Evaluation of the Surface Launch of a Single-Stage-to-Orbit Nuclear Thermal Rocket

Jeffrey C. King and Satira I. Labib

Nuclear Science and Engineering Program

Metallurgical and Materials Engineering Department

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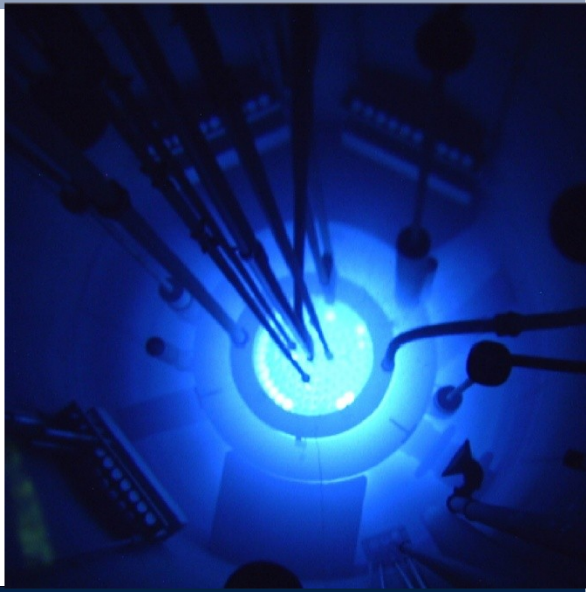

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Introduction

- Development of a ground launch vehicle with high specific impulse could pave the way for next generation manned space exploration
  - Nuclear thermal rockets (NTRs) with high specific impulses were demonstrated in the 1960s
- NTRs have not generally been considered for a ground launch
- Recent advances in tungsten cermet fuels may significantly reduce the risk of an NTR launch failure
- This project designed three nuclear thermal rocket reactors using tungsten cermet fuels.
  - Sized to accommodate a range of payloads (1-15 MT) launched to low earth orbit.

Background

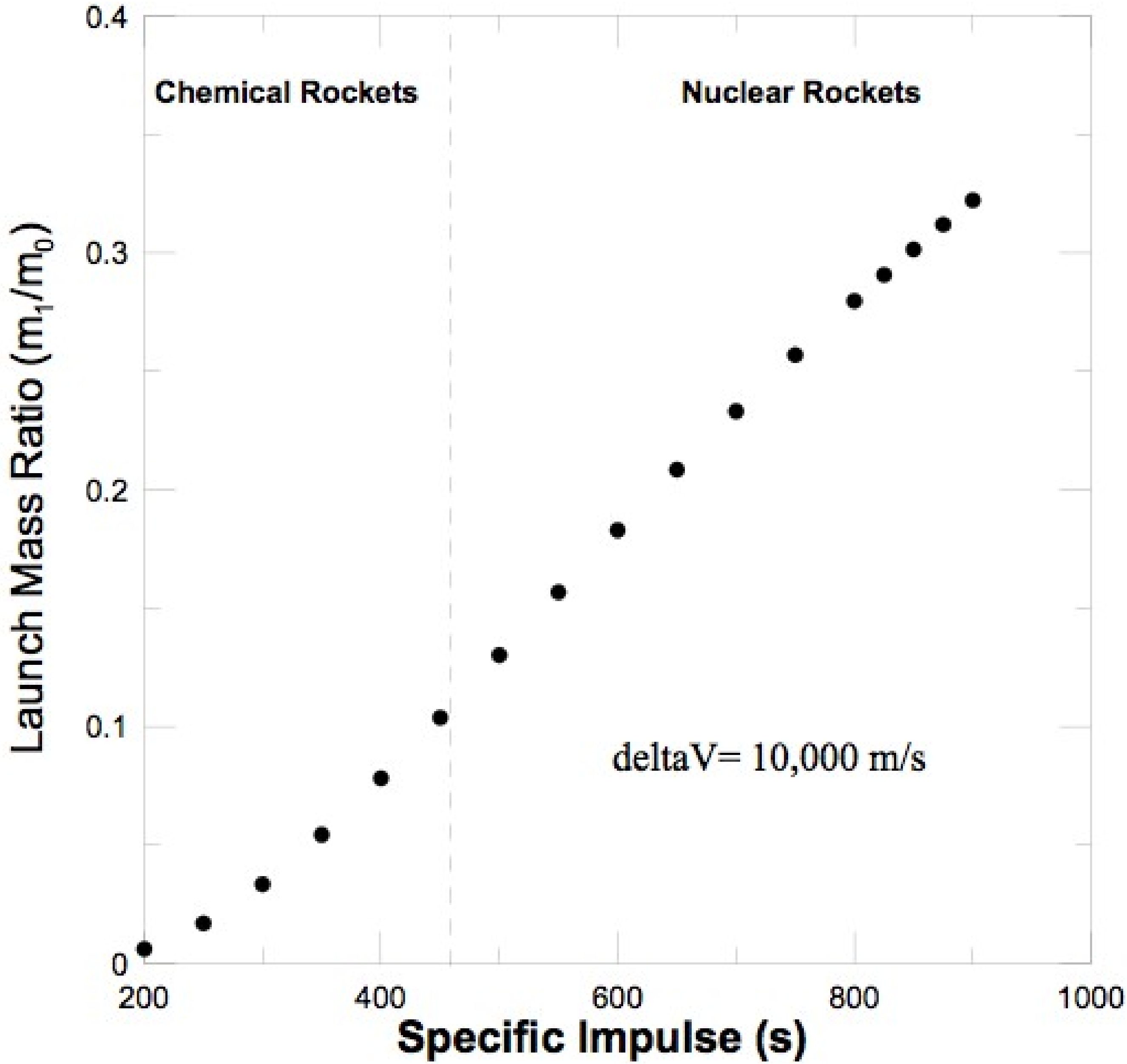
Propulsion Basics

- In a chemical rocket, the propellant is typically heated by a chemical reaction with an oxidizer
- In a nuclear thermal rocket, the propellant is heated by nuclear fission
- An NTR allows for the use of a light weight monopropellant, thus increasing specific impulse
- Specific impulse (I_{SP}) is a rocket performance measurement
  - Thrust with respect to propellant used per unit time
  - $I_{SP} = \frac{F}{\dot{m}} = AC_f\sqrt{T_m/M_{prop}}$
- Specific impulse is controlled by the exhaust temperature and molar mass of the propellant
- Therefore, NTRs can theoretically achieve much higher specific impulses than conventional chemical rocket
- The advantage of increasing specific impulse can be shown using the Tsiolkovsky rocket equation.

