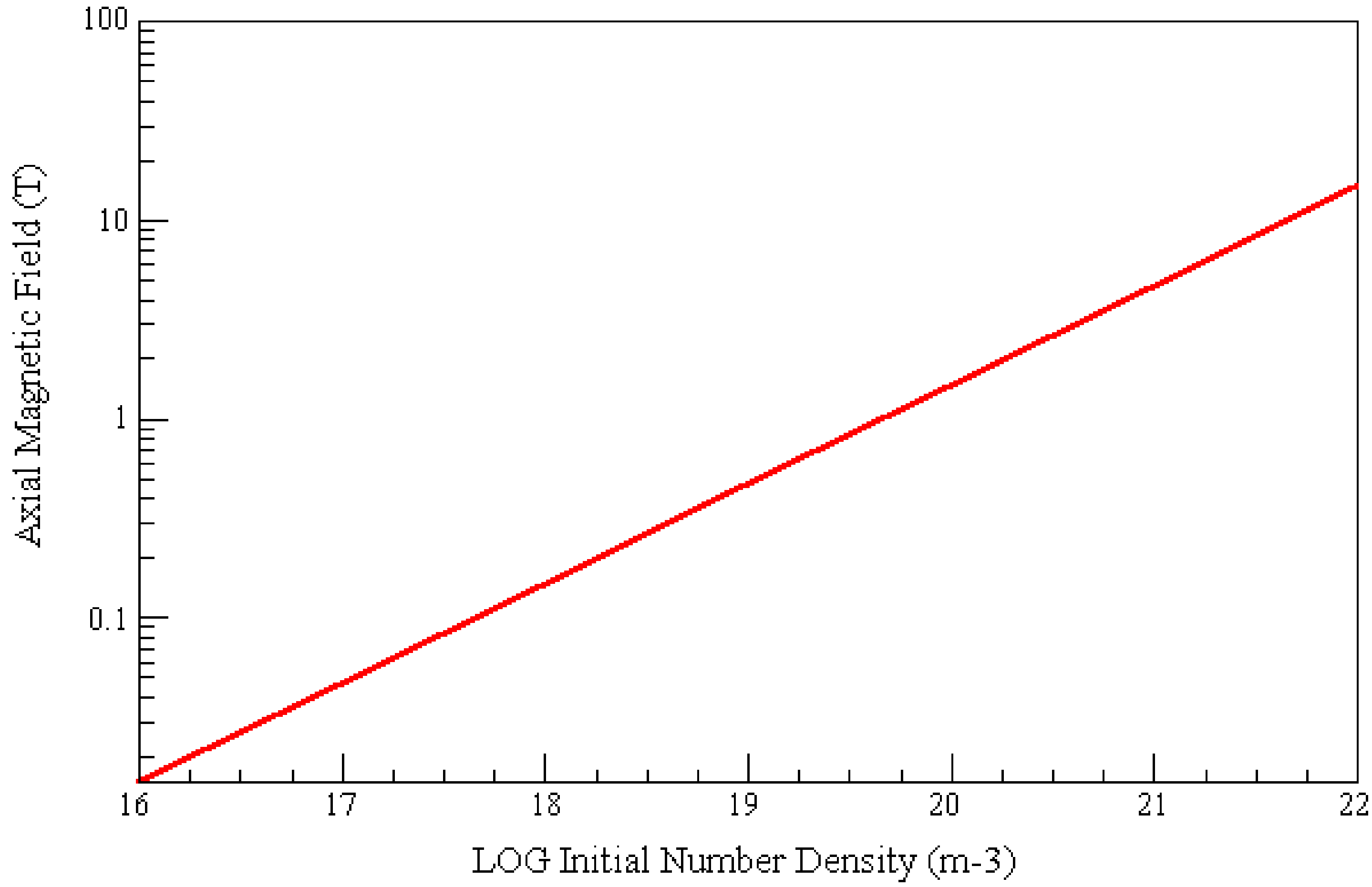
THRUST (100% DUTY CYCLE) vs. INITIAL NUMBER DENSITY

