NASA/TM—2005-213626

Design and Off-Design Performance of 100 kWe-Class Brayton Power Conversion Systems

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June 2005

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Prepared for the
Space Technology and Applications International Forum (STAIF–2005)
sponsored by the University of New Mexico's Institute for Space
and Nuclear Power Studies (UNM-ISNPS)
Albuquerque, New Mexico, February 13–17, 2005

National Aeronautics and
Space Administration

Glenn Research Center

June 2005

Acknowledgments

The work in this paper was performed for NASA Headquarters, Exploration Systems Mission Directorate (Code T).

This report contains preliminary findings, subject to revision as analysis proceeds.

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Abstract

The NASA Glenn Research Center in-house computer model Closed Cycle Engine Program (CCEP) was used to explore the design trade space and off-design performance characteristics of 100 kWe-class recuperated Closed Brayton Cycle (CBC) power conversion systems. Input variables for a potential design point included the number of operating units (1, 2, 4), cycle peak pressure (0.5, 1, 2 MPa), and turbo-alternator shaft speed (30, 45, 60 kRPM). The design point analysis assumed a fixed turbine inlet temperature (1150 K), compressor inlet temperature (400 K), helium-xenon working-fluid molecular weight (40 g/mol), compressor pressure ratio (2.0), recuperator effectiveness (0.95), and a Sodium-Potassium (NaK) pumped-loop radiator. The design point options were compared on the basis of thermal input power, radiator area, and mass. For a nominal design point with defined Brayton components and radiator area, off-design cases were examined by reducing turbine inlet temperature (as low as 900 K), reducing shaft speed (as low as 50% of nominal), and circulating a percentage (up to 20%) of the compressor exit flow back to the gas cooler. The off-design examination sought approaches to reduce thermal input power without freezing the radiator.

Introduction

Closed-Brayton-Cycle (CBC) is a candidate thermodynamic cycle for space applications because it lends itself to power classes ranging from milliwatts to megawatts (Baggenstoss and Ashe, 1992). Potential missions include low power for scientific instruments (Zagarola, 2003), tens-to-hundreds of kilowatts for spacecraft (Barrett and Reid, 2004; Mason, 2004; Tilliette, 1990), and surface power (Mason, 1999; Mason et al., 1992). Heat sources for electrical power generation can be, but are not limited to, a radioisotope, solar concentrator (Shaltens and Mason, 1996), or nuclear reactor (Baggenstoss and Ashe, 1992; Barrett and Reid, 2004; Mason, 1999; Mason et al., 1992; Tilliette, 1990).

This study focuses on the CBC and heat rejection system (HRS) design for a 100 kWe nuclear reactor power conversion system (PCS), as well as off-design performance for one of the design points. Numerous variables exist in the design of a CBC PCS; this analysis considers variations in cycle peak pressure, turbine-alternator-compressor (TAC) shaft speed, and the number of CBC units. Pressure has a large influence on heat transfer and duct wall thicknesses. Shaft speed most directly affects alternator, bearing, and turbomachinery design. The number of CBC units could play an important role in redundancy considerations. Mission requirements ultimately dictate how the CBC PCS should be optimized, but concentrating on only a portion of the entire PCS could result in less than desirable system-level effects such as a low efficiency PCS, large radiator, or excessive system mass.

Operating in an off-design mode could be advantageous (or required) for missions where the PCS needs to run continuously for several years, but does not need to produce full power for extended lengths of time. Reducing the amount of heat input could extend reactor life; lowering turbine inlet temperature could reduce secondary creep in hot-end materials. Other aspects to consider when operating at off-design conditions are ancillary electronic power demands, alternator frequency variation with shaft speed changes, and the desire to keep radiator coolant temperatures above freezing. Off-design operational variations considered herein are reduced TAC shaft speed, lowered turbine inlet temperature (TIT), and compressor exit flow recirculation.

The method for modeling several CBC PCS design and off-design operating points is outlined in this paper. The results that are highlighted in this paper are CBC mass (TAC, ducting, recuperator, and gas cooler), radiator area, and required heat input for the design cases; alternator power, required heat input, and radiator coolant temperature are presented for the off-design cases.

Method

A NASA Glenn Research Center in-house modeling code, called the Closed Cycle Engine Program (CCEP) (Barrett and Reid, 2004), was used for the CBC PCS study. The program originated in the mid 1980's from a FORTRAN aircraft gas turbine engine code known as the Navy/NASA Engine Program (NNEP) (Fishbach, 1975). Components such as a solar collector, heat exchangers, ducting, a pumped-loop radiator, a nuclear heat source, and radial turbomachinery were added to NNEP, transforming it into a high fidelity (approximately 34,000 lines of code) design and performance tool for CBC PCS and HRS. The user constructs the CBC PCS component by component and has command of up to 36 inputs for some components. Components are integrated in CCEP with user-defined control variables to calculate converged solutions.

Subsystems with the highest fidelity are the CBC (TAC, ducting, recuperator, and gas cooler) and radiator HRS. Their mass and performance are of most interest to this study. The power management and distribution (PMAD) subsystem, nuclear reactor subsystem, and reactor shield are also modeled in CCEP. Their masses are used in the total PCS optimization scheme, but are not included in the results presented in this paper.

Most design variables (turbine and compressor inlet temperatures, compressor pressure ratio, working-fluid composition, alternator power, radiator far-field temperature, heat exchanger effectiveness) are fixed for each design case, while different combinations of system peak pressure, shaft speed, and number of CBC units are examined. Brayton cycle and HRS geometries are fixed for the transition to off-design and cycle state-point conditions vary as needed, with the exception of shaft speed, TIT, and compressor exit flow circulation, where two are held constant while the third is varied. Turbomachinery performance maps are used during off-design calculations.