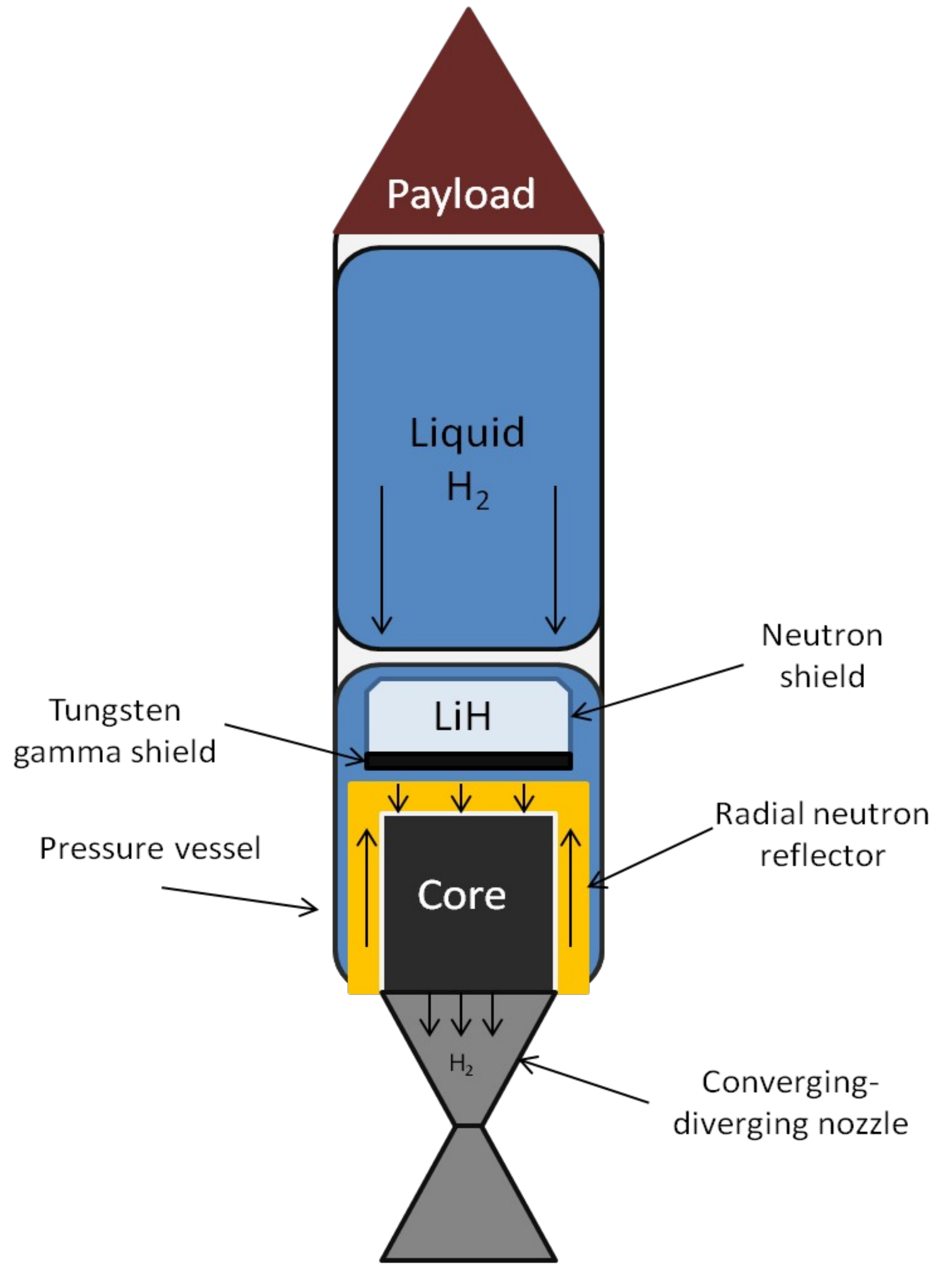
$$\Delta v = I_{SP} * g_0 * ln\left(\frac{m_0}{m_1}\right)$$

Turner, Martin J.L., Rocket and Spacecraft Propulsion. Praxis Publishing, Chichester, UK, 2009, pp. 10-20
Corliss, W. R., Nuclear Propulsion for Space, Understanding the Atom Series, Atomic Energy Commission, Oak Ridge, TN, 1971.

