Turbopump Design and Analysis Approach for Nuclear Thermal Rockets

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Abstract. A rocket propulsion system, whether it is a chemical rocket or a nuclear thermal rocket, is fairly complex in detail but rather simple in principle. Among all the interacting parts, three components stand out: they are pumps and turbines (turbopumps), and the thrust chamber. To obtain an understanding of the overall rocket propulsion system characteristics, one starts from analyzing the interactions among these three components. It is therefore of utmost importance to be able to satisfactorily characterize the turbopump, level by level, at all phases of a vehicle design cycle. Here at NASA Glenn Research Center, as the starting phase of a rocket engine design, specifically a Nuclear Thermal Rocket Engine design, we adopted the approach of using a high level system cycle analysis code (NESS) to obtain an initial analysis of the operational characteristics of a turbopump required in the propulsion system. A set of turbopump design codes (PumpDes and TurbDes) were then executed to obtain sizing and performance characteristics of the turbopump that were consistent with the mission requirements. A set of turbopump analyses codes (PUMPA and TURBA) were applied to obtain the full performance map for each of the turbopump components; a two dimensional layout of the turbopump based on these mean line analyses was also generated. Adequacy of the turbopump conceptual design will later be determined by further analyses and evaluation. In this paper, descriptions and discussions of the aforementioned approach are provided and future outlooks are discussed.

Keywords: Turbopump; Nuclear Thermal Rocket Engine; Conceptual Design; System Analysis.

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Presented at STAIF-2006 Conference
Albuquerque, NM, February 15, 2006
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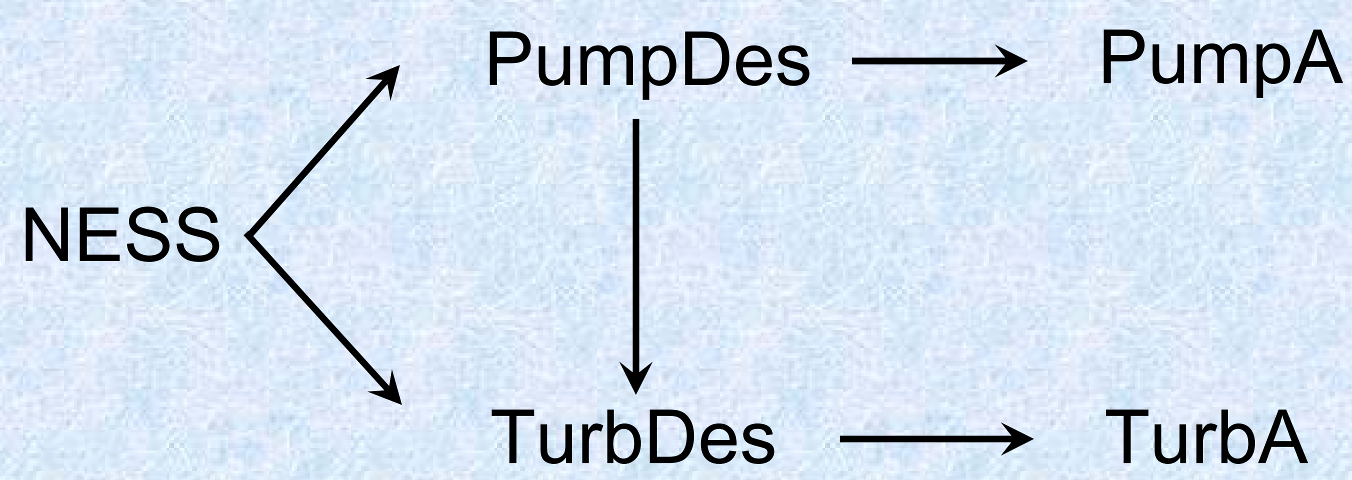
Turbopump Design Methodology Data Flow