HYDROGEN PROPELLANT, Isp = 5000 s



MAGNETIC FIELD STRENGTH vs. INITIAL NUMBER DENSITY

HYDROGEN PROPELLANT, Isp = 10,000 s



THRUST (100% DUTY CYCLE) vs. INITIAL NUMBER DENSITY

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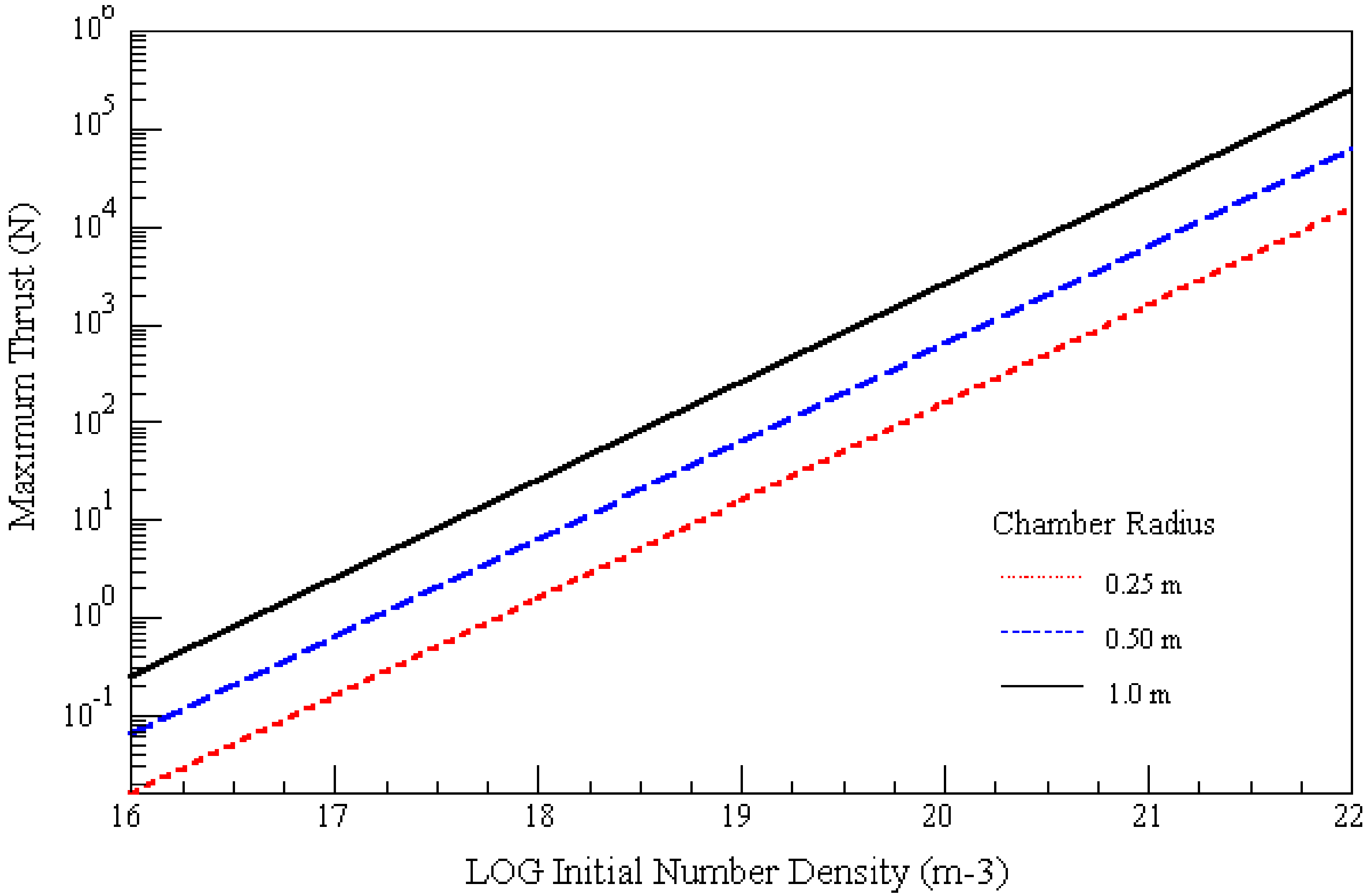


RESULTS FROM SIMPLE THEORY

- USEFUL THRUST OVER RANGE OF Isp
- REASONABLE MAGNETIC FIELD STRENGTHS
- REASONABLE PLASMA NUMBER DENSITIES, TEMPERATURES
- ELECTRODELESS DEVICE MITIGATES EROSION FOR LONG LIFE

THETA-PINCH PLASMA THRUSTER APPEARS VIABLE

ANALYTIC THETA-PINCH MODEL

- **TIME DEPENDENT NUMERICAL SIMULATION**
  - Stover, Computer Simulation of Plasma Behavior in Open-Ended Theta Linear Machines, Dept. of Energy DOE/ET/53018-6, 1981.
- **INCORPORATES ADDITIONAL PLASMA PHYSICS**
  - Time Dependent Plasma End Loss
  - Bremsstrahlung Radiation Losses
- **COMPARE WITH EXPERIMENTAL THETA-PINCH DATA**
  - **Scylla I-C Collisional Theta-Pinch**
- **EVALUATE THETA-PINCH THRUSTER PERFORMANCE**

THETA-PINCH MODEL

DURING COMPRESSION:

INITIAL PARTICLE NUMBER: $$N_0 = \frac{P_0}{kT_0}(pr_0^2 L)$$

RADIAL PRESSURE BALANCE: $$\overline{P}(t) = \frac{B_0^2(t)}{2m_0}$$

ADIABATIC COMPRESSION: $$\frac{\overline{P}(t)}{P_0} = \left(\frac{r_0}{r(t)}\right)^{10/3}$$

PLASMA NUMBER DENSITY: $$\overline{n}(t) = \frac{N_0}{pr^2(t)L}$$

PLASMA TEMPERATURE: $$\overline{T}(t) = \frac{\overline{P}(t)}{k\overline{n}(t)}$$