Model Description

Some design parameters are drawn from previous test hardware such as the 10 kWe Brayton Rotating Unit (BRU) (Davis, 1972) and from the detailed conceptual design report for the Space Station *Freedom* Solar Dynamic Power Module (NASA Lewis Research Center, 1993). Although exact values are not necessarily taken from these sources, they are used as guides for developing the physical model for this study because they reflect previously developed CBC designs and configurations.

Compressor pressure ratio and helium-xenon (He-Xe) working-fluid molecular weight are 2.0 and 40 g/mol, respectively, because Barrett and Reid (2004) showed in a previous CCEP study that at this power level total system mass minimized at these design points. One difference between Barrett and Reid's study and this work is the calculation method for bearing and windage losses. Barrett and Reid scaled bearing and windage losses on shaft speed, shaft diameter, gas viscosity, and cavity pressure; this study scales bearing and windage losses on alternator power and CBC peak pressure alone and losses are smaller than Barrett and Reid's predictions, especially for higher power and higher pressure cases.

The turbine and compressor are both single-stage, radial machines whose design performances (functions of corrected mass flow rate, pressure ratio, and specific speed) are determined using conventional design efficiency tables. The TAC is integrated on a single rotating shaft supported by gas-foil journal and thrust bearings. Inlet temperatures for the turbine and compressor are fixed at 1150 K and 400 K, respectively, for this study. Turbomachinery rotordynamics are not evaluated by CCEP and could severely affect the feasibility of cases examined. Both the gas cooler and the recuperator are counterflow, compact, plate-fin heat exchangers with offset strip-fin surfaces; effectiveness values for the gas cooler and recuperator are 97 and 95%, respectively. Gas duct diameters are sized to produce desired relative pressure losses. Each duct wall thickness is sized to withstand 100,000 hours of creep stress at design-point temperature and pressure with a 2.0 factor of safety. A duct exists between the compressor exit and the gas cooler entrance to allow a percentage, λ, of the working-fluid to be "short-circuited" and flow from the compressor discharge directly to the gas cooler during off-design operation.

The radiator is a pumped-loop configuration with sodium-potassium (NaK-78) coolant and Annular Linear Induction Pump(s) (ALIP). Materials and geometries are similar to those described in the Space Station Freedom report (NASA Lewis Research Center, 1993). For power conversion systems with more than one CBC converter, a separate NaK loop and pump is provided for each converter. The NaK tube inside diameter is sized to achieve a desired pressure drop across the radiator. The effective sink temperature for the radiator is 200 K, representative of earth-orbital conditions.

The results reported herein focus on the Brayton PCS and HRS. However, CCEP is configured to optimize the overall system, from the reactor heat source to the PMAD electrical bus, based on various design parameters. Some of these typical optimization parameters have been fixed for this study to evaluate the performance sensitivities attributed specifically to the Brayton and heat rejection subsystems. The reported masses and radiator areas are based on a single-string power train with no spare units. Some mission architectures would benefit by spare converter units or heat rejection cooling loops.

Design Case Definition

Three parameters are varied so that their effects on CBC mass (TAC, ducting, recuperator, and gas cooler), radiator area, A_{Rad}, and required heat input, Q_{HeXe}, can be examined. The first parameter is the number of CBC units; we consider four units operating at 25 kWe each, two units operating at 50 kWe each, and one unit operating at 100 kWe. The other two parameters are shaft speed, N, (30, 45, 60 kRPM) and CBC peak pressure, P_{peak}, (0.5, 1.0, 2.0 MPa). The CCEP input deck is configured to minimize total system mass (PMAD, HRS, CBC, reactor, and shield) by determining the optimal NaK mass flow rate.

Off-Design Performance Case Definition

A nominal design point is subsequently selected to investigate off-design performance. Radiator coolant mass flow rate is held constant from design to off-design to keep the ALIP pumps operating near design-point efficiency. The radiator far-field temperature is maintained at 200 K.

Off-design baseline.—The design point chosen for off-design study is the two-unit, 45000 RPM, 1.0 MPa case, which falls in the mid-range for CBC mass, A_{Rad}, and Q_{HeXe} of the design cases considered. Figure 1 shows the baseline off-design CBC and HRS schematic.

Off-design operating conditions.—Three operating conditions are varied in the transition to off design: N (as low as 50% design speed), λ (as high as 20%), and TIT (as low as 900 K). Each off-design case varies only one operating condition at a time to examine independently the effects on Q_{HeXe}, alternator power, W_{Alt}, and NaK cold temperature, $T_{Cold,NaK}$. Sodium-potassium-78 freezes at 262 K.