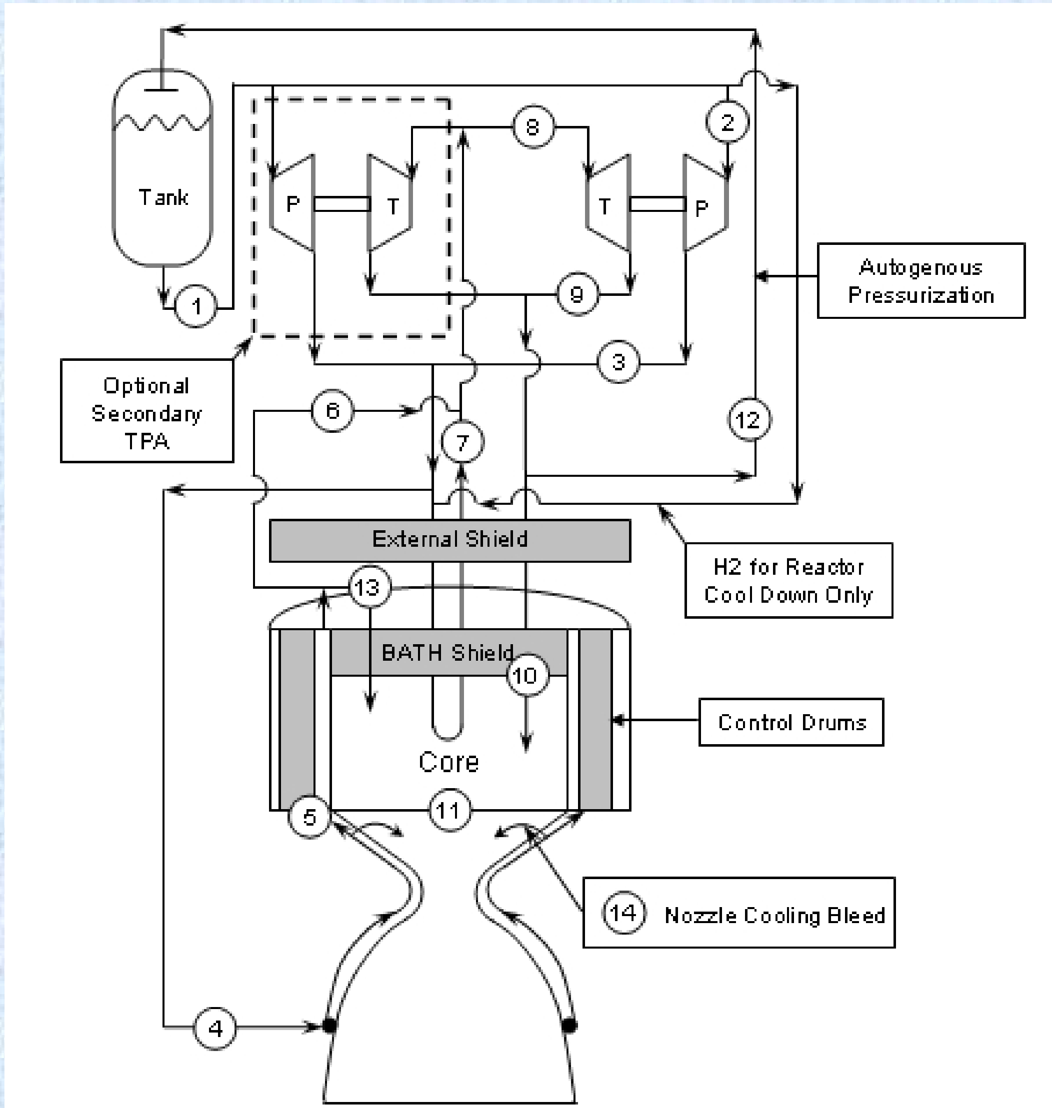


NESS (Nuclear Engine System Simulation) Code Features and Capabilities

- Developed by NASA/LeRC, SAIC, and Westinghouse in early 1990's to support ongoing and future studies of NERVA-based NTR engine system and stage design efforts
- NESS is based on the Expanded Liquid Engine Simulation (ELES) program modified to include solid-core reactor design models
- Westinghouse (responsible for the reactor subsystem during the NERVA program) provided reactor design models for a near-term NERVA-derived system (ENABLER I) and an upgraded version of this engine (ENABLER II)
- NESS can model expander, gas generator and bleed cycles, along with multi-redundant propellant pump feed systems
- Turbomachinery design options include multistage axial and traditional centrifugal pumps
- NESS is used for rapid, preliminary detailed design analysis of both the reactor and key engine subsystems. The code designs the reactor, turbomachinery, tankage, nozzle, lines and valves in terms of both weight and performance/operating characteristics

NESS Expander Cycle Flow Path

(Enabler 1)



NESS Turbopump Design Features

- Design both Axial Pumps (20 stages Max) or Centrifugal Pumps (4 stages Max w/ Inducer)
- Maximum Allowable Tip Speed of 457.2m/s for Hydrogen
- Pump and Inducer have the Same RPM
- Pumps Staged by Specific Speed (~3200 for Axial and ~800 for Centrifugal)
- Designs a Partial Admission Turbine if Blade Height < 0.762cm
- Turbine is RPM Limited to Avoid Unrealistic Designs
- Turbine is Staged if Inlet Mach Number >1.7 or if Specific Speed is Below Minimum
- Efficiency Curves Based on Empirical Data

Key NESS Turbopump Values

Inputs:

- Pump Type (Axial or Centrifugal)
- Turbine Bypass Fraction
- TPA Configuration (Multiple or Single)
- Fraction of Design Thrust for Loss of Turbo-pump
- Specific Suction Speed

Outputs:

- Pump and Turbine Performance (On and Off Design)
- Number of Stages, Including Inducer
- Mass Flow Rate, Temperature, and Pressure Schedules
- Detailed Reactor Subsystem Mass Break Down

NESS System Inputs Summary

- Expander Cycle
- Enabler-I (Increased Computational Design Space)
- 2700K Chamber Temperature
- 6894.75kPa Chamber Pressure
- 300:1 Nozzle Area Ratio
- 66.7kN and 111.2kN Thrust Levels
- Single Centrifugal Pump
- Pump and Turbine on Common Shaft
- Centrifugal Pump (Specific Suction Speed of 20,000)
- Regenerative Nozzle Cooling to an Area Ratio of 25:1

NESS Pump Design Outputs

Thrust Level (kN)	66.72	111.2
Pressure Rise (MPa)	11.49	11.64
RPM	30937	23967
Suction Specific Speed	20000	20000
Number of Stages	3	3
NPSP (kPa)	34.47	534.47
Mass Flow Rate (kg/s)	7.53	12.56
Shaft Work (kW)	1809.1	3057.6
Efficiency	68.30%	68.20%
Diameter (cm)	19.53	25.35
Weight (N)	392.87	678.93

NESS Turbine Design Outputs

Thrust Level (kN)	66.72	111.2
Pressure Drop (MPa)	2.0567	2.2063
Temperature Drop (K)	27.7	27.8
Specific Speed	48	46
RPM	30937	23967
Number of Stages	2	2
Mass Flow Rate (kg/s)	6.273	10.564
Pressure Ratio	1.274	1.294
Efficiency	70%	70%
Diameter (cm)	15.8	20.42
Weight (N)	172.2	269.2

PumpDes Pump Design Code

- Station-by-Station Mean Line Code
- Estimates Hydraulic Losses Along the Flow Path (Fully Developed Internal Flow based on Empirical and Semi-Empirical Data)
- Flow Assumed to be in Thermodynamic Local Quasi-Equilibrium
- Empirical and Semi-Empirical Flow Path Losses
- Can Perform Inverse Design and Constrained Optimization
- Axial Inducer and Centrifugal Models are Functionally Integrated
- Real Gas Properties
- Validated Against the P&W ATDLH2, MK15-O, and MK48-O Pumps

PumpDes NTR Pump Characteristics

Thrust Level (kN)	66.72	111.2
Fluid	LH2	LH2
Overall Efficiency	82.60%	82.10%
Shaft Work (kW)	1698.7	2874.6
Number of Stages	1 + 3(Cent.)	1 + 3(Cent.)
Inlet Pressure (KPa)	139.27	139.27
Inlet Temperature (K)	20.39	20.39
Inlet Tip Diameter (cm)	9.37	11.5
Inlet Hub Diameter (cm)	6.09	6.91

