

# System Mass Variation and Entropy Generation in 100-kWe Closed-Brayton-Cycle Space Power Systems

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**Abstract.** State-of-the-art closed-Brayton-cycle (CBC) space power systems were modeled to study performance trends in a trade space characteristic of interplanetary orbiters. For working-fluid molar masses of 48.6, 39.9 and 11.9 kg/kmol, peak system pressures of 1.38 and 3.0 MPa and compressor pressure ratios ranging from 1.6 to 2.4, total system masses were estimated. System mass increased as peak operating pressure increased for all compressor pressure ratios and molar mass values examined. Minimum mass point comparison between 72% He at 1.38 MPa peak and 94% He at 3.0 MPa peak showed an increase in system mass of 14%. Converter flow loop entropy generation rates were calculated for 1.38 and 3.0 MPa peak pressure cases. Physical system behavior was approximated using a pedigreed NASA-Glenn modeling code, Closed Cycle Engine Program (CCEP), which included realistic performance prediction for heat exchangers, radiators and turbomachinery.

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Presented at the 21<sup>st</sup> Symposium on Space Nuclear Power and Propulsion  
Space Technology and Applications International Forum (STAIF)  
Albuquerque, New Mexico USA  
February 8-11, 2004

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# Acknowledgment

Project Prometheus, NASA's Nuclear Systems Program, supported the work described within this paper, in whole or part, as part of the program's technology development and evaluation activities. Any opinions expressed are those of the authors and do not necessarily reflect the views of Project Prometheus or the JIMO Project.



# Outline

- Introduction
- Method
- CBC PCS Physical Model Description
- Case Definition
  - Baseline
  - Variations
- Results
- Conclusions

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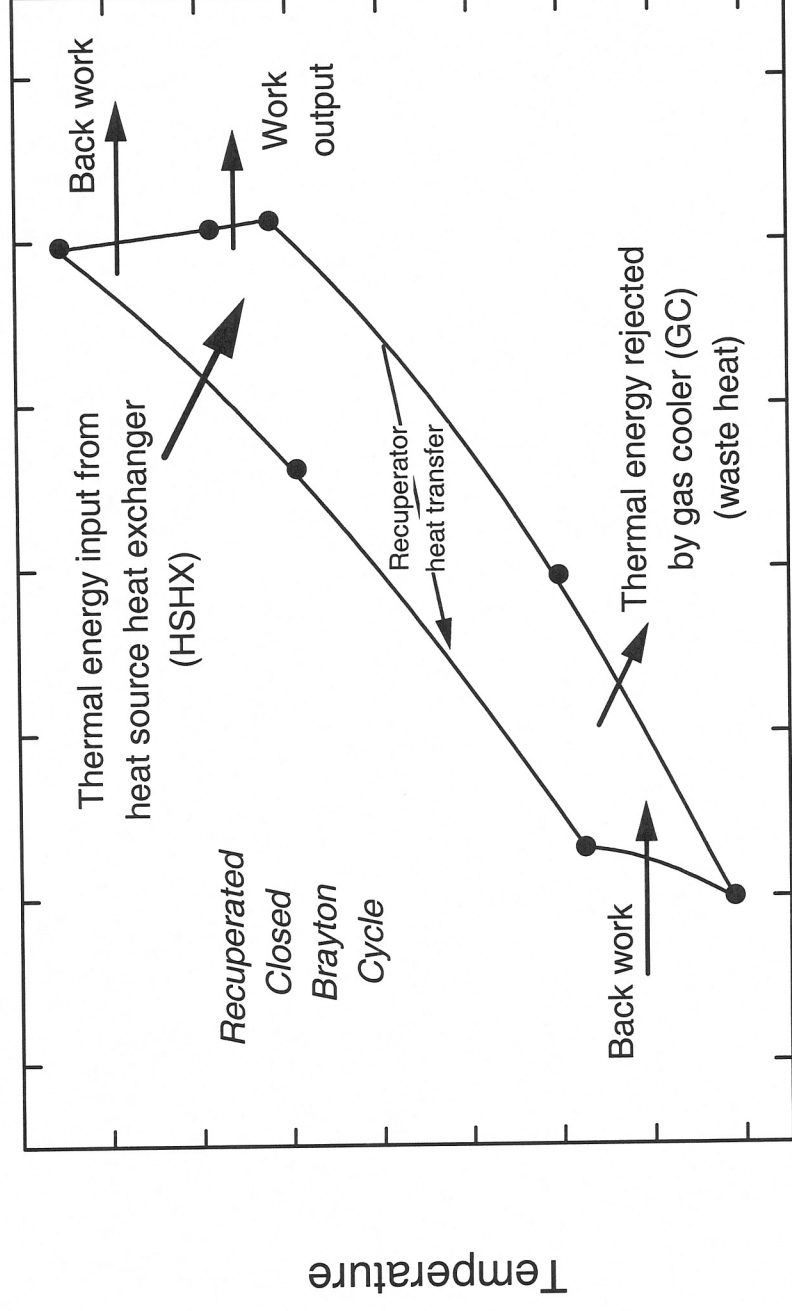


# Introduction

- Safe nuclear space power systems enable enhanced science missions to the outer planets (low solar flux destinations)
- Potential mission scenarios using 100-kWe-class systems are being studied
- Closed Brayton cycle conversion is one available power option



# Closed Brayton Cycle T-s Diagram



Specific entropy

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# Brayton Converter Turbo-alternator-compressor (TAC)