THETA-PINCH MODEL

AFTER COMPRESSION:

CHANGE IN PARTICLE NUMBER: $$\frac{\partial N}{\partial t} = -\frac{N}{\tau_c}$$

PARTICLE CONFINEMENT TIME: $$\tau_C = \frac{L}{2}\left(\frac{M_i}{2kT}\right)^{1/2} \chi$$

RADIAL PRESSURE BALANCE: $$\overline{P}(t) = \frac{B_0^2(t)}{2\mu_0}$$

PLASMA NUMBER DENSITY: $$\overline{n}(t) = \frac{N(t)}{\pi r^2(t) L}$$

PLASMA TEMPERATURE: $$\frac{\partial E}{\partial t} = -\varepsilon \frac{\partial N}{\partial t} - \overline{P}\frac{\partial A}{\partial t} - \frac{E}{\tau_{th}}$$

ε = (5/2)T, E = internal ion energy, τ_{th} = thermal conduction time, A = plasma column area, $\chi \approx 2.5$

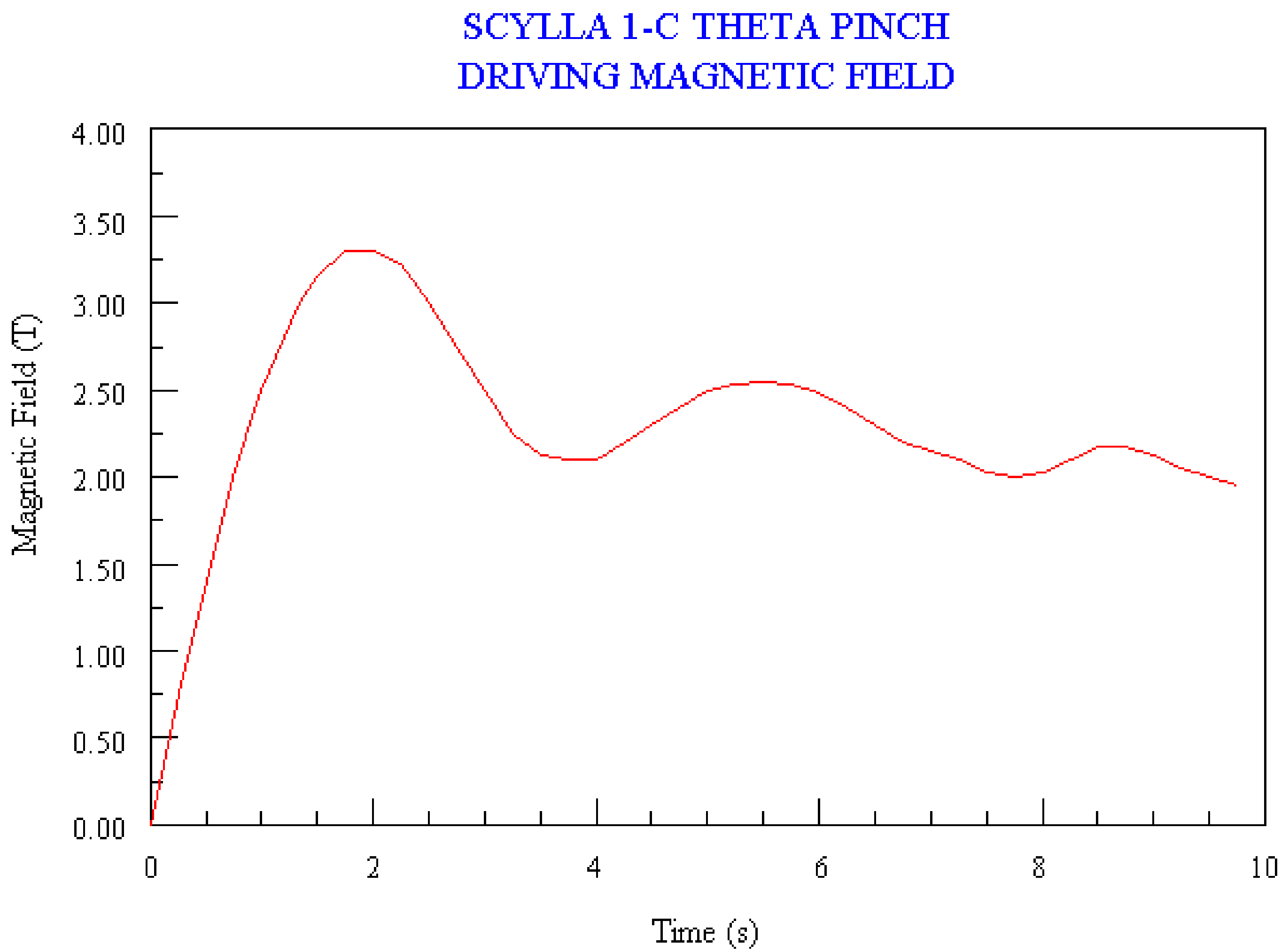
THETA-PINCH MODEL

COMPARISON WITH SCYLLA I-C EXPERIMENT*

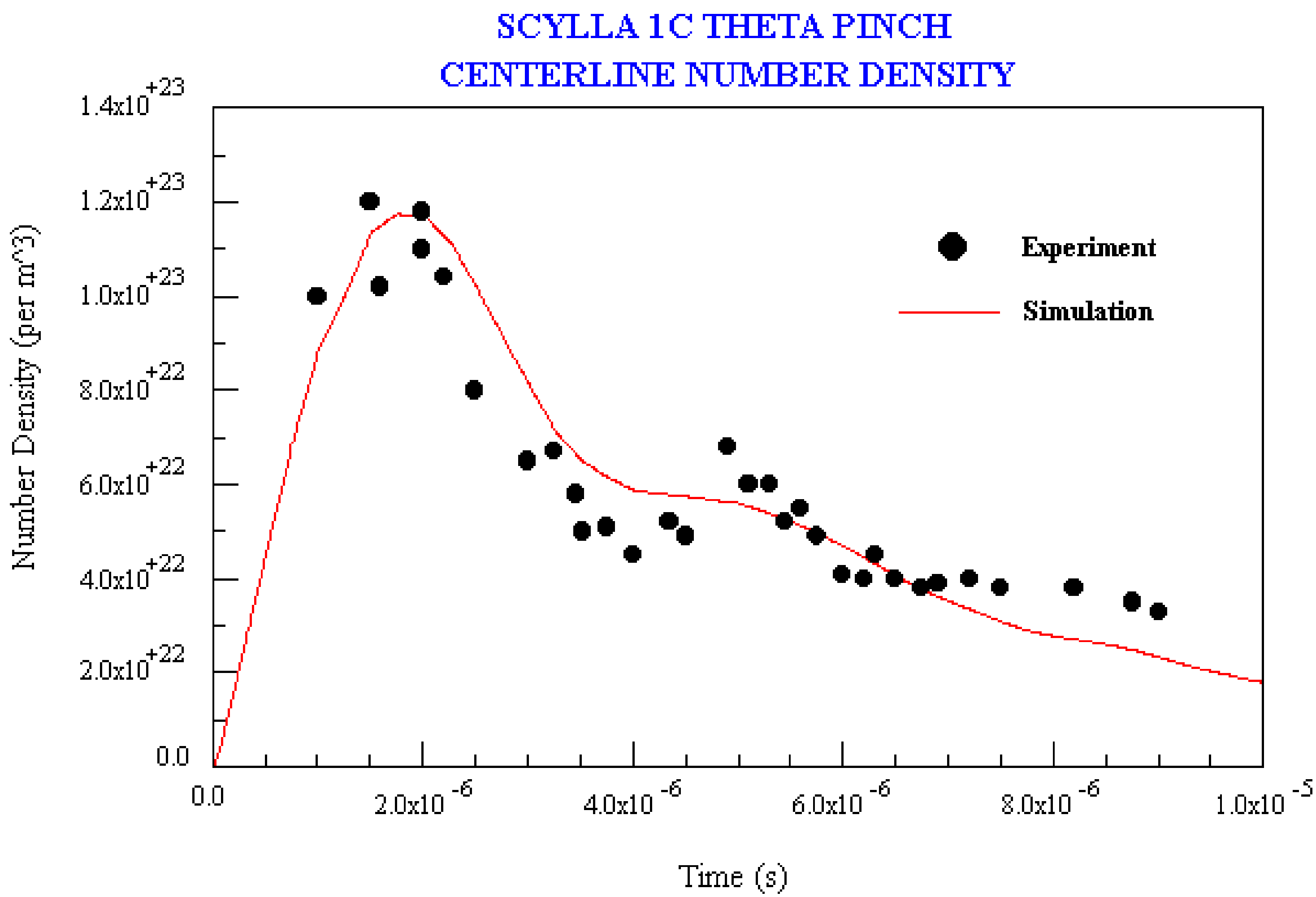
CHAMBER RADIUS:	**0.018 m**
CHAMBER LENGTH:	1.0 m
INITIAL PRESSURE:	100 mTorr
INITIAL TEMPERATURE:	1-eV
EST. CONFINEMENT TIME:	14-μs

*McKenna, K. F. and York, T. M., "Plasma End Loss Studies in Scylla I-C", *Phys. Fluids*, **20**, pp 1556-1570, 1979.