PumpDes NTR Pump Specifications

	Axial Inducer		First Pump Stage	
Thrust Level (kN)	66.72	111.2	66.72	111.2
Blade Number	3	3	8/16	8/16
BETA2 (Deg)	21.5	23.0	48.0	50.0
Chord Length (cm)	11.96	14.22	-	-
Tip Diameter (cm)	-	-	18.28	23.75
Tip Span (cm)	-	-	0.521	0.620
Blade Axial Length (cm)	-	-	2.733	3.708
Wrap Angle (Deg)	164	161	100	95
Stage Pressure Rise (kPa)	208.91	196.50	3763.2	3813.5
Inlet NPSP	60.01	59.87	357.84	335.09
Cavitation Index* (kPa)	-51.34	-43.17	+160.65	+153.06

*Note: Cavitation Index is defined as: NPSP_available – NPSP_required.

PumpDes NTR Pump Specifications (Cont.)

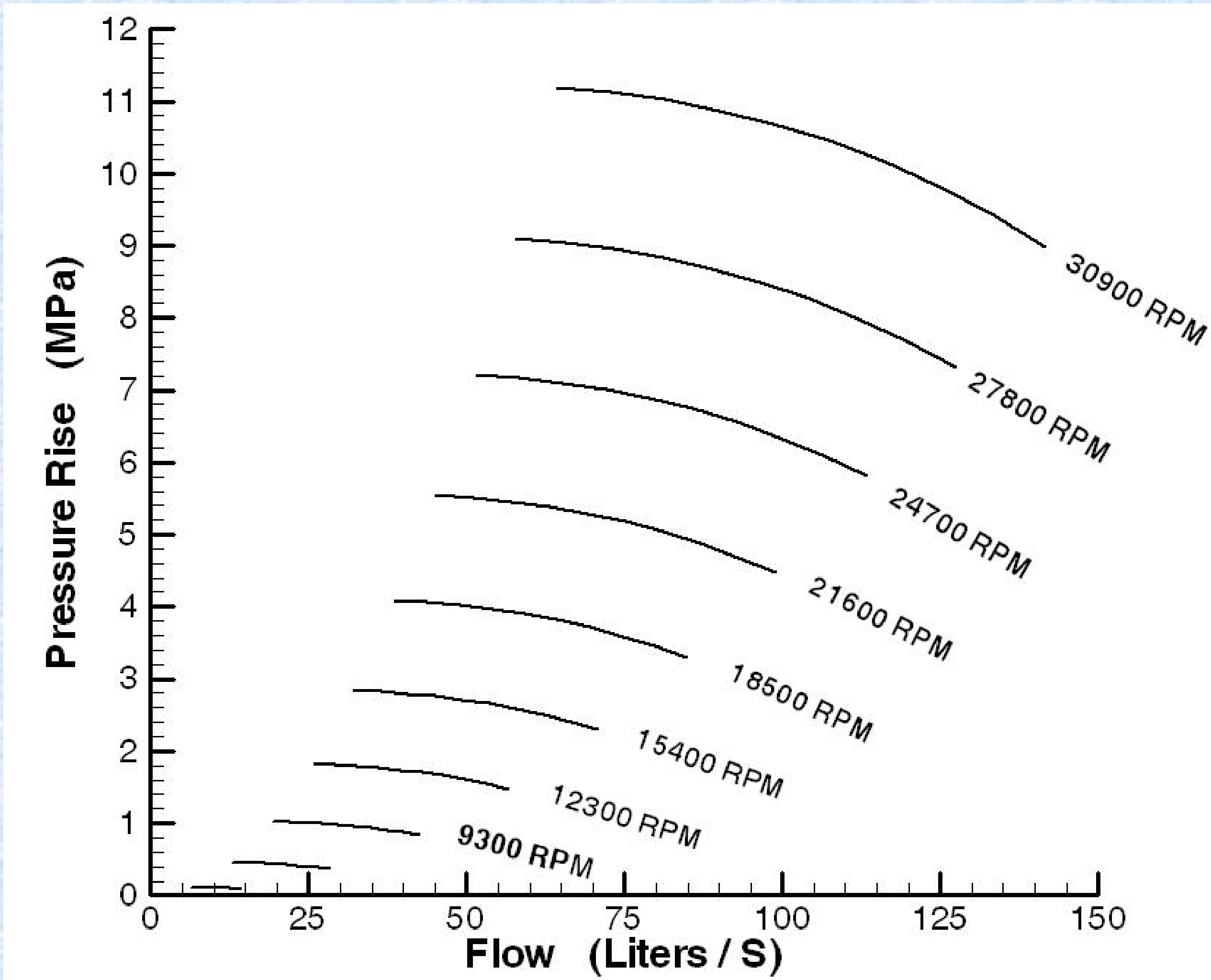
	Second Pump Stage		Third Pump Stage	
Thrust Level (kN)	66.72	111.2	66.72	111.2
Blade Number	6/12	6/12	8/16	9/18
BETA2 (Deg)	38.0	41.0	48.0	54.0
Tip Diameter (cm)	18.56	23.97	19.25	24.35
Tip Span (cm)	0.490	0.589	0.282	0.356
Blade Axial Length (cm)	2.764	3.731	2.837	3.772
Wrap Angle (Deg)	124	116	100	86
Stage Pressure Rise (kPa)	3763.2	3813.5	3763.2	3813.5
Inlet NPSP	High	High	Very High	Very High
Cavitation Index	Redundant	Redundant	Redundant	Redundant

PUMPA Pump Analysis Code

- Utilizes Mean Line Modeling Method to Model Off-Design Pump Performance
- Empirical Correlations used to Model:
  - Off-Design Efficiency
  - Slip Factor
  - Diffuser Pressure Recovery
- PUMPA Can Model:
  - Axial, Centrifugal, and Multistage Pumps
  - Inducers (Including Mixed Flow)
- Real Gas Properties Obtained from GASPLUS