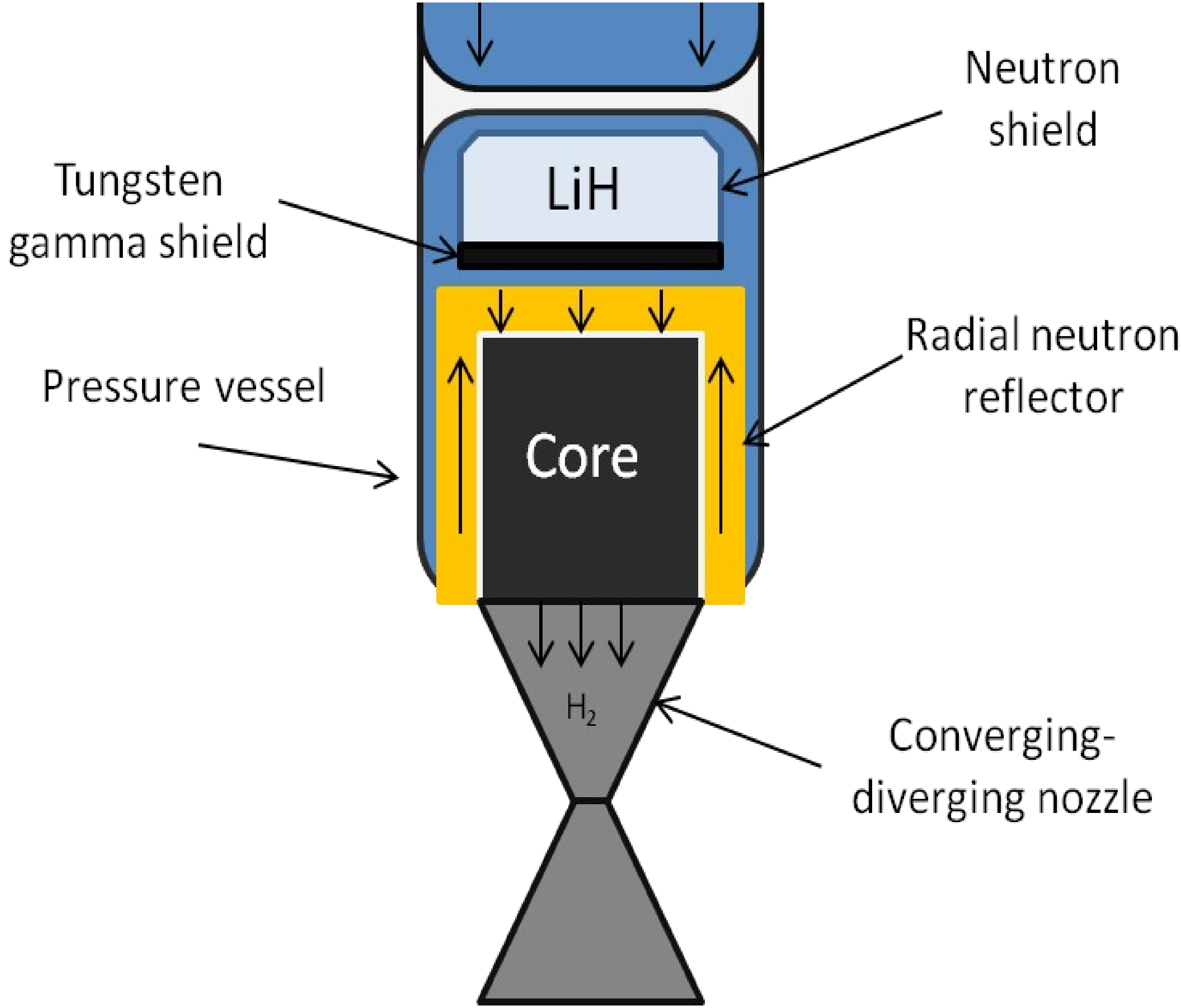
Launch Mass Ratio



Nuclear Thermal Rocket Basics

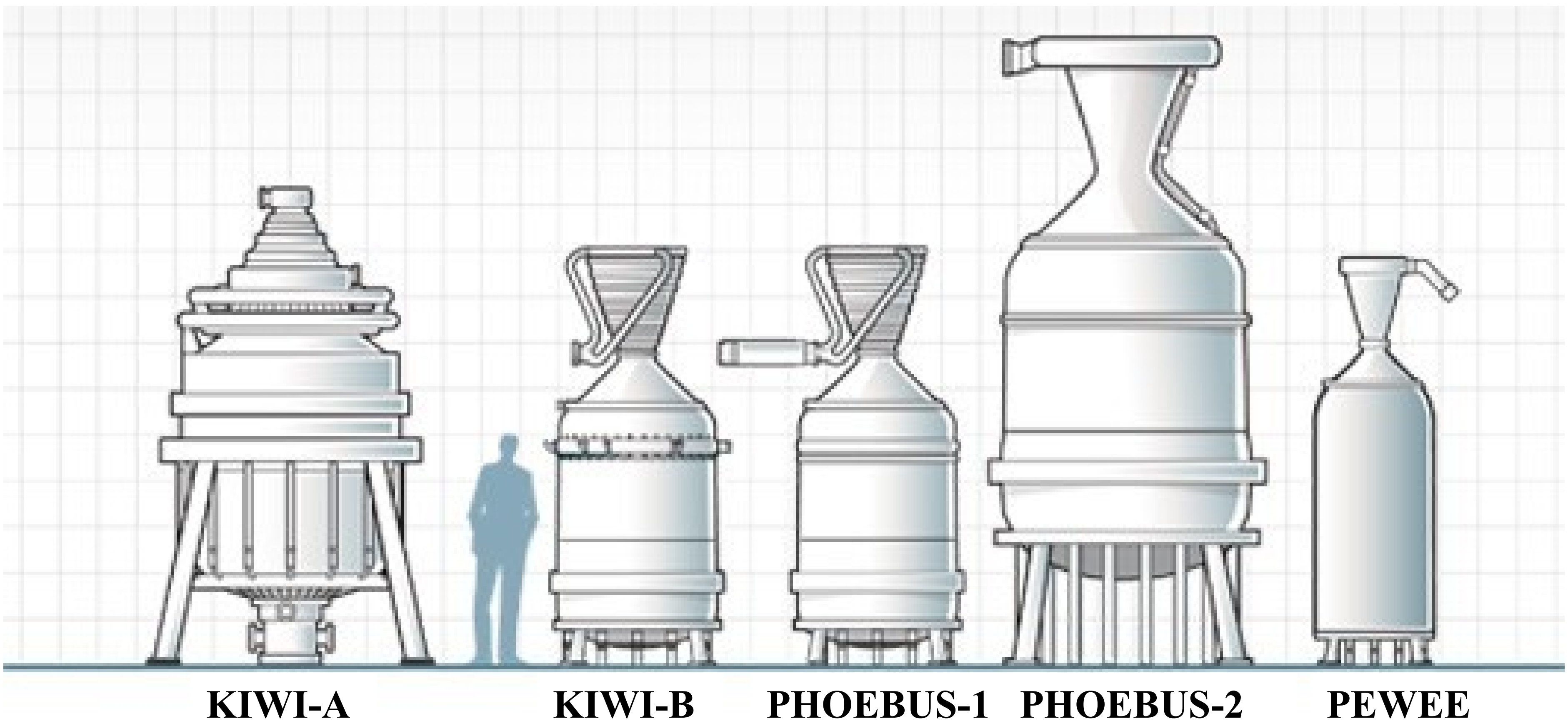


Nuclear Thermal Rocket Basics



NERVA Downfire Tests

US NTR Reactor Comparison

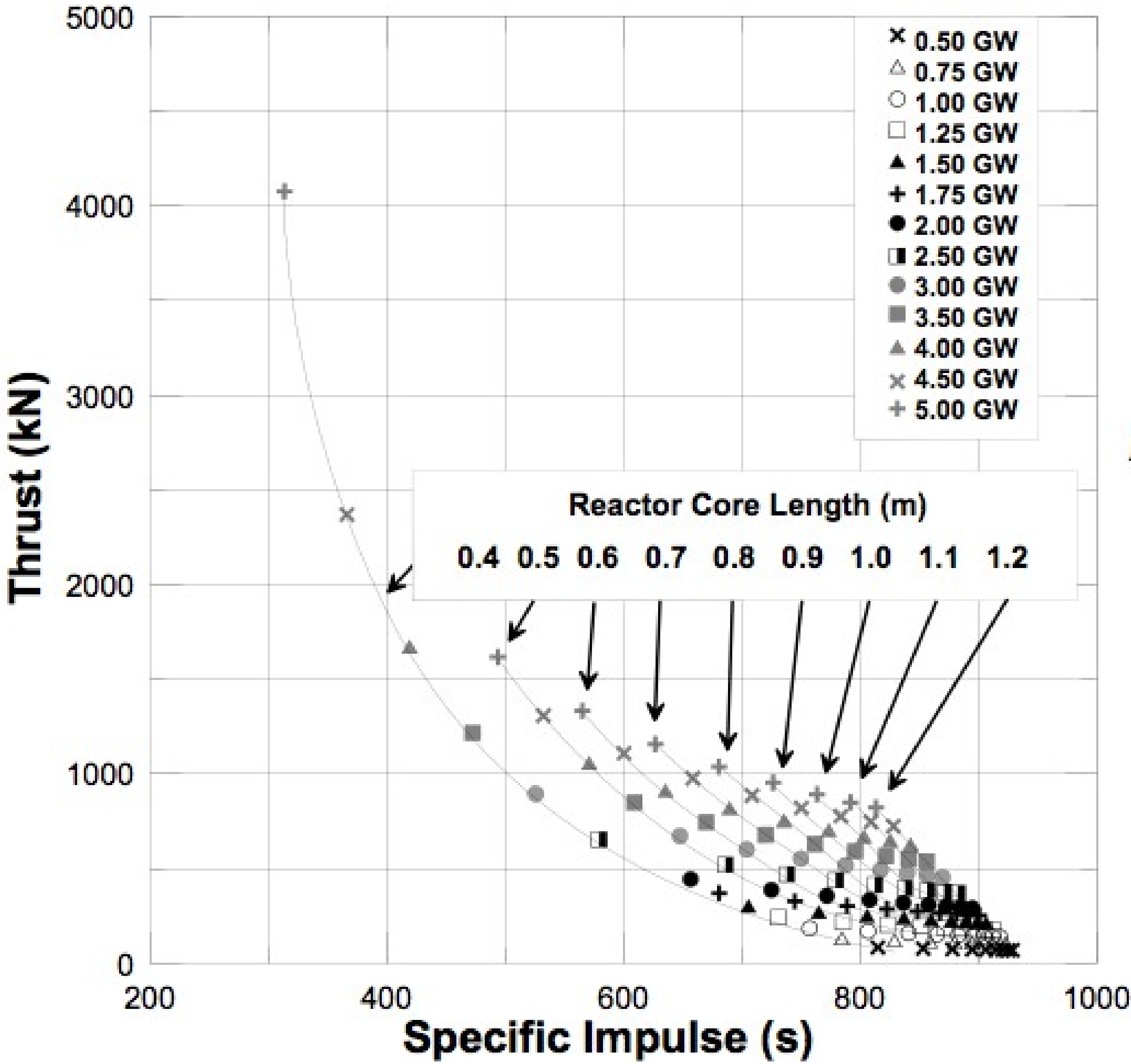


Nuclear Thermal Rocket Reactor Design

Thermal Hydraulics

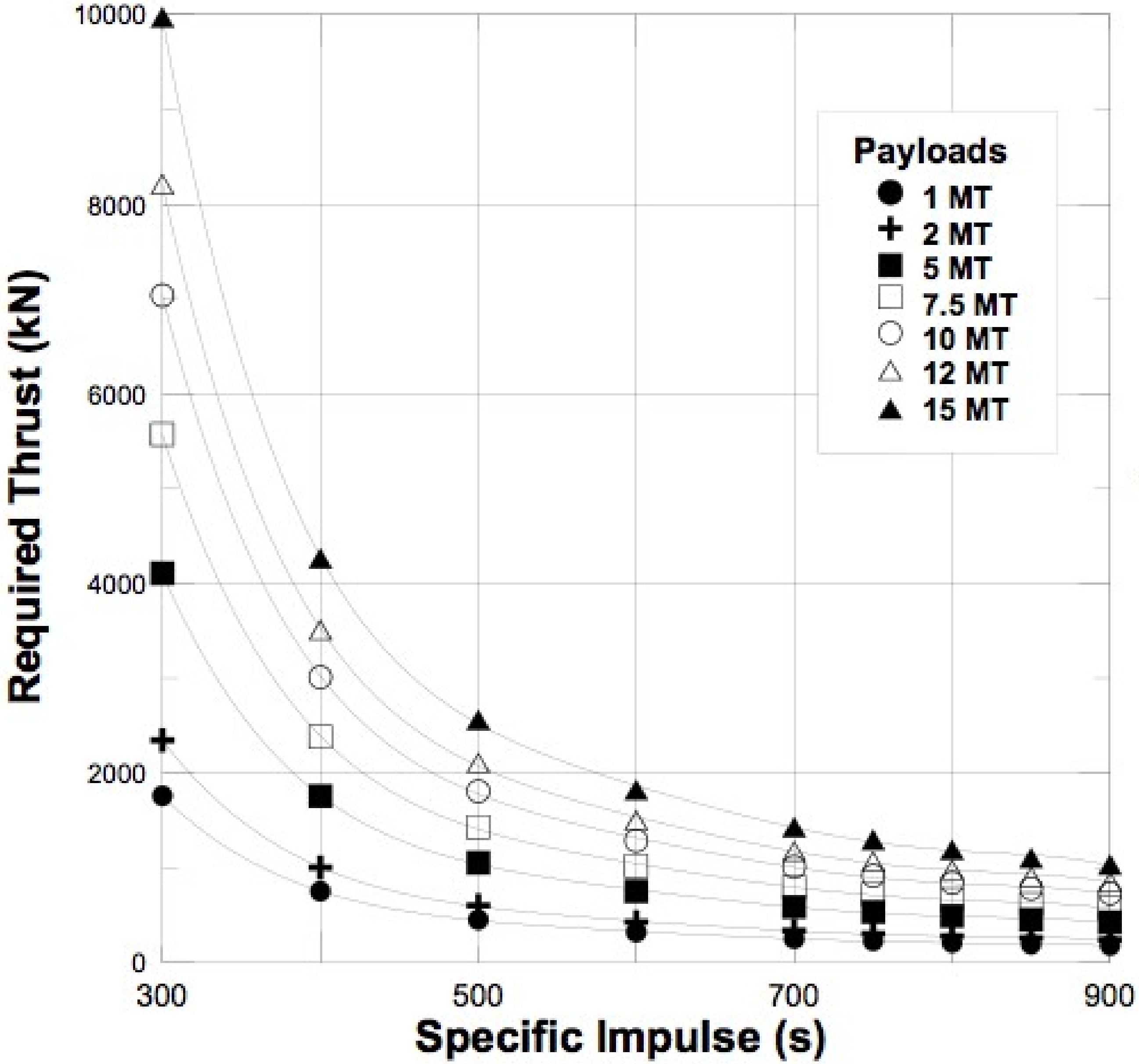
- Assumptions
  - Fuel has a 40/60 vol% fuel/matrix ratio
    - Fuel is uranium nitride, matrix is W-25Re alloy
