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

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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 number of operating units (1, 2, 4), working-fluid molecular weight (20, 40, 80 g/mol), 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), peak cycle pressure (1 MPa), compressor pressure ratio (2.0), and 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 fixed 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 considering several component by-pass flow arrangements. The off-design analysis was focused on approaches to reduce thermal input power without freezing the radiator.

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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), 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.

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Outline

- Introduction
- Conceptual design methodology
- Method description
- Model description
- Design case definition
- Design case results
- Off-Design case definition
- Off-Design case results
- Conclusions

Introduction

- Closed-Brayton-cycle (CBC) is a candidate thermodynamic cycle for a 100 kWe-class Jupiter Icy Moons Orbiter (JIMO) type spacecraft
- CBC space power conversion systems (PCS) must be designed to minimize thermal input power, converter mass, and heat rejection system (HRS) radiator area
  - Chose to vary three design parameters: shaft speed, cycle peak pressure, and number of CBC units
- Off-design operation for an extended period of time could extend reactor life by reducing the thermal power requirement and/or peak operating temperature
  - Chose to reduce turbine inlet temperature, shaft speed, and mass flow rate through the turbine (by circulating a percentage of compressor exit flow back to the gas cooler)

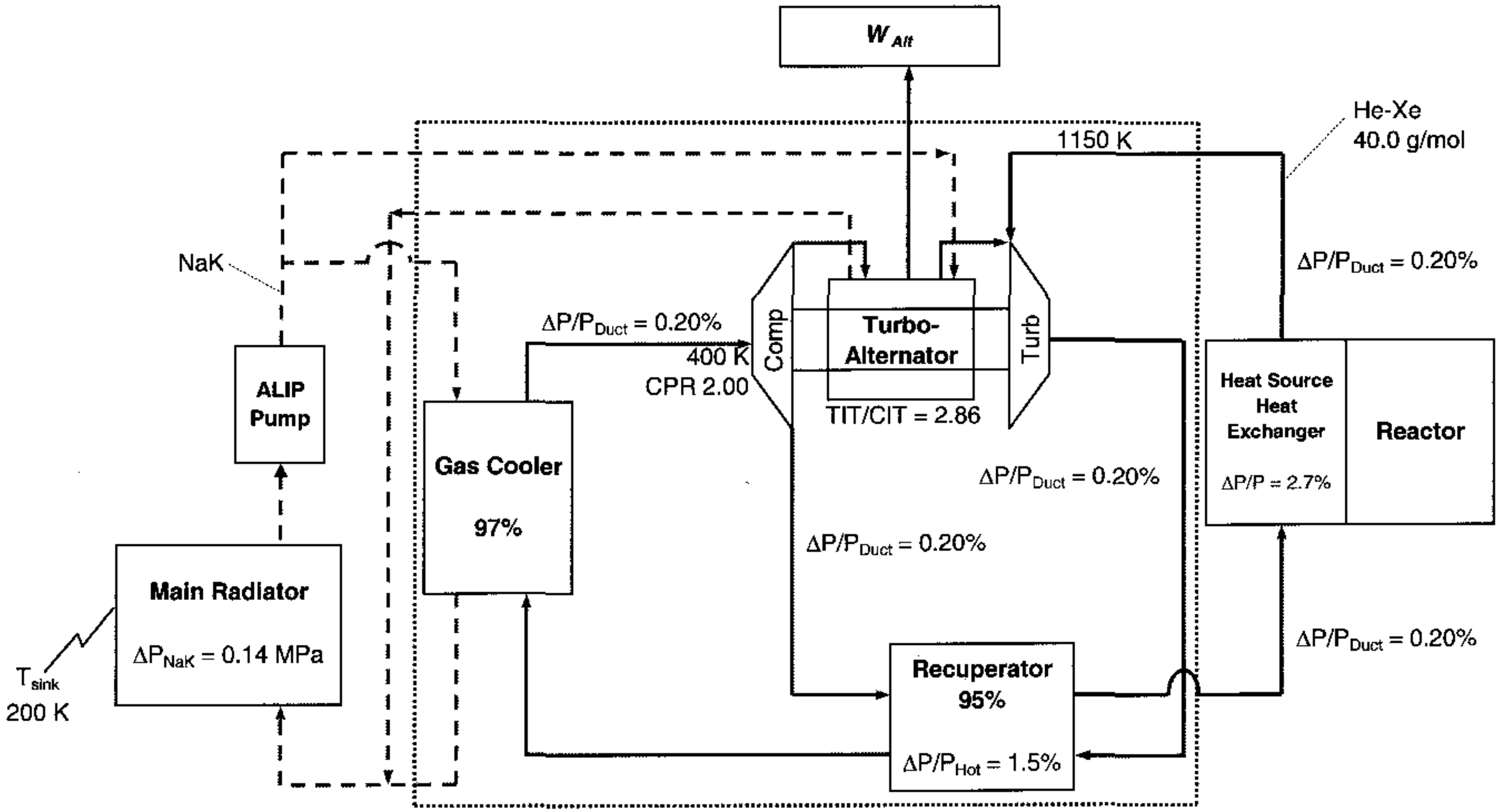
Method

- In-house code Closed Cycle Engine Program (CCEP)
  - Design and off-design performance analysis and mass estimates
  - Single-stage, radial turbomachinery design tables
  - Bearing and windage losses based on alternator power and cycle peak pressure
  - Kays and London based recuperator and gas cooler
  - Gas ducting
  - Pumped-loop radiator
  - Solar collector or nuclear heat source
- Majority of design variables are identical for all design cases
  - Turbine inlet temperature (TIT), compressor inlet temperature (CIT) compressor pressure ratio (CPR), working-fluid composition, alternator power, radiator far-field temperature, heat exchanger effectiveness, relative pressure drop across the components
- Vary only select variables during design
  - Combinations of cycle peak pressure, shaft speed, and number of CBC units/engines
- One design-point is selected for the transition to off-design
  - Hardware geometries and gas inventory are fixed
  - Vary one off-design variable at a time
    - Shaft speed, turbine inlet temperature, and compressor exit flow recirculation
  - Map scaling technique used for off-design turbine and compressor performance

