Research and Technology Activities Supporting Closed-Brayton-Cycle Power Conversion System Development

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The elements of Brayton technology development emphasize power conversion system risk mitigation. Risk mitigation is achieved by demonstrating system integration feasibility, subsystem/component life capability (particularly in the context of material creep) and overall spacecraft mass reduction. Closed-Brayton-cycle (CBC) power conversion technology is viewed as relatively mature. At the 2-kWe power level, a CBC conversion system Technology Readiness Level (TRL) of six (6) was achieved during the Solar Dynamic Ground Test Demonstration (SD-GTD) in 1998. A TRL 5 was demonstrated for 10 kWe-class CBC components during the development of the Brayton Rotating Unit (BRU) from 1968 to 1976. Components currently in terrestrial (open cycle) Brayton machines represent TRL 4 for similar uses in 100 kWe-class CBC space systems. Because of the baseline component and subsystem technology maturity, much of the Brayton technology task is focused on issues related to systems integration. A brief description of ongoing technology activities is given.

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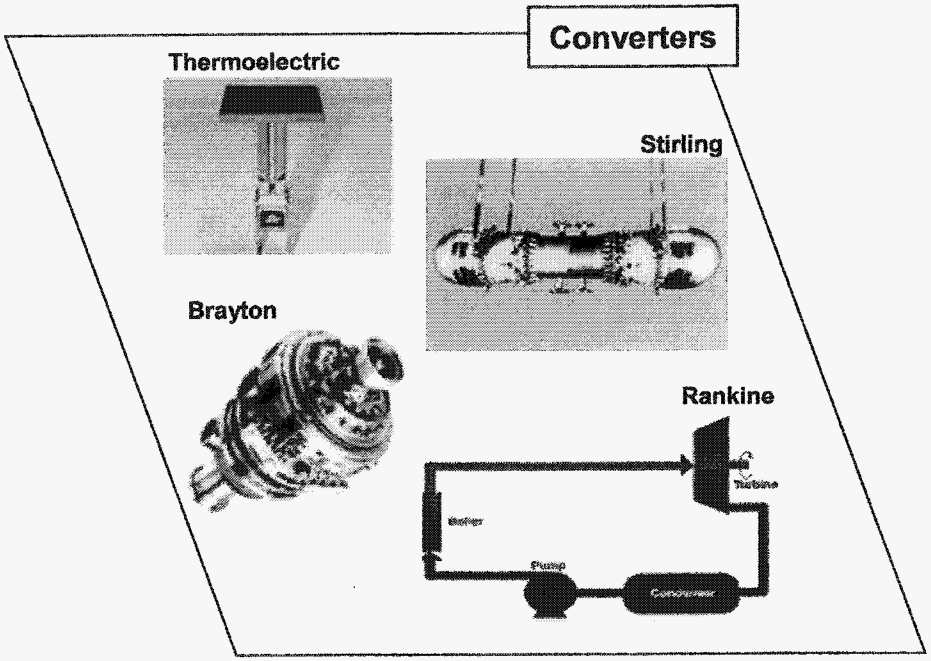
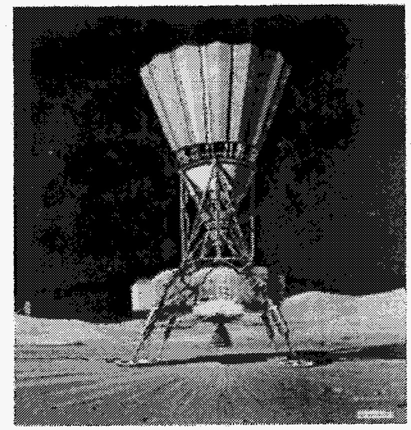
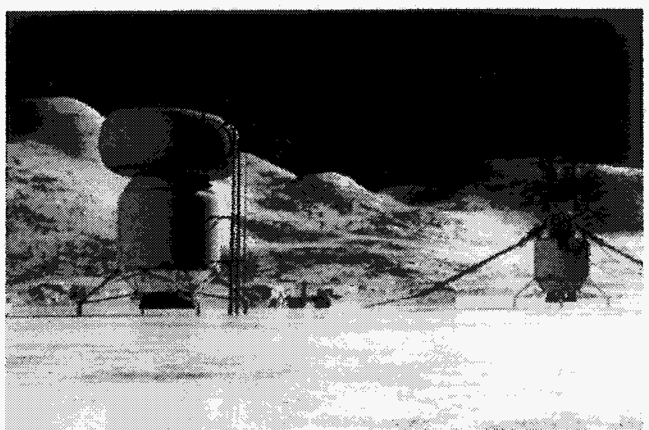
Some Nuclear Electric Power Possibilities