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# Method

## Numerical Tool

- **CCEP: Integrated CBC PCS modeling code developed at NASA-GRC used to evaluate system performance and architecture**
  - FORTRAN code
  - Progressively developed versions in use since early 1980's
  - Used to model solar-dynamic and nuclear-based CBC space systems
  - Originally developed as major revision to the Navy/NASA Engine Program (NNEP) – aircraft gas-turbine code
- **CCEP integrates subsystem models for reactor, converter, PMAD and HRS**
  - Detailed control of each subsystem configuration permitted (e.g., radiator model has 35 controllable inputs)
  - Optimization scheme enables automatic manipulation of user-specified parameters

## Investigative Approach

- “Conventional-technology” CBC PCS modeled
- Baseline reference case selected
- Case variants generated by varying peak system pressure, compressor pressure ratio (CPR), and working fluid composition (MW)
- Electrical output, radiator sink temp & turbine inlet temp held constant
- Results compared to baseline to illustrate relative trends

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# CBC PCS Physical Model Description

- **CBC PCS model parameters represent “state-of-the-art” technology**
  - Advanced materials and technology may be needed to support future missions
  - General “conventional-technology” results meaningful to advanced-technology systems
  - Observations can suggest critical technology-development focus areas
- **Configuration**
  - Nickel-based superalloys as converter hot-section materials
  - LM-cooled reactor (some cycle-driven implications still relevant to other reactors)
  - Single-stage centrifugal compressor; single-stage radial turbine
  - Integrated turbine-alternator-compressor (TAC); single rotating shaft; gas-foil bearings
  - Constant electrical load maintained using control electronics and parasitic load radiator
  - He-Xe working fluid; composition varies with molar mass
  - Ducts sized for allowed  $\Delta P$ ; wall thicknesses from max hoop stress with 2.0 safety factor
  - Metallic counterflow heat exchangers (Recup, GC); HSHX part of reactor module
  - Al honeycomb/face-sheet radiator (panel similar to ISS PV radr); n-heptane pumped loop
- **Model represents single-string CBC converter with single pumped loop in HRS**
  - Zero-redundancy system to evaluate fundamental mass trends in most basic system
  - Actual flight system would need to meet flight project redundancy requirements

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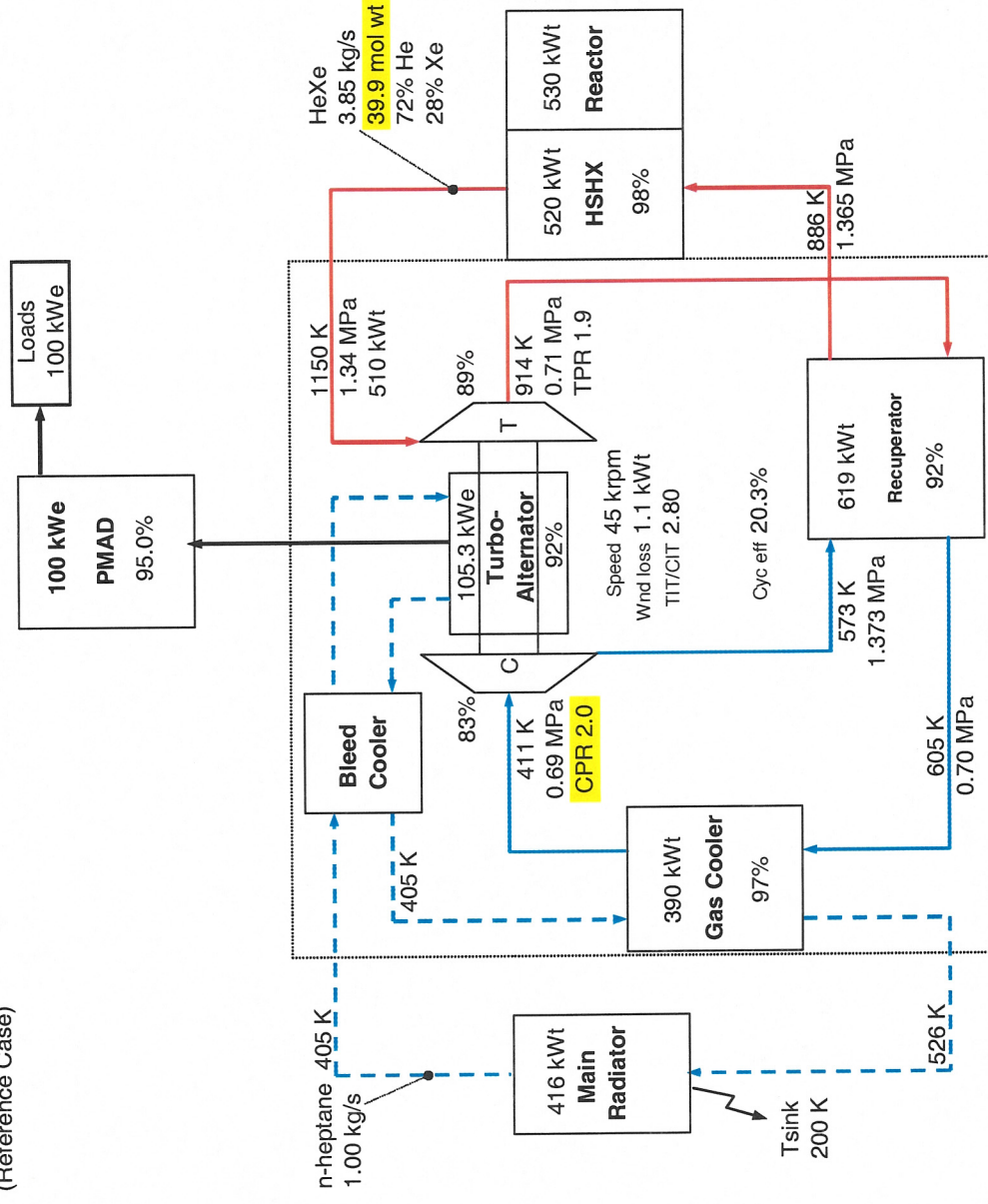
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Baseline @ 1.38 Mpa  
(Reference Case)