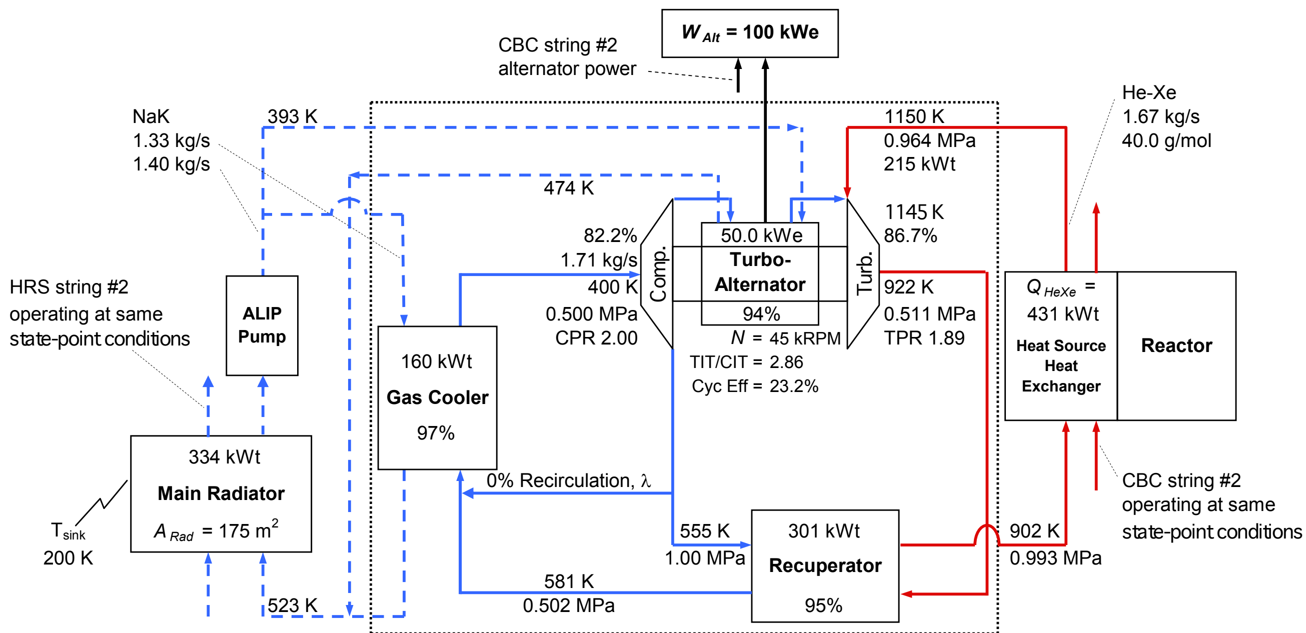


Figure 1. CBC and HRS Off-Design Baseline Case.

Results and Discussion

The first data set examines the CBC and HRS dependence on three design parameters. A total of 22 combinations of design points were obtained. Cases for which the code did not converge were one unit operating at 0.5 MPa, one unit operating at 1.0 MPa and 60000 RPM, and two units operating at 0.5 MPa and 60000 RPM. Convergence did not occur because the design points were outside the realm of CCEP's turbomachinery design tables. The second data set examines CBC and HRS performance at three off-design operating conditions.

Design Point Dependence on Number of CBC Units, Shaft Speed, and Peak Pressure

Figures 2 through 4 show the dependence of CBC mass, A_{Rad}, and Q_{HeXe} on the number of CBC units and P_{peak} for a fixed N of 45000 RPM. Over the P_{peak} range of 0.5 to 2.0 MPa, A_{Rad} and Q_{HeXe} increase linearly, with the four-unit case increasing fastest. Mass for the one-unit case is slightly less at 2.0 MPa than at 1.0 MPa. Mass for the two-unit case minimizes at 1.0 MPa, and mass increases less than linearly for the four-unit case. For a given P_{peak}, the one-unit CBC exhibits the lowest mass, A_{Rad}, and Q_{HeXe}. Trends similar to those shown in figures 2 through 4 were observed for values of N fixed at 30000 and 60000 RPM. Plots at all three speeds are presented in appendix A.

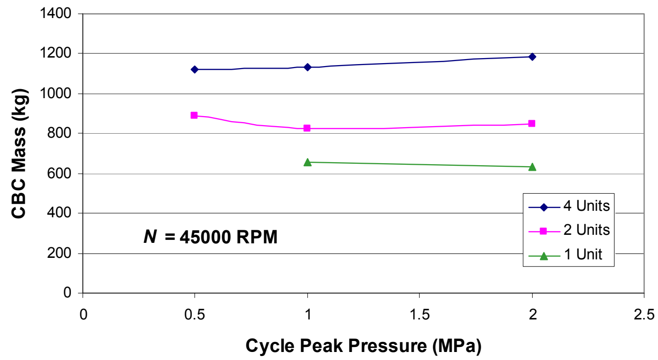


Figure 2. CBC Mass Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 45000 RPM.

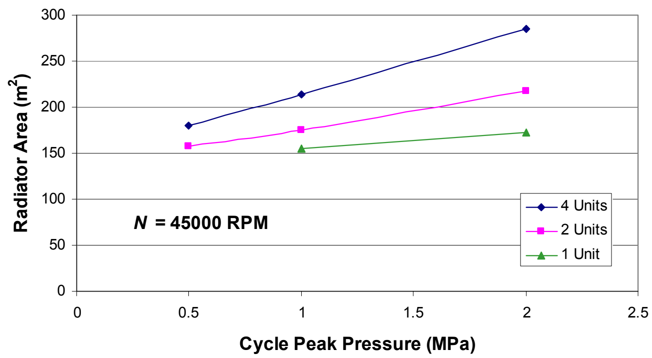


Figure 3. Radiator Area Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 45000 RPM.

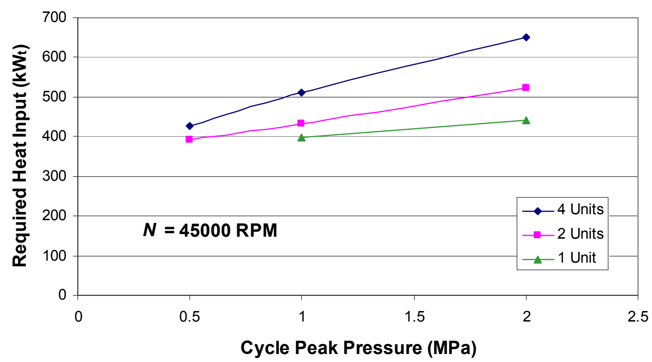


Figure 4. Required Heat Input Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 45000 RPM.

Figures 5 through 7 show the dependence of CBC mass, A_{Rad}, and Q_{HeXe} on the number of CBC units and N for a fixed P_{peak} of 2.0 MPa. Over the N range of 30000 to 60000 RPM, A_{Rad}, and Q_{HeXe} decrease nearly linearly, and mass decreases less than linearly, with the four-unit case decreasing fastest in each figure. For a given N, the one-unit case exhibits the lowest mass, A_{Rad}, and Q_{HeXe}. Trends similar to those shown in figures 5 through 7 were observed for values of P_{peak} fixed at 0.5 and 1.0 MPa. Plots at all three pressures are presented in appendix B.