Model Description

- Design-point constants
  - TIT: 1150 K
  - CIT: 400 K
  - Compressor pressure ratio: 2.0
  - Working-fluid composition: He-Xe 40 g/mol
  - Total output power: 100 kWe
  - Radiator far-field temperature: 200 K
  - Radiator pressure drop: 0.14 MPa (20 PSI)
  - Recuperator
    - Effectiveness: 95%
    - Hot-side relative pressure drop: 1.5%
  - Gas cooler effectiveness: 97%
  - Relative pressure drop for each gas duct: 0.20 %
  - Heat source heat exchanger relative pressure drop: 2.7%
- Radiator is pumped-loop configuration with NaK-78 coolant pumped by an Annular Linear Induction Pump (ALIP)
  - Separate NaK loop and ALIP pump for each CBC converter
- Recuperator and gas cooler are counter flow, offset strip fin
- Duct wall thicknesses sized for 100,000 hours of creep stress, 2.0 factor of safety

Power Conversion Schematic



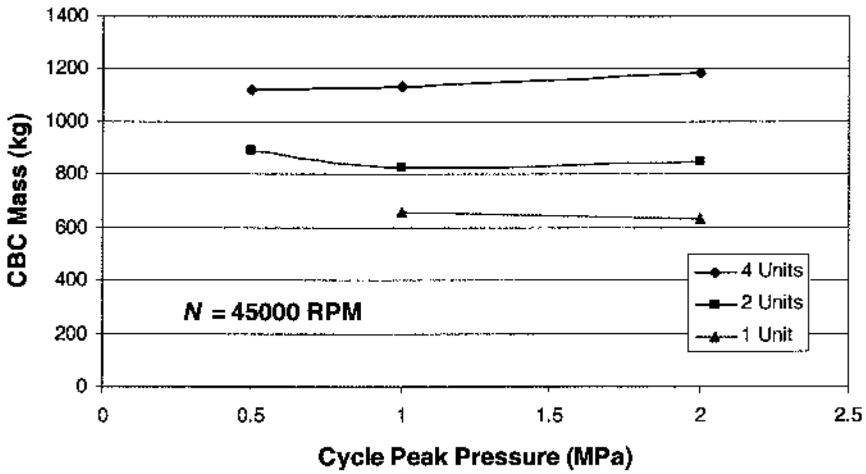
Design Case Definition

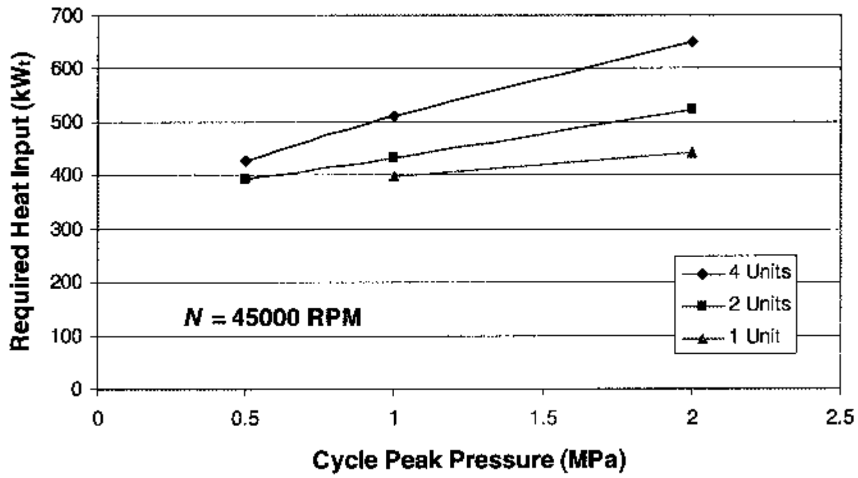
- Varied three design parameters
  - Shaft speed (30000, 45000, 60000 RPM)
  - Cycle peak pressure (0.5, 1.0, 2.0 MPa)
  - Number of CBC units (1 at 100kWe, 2 at 50kWe, 4 at 25kWe)
- Compared on basis of CBC mass (recuperator, gas cooler, turbine-alternator-compressor, and ducting), thermal input power, and radiator area (two-sided)
- Total of 22 converged cases examined

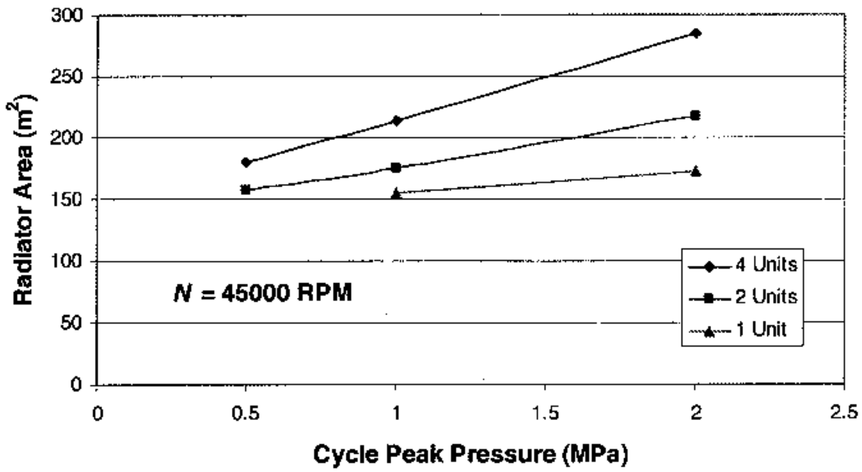
Converged Cases for 1, 2, and 4 CBC units