# Case Variations

Variations in  $P_{\text{peak}}$ , CPR and MW were evaluated

- Peak pressures: 1.38 and 3.0 MPa
- CPR: 1.6 to 2.4
- MW: 39.9 kg/kmol (72% He by volume)  
48.55 kg/kmol (65% He)  
11.9 kg/kmol (94% He)

## NOTE

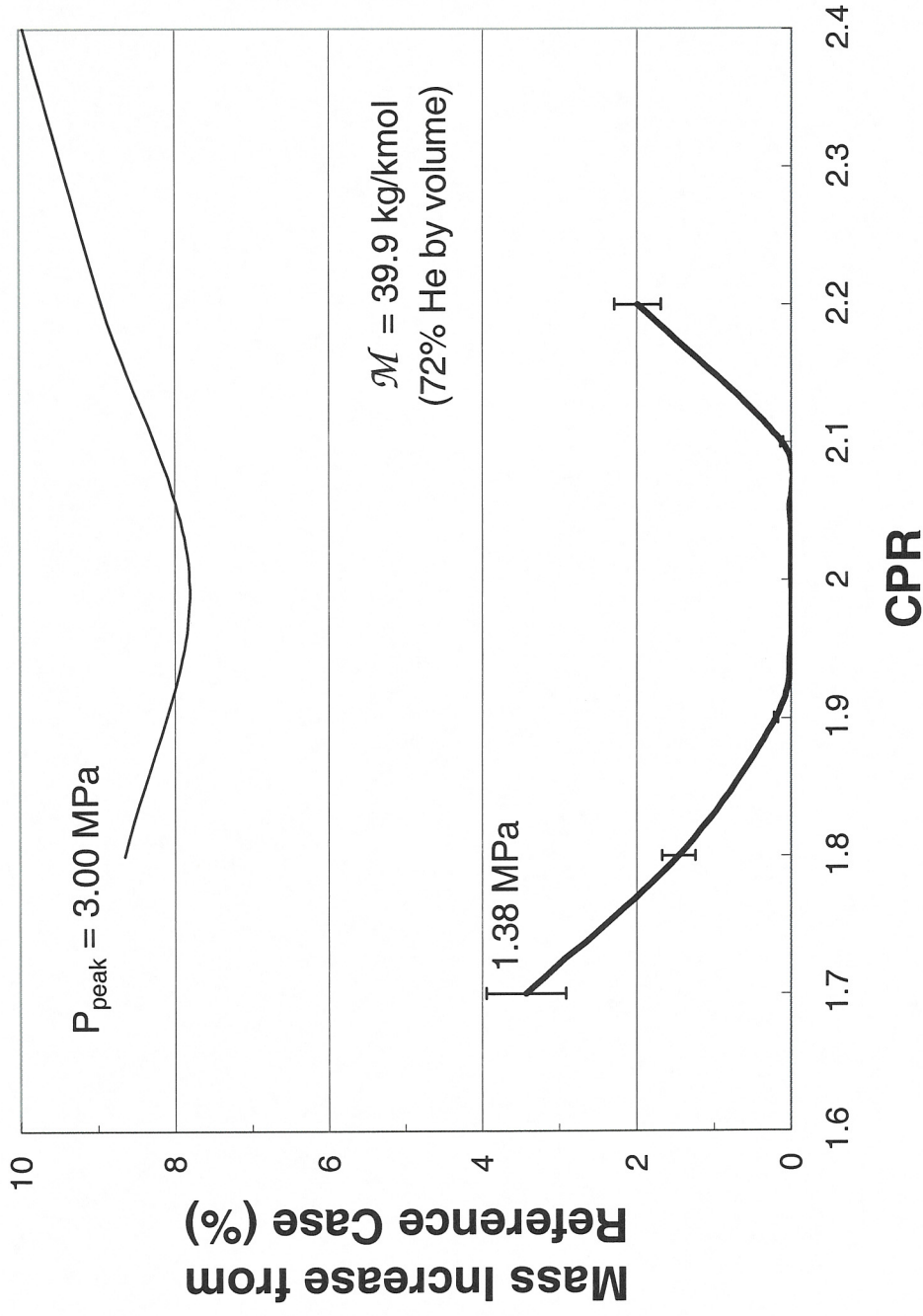
Because of the thermal power ranges involved, the maximum estimated mass variation of the reactor subsystem is only 0.07% of the baseline total system mass. (Reactor mass is effectively the same in all cases examined.)