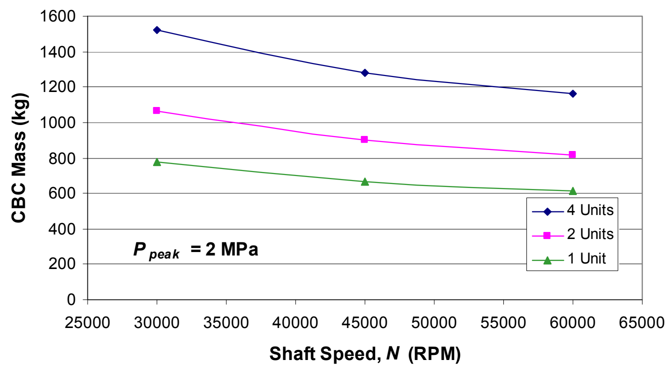


Figure 5. CBC Mass Dependence on N and Number of CBC Units for a Fixed P_{peak} of 2.0 MPa.

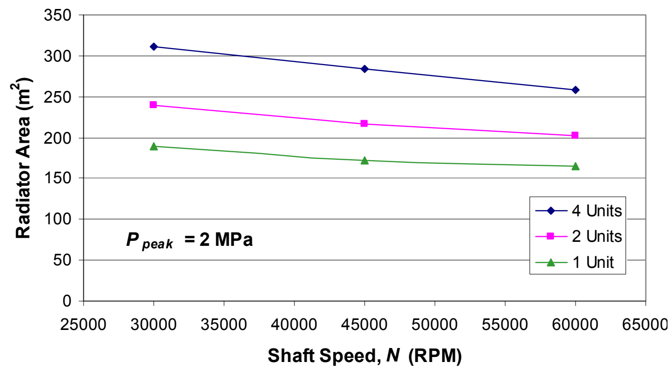


Figure 6. Radiator Area Dependence on N and Number of CBC Units for a Fixed P_{peak} of 2.0 MPa.

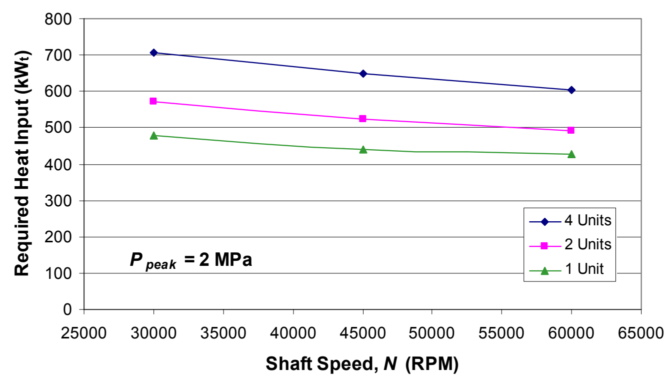


Figure 7. Required Heat Input Dependence on N and Number of CBC Units for a Fixed P_{peak} of 2.0 MPa.

Performance tradeoffs among components occur when design parameters are varied. For example, the recuperator, accounting for 30 to 50% of the Brayton converter mass, becomes less massive as P_{peak} increases, but duct walls become thicker, thus heavier, at higher pressures. On the other hand, turbomachinery efficiencies decrease with increased pressure, requiring more heat input and a larger radiator area. This effect can be somewhat mitigated by increasing shaft design speed. It is the resulting combination of performances among components that must be examined. Table 1 summarizes the design cases that yield the minimum CBC mass, A_{Rad}, and Q_{HeXe}.

TABLE 1. DESIGN-POINT CASES FOR THE MINIMUM CBC MASS, REQUIRED HEAT INPUT, AND RADIATOR AREA.

Minimum Case	# Units	Mass (kg)	Q_{HeXe} (kWt)	A_{Rad} (m^2)	P_{peak} (MPa)	N (RPM)
CBC Mass	1	580	426	165	2.0	60000
Radiator Area	1	656	398	155	1.0	45000
Heat Input	2	890	393	158	0.5	45000

Off-Design Performance of a Two-Unit, 1 MPa, 45000 RPM Design-Point CBC

Figure 8 shows the resulting off-design performance of a two-unit, 1.0 MPa, 45000 RPM design-point CBC when N is reduced from 100 to 50% of design speed. Alternator power, Q_{HeXe}, and $T_{Cold,NaK}$ all decrease as shaft speed is reduced, with Q_{HeXe} decreasing fastest and off-design efficiency (W_{Alt}/Q_{HeXe}) remaining about the same. At 50% of design speed, W_{Alt}, Q_{HeXe}, and $T_{Cold,NaK}$ are 24 kWe, 101 kWt, and 303 K, respectively.

Figure 9 shows the resulting off-design performance when λ is increased from 0 to 20%. Alternator power and Q_{HeXe} decrease at about the same rate, indicating that off-design efficiency decreases as λ increases; $T_{Cold,NaK}$ remains almost constant. At λ of 20%, W_{Alt}, Q_{HeXe}, and $T_{Cold,NaK}$ are 16 kWe, 369 kWt, and 398 K, respectively.

Figure 10 shows the resulting off-design performance when TIT is reduced from 1150 to 900 K. Alternator power and Q_{HeXe} decrease linearly at as TIT decreases, while $T_{Cold,NaK}$ decreases slightly. At a TIT of 900 K, W_{Alt}, Q_{HeXe}, and $T_{Cold,NaK}$ are 25 kWe, 300 kWt, and 381 K, respectively.