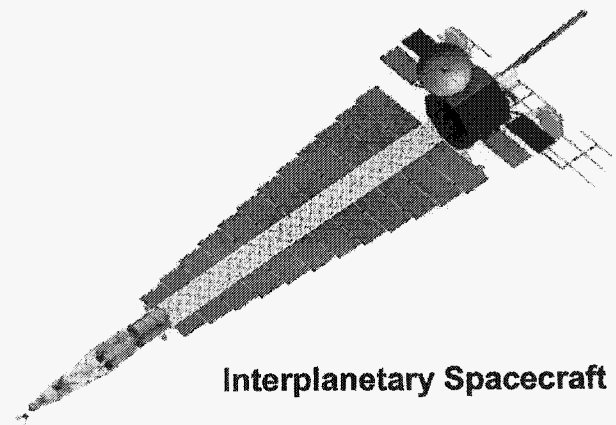




Landers



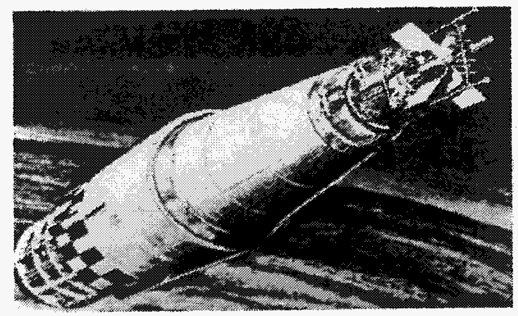
Surface Bases



Interplanetary Spacecraft

Some Advanced Power Conversion Challenges

1. Multiple year operation
   - High reliability components & systems
   - Long life materials with conservative design margins
   - Hermetic sealing to prevent fluid leakage
2. Generate power ~200X that of previous U.S. nuclear-fission space system
   - High-power static-conversion designs
   - Alternative dynamic-conversion approaches
3. Rapid and rigorous development
   - Focused development programs
   - High-TRL component technologies
4. Provide minimum mass designs
   - High-temperature operation
   - Alternative lightweight materials
   - System-level mass optimization
5. Operate in severe environments
   - Radiation-tolerant materials and components
   - Micrometeoroid/Orbital Debris (MMOD) and Atomic Oxygen (AO) protection
6. Assure mutually compatible interfaces with reactor, heat rejection, and PMAD
   - Effective inter-agency (NASA/DoE) & government/industry teaming relationships
   - Strong system engineering & integration

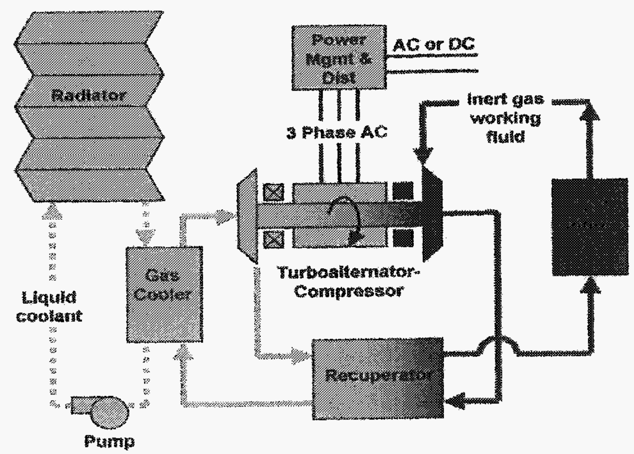


SNAP-10A (USA, 1965)

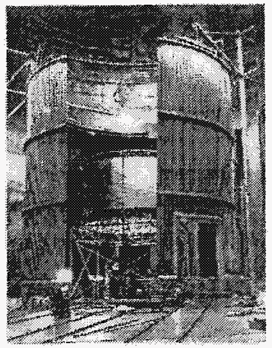
R&T for Closed-Brayton-Cycle (CBC) Power Conversion