		Peak Pressure (MPa)		
		0.5	1.0	2.0
RPM	30000	1, 2	1, 2, 4	1, 2, 4
	45000	1, 2	1, 2, 4	1, 2, 4
	60000	1	1, 2	1, 2, 4

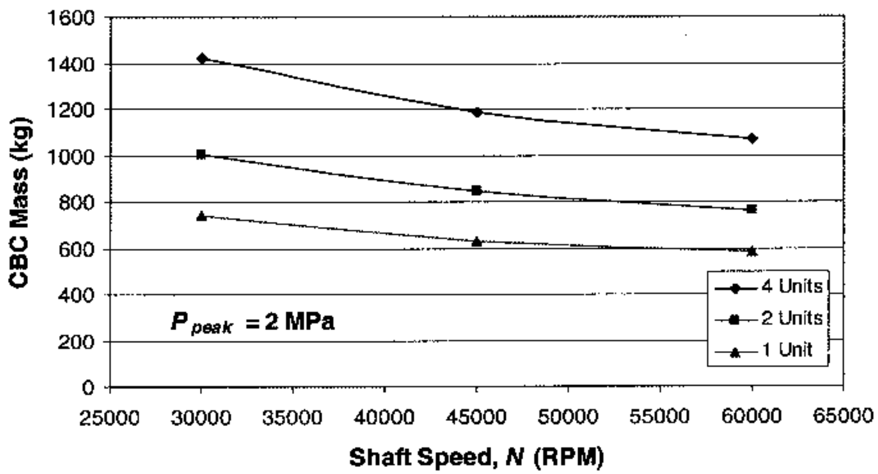
Design Results at 45000 RPM

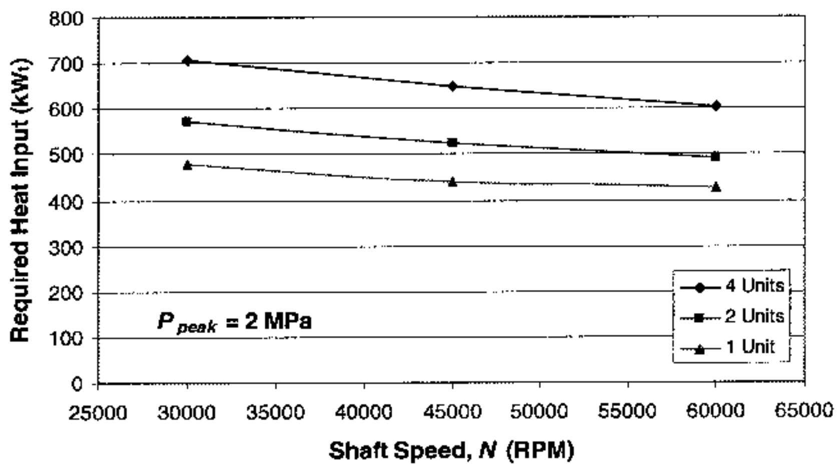


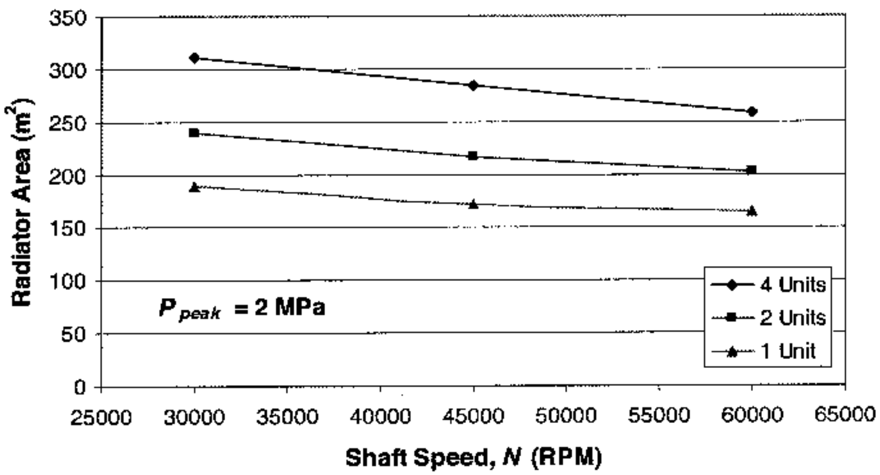




Design Results at 2.0 MPa







Minimum Cases

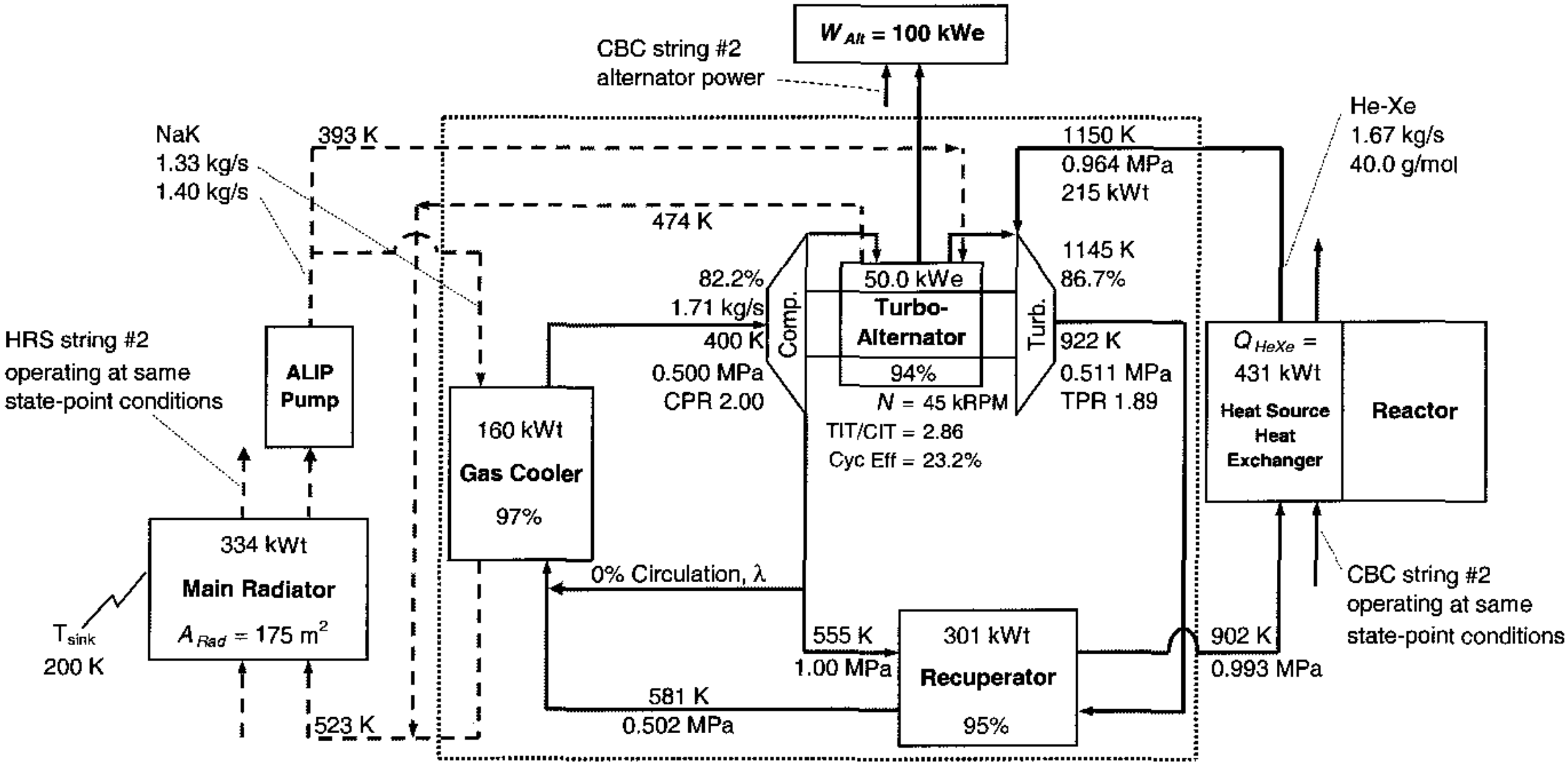
Minimum Case	# Units	Mass (kg)	Q_{HeXe} (kWt)	A_{Rad} (m^2)	P_{peak} (MPa)	N (RPM)
CBC Mass	1	580	426	165	2	60000
Radiator Area	1	656	398	155	1	45000
Heat Input	2	890	393	158	0.5	45000

- Resulting combination of performances among components
  - Recuperator mass (30 – 50% of CBC mass) decreases with increased pressure
  - Duct wall thicknesses increase with increased pressure
  - Bearing and windage losses increase with increased pressure