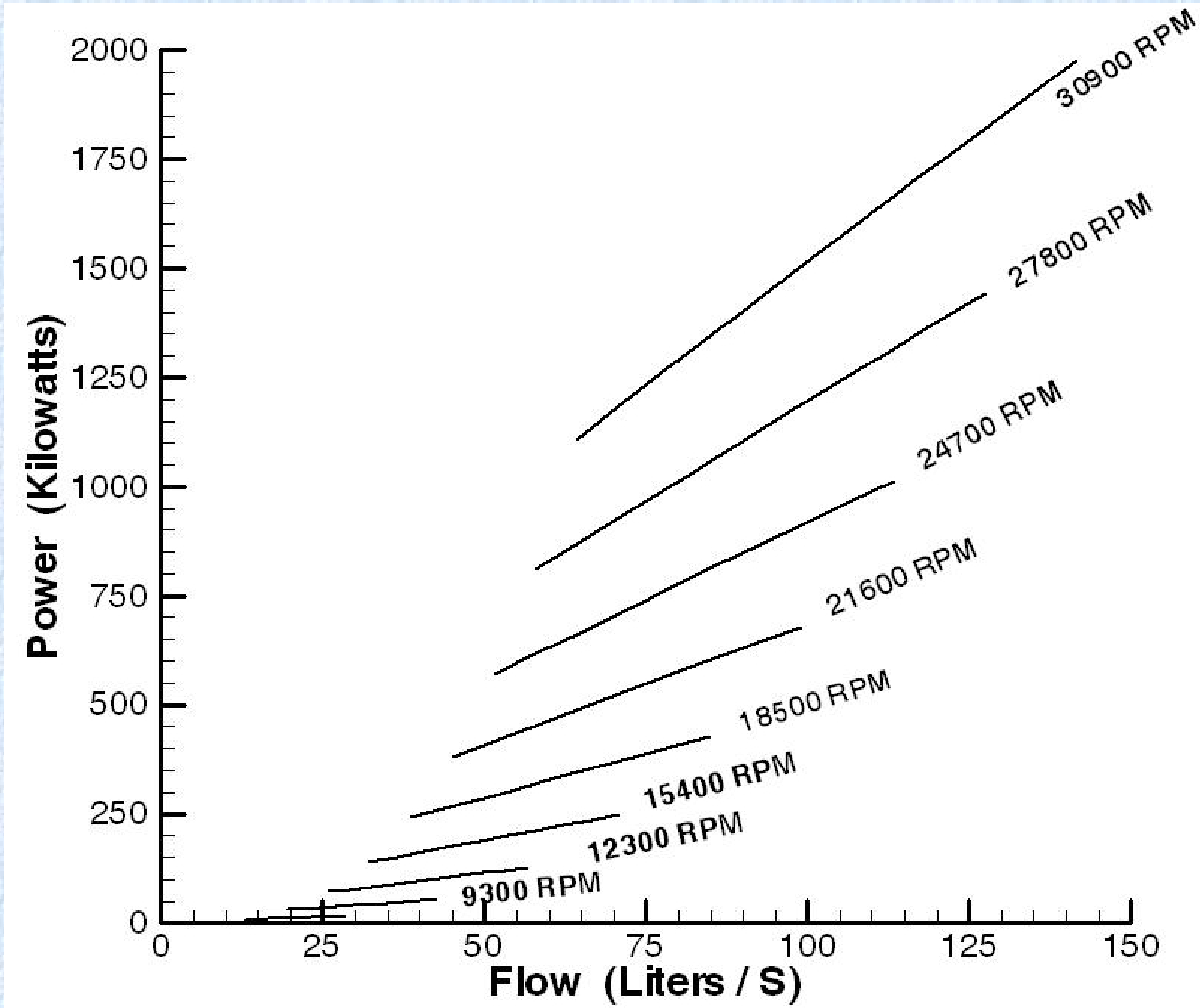
PUMPA NTR Pump Performance Map

(Pressure Rise vs. Volumetric Flow Rate)



PUMPA NTR Pump Performance Map (Cont.)

(Power Required vs. Volumetric Flow Rate)



TurbDes Turbine Design Code

- Axial Flow Turbine Design Code
- Designs Multiple Turbine Types:
  - Partial Admission (Single Stage Only)
  - Full Admission Impulse (Single or Dual Stages)
  - Full Admission 50% Reaction (Single or Dual Stages)
- Utilizes Empirical Correlations for both Geometric Layout and Loss Estimates
- Different Data Sources and Loss Evaluation Rational for Each Turbine Type
- Real Gas Effects

Thermodynamic Characteristics of 50% Reaction Turbines for NTR

Thrust Level (kN)	66.72	111.2
Fluid	H2	H2
Overall Efficiency (T-to-S)	86.60%	87.00%
Work Output (kW)	1698.7	2874.7
Inlet Pressure (kPa)	8416.4	8493.7
Inlet Temp. (K)	354	332.9
Exit Pressure (kPa)	6839.6	6812
Exit Temp. (K)	336.1	315
Pressure Ratio (T-to-S)	1.236	1.252
Tip Speed (m/s)	344.12	340.46
U/C	0.392	0.384

Geometric Characteristics of 50% Reaction Turbines for NTR

Thrust Level	66.72	111.2
Number of Stages	2	2
1st Nozzle Inflow Angle (Deg)	90	90
1st Nozzle Exit Angle (Deg)	18	16
Mean Diameter (cm)	19.16	24.22
First Rotor Blade Height (cm)	1.93	2.67
Second Rotor Blade Height (cm)	2.08	2.9

Thermodynamic Characteristics of Impulse Turbines Designed for NTR

Thrust Level (kN)	66.72	111.2
Fluid	H2	H2
Overall Efficiency (T-to-S)	63.6%	65.5%
Work Output (kW)	1698.7	2874.7
Inlet Pressure (kPa)	8416.4	8493.7
Inlet Temp. (K)	345.0	332.9
Exit Pressure (kPa)	6350.1	6329.4
Exit Temp. (K)	335.6	314.4
Pressure Ratio (T-to-S)	1.339	1.353
Tip Speed (m/s)	227.99	229.21
U/C	0.219	0.224

