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

Michael J. Barrett¹ and Bryan M. Reid¹,²

¹Power and On-Board Propulsion Technology Division, NASA Glenn Research Center, Cleveland, OH 44135
²Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48109
(216) 433-5424, Michael.J.Barrett@nasa.gov

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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Michael J. Barrett
NASA Glenn Research Center
Cleveland, OH 44135
Michael.J.Barrett@nasa.gov

Bryan M. Reid
University of Michigan
Ann Arbor, MI 48109
reidb@engin.umich.edu

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Outline

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

- Thermal energy input from heat source heat exchanger (HSHX)
- Recuperated Closed Brayton Cycle
- Work output
- Back work
- Thermal energy rejected by gas cooler (GC) (waste heat)

Specific entropy

Temperature

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Brayton Converter

Turbo-alternator-compressor (TAC)
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 ΔP; 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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Baseline Case State Points

Baseline @ 1.38 Mpa
(Reference Case)

100 kWe
PMAD
95.0%

Loads
100 kWe

1150 K
1.34 MPa
510 kWt

105.3 kWt
Turbo-Alternator
92%

520 kWt
HSHX
98%

530 kWt
Reactor

89%

914 K
0.71 MPa
TPR 1.9

416 kWt
Main Radiator

411 K
0.69 MPa
CPR 2.0

619 kWt
Recuperator
92%

605 K
0.70 MPa

573 K
1.373 MPa

39.9 mol wt
72% He
28% Xe

3.85 kg/s

83%

405 K

T

686 K
1.365 MPa

526 K

n-heptane
1.00 kg/s

405 K

390 kWt
Gas Cooler
97%

Tsink
200 K

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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.)
Mass Dependence for MW = 39.9

- $P_{\text{peak}} = 3.00 \text{ MPa}$
- $M = 39.9 \text{ kg/kmol}$
- (72% He by volume)

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Mass Dependence for MW = 48.6

$P_{\text{peak}} = 3.00 \text{ MPa}$

$M = 48.6 \text{ kg/kmol}$

(65% He by volume)
Mass Dependence for MW = 11.9

\[ P_{\text{peak}} = 3.00 \text{ MPa} \]
\[ \dot{M} = 11.9 \text{ kg/kmol} \]
\[ (94\% \text{ He by volume}) \]

\[ 1.38 \text{ MPa}, \]
\[ 39.9 \text{ kg/kmol} \]
\[ (\text{for reference}) \]

CPR

Mass Increase from Reference Case (%)
Mass Dependence on MW

![Graph showing mass dependence on MW]

- Design Difficulties for Conventional Superalloy Turbomachinery Wheels

$P_{\text{peak}} = 3.00 \text{ MPa}$

$1.38 \text{ MPa}$
Entropy Generation Rates from CBC Flow Loop Components

- $P_{\text{peak}} = 1.38 \text{ Mpa}, \ M = 39.9 \text{ kg/kmol}$
- $P_{\text{peak}} = 3.00 \text{ Mpa}, \ M = 11.9 \text{ kg/kmol}$
Entropy Generation Numbers for CBC Flow Loop Components

- $P_{\text{peak}} = 1.38 \text{ Mpa, } \dot{M} = 39.9 \text{ kg/kmol}$
- $P_{\text{peak}} = 3.00 \text{ Mpa, } \dot{M} = 11.9 \text{ kg/kmol}$

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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
Nuclear Electric Propulsion

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

Higher Efficiency
Reduced Mass
Longer Life

Deep Space Missions

Mars Rovers

Thermoelectric
Brayton
Thermo-Photovoltaic
AMTEC

Heat Source Integration
Advanced Electronics
Lightweight Radiators