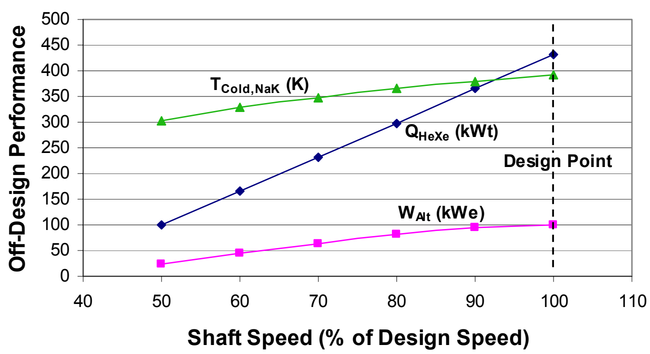


Figure 8. CBC and HRS Off-Design Performance Dependence on Reduced Shaft Speed.

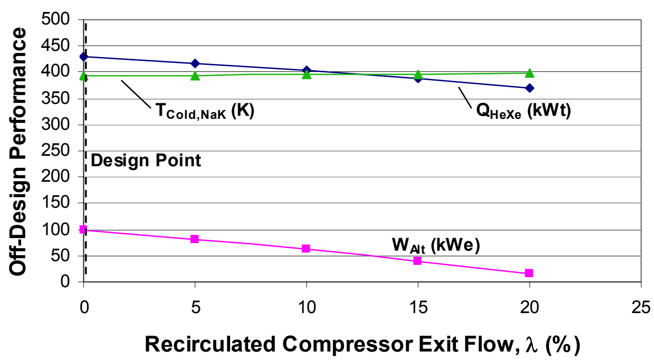


Figure 9. CBC and HRS Off-Design Performance Dependence on Percentage of Compressor Exit Flow Recirculation.

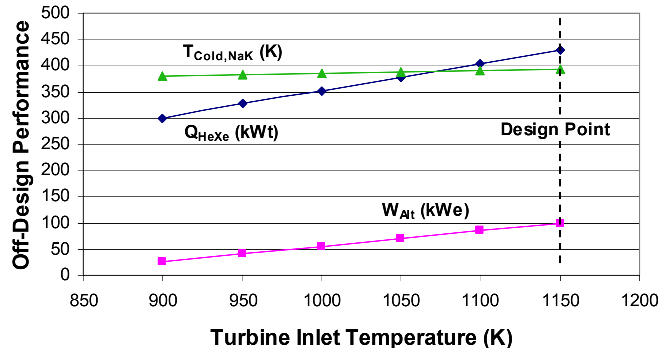


Figure 10. CBC and HRS Off-Design Performance Dependence on Reduced Turbine Inlet Temperature.

Varying shaft speed is the single most effective method for reducing the required heat input; running at 50% of design speed reduces q_{hexe} by 77% because the he-xe mass flow rate is slowed and less heat is required to achieve the 1150 k tit. However, $t_{cold,nak}$ drops to 303 k and compressor operation is very close to surge. Circulating the compressor outlet flow and lowering the tit are much less effective at reducing q_{hexe}, but $t_{cold,nak}$ does not drop below 381 k. The λ of 20% operating point requires 23% more q_{hexe} than the 900 k tit operating point, but the 900 k tit case produces 36% more alternator power.

Conclusions

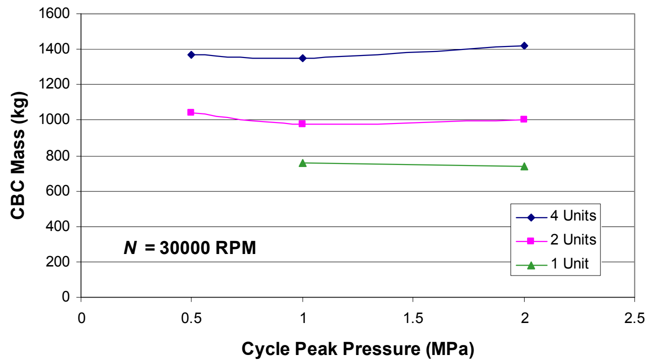
Design-point radiator area and required heat input increased as cycle peak pressure increased from 0.5 to 2.0 Mpa and the number of CBC units increased from one to four for a 100 kwe Brayton power conversion system. Closed-Brayton-Cycle mass increased as the number of CBC units increased from one to four, with the one-unit and four-unit minimum masses occurring at peak pressures of 2.0 and 1.0 MPa, respectively. This supports the well-accepted view that Brayton units scale well at higher power classes. As shaft speed increased from 30000 to 60000 RPM and the number of CBC units decreased from four to one, CBC mass, radiator area, and required heat input all decreased.

For a two-unit CBC design-point, off-design operating conditions showed that reducing shaft speed was the most effective method for reducing required heat input; circulating compressor exit flow was the least effective. None of the off-design operating points resulted in radiator cold temperatures below the NaK freezing point. Of the three off-design parameters examined, a combination of reduced shaft speed and lowered TIT might prove to be most effective at keeping NaK from freezing, decreasing required heat input, and slowing secondary creep in hot-end materials.

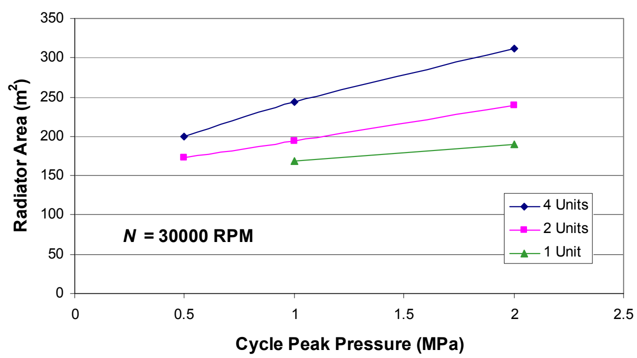
Nomenclature

A_{Rad}	radiator total surface area (m^2)
CIT	compressor inlet temperature (K)
CPR	compressor pressure ratio
λ	compressor exit flow recirculation (%)
N	turbine-alternator-compressor shaft speed (RPM)
P_{peak}	Brayton cycle peak pressure (MPa)
Q_{HeXet}	heat input to Helium-Xenon working-fluid (kWt)
$T_{Cold,NaK}$	sodium-potassium cold temperature (K)
TIT	turbine inlet temperature (K)
TPR	turbine pressure ratio
T_{sink}	radiator effective sink temperature (K)
W_{Alt}	alternator power (kWe)

Appendix A
Design Point Results at Three Shaft Speeds



CBC Mass Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 30000 RPM.