  - Maximum fuel temperature (3000 K) is ~90% of T_{melt} (3350 K)
  - Hydrogen enters the top of the core at 120 K
  - Chamber pressure is 6 MPa

Rocket Engine Analysis - Thrust



$$F(N) = I_{SP} * \dot{m} * g_0$$

Rocket Engine Analysis - Required Thrust

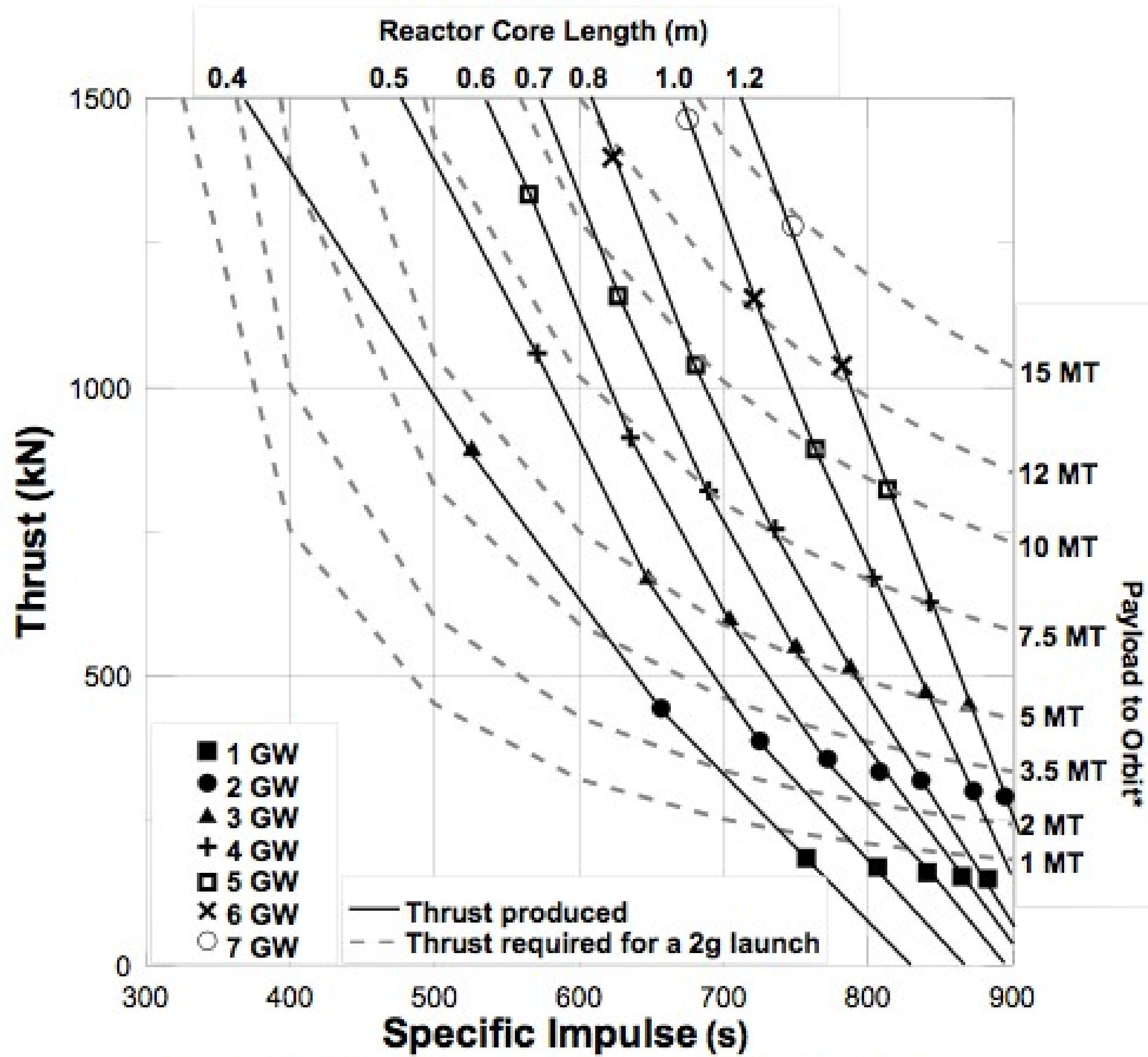


Delta v for ground to LEO ~ 10,000 m/s

$$\Delta v = I_{SP} * g_0 * ln\left(\frac{m_0}{m_1}\right)$$

Assumes 2 g of thrust ($9.8\ m/s^2$ upward acceleration) and 2 MT of reactor and tankage mass.