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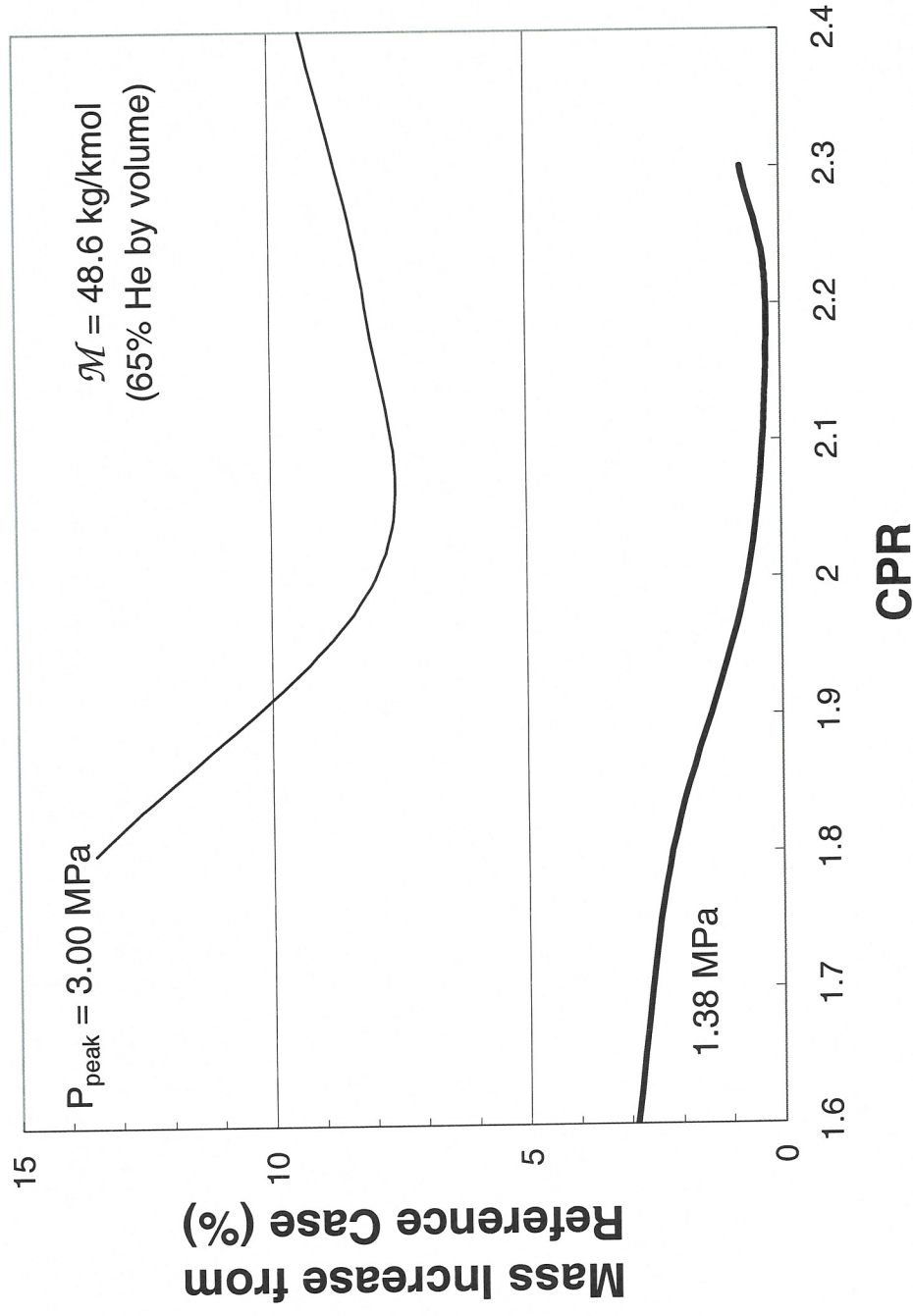