  - Turbomachinery efficiencies decrease with increased pressure, but increase with increased shaft speed
  - Turbine-alternator-compressor mass decreases at higher shaft speeds

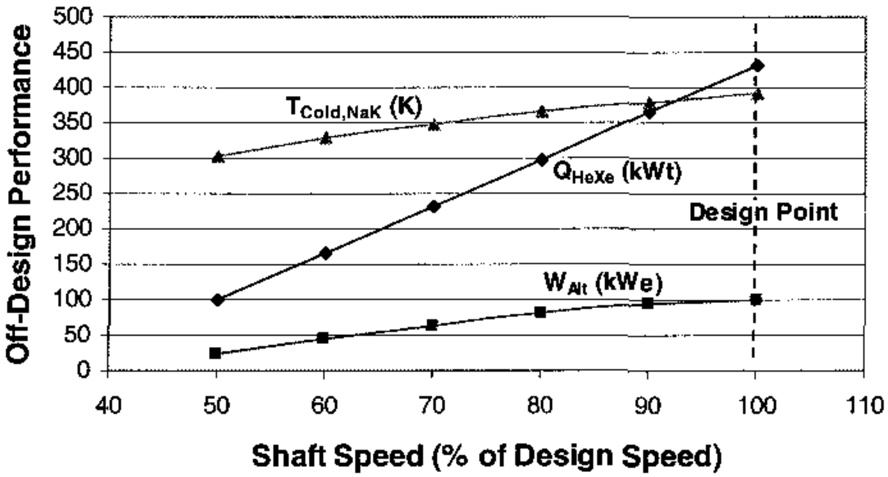
Off-Design Case Definition

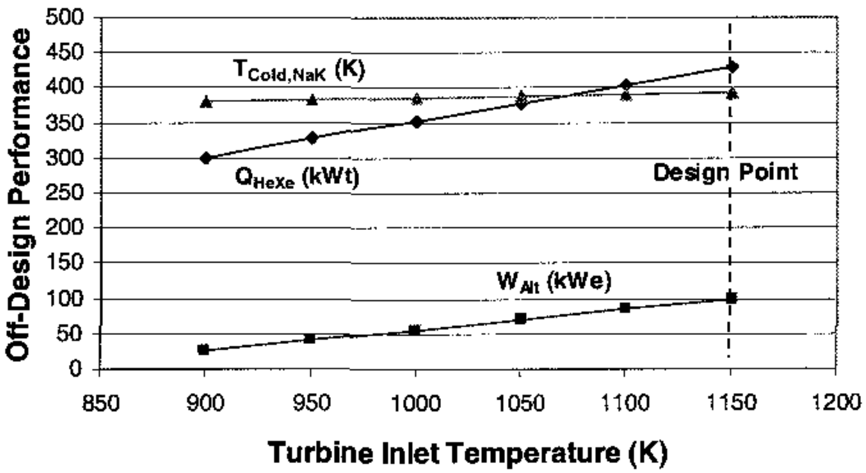
- Nominal Design Point:
  - 45000 RPM shaft speed
  - 1.0 MPa cycle peak pressure
  - Two 50 kWe Brayton units
  - Geometries and gas inventory fixed for the transition to off-design
- Varied three operating parameters, one at a time
  - Shaft speed (100 – 50%)
  - Turbine inlet temperature (1150 – 900 K)
  - Compressor exit flow circulation (0 – 20%)
- Reduce thermal input power without freezing the radiator
  - Radiator far-field temperature maintained at 200 K
  - $T_{NaK} > 262$ K
  - NaK mass flow rate kept constant