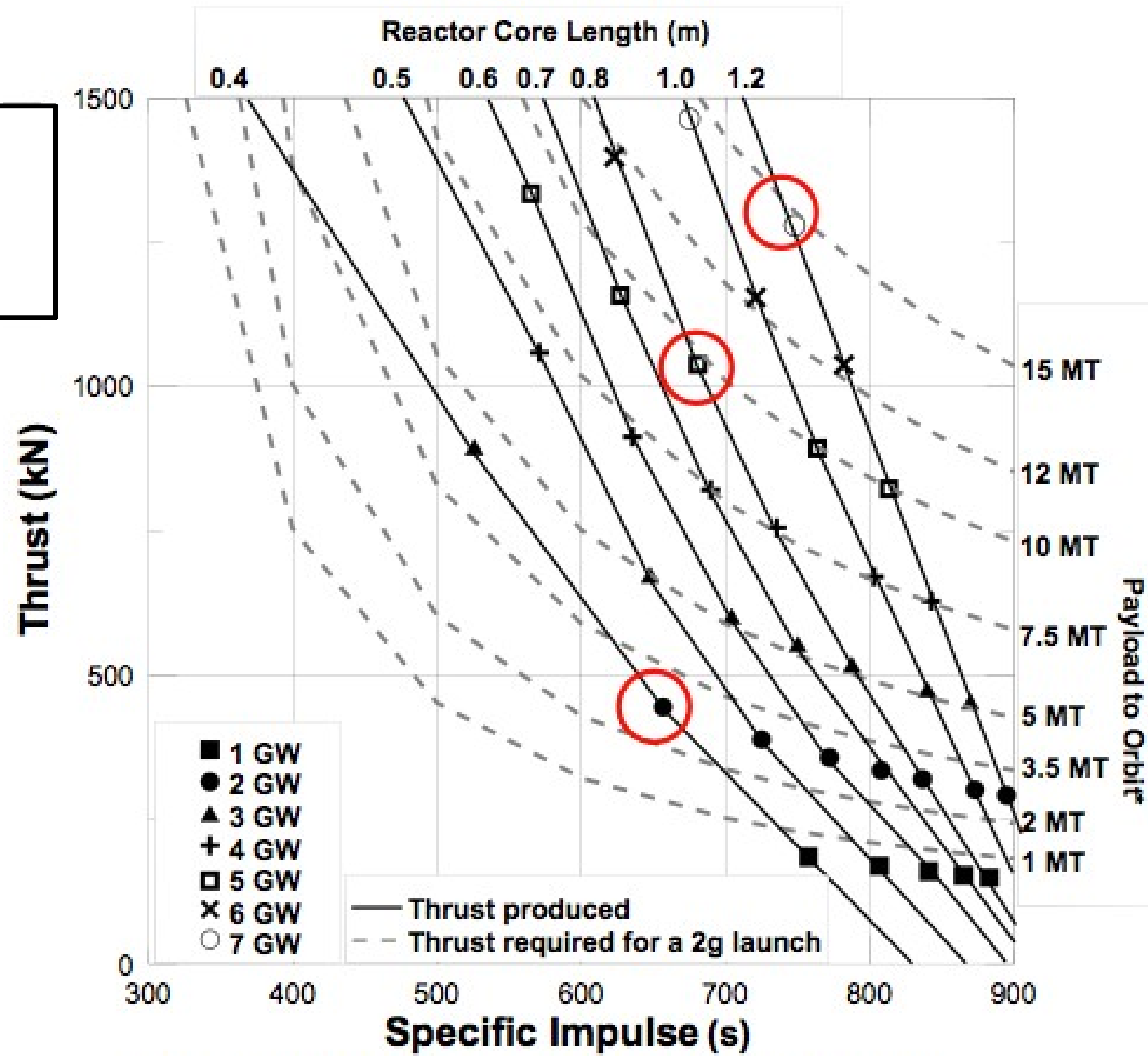
Rocket Engine Selection



*Assuming 2 MT for reactor, tankage, and support structure

Rocket Engine Selection

Selected Reactors
Payloads up to 3.5 MT: 0.4 m
Payloads 3.5 to 10 MT: 0.8 m
Payloads 10 to 15 MT: 1.2 m



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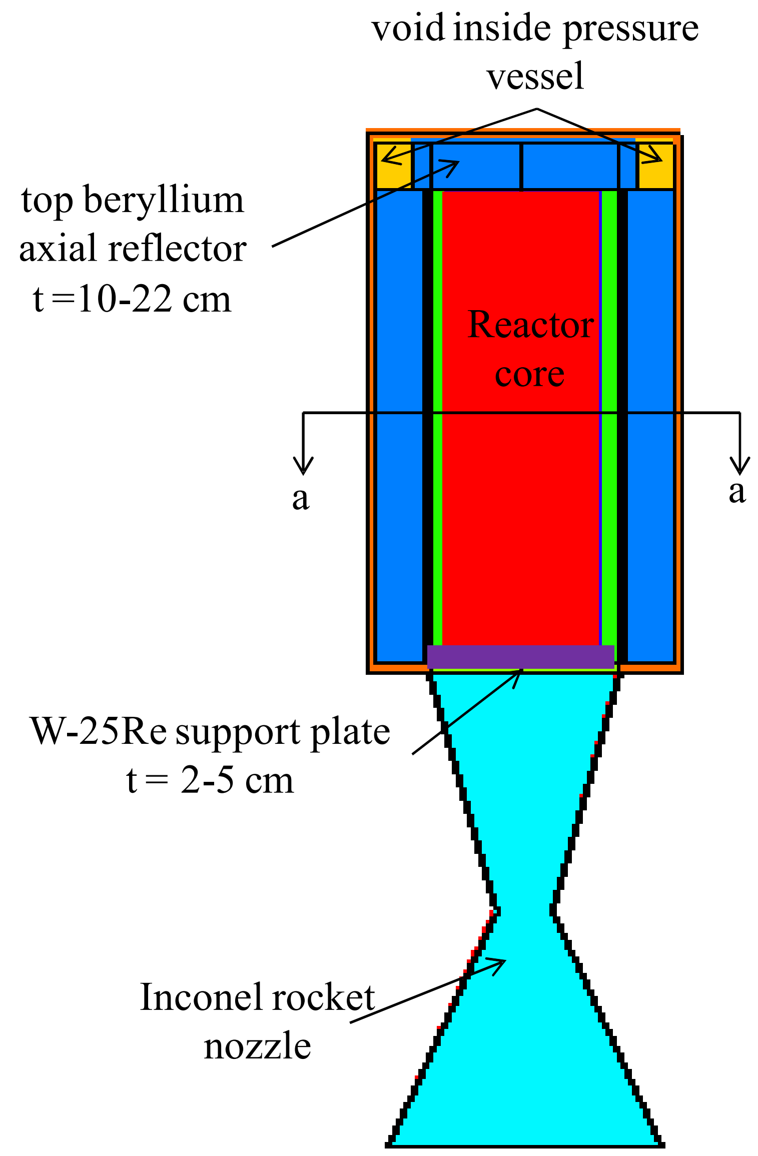
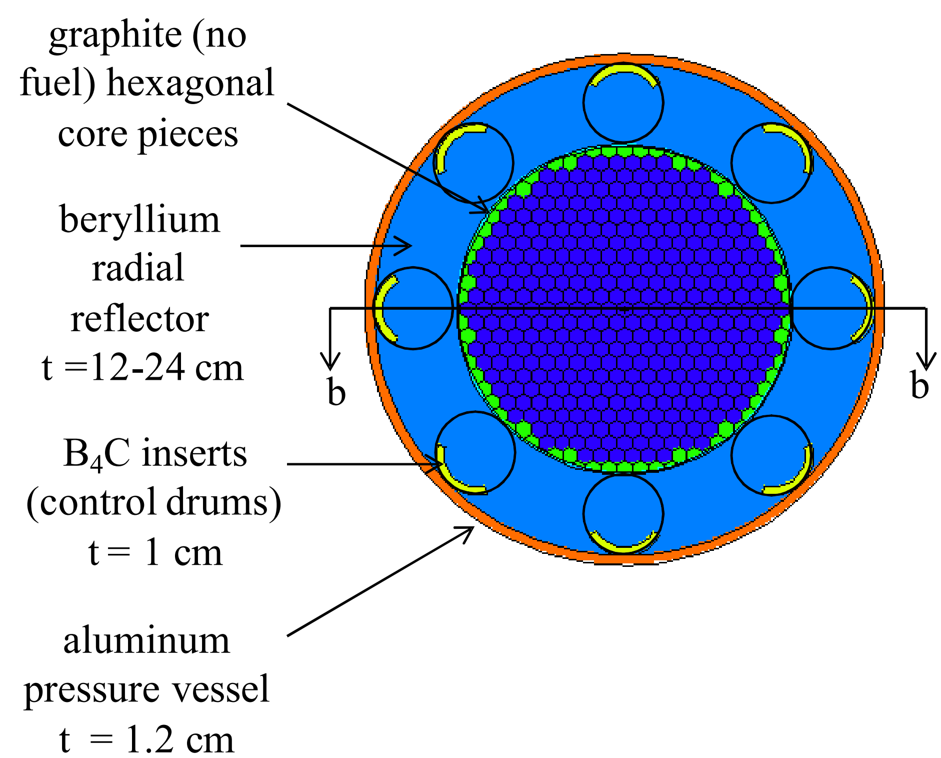
MCNP Model