Geometric Characteristics Impulse Turbines for NTR

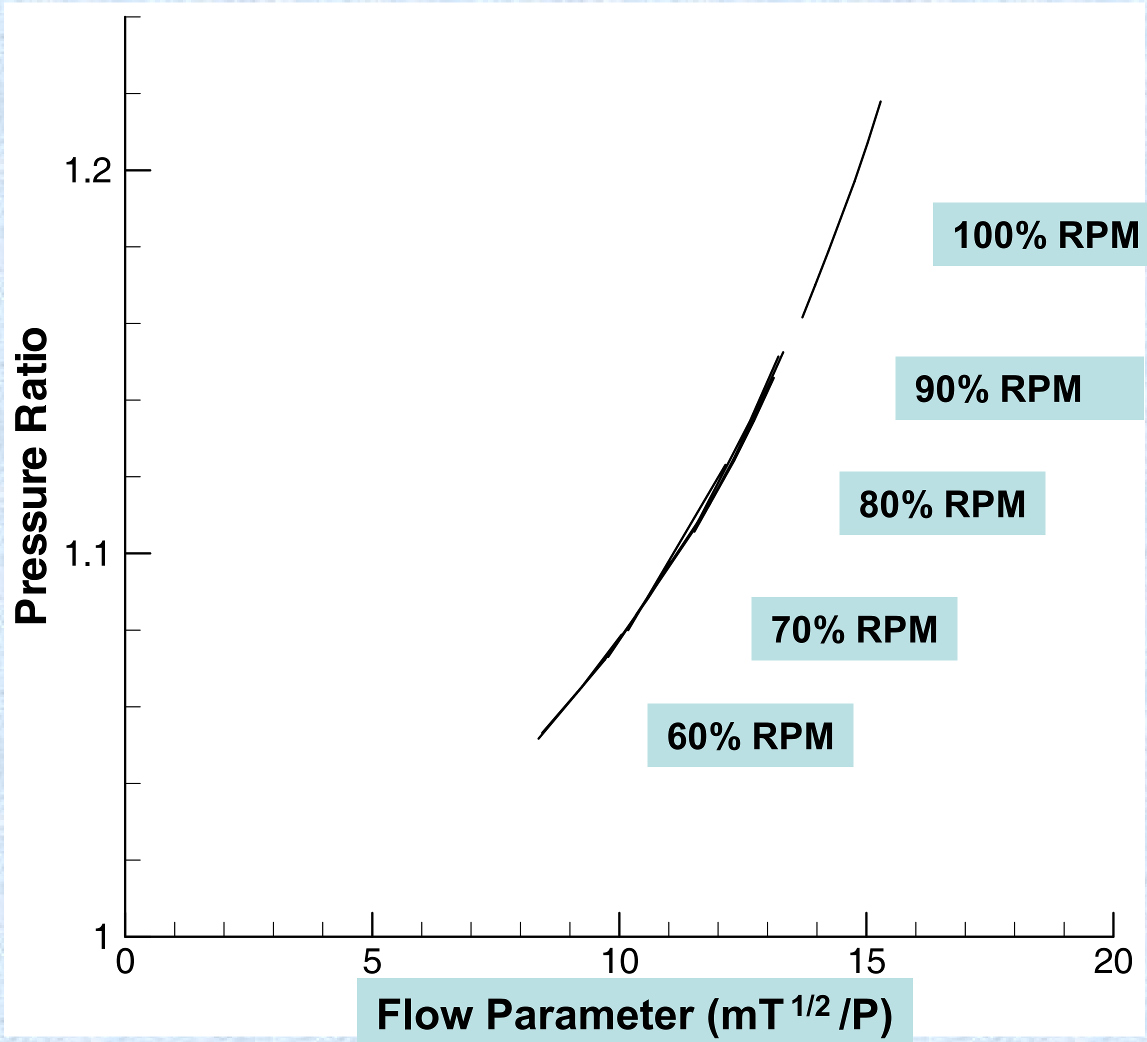
Thrust Level	66.72	111.2
Number of Stages	2	2
1st Nozzle Inflow Angle (Deg)	90	90
1st Nozzle Exit Angle (Deg)	18	16
Mean Diameter (cm)	12.49	16.27
First Rotor Blade Height (cm)	1.52	1.90
Second Rotor Blade Height (cm)	1.58	2.00

TURBA Turbine Analysis Code

- Utilizes Meal Line Flow Modeling
- Obtains Design Point Performance and Generates Characteristic Maps
- Empirically Derived Correlations From Existing Engines and Test Rigs
- Design Point Obtained from Correlations of Efficiency to Spouting Velocity Ratio
- Off-Design Efficiency Obtained from Empirical Data Normalized Relative to Design
- Flow Conditions Calculated at Tip, Hub, and Mean Line
- Real Gas Properties from GASPLUS