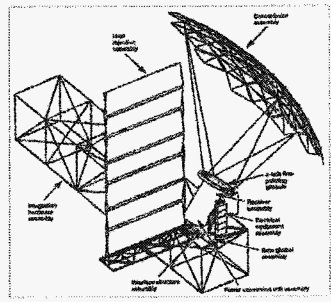
- Current Power Conversion Subsystem R&T effort is focused on risk-reduction activities

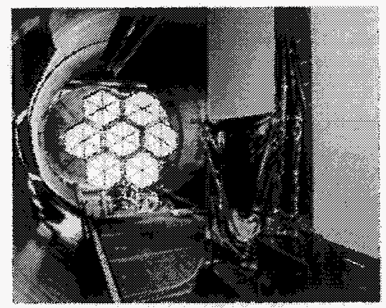
- Focus Areas
  - Power Converter Subsystem
  - Power Conditioning & Distribution Subsystem
  - Heat Rejection Subsystem
  - Power Conversion System Materials

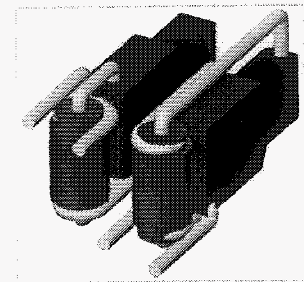


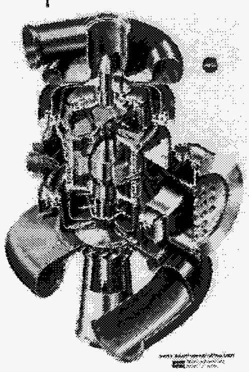
Space Brayton History

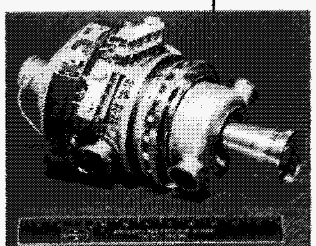


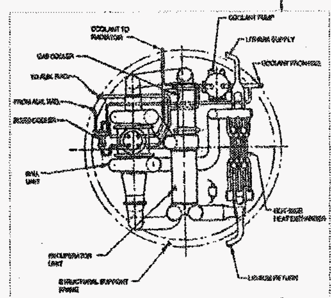


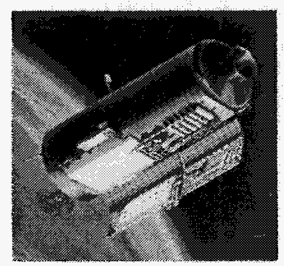


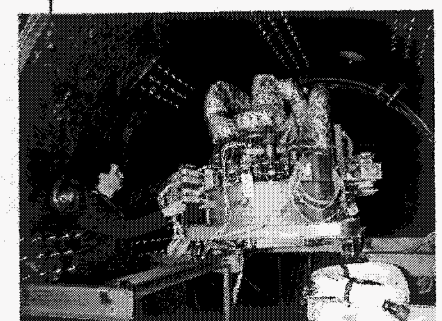












1970

- 10 kW Brayton Rotating Unit (BRU)
- 2 kW Mini-BRU
- 1.3 kW Brayton Isotope Power System (BIPS)
- 100 kW to MW Class NEP Concepts

1980

- 25 kW Space Station Freedom Solar Dynamic (SD) Power Module
- 20 kW SP-100 Design

1990

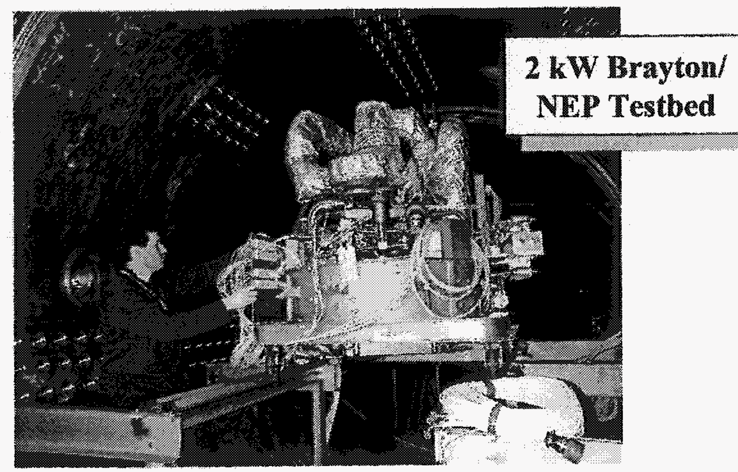
- 2 kW SD Ground Test Demonstration
- SD-Mir Flight Experiment
- 0.5 to 6 kW Dynamic Isotope Power System (DIPS)