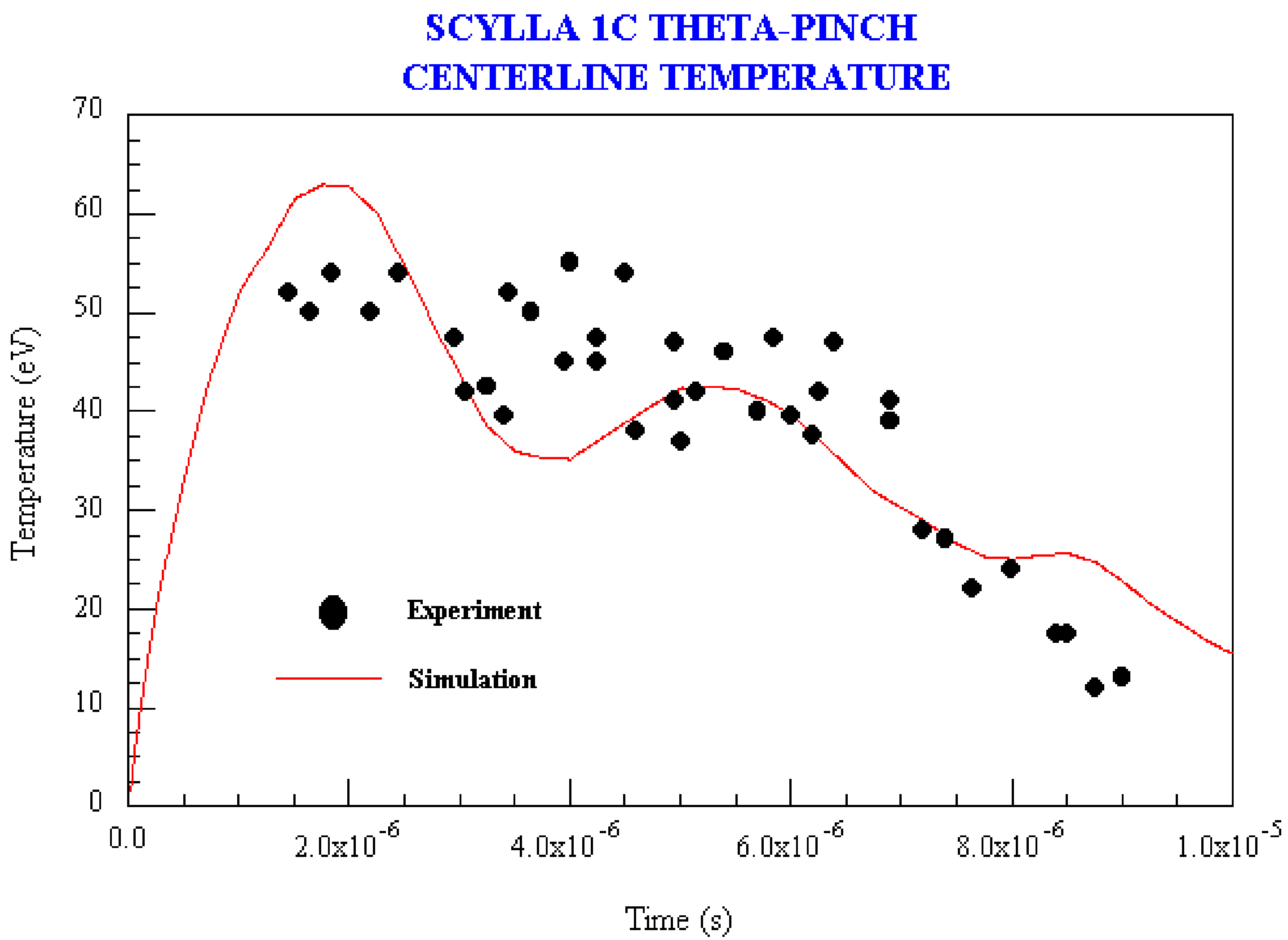
APPLIED MAGNETIC FIELD



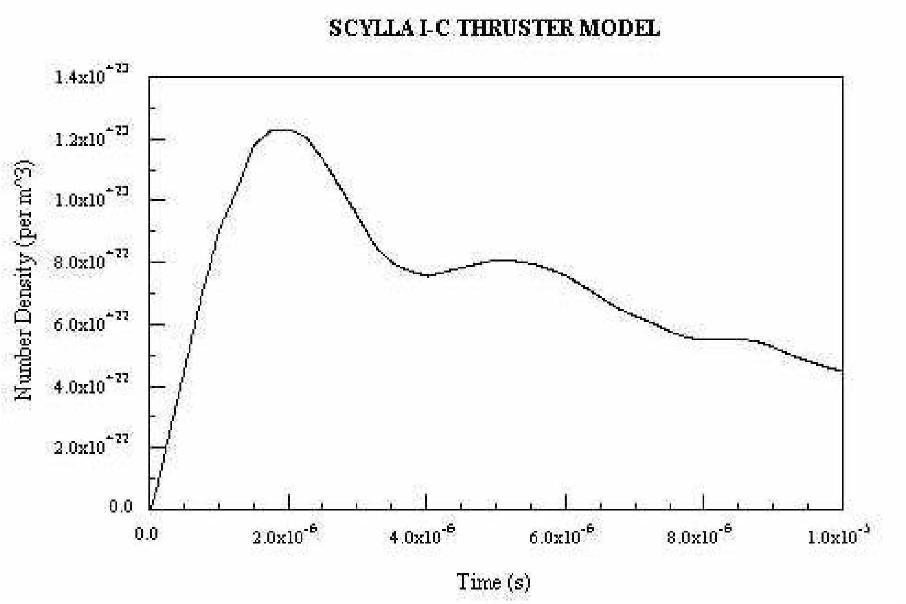
NUMBER DENSITY PREDICTIONS



ION TEMPERATURE PREDICTIONS

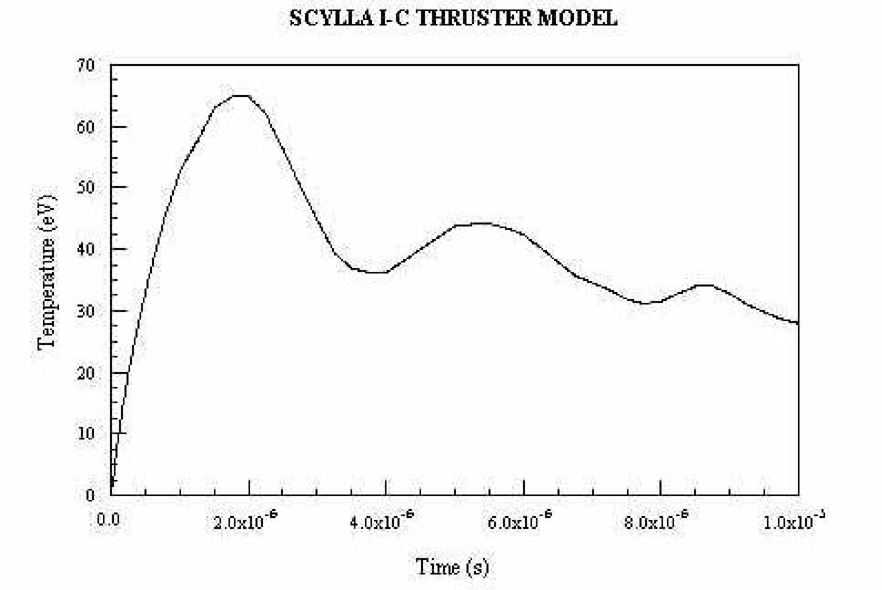