# Mass Dependence for $MW = 39.9$

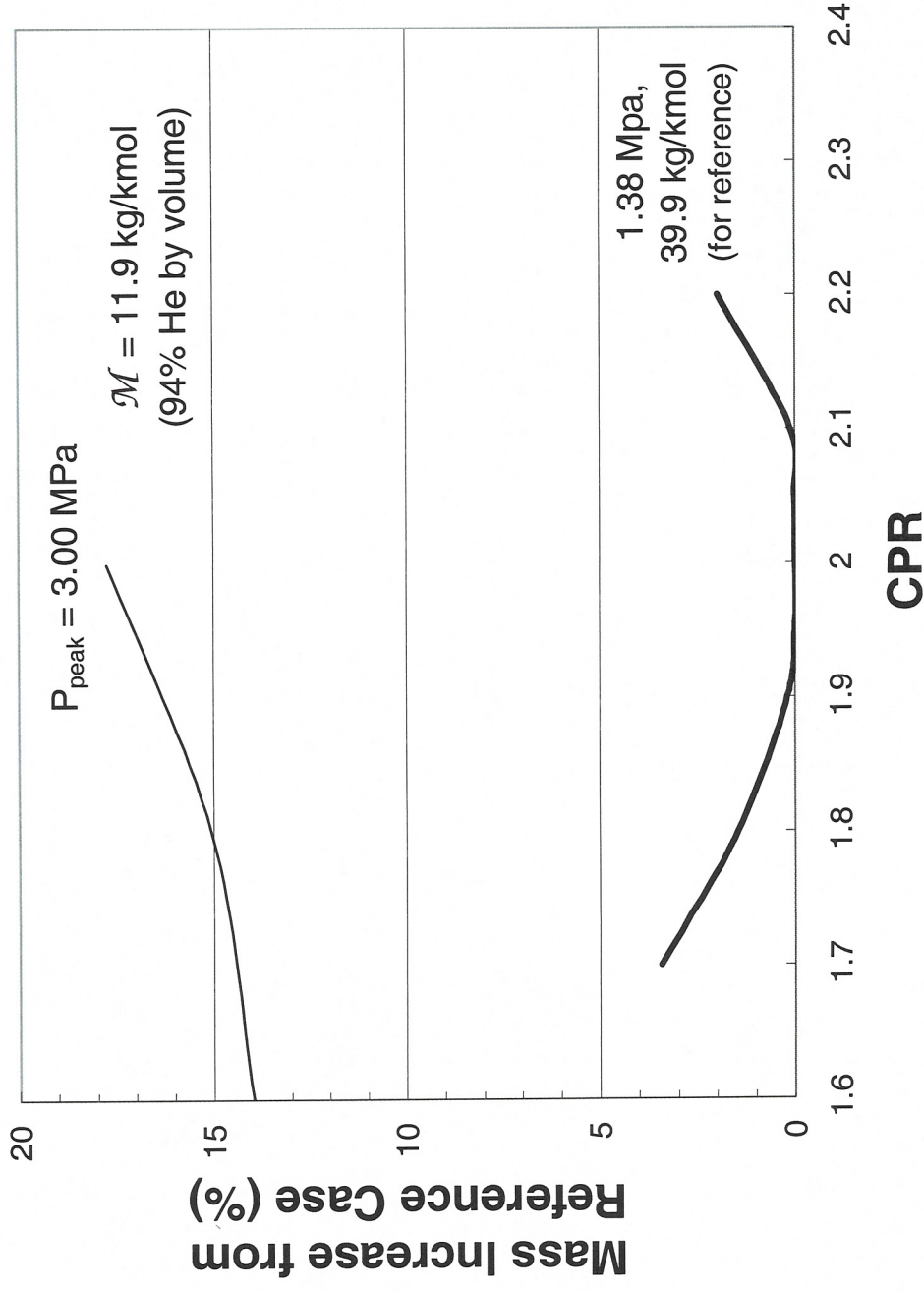




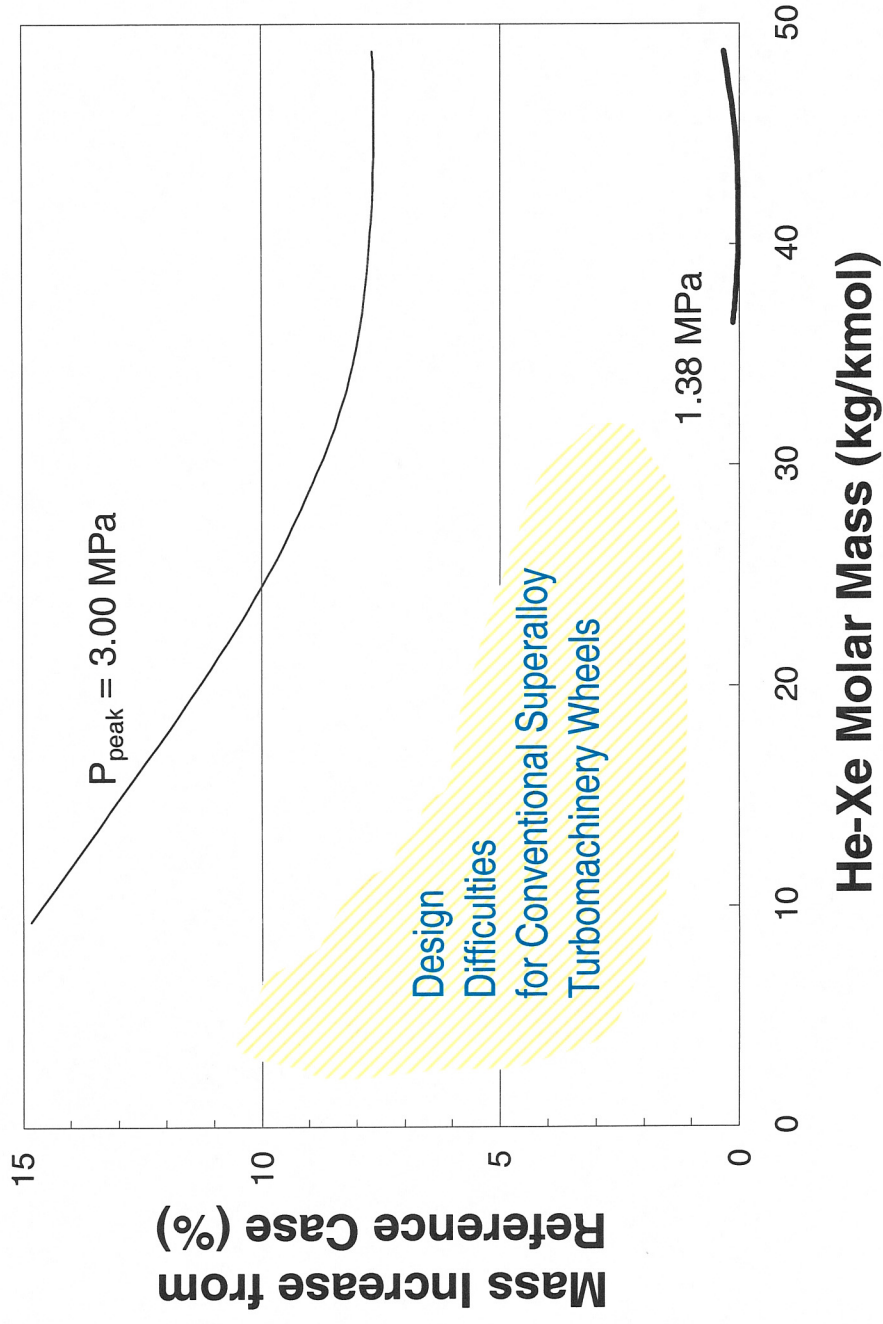
# Mass Dependence for $MW = 48.6$



# Mass Dependence for MW = 11.9

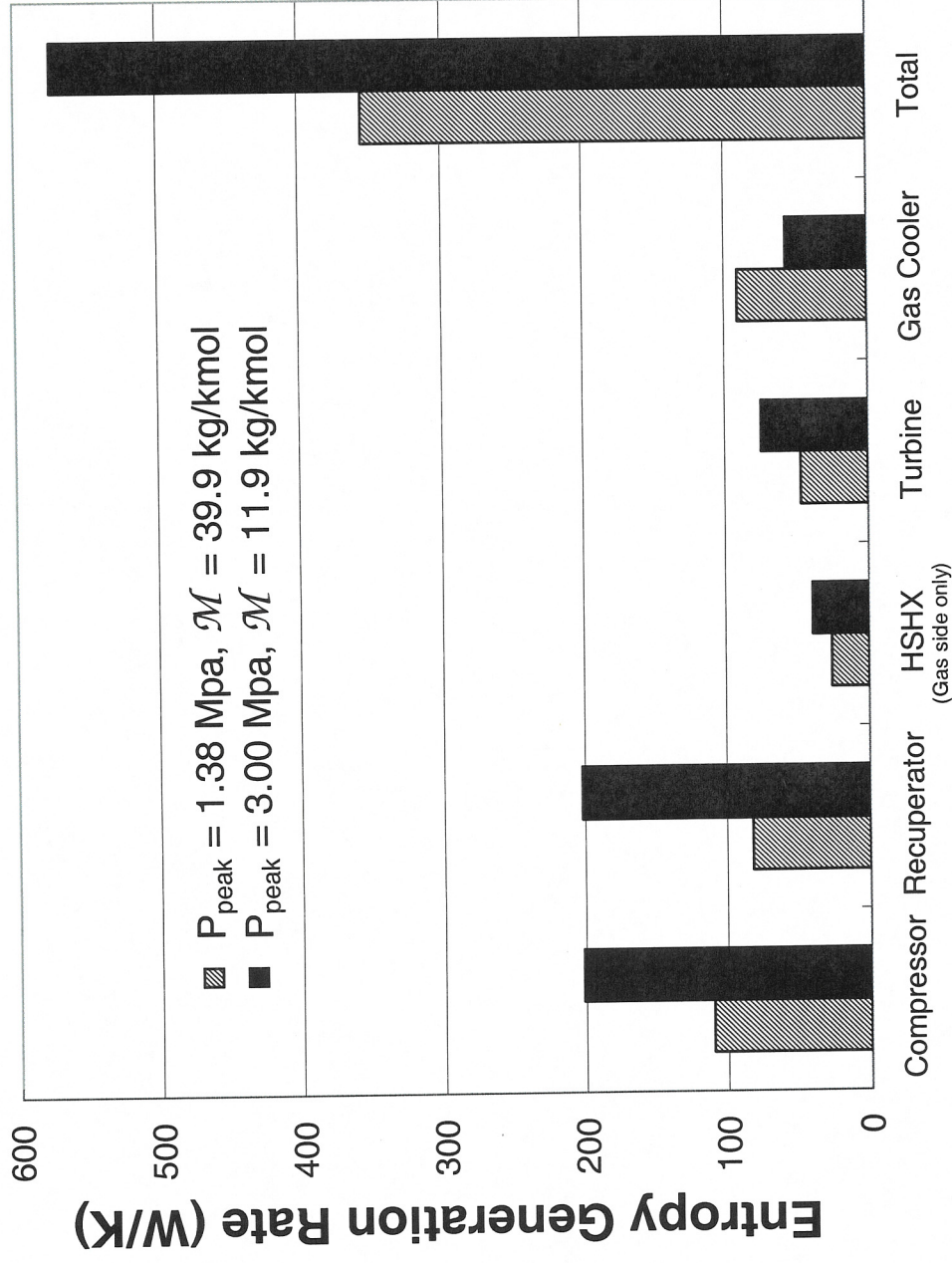