a) Axial view b-b.



b) Radial view a-a.

Reactivity Requirements

- MCNP5 results determined the initial geometry of the three reactors.
  - Adjusted radial and axial reflector sizes, enrichment, and boron carbide absorber thickness.
  - Need $2 hot clean excess, $5 shutdown margin

Initial Geometry

Reactor	Radial Reflector (cm)	Top Be Axial Reflector (cm)	Bottom W-25Re Axial Reflector (cm)[1]	Enrichment (at%)	Cold Excess Reactivity[2] ($)	Hot Excess Reactivity[2] ($)	Shutdown Margin[2] ($)
40 cm	24	22	3	97	5.78	2.00	-16.95
80 cm	11	10	0	96	7.17	2.24	-5.98
120 cm	10	10	0	92	6.32	2.52	-5.16

[1]In addition to the 2 cm W-25Re support plate
[2]Assuming a delayed neutron fraction of 0.007

Submersion Criticality

- In the case of a launch abort, there is a possibility that the NTR reactor could become submerged.
- This causes a shift in the neutron energy spectrum of the reactor from fast to epithermal/thermal. This causes an increase in neutron cross-section and reactivity.
- MCNP5 evaluated the reactivity of the reactors when:
  - Submerged in seawater with and without flooded channels
  - Submerged in wet sand with and without flooded channels
  - Submerged in dry sand
- Reactor compositions and geometries were adjusted to provide $1 of submerged shutdown margin
  - GdN added to the reactor fuel in the 80 and 120 cm cases

Final Reactor Geometry

Reactor Length	Reflector	B_4C thickness (cm)	GdN (wt%)	Enrichment (at%)
40 cm	24 cm radial (Be) 22 cm top axial (Be) 3 cm axial (W-25Re)[1]	1.30	0.0	97
80 cm	14 cm radial (Be 10 cm axial (Be)	1.25	0.3	97
120 cm	12 cm radial (Be) 10 cm axial (Be)	1.25	0.6	97

[1] In addition to the 2 cm axial support plate

Launch Dose Assessment

Radiation Dose Assessment

- One of the primary goals of this study is to determine the radiation dose at various distances from the NTR launch site.
- Concern over the radiation doses resulting from the launch of an NTR is one of the major objections to a surface launched NTR.
- The radiation dose field produced by the three NTR reactors are estimated by MCNP5 models.
- Tally cards (F2) added to the MCNP models of the reactor provide dose estimates.

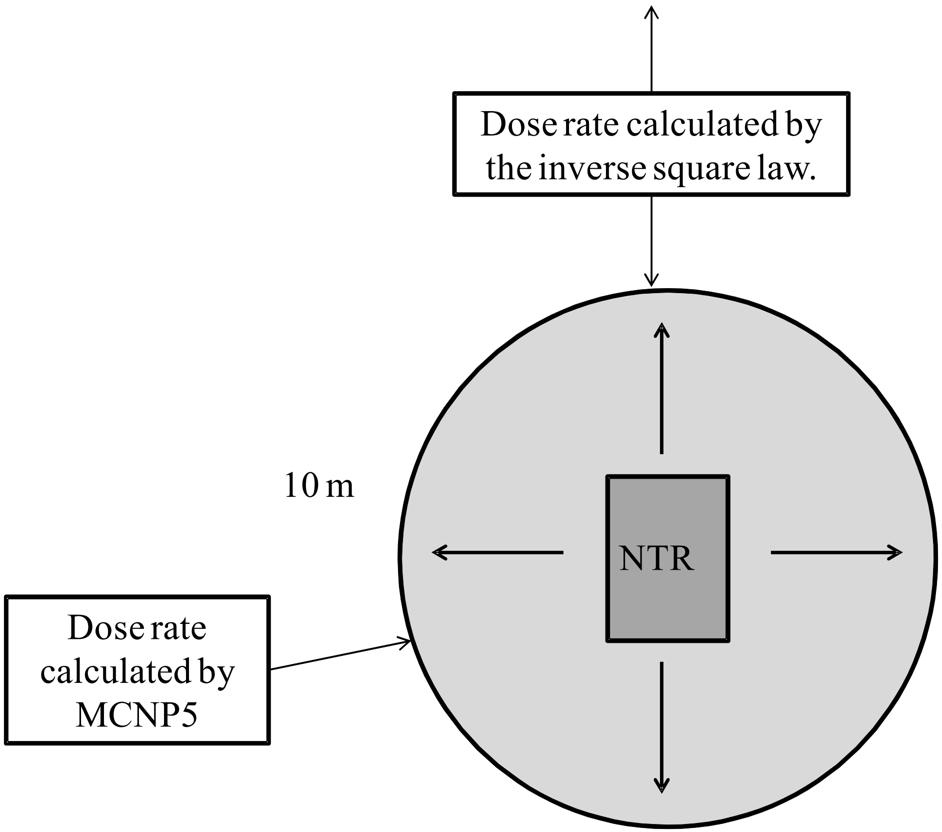
Radiation Zone Boundaries

- Radiation area boundaries in this thesis are based on the dose limits set by the Nuclear Regulatory Commission (NRC) in Subpart C (Occupational Dose Limits) of Section 10 Part 20 of the Code of Federal Regulations.