Radiator Area Dependence on P_{peak} and
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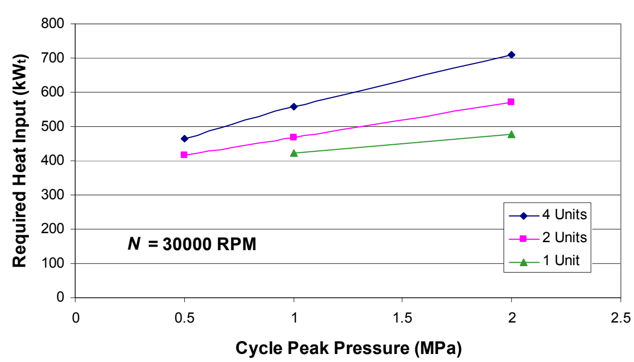
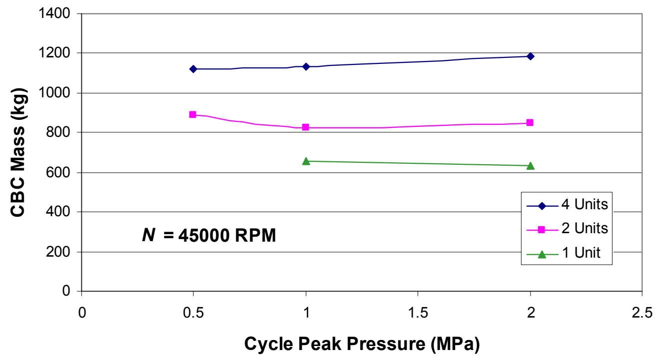
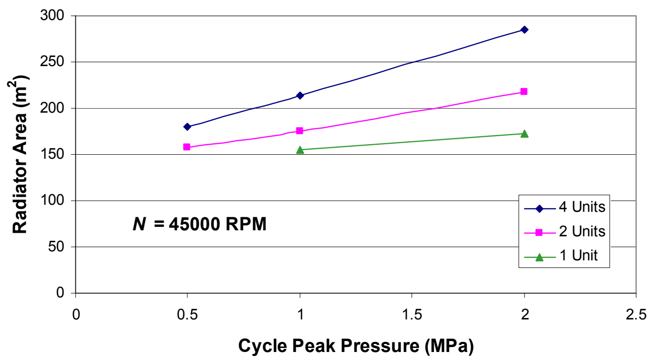


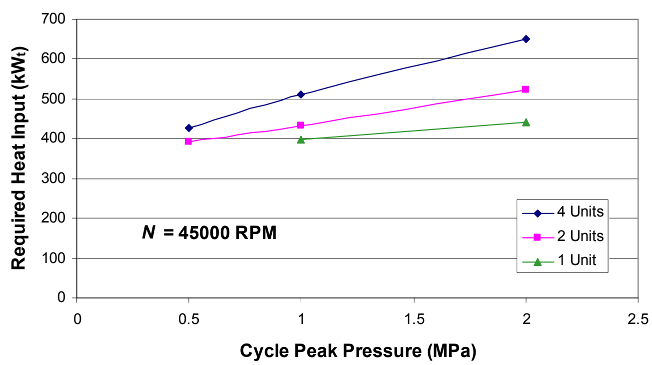
Required Heat Input Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 30000 RPM.



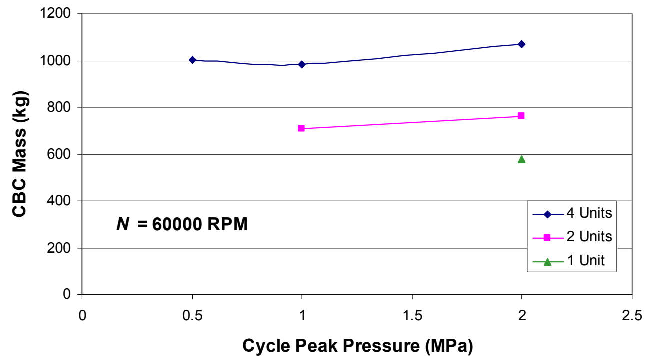
CBC Mass Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 45000 RPM.



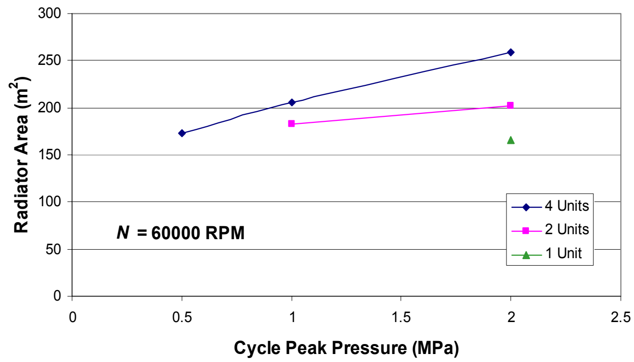
Radiator Area Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 45000 RPM.