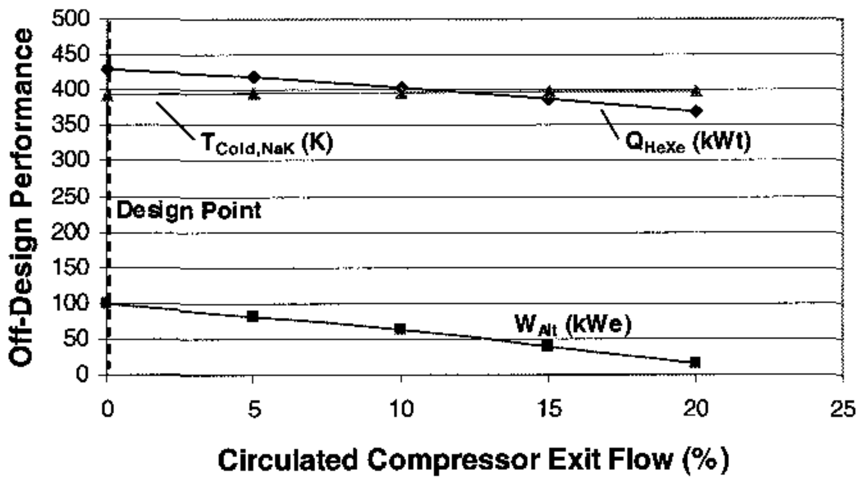
Off-Design Nominal Operating Point



Off-Design Performance Results





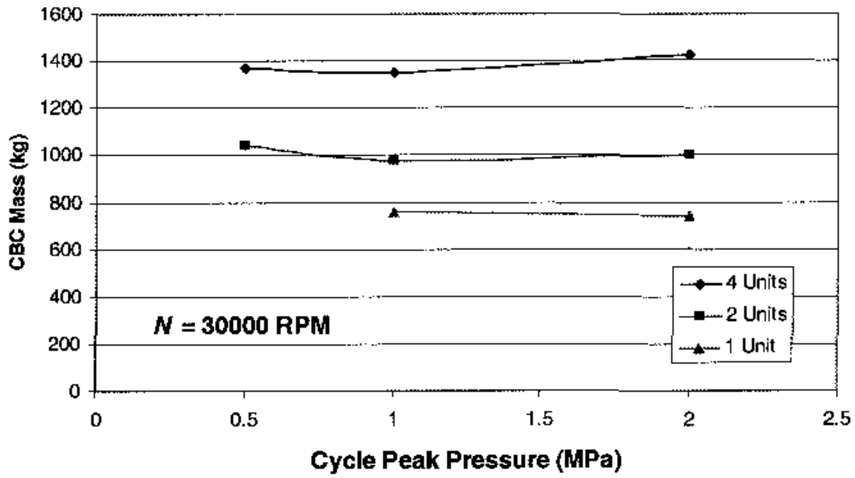


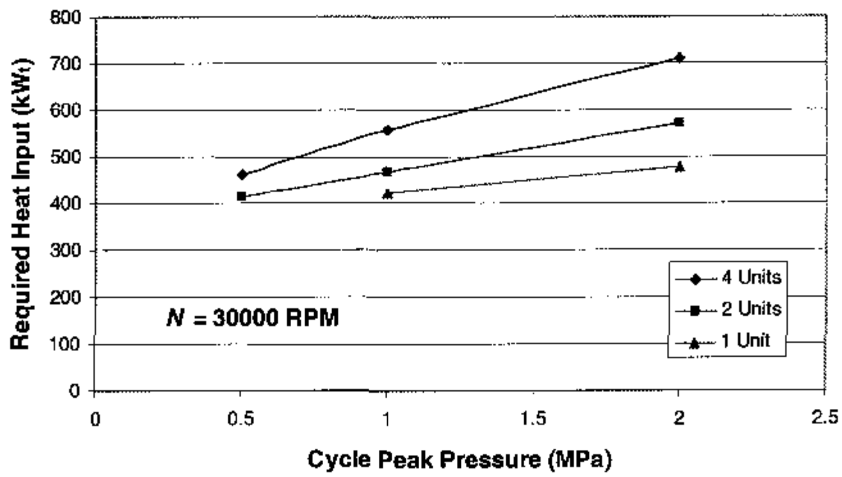
Conclusions

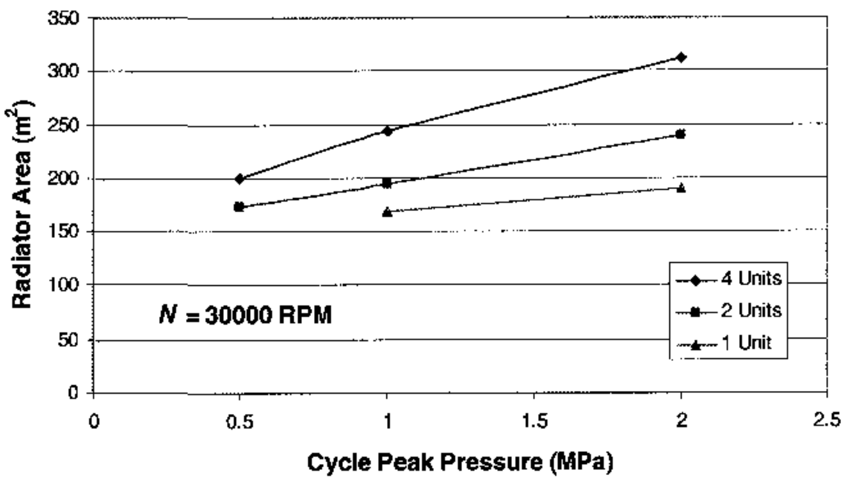
- Design point conclusions
  - The one-Brayton-unit system always exhibited lower mass, radiator area, and thermal input power than the two-unit and four-unit power conversion systems
  - Lower cycle peak pressure resulted in a smaller radiator and less thermal input power
    - Mass not as sensitive to cycle peak pressure over the range of 0.5 – 2.0 MPa
  - Higher shaft speeds resulted in lower Brayton mass, smaller radiator area, and less thermal input power
  - Suggested improvements to the method
    - Use a bearing and windage loss model that accounts for shaft speed. We do have a physics-based model, but it is believed to have high uncertainty. Experiments are underway at GRC
- Off-design performance conclusions
  - Reducing the shaft speed was most effective at reducing thermal input power, but also lowered the NaK temperature the most and changes alternator frequency
  - Lowering the turbine inlet temperature was next most effective at reducing thermal input power, NaK temperature dropped very little
  - Circulating compressor exit flow was least effective at reducing thermal input power, NaK temperature actually increased slightly
  - Of the cases considered, probably a combination of reduced shaft speed and lowered turbine inlet temperature would be most effective at extending reactor life as well as slowing secondary creep in the hot-end materials
  - Suggested improvements to the method
    - Examine combinations of off-design operating points
    - Look at the effects of changing the gas inventory