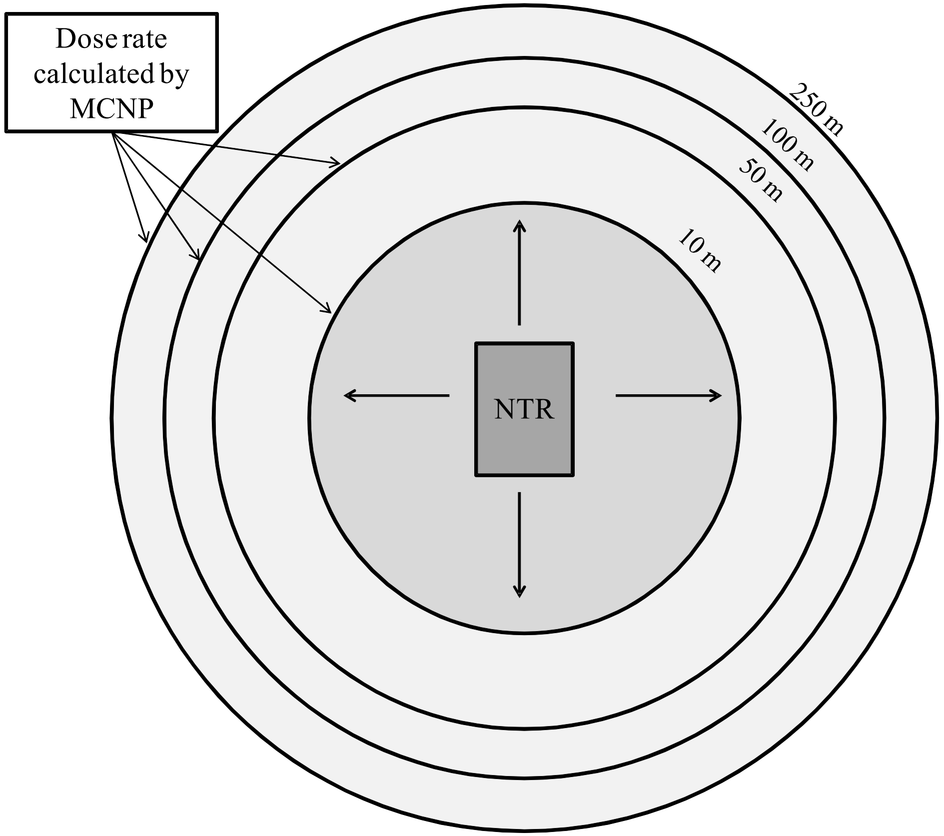
Radiation Zone	Upper Limit	Lower Limit
Very High Radiation Area	N/A	> 5 Sv/hr
High Radiation Area	5 Sv/hr	1 mSv/hr
Radiation Area	1 mSv/hr	50 µSv/hr
Controlled Area	50 µSv/hr	6.2 mSv/yr
Background	6.2 mSv/yr	N/A