# Mass Dependence on MW





# Entropy Generation Rates from CBC Flow Loop Components



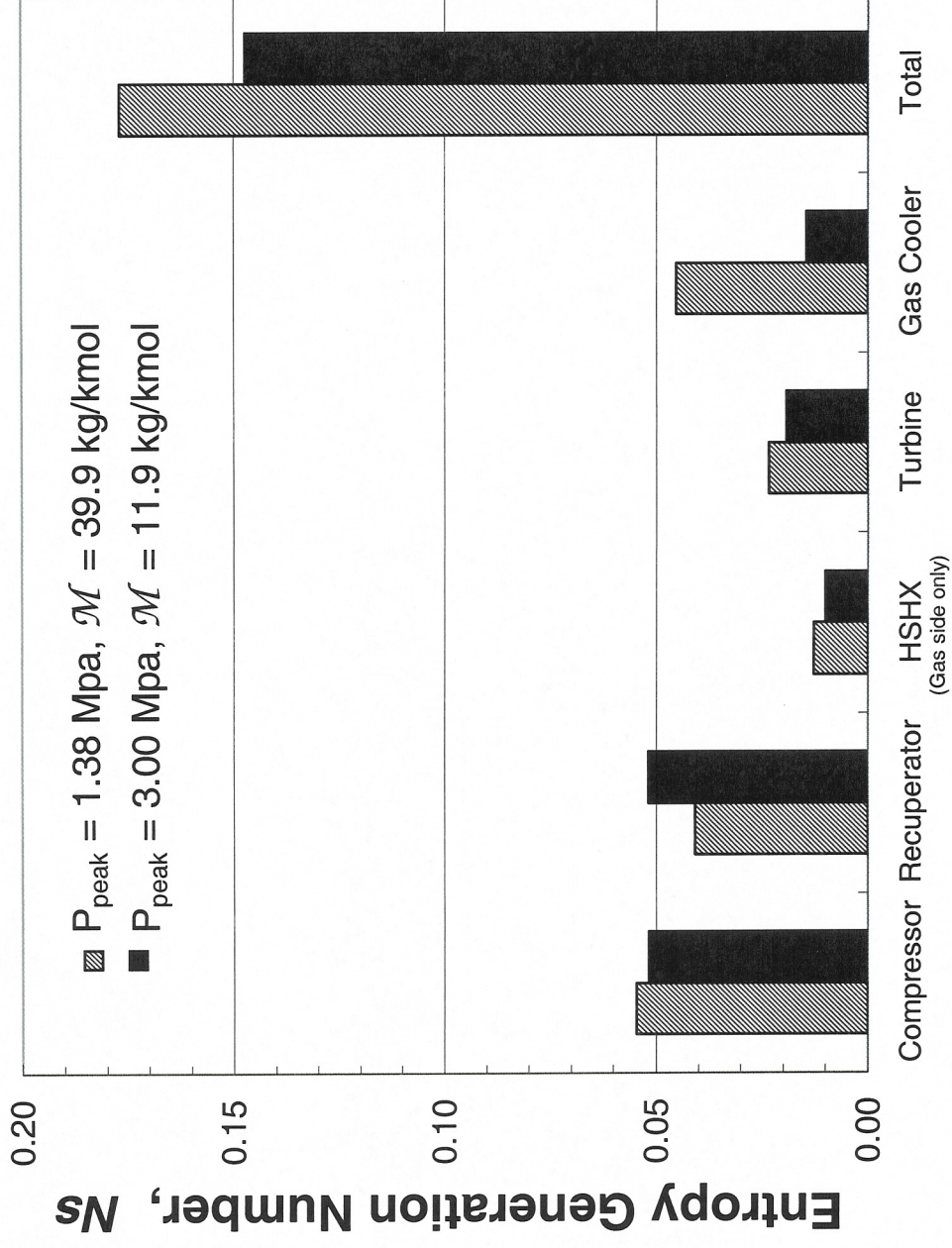
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# Entropy Generation Numbers for CBC Flow Loop Components