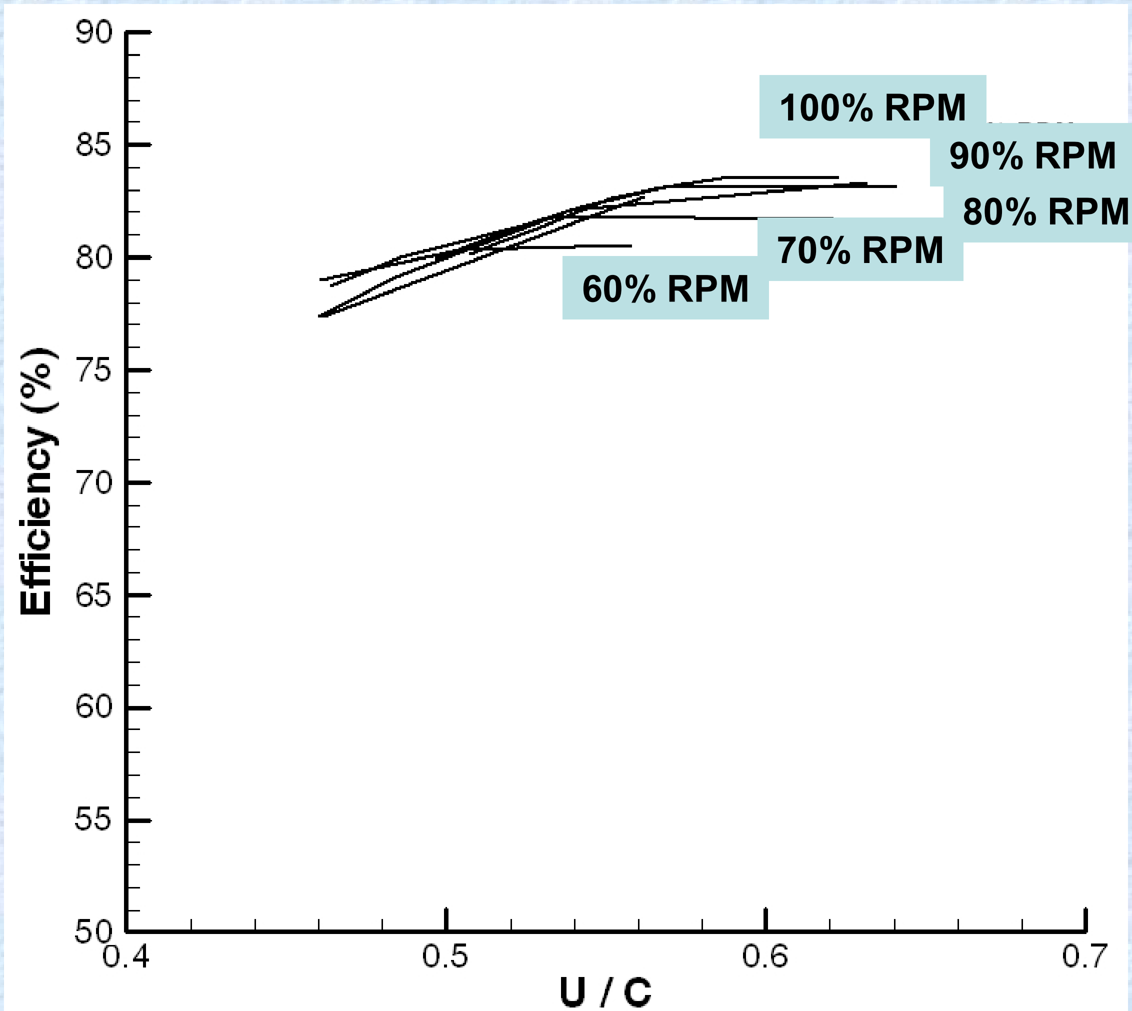
Two-Stage NTR Turbine Performance

(Turbine Pressure Ratio vs. Flow Parameter)

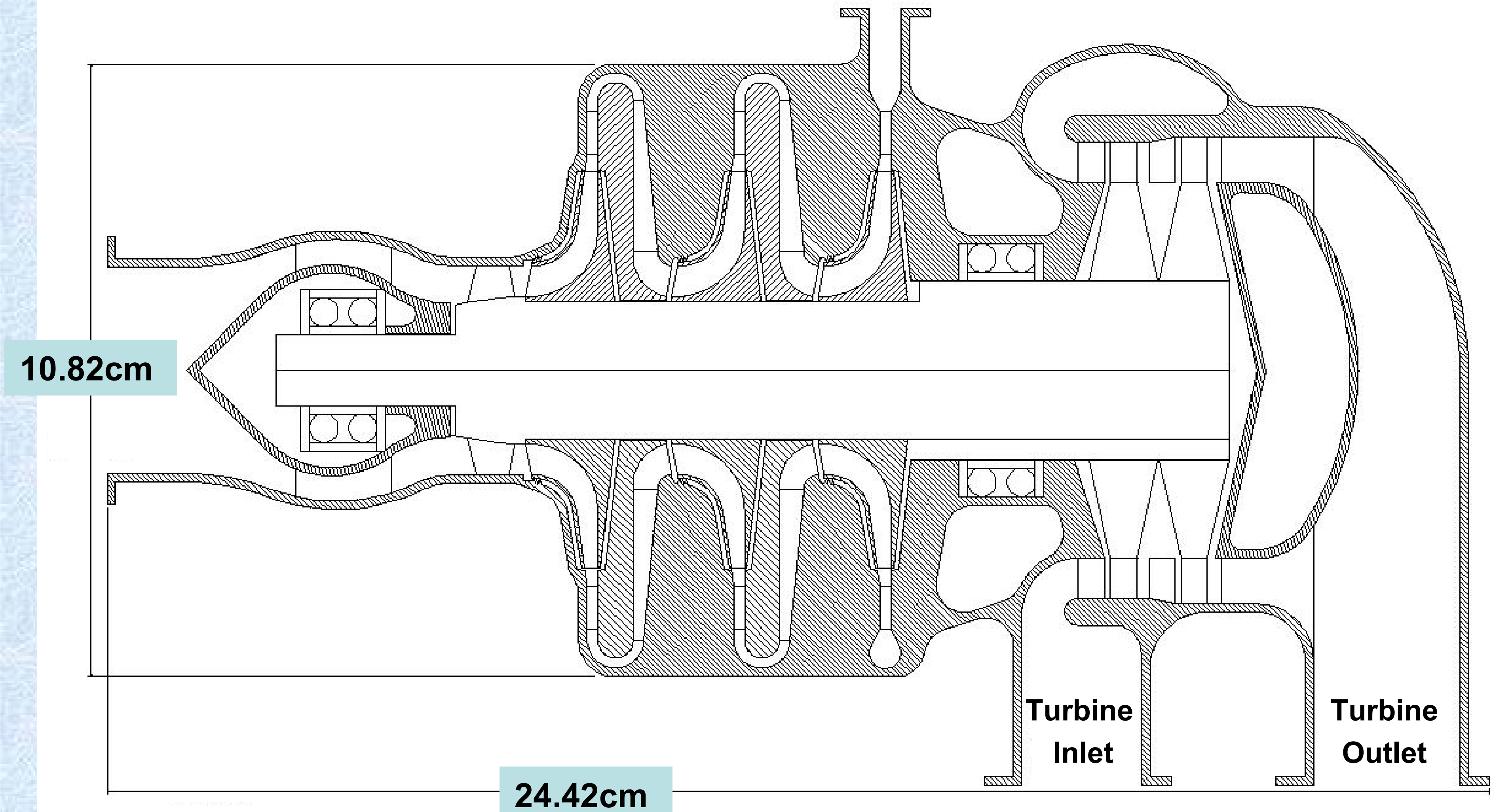


Two-Stage NTR Turbine Performance Cont.