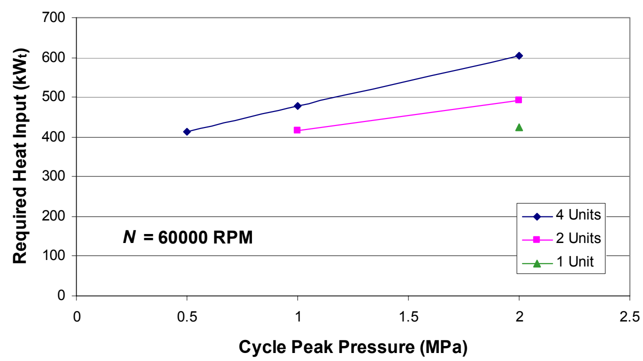
Required Heat Input Dependence on P_{peak} and
Number of CBC Units for a Fixed N of 45000 RPM.



CBC Mass Dependence on P_{peak} and Number of CBC Units for a Fixed N of 60000 RPM.

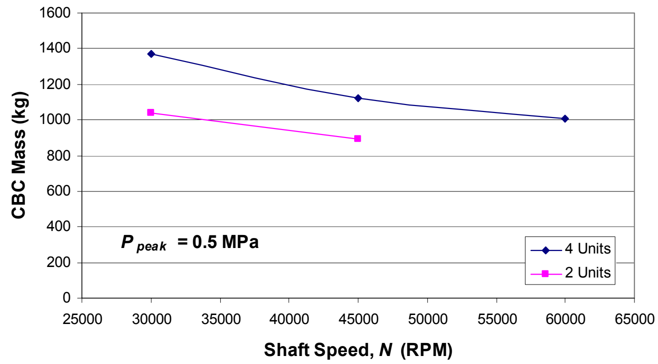


Radiator Area Dependence on P_{peak} and Number of CBC Units for a Fixed N of 60000 RPM.

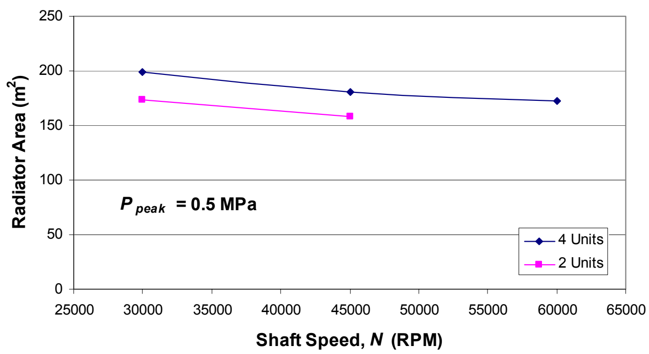


Required Heat Input Dependence on P_{peak} and Number of CBC Units for a Fixed N of 60000 RPM.

Appendix B
Design Point Results at Three Cycle Peak Pressures



CBC Mass Dependence on *N* and
Number of CBC Units for a Fixed P_{peak} of 0.5 MPa.



Radiator Area Dependence on *N* and
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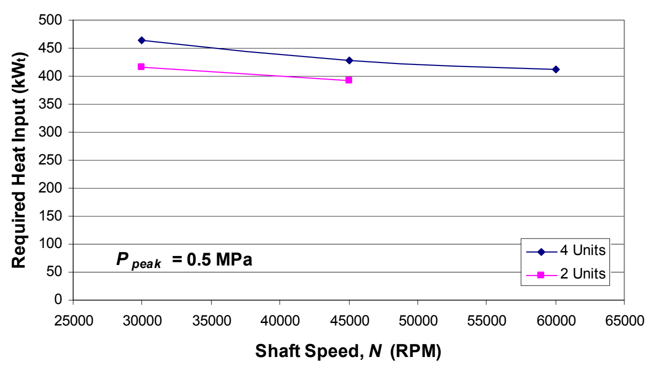
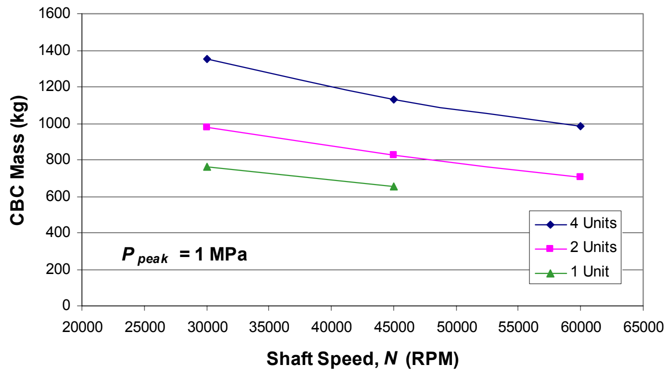
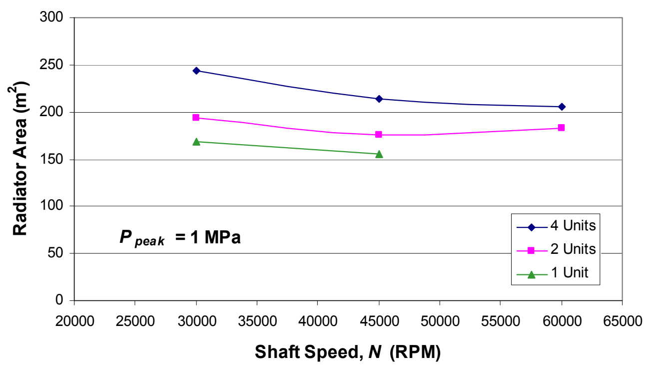


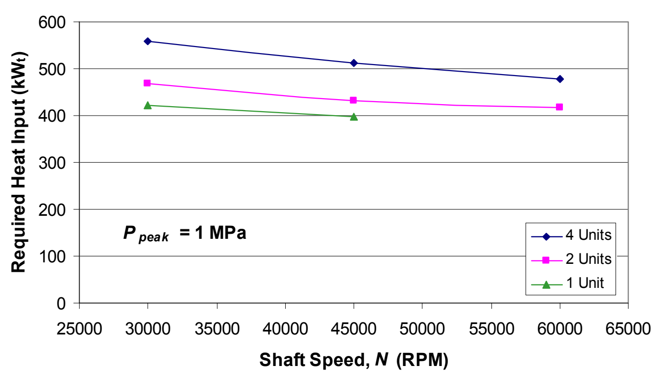
Required Heat Input Dependence on *N* and
Number of CBC Units for a Fixed P_{peak} of 0.5 MPa.