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# Conclusions

- System mass increased as  $P_{\text{peak}}$  was increased from 1.38 to 3.0 MPa for all CPR and MW values examined
- Single-string CBC PCS minimum mass increased 14% from baseline case of 72% He at 1.38 MPa peak to case of 94% He at 3.0 MPa peak
- For most cases examined, system mass increased as MW decreased
  - Exception: negligible increase from 48.6 to 39.9 kg/kmol at 1.38 MPa  $P_{\text{peak}}$
  - Turbomachinery maps limited evaluation of MW effects at low  $P_{\text{peak}}$
- At respective minimum mass points, converter entropy generation increased when  $P_{\text{peak}}$  increased and MW simultaneously decreased
- Converter subsystem entropy generation rate rose 62% from the baseline to the case of 94% He at 3.0 MPa peak (355 vs. 574 W/K)
- Component dimensionless entropy generation numbers were similar between cases except for rise in recuperator and decrease in GC values



# Back-up Charts

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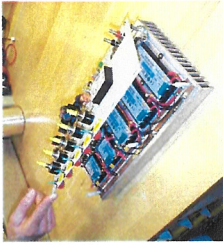
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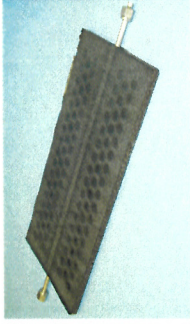
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# Nuclear Electric Propulsion

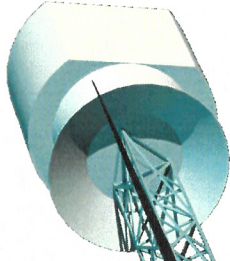
Power Management  
& Distribution



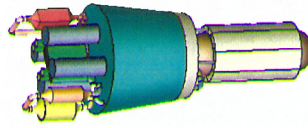
Heat Rejection



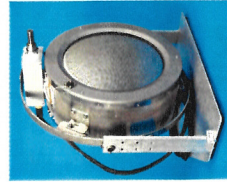
Science  
Payload



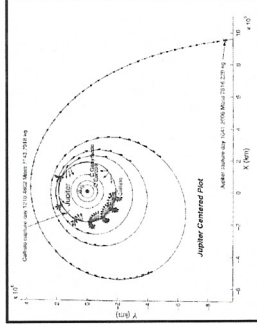
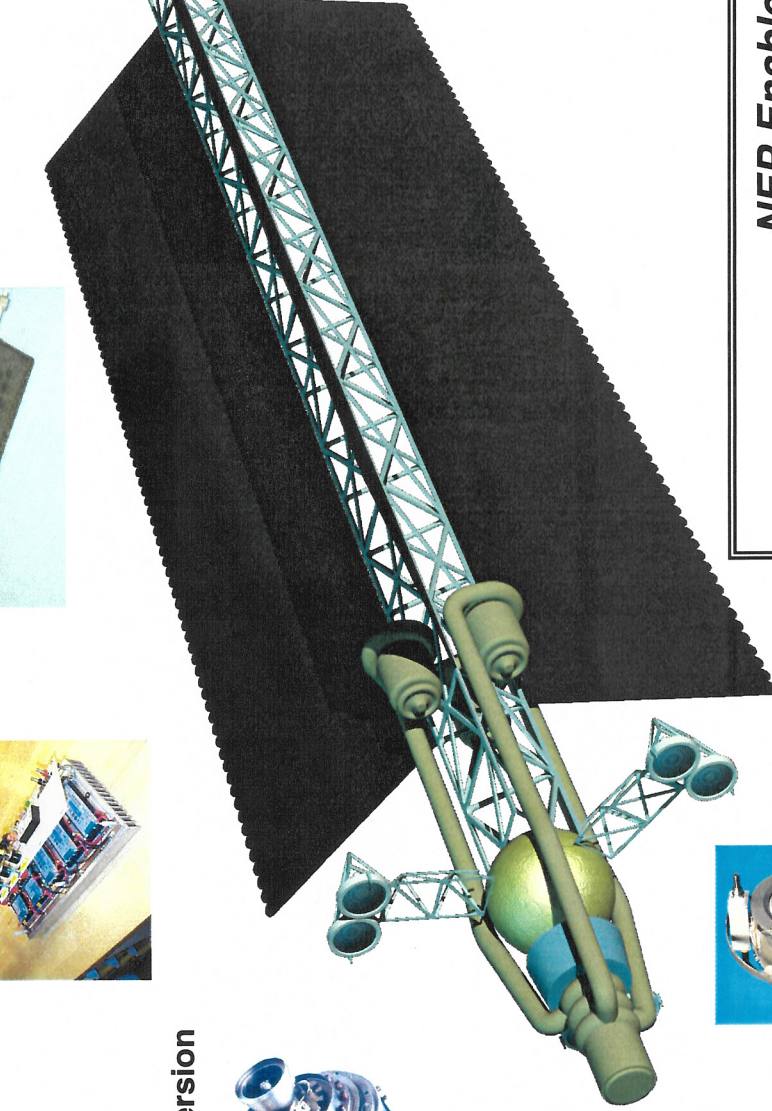
Power Conversion