2000

- 100 kW-Class NEP Concepts
- 2 kW Brayton Testbed
- 55 watt Micro-Turbine

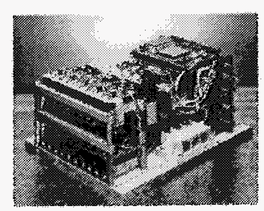
2-kWe Brayton Converter Unit

- Existing 2-kW Brayton Unit Available for NEP Risk Reduction
  - SD GTD Brayton Converter
  - Electrical Gas Heater
  - Commercial Chiller
  - Alternator Test Rig (ATR)
- Tasks Completed
  - Replaced SD Receiver w/Gas Heater
  - Designed & Assembled New (In-House) Electrical Controller
  - Completed Initial Checkout & Performance Mapping (June '02)
  - Designed & Assembled 1100 Vdc Transformer-Based Controller for Ion Thruster Demo
  - Ion Thruster (NSTAR) Demo
- Current Plans
  - Mechanical Dynamic Modes Test (FY04)
  - Thermal Transient Modes Test (FY05)
  - Integrate & Test Advanced Radiator (FY06)

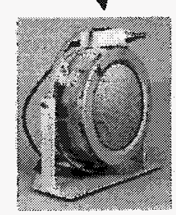


Evaluate Control Methods & Transient Thermal Response

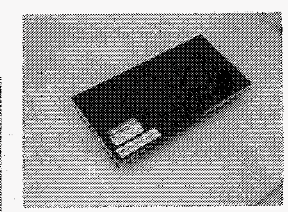
Demonstrate High Voltage Distribution



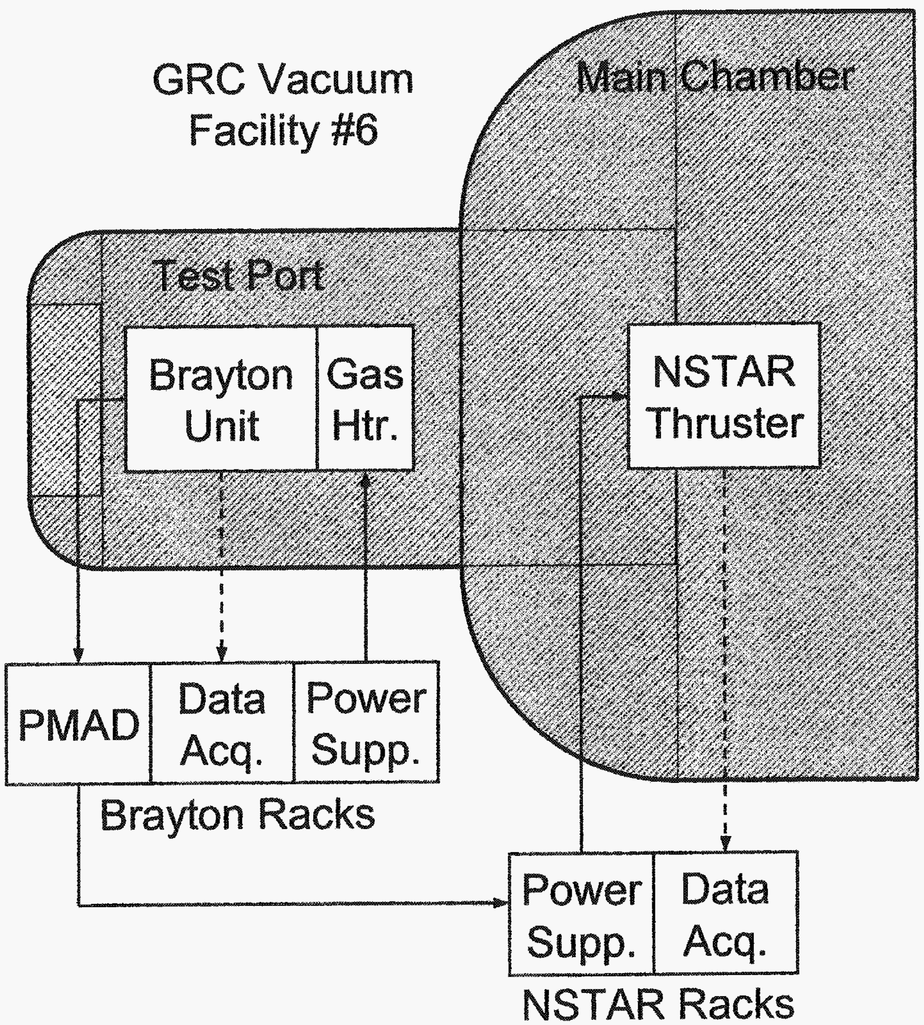
Characterize Ion Thruster Interactions

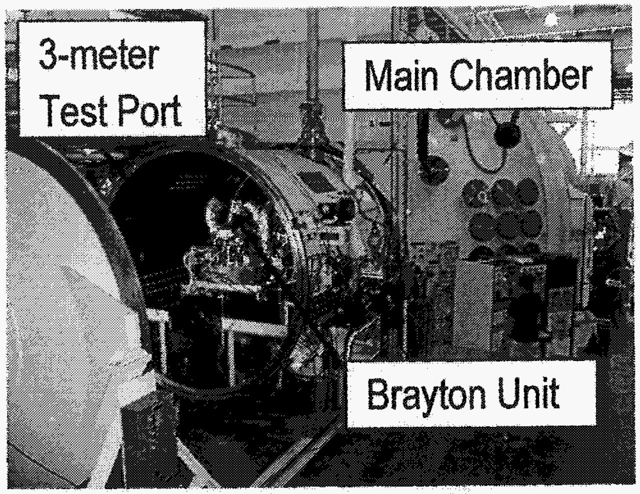


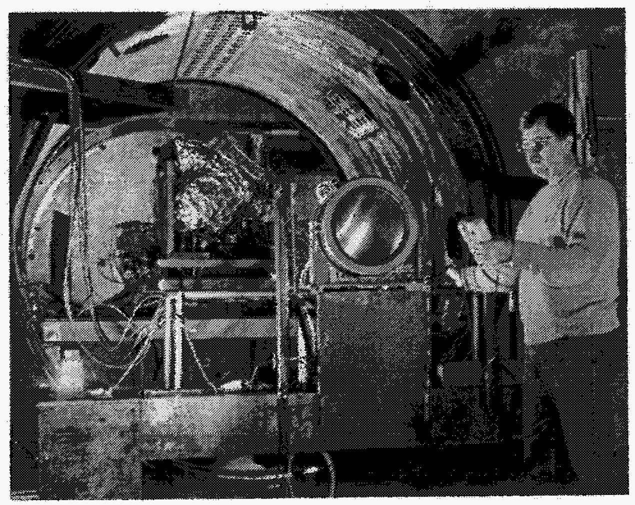
Demonstrate Composite Radiator Technology