Backup Charts

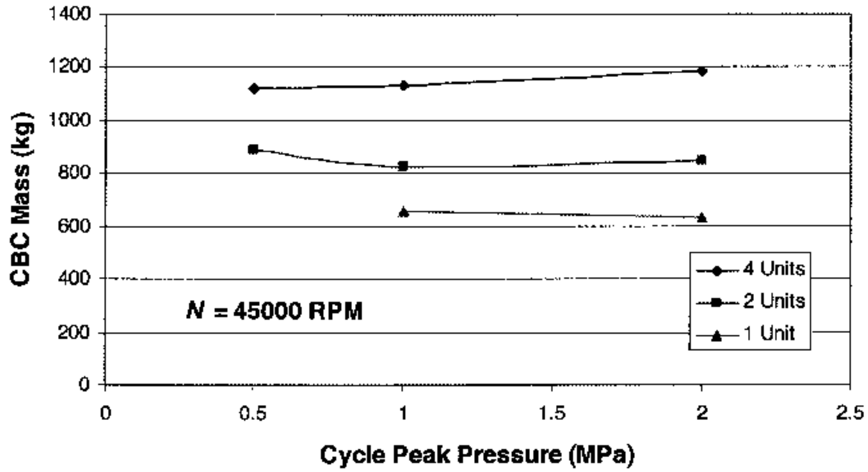
Design Results at 30000 RPM

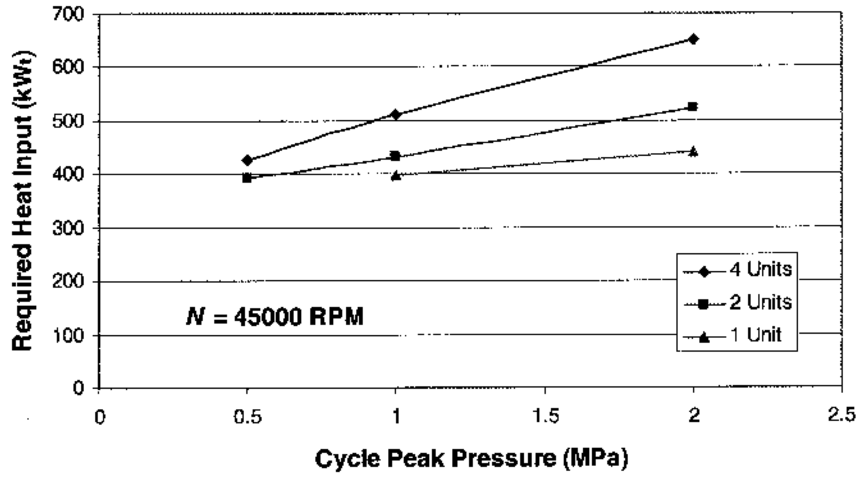


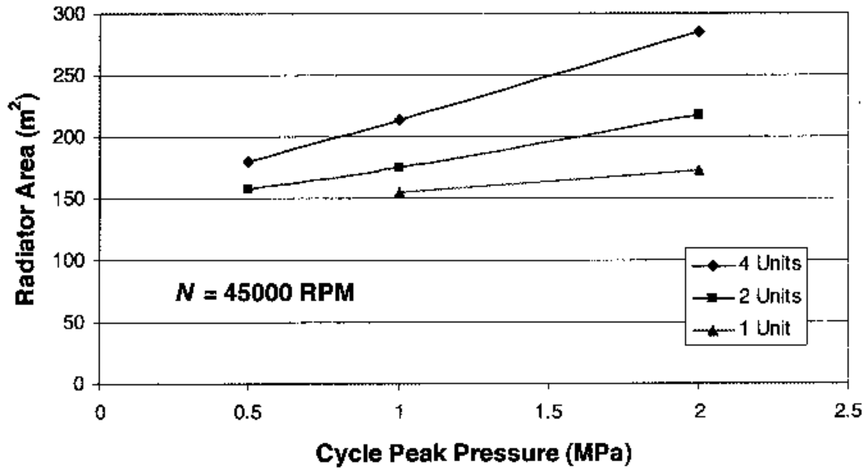




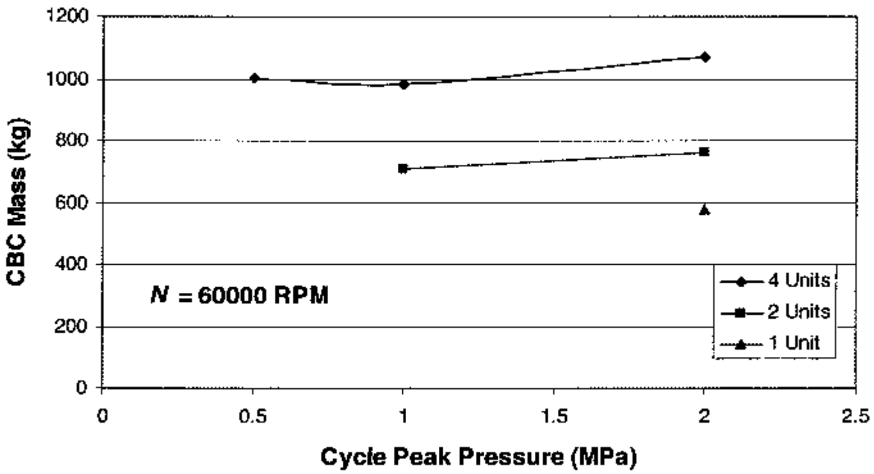
Design Results at 45000 RPM