USING SCYLLA I-C AS A THRUSTER…

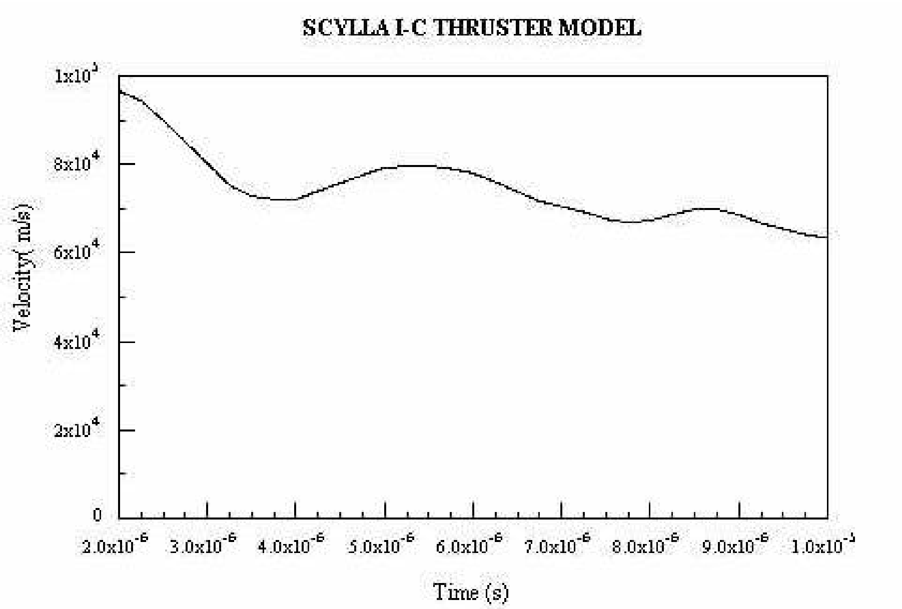


NUMBER DENSITY

TEMPERATURE

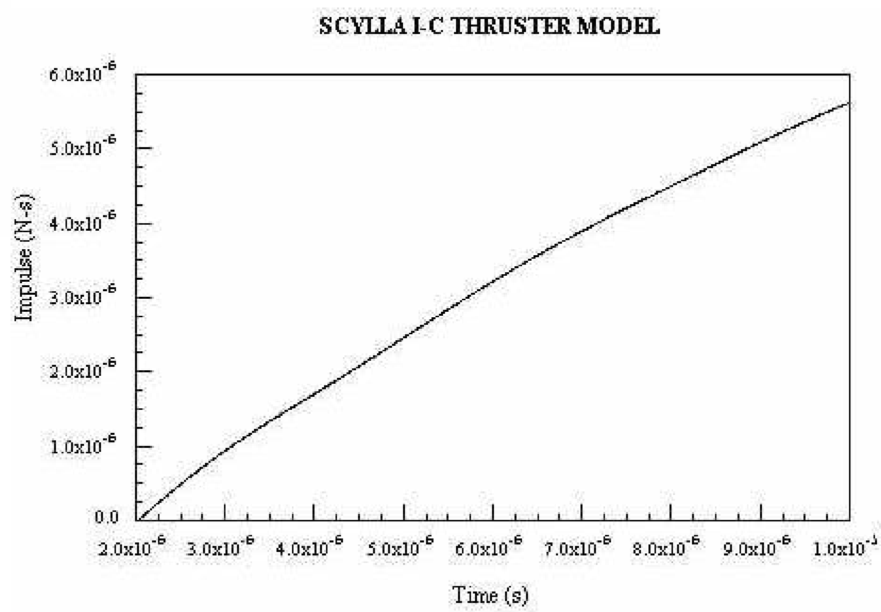


… IS NOT A GOOD IDEA



EXHAUST VELOCITY