Brayton NSTAR Test Layout

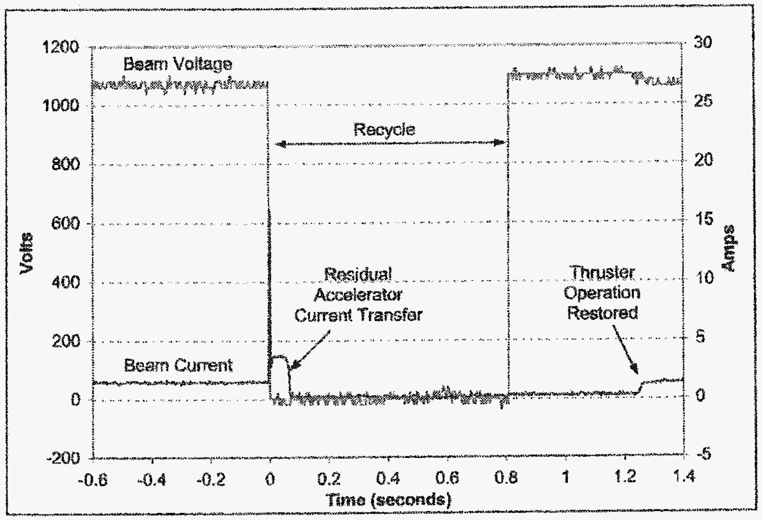


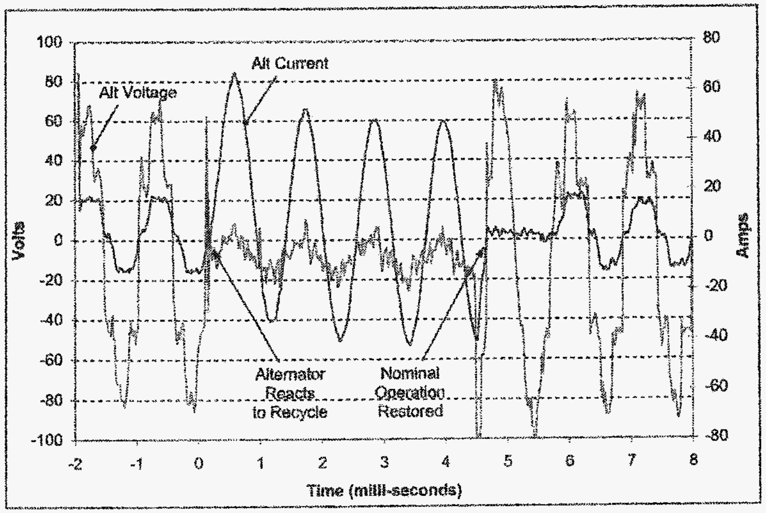




Test Results

- Stable thruster operation demonstrated at all test points
- Demonstrated high AC-to-DC conversion efficiency
- High-speed load switching from ion thruster to PLR during thruster recycles





Alternator Test Unit

Objective - Design, build, and test a high speed 25-100 kWe Closed Brayton Cycle Alternator Test Unit to examine and characterize electrical performance and interactions with the balance of an NEP electrical system.

- **Phase 1 - Alternator Design Studies (6 mo.)**
  - Perform trade studies to evaluate alternator design options over a range of potential operating parameters (see table)
  - Develop an ATU conceptual design including drive system and electrical controller
- **Phase 2 - ATU Fabrication and Test (15 mo.)**
  - Complete a detailed design and fabricate the ATU, drive system, and controller
  - Perform operational checkout of ATU at contractor facility
  - Deliver ATU, drive system, and controller to NASA GRC for integration into High Power PMAD Testbed

Design Parameter	Values
Net Alternator Power, kWe	**25, 50, 100**
Line-to-Line Voltage, Vrms	**400, 4000**
Operating Speed, RPM	**30000, 60000**
Number of Magnetic Poles	**2, 4, 6, 8**

- **Status**
  - Phase 1 contracts awarded (Hamilton-Sundstrand, Honeywell)
  - Phase 1 concluding: trade study prelim results and concept designs
  - Phase 2: detailed design Jan 05; hardware delivery Jan 06