(Turbine Efficiency vs. Spouting Velocity Ratio)



Conceptual Design of the Liquid Hydrogen Turbopump for the 66.72kN Thrust NTR



Summary

- A Sequence for NTR TPA Design and Analysis has been Utilized and Presented
- Design Point Performance and Off-Design Performance Maps for both the Pump and Turbine were Calculated
- Initial Conceptual Design of TPA’s for a 66.7kN and 111.2kN Thrust NTR Engine have been Completed
- For Further Information About PumpDes, PUMPA, TurbDes, or TURBA see NASA/TM-2005-214004

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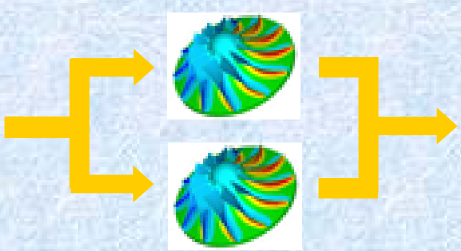
Back-up Charts

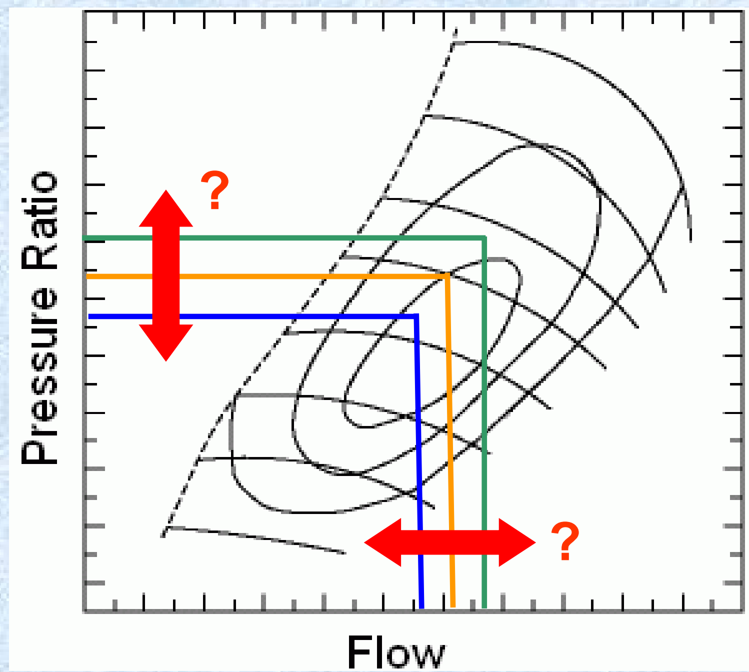
Single vs. Dual Turbo-Pump Assemblies

- Single TPA
  - Single Point of Failure
  - Simpler Design and Integration

- Dual TPA
  - More Robust System
  - More Complex Design and Integration



- Dual TPA Integration Issues
  - What Thrust Level During Pump-Out Scenario?
  - Operate TPA at Design or Off-Design?