INTEGRATED IMPULSE-BIT

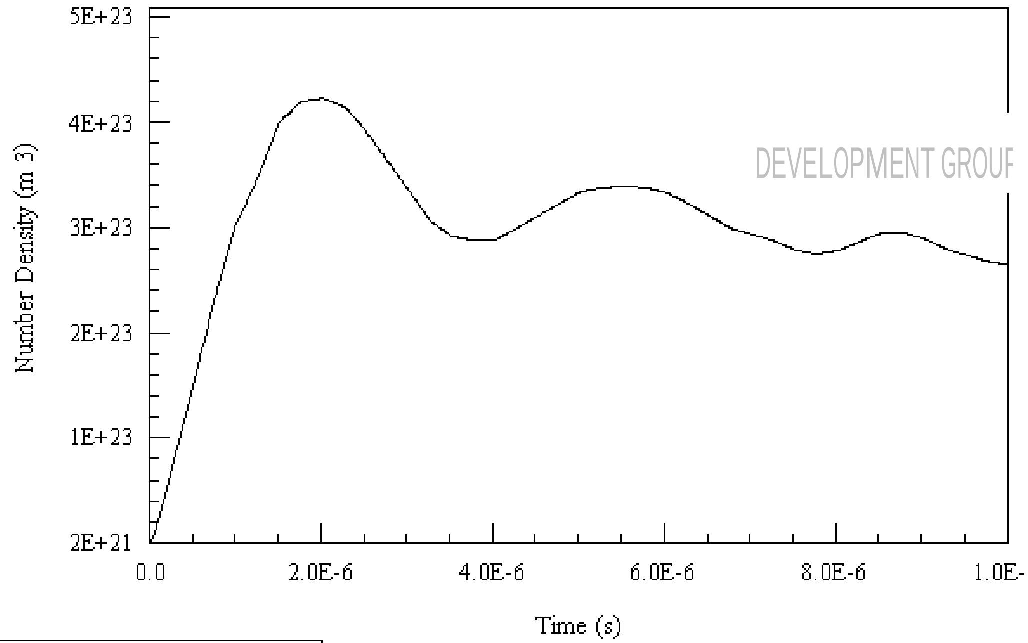


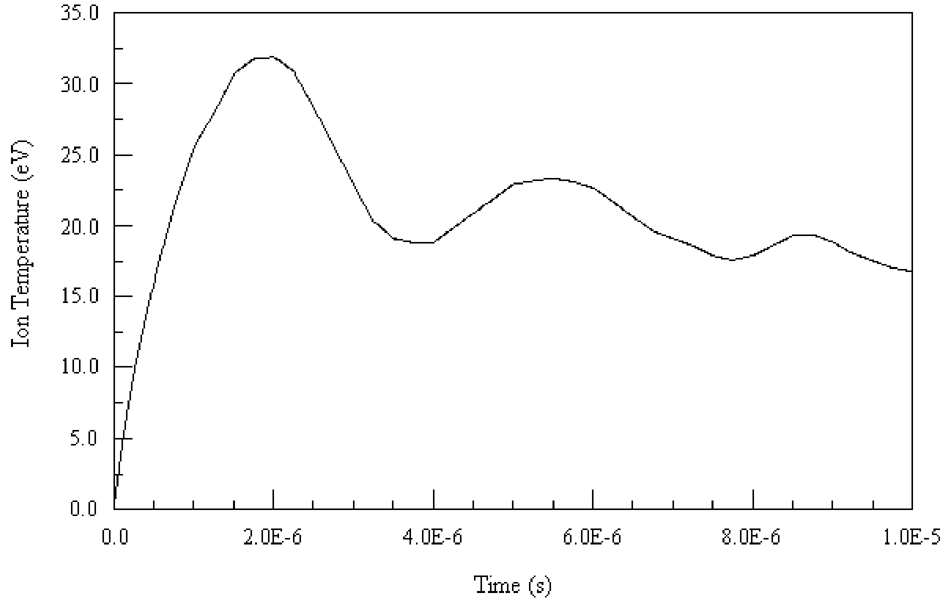
- EXHAUST VELOCITY IS HIGH, BUT TOTAL PROPELLANT MASS IS TOO LOW TO PROVIDE USEFUL THRUST