Surface Tally Models

Single Sphere

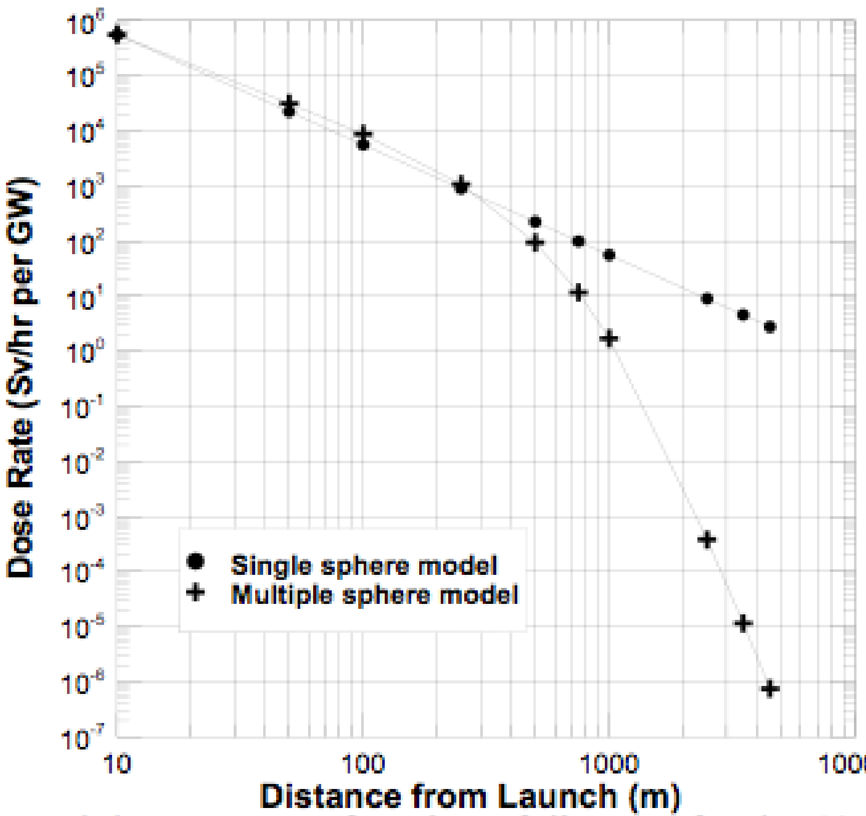


Multi-sphere

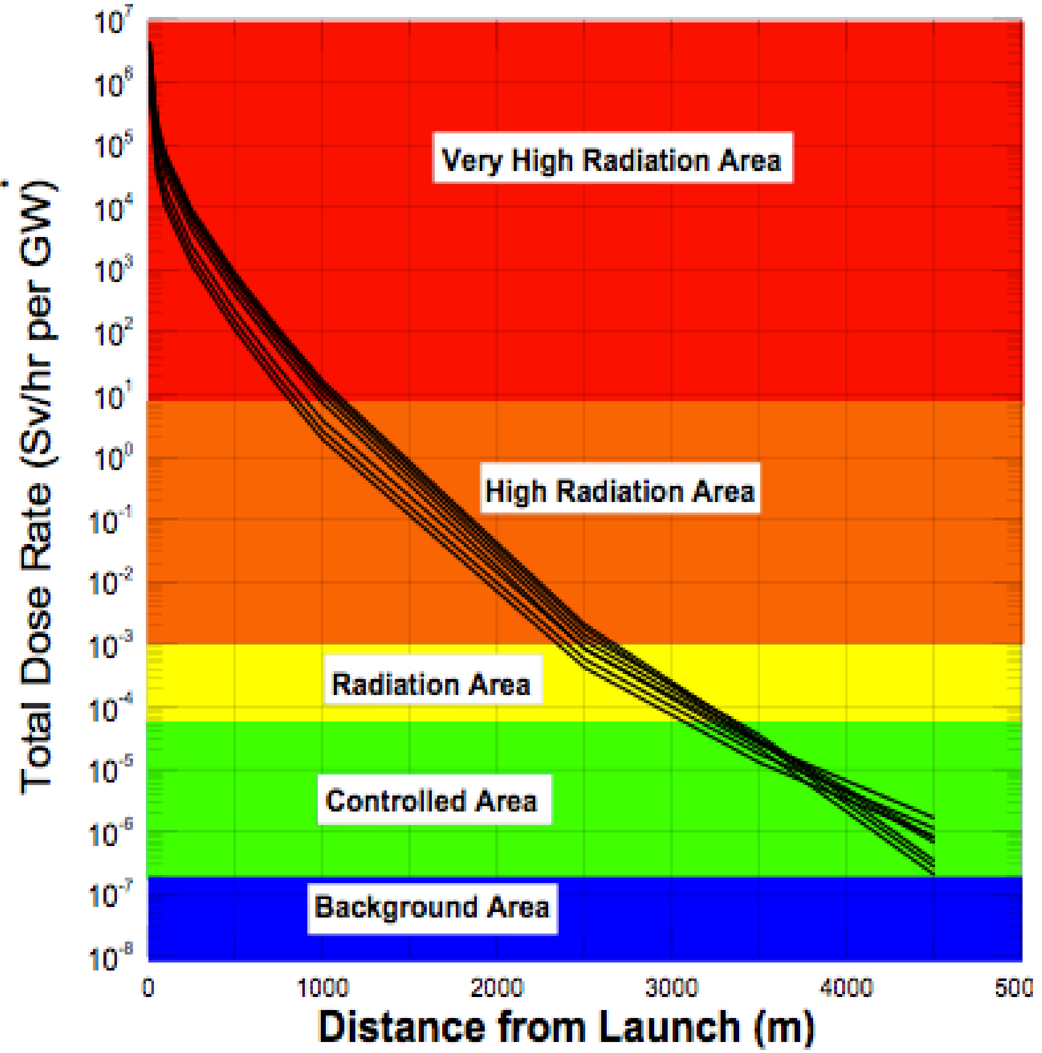


Surface Tally Dose Results

- 40 cm yields 5.60 x10^5 Sv/hr per GW at 10 m.
- 80 cm yields 6.64 x10^5 Sv/hr per GW at 10 m.
- 120 cm yields 6.27 x10^5 Sv/hr per GW at 10 m.



Total dose rate as a function of distance for the 40 cm length reactor.

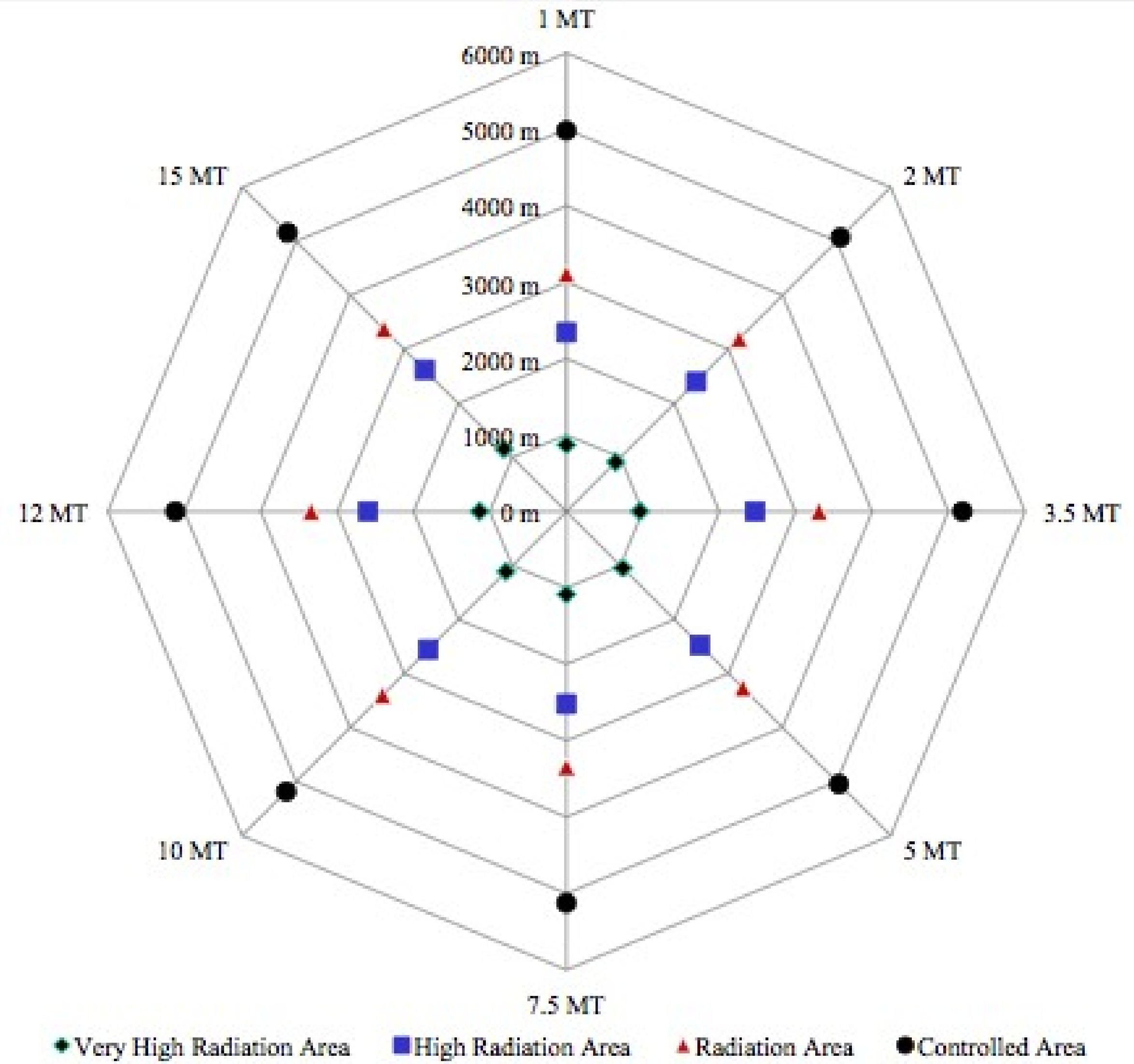


Total dose rate as a function of launch distance showing approximate distance to the radiation zone boundaries. All payloads are shown.

Predicted Radiation Zones

Reactor length	**0.4 m**	**0.4 m**	**0.4 m**	**0.8 m**	**0.8 m**	**0.8 m**	**1.2 m**	**1.2 m**
Power (GW)	**1.1**	**1.5**	**2.2**	**3.0**	**4.0**	**5.0**	**6.0**	7.0
Zone				**Distance to Outer Boundary (km)**				
Very High Radiation Area	0.87	0.91	0.96	1.05	1.09	1.11	1.13	1.15
High Radiation Area	2.35	2.40	2.47	2.47	2.52	2.56	2.59	2.62
Radiation Area	3.11	3.20	3.31	3.26	3.34	3.34	3.34	3.38
Controlled Area	4.98	5.07	5.18	5.04	5.12	5.18	5.12	5.16
Background	>4.98	>5.07	>5.18	>5.04	>5.12	>5.18	>5.12	>5.16

Radiation Zones Illustrated



Outer radiation zone boundaries for each of the rocket payloads based on the multi-sphere models.

Summary and Conclusions

Summary and Conclusions

- By developing a launch vehicle with increased specific impulse, the mass of the propellant needed to place a given mass in orbit can be greatly reduced, potentially decreasing the cost of launching material from the Earth's surface.
- The reactors described in this work, with specific impulses in excess of 700 s, could significantly reduce the propellant mass needed to place payloads in orbit.
- Three reactor sizes were chosen to deliver a range of payloads to low earth orbit:
  - A 40 cm reactor for payloads between 1 and 3.5 metric tons.
  - A 80 cm reactor for payloads between 3.5 and 10 metric tons.
  - A 120 cm reactor for payloads between 10 and 15 metric tons.

Summary and Conclusions, cont.

- The three reactors all have 40/60 vol% UN/W-25Re cermet fuel elements enriched to 97 at% U-235.
- The designed reactors meet the design reactivity requirements:
  - Hot excess reactivity of $2.
  - Shutdown margin of $5.
  - Submerged shutdown margin of $1 subcritical.
- The 80 cm and 120 cm reactors have GdN included in the fuel elements as a spectral shift absorber.
- Initial dose assessments indicate that the dose to the public at the current viewing distance at Cape Canaveral would be comparable to the U.S. background dose rate.

Acknowledgements

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Questions?