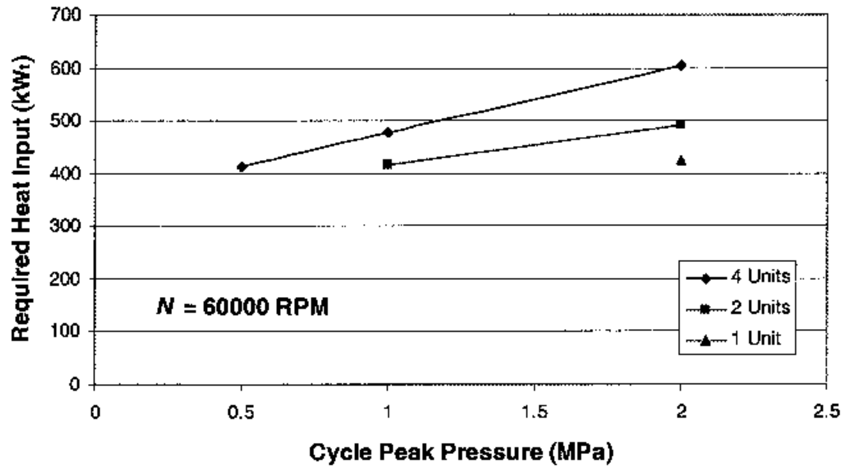


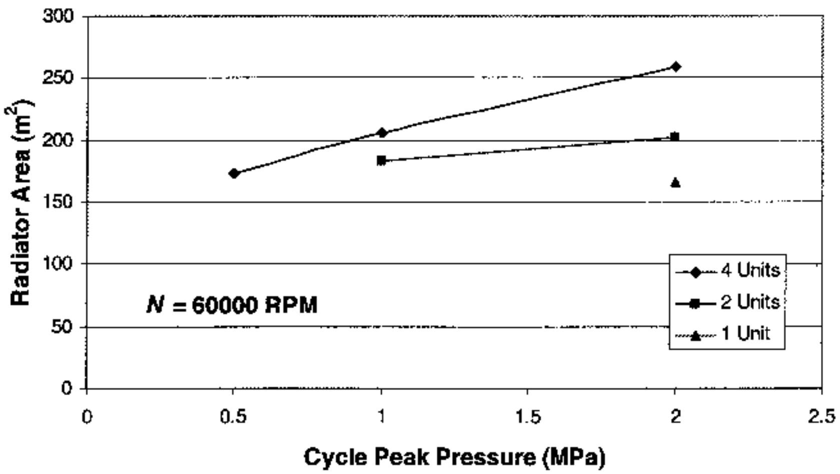




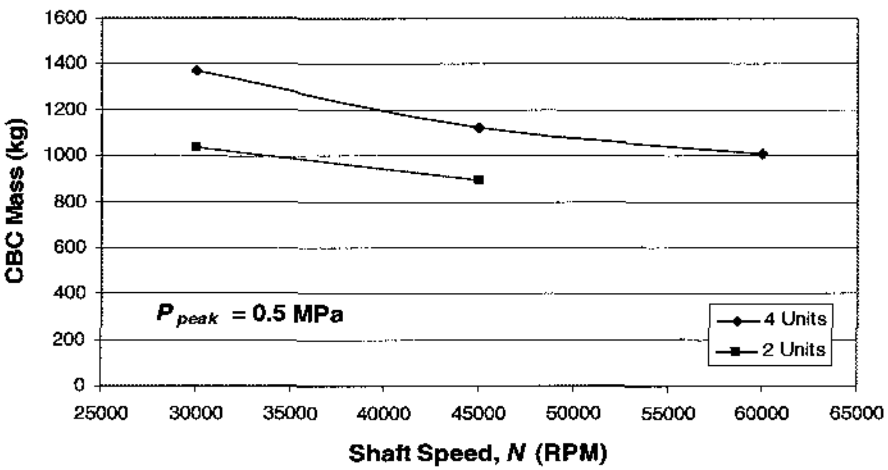
Design Results at 60000 RPM

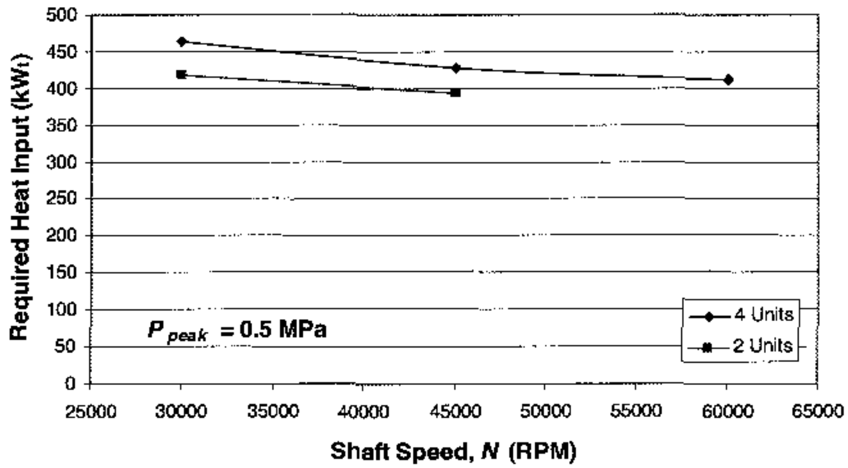


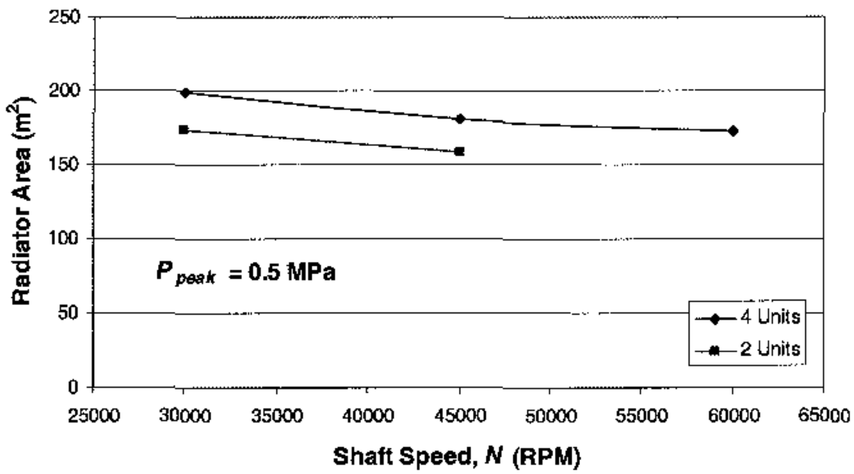