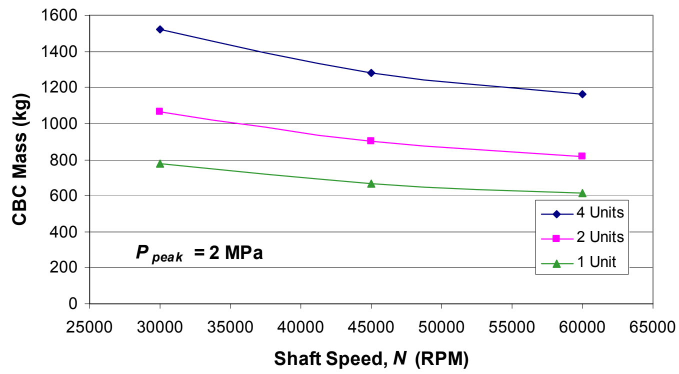
CBC Mass Dependence on N and
Number of CBC Units for a Fixed P_{peak} of 1.0 MPa.



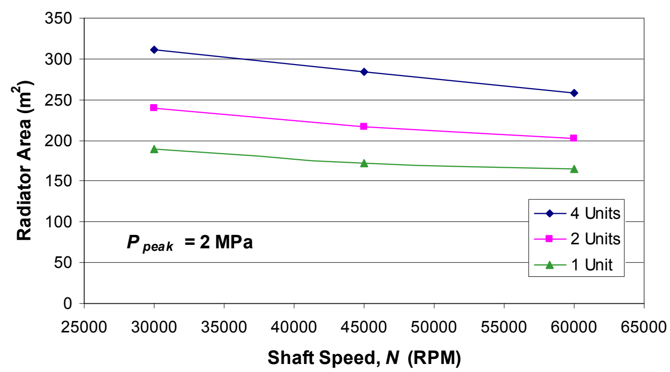
Radiator Area Dependence on N and
Number of CBC Units for a Fixed P_{peak} of 1.0 MPa.



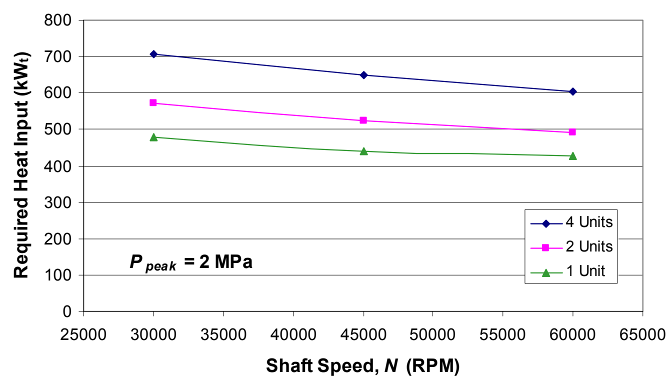
Required Heat Input Dependence on N and
Number of CBC Units for a Fixed P_{peak} of 1.0 MPa.



CBC Mass Dependence on N and
Number of CBC Units for a Fixed P_{peak} of 2.0 MPa.



Radiator Area Dependence on N and
Number of CBC Units for a Fixed P_{peak} of 2.0 MPa.



Required Heat Input Dependence on N and
Number of CBC Units for a Fixed P_{peak} of 2.0 MPa.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 2005	Technical Memorandum

4. TITLE AND SUBTITLE

Design and Off-Design Performance of 100 kWe-Class Brayton Power Conversion Systems

5. FUNDING NUMBERS

WBS–22–982–10–03

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Cleveland, Ohio 44135−3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E−15110

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546−0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2005-213626

11. SUPPLEMENTARY NOTES

Prepared for the Space Technology and Applications International Forum (STAIF–2005) sponsored by the University of New Mexico's Institute for Space and Nuclear Power Studies (UNM-ISNPS), Albuquerque, New Mexico, February 13–17, 2005. Paul K. Johnson, Analex Corporation, 1100 Apollo Drive, Brook Park, Ohio 44142; and Lee S. Mason, NASA Glenn Research Center. Responsible person, Paul K. Johnson, organization code RPT, 216–433–3814.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 20

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The NASA Glenn Research Center in-house computer model Closed Cycle Engine Program (CCEP) was used to explore the design trade space and off-design performance characteristics of 100 kWe-class recuperated Closed Brayton Cycle (CBC) power conversion systems. Input variables for a potential design point included the number of operating units (1, 2, 4), cycle peak pressure (0.5, 1, 2 MPa), and turbo-alternator shaft speed (30, 45, 60 kRPM). The design point analysis assumed a fixed turbine inlet temperature (1150 K), compressor inlet temperature (400 K), helium-xenon working-fluid molecular weight (40 g/mol), compressor pressure ratio (2.0), recuperator effectiveness (0.95), and a Sodium-Potassium (NaK) pumped-loop radiator. The design point options were compared on the basis of thermal input power, radiator area, and mass. For a nominal design point with defined Brayton components and radiator area, off-design cases were examined by reducing turbine inlet temperature (as low as 900 K), reducing shaft speed (as low as 50 percent of nominal), and circulating a percentage (up to 20 percent) of the compressor exit flow back to the gas cooler. The off-design examination sought approaches to reduce thermal input power without freezing the radiator.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Brayton cycle; Nuclear electric power generation	21
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	