IMPROVE THRUSTER PERFORMANCE

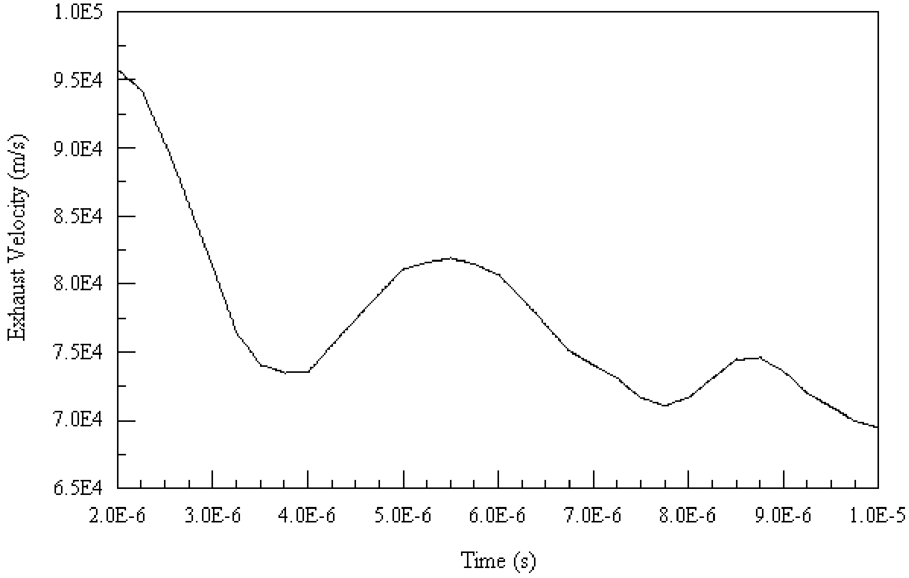
- CHAMBER RADIUS: 1 m
- CHAMBER LENGTH: 10 m
- INITIAL PRESSURE: 1 Torr
- INITIAL TEMPERATURE: 1-eV
- USE SAME DRIVING FIELD AS SCYLLA I-C

NUMBER DENBSITY vs. TIME

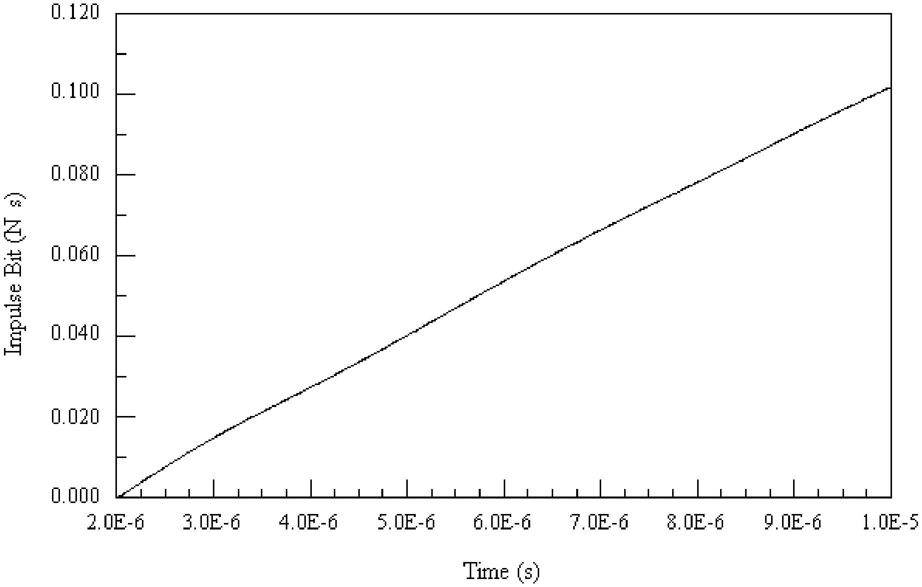




TEMPERATURE vs. TIME



EXHAUST VELOCITY



IMPULSE-BIT

- **LARGER CHAMBER, HIGHER INITIAL PRESSURE INCREASES IMPULSE**
- **CAN TAILOR AXIAL MAGNETIC FIELD TO IMPROVE COMPRESSION**

PROGRAM STATUS

- ANALYTIC MODEL PREDICTS THAT USEFUL THRUST, Isp CAN BE OBTAINED FROM A THETA-PINCH THRUSTER
- DETAILED THRUSTER PHYSICS REQUIRES 2-D MODEL DEVELOPMENT (UNDERWAY)

POTENTIAL ISSUES

- MHD INSTABILITIES MIGHT ARISE THAT LIMIT COMPRESSION TIMES IN LONG THRUSTER CHAMBERS
- NEED TO ESTABLISH OPTIMUM DRIVING FIELD CONFIGURATION FOR EFFICIENT THRUSTER OPERATION

PROGRAM PLANS

- DEVELOPMENT OF ROBUST 2-D NUMERICAL MODEL TO BETTER SIMULATE THETA-PINCH THRUSTER PHYSICS
- USE CODE TO IDENTIFY OPTIMUM THRUSTER GEOMETRY FOR DEEP SPACE MISSION APPLICATIONS
- USE DYNAMIC SIMILARITY TO DEFINE SMALL-SCALE THETA-PINCH THRUSTER EXPERIMENT
- EXPERIMENTALLY EVALUATE SCALED THETA-PINCH THRUSTER PERFORMANCE

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