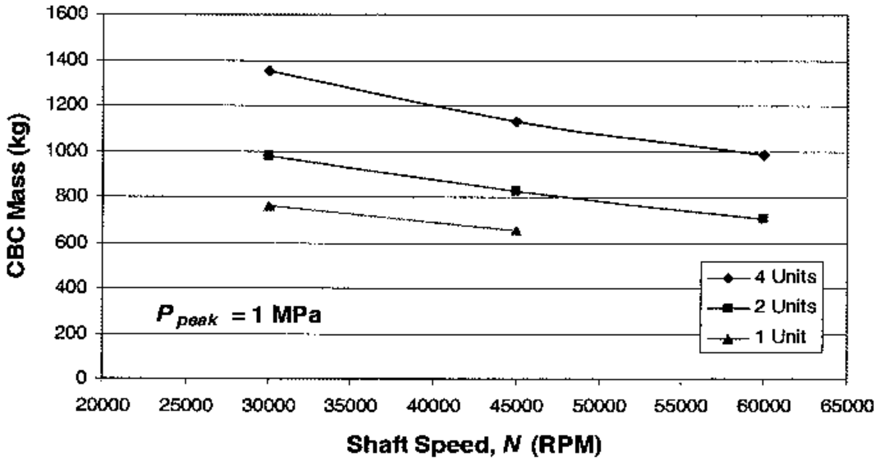
Design Results at 0.5 MPa

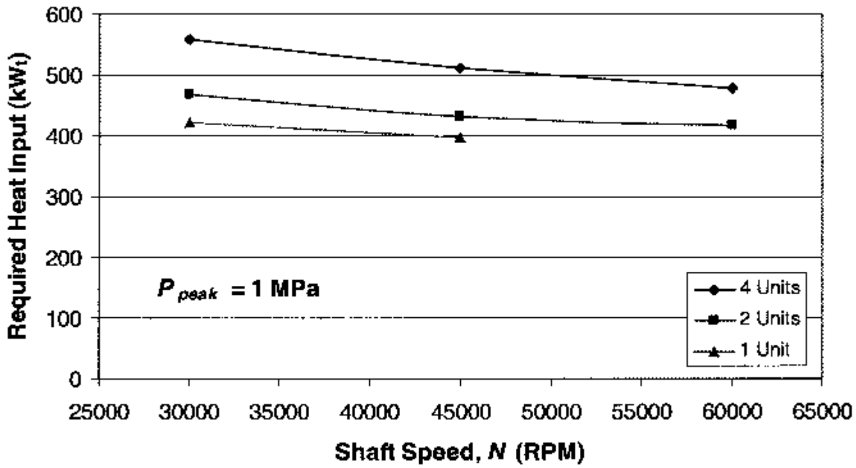


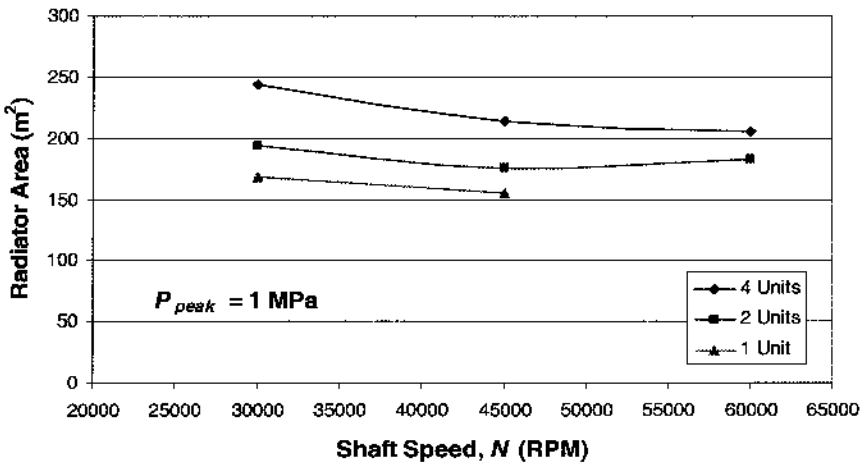




Design Results at 1.0 MPa







Design Results at 2.0 MPa