Reactor  
Heat Source



Electric Propulsion

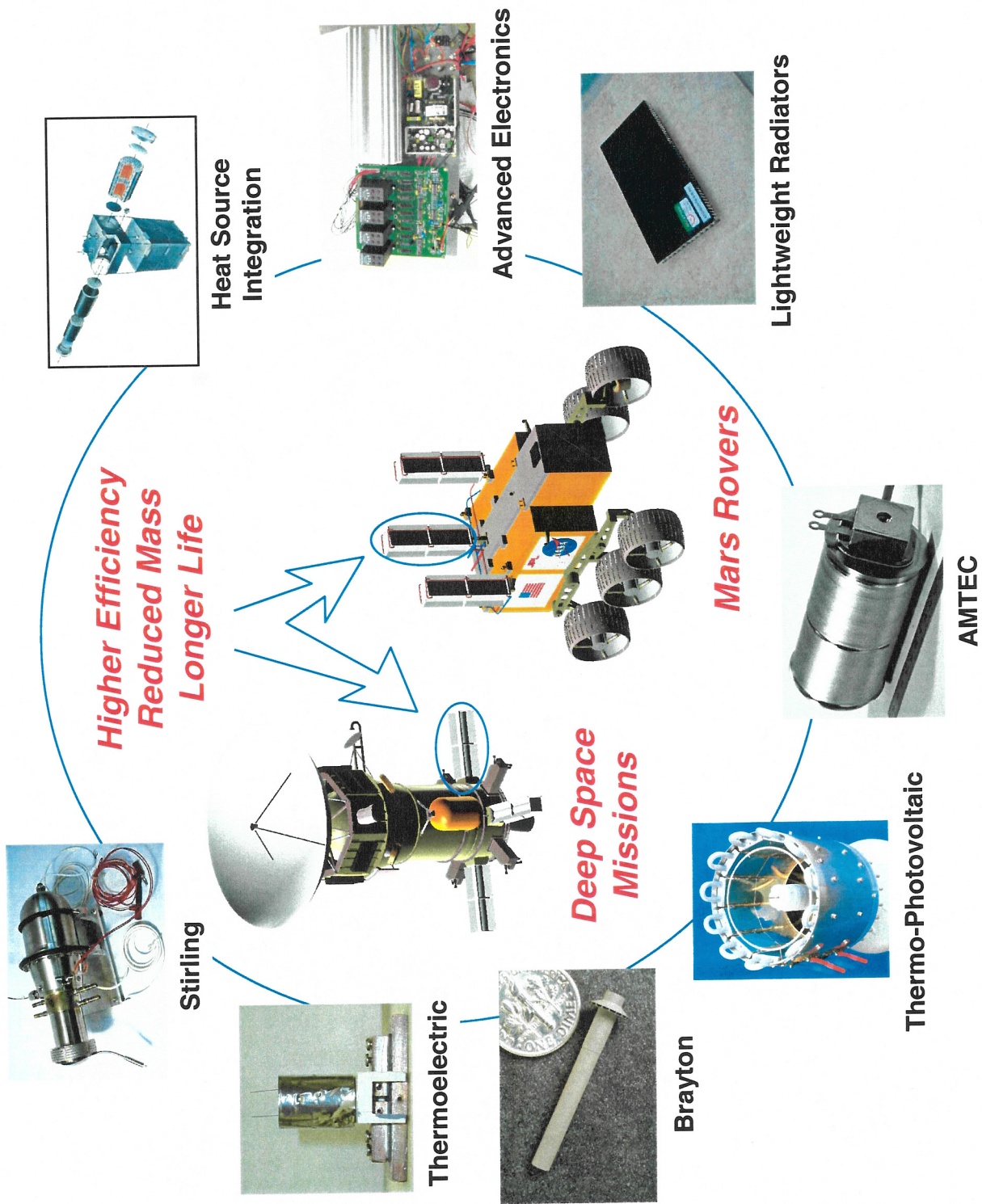


Trajectory Analysis

**NEP Enables:**  
*Outer Planet Orbiters (rather than Flybys)*  
*Multiple Targets on Single Mission*  
*High Power, Long Duration In-Situ Science*  
*High Data Rate Communications*



# Radioisotope Power Systems



S Y S T E M   -   I N T E G R A T I O N

P O W E R   C O N V E R S I O N