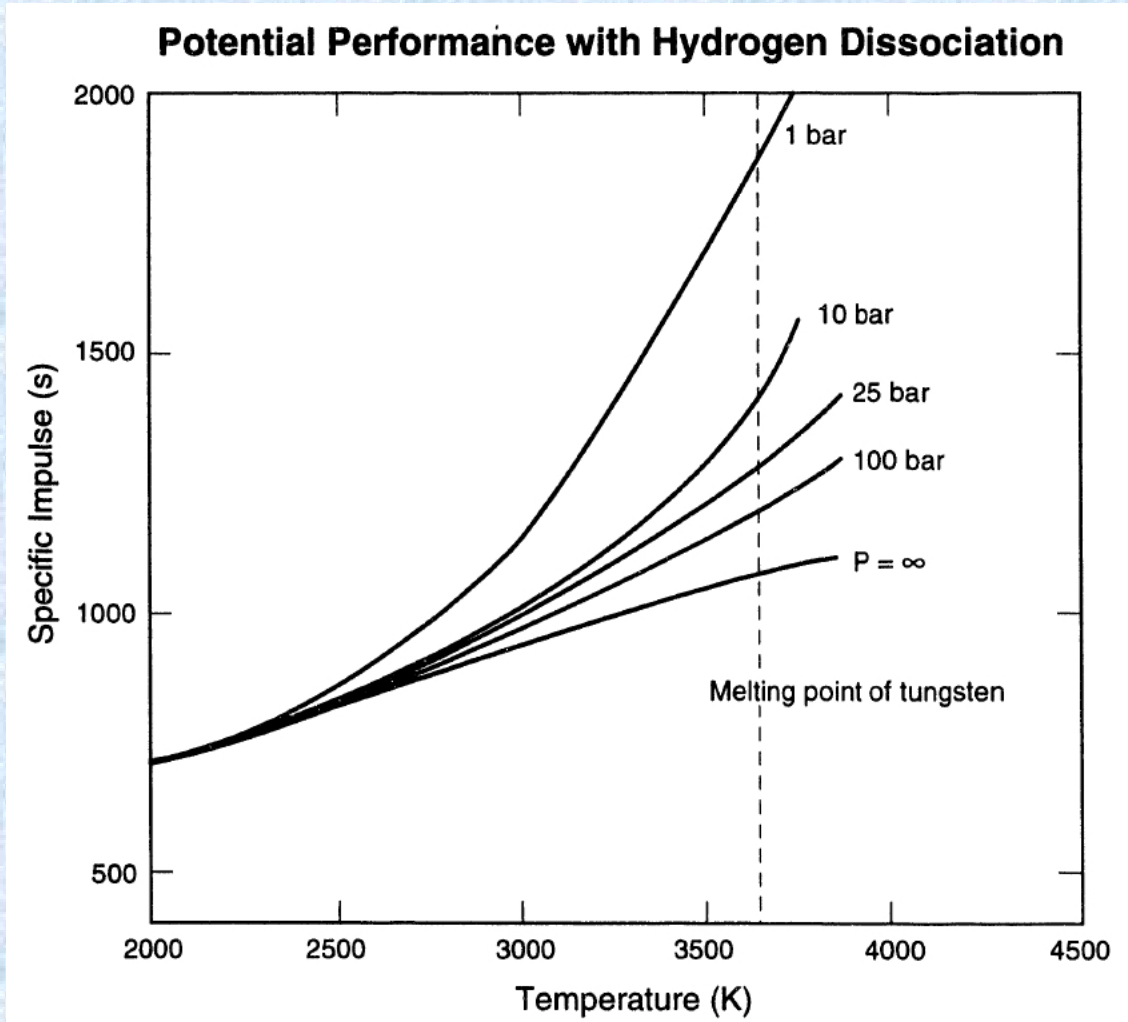


NESS (Nuclear Engine System Simulation) Code Features and Capabilities (Cont.)

- NESS can model expander, gas generator and bleed cycles, along with multi-redundant propellant pump feed systems
- Turbomachinery design options include multistage axial and traditional centrifugal pumps
- Key code outputs include reactor operating characteristics and weights, as well as, the engine subsystem parameters including performance, weights, dimensions, pressures, temperatures, specific impulse (Isp) values, LH2 mass flows, and turbopump operating characteristics for both nominal and off-design operating conditions
- NESS is written in standard FORTRAN
- NESS hydrogen properties package was recently upgraded from tabular lookups to GASPLUS

Hydrogen Dissociation

- ISP ~ (Tc/Mw)^0.5
- Potential Performance Increase with Hydrogen Dissociation
- Lower Pressure and Higher Temperature Allow for Dissociation
- NTR System Size and Mass Tend to Increase with Lower Pc



ROVER/NERVA Program Achievements

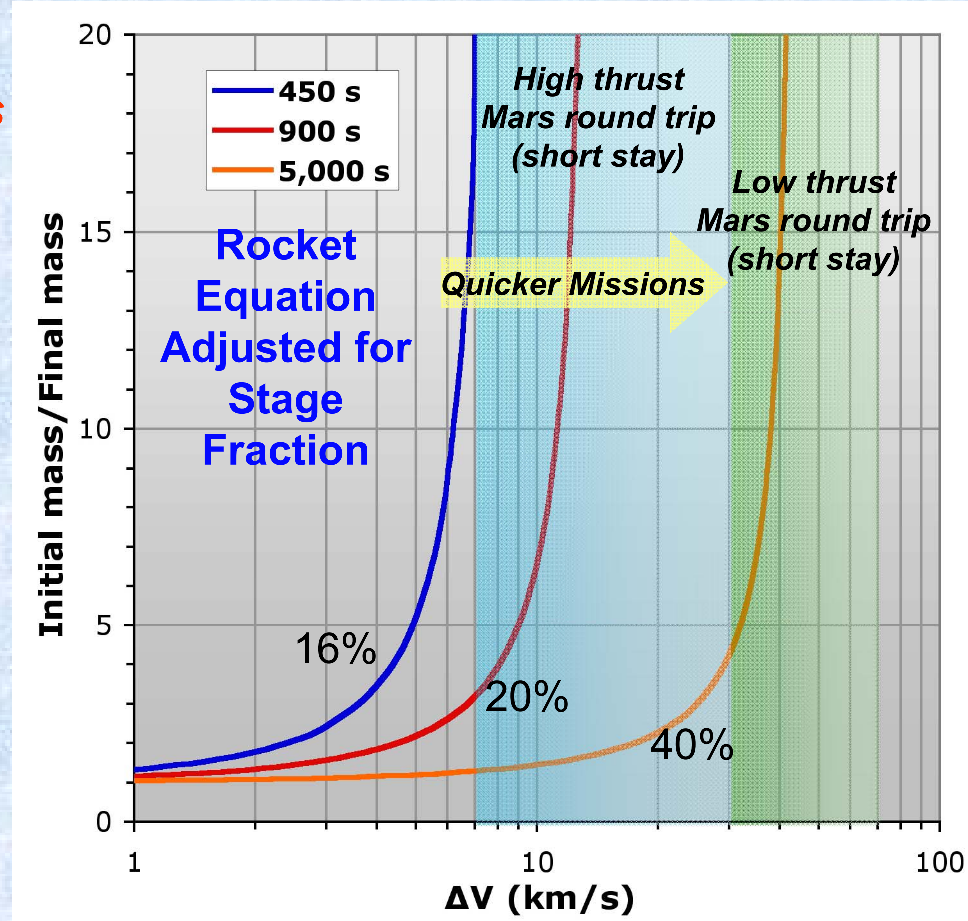
- Biggest: Phoebus 2 with 4086 elements (4100MW Thermal)
- Highest Thrust: Phoebus 2A with 930 kN
- Highest Propellant Flow Rate: Phoebus2A with 120kg/s
- Highest ISP: Pewee with 838s
- Minimum Reactor Specific Mass: Phoebus 2A at 2.3kg/MW
- Smallest: Nuclear Furnace with 49 Elements (44MW Thermal)
- Hottest: Pewee with 2550K Exit Gas and a 2750K Fuel Temp.
- Longest Lived: Nuclear Furnace at 109min
- Highest Power Density: Pewee with 1.3 MW/Fuel Element 5200 MW/M3 (Fuel)

Why NTP Enables Faster Missions

Typical Attributes:	LOX/LH_2	NTP
Specific Impulse	*420–460 s*	***800–950 s***
Thrust/Weight	*50–70*	*3–6*
Exhaust Temperature	*3000 K+*	*~2700 K*

For the same payload mass, high ISP allows:

- Much lower propellant mass for the same ΔV / trip time
- Much higher ΔV / faster trip time for same propellant mass
- Or a balance of both benefits



Typical NTR Vehicle Design