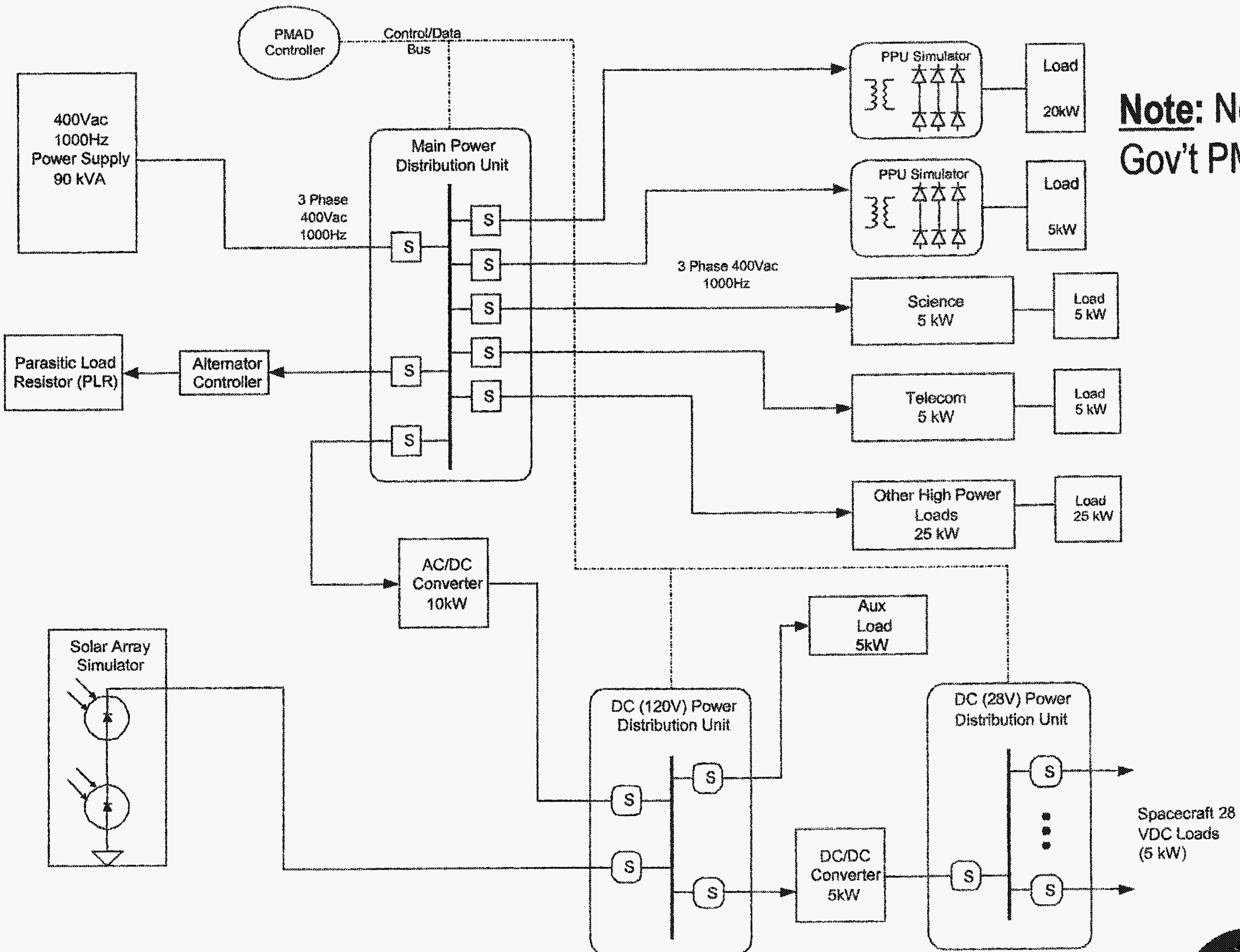
High Power PMAD

Objective – **Design and develop a high power breadboard PMAD system to support technology development and design activities associated with the development of a generic NEP-Brayton spacecraft system for deep-space applications**

Note: **not the Jupiter Icy Moons Orbiter (JIMO) Gov't PMAD design**

- Initial Capability
  - Built using readily available, off-the-shelf components
  - Supports trade studies and technology development activities
- Final Configuration
  - Brassboard hardware; spacecraft-like architecture option
  - PMAD design verification testbed
  - Characterize electrical performance of ATU
  - Representative PPU and Bus load accommodation
  - ATU / PPU / Ion thruster end-to-end characterization tests
- Status
  - Preliminary design complete (initial capability stage)
  - Description document distributed
  - Initial configuration in fabrication
  - Final configuration design ongoing

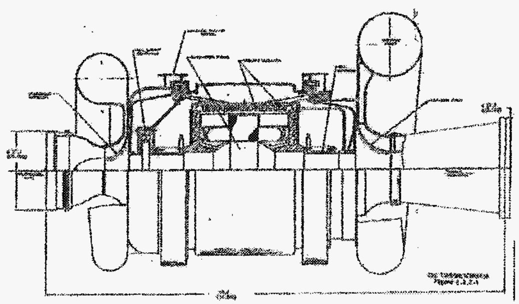
High Power PMAD Initial Capability Configuration

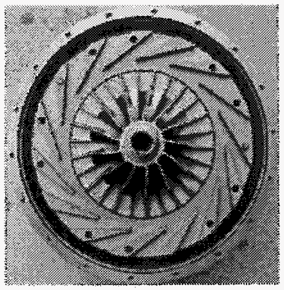


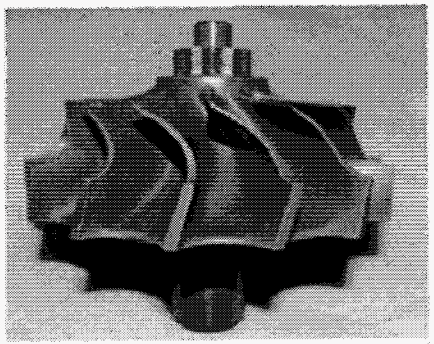
Note: Not the JIMO Gov't PMAD design

Turbomachinery

- **Advanced rotor/wheel conceptual design studies**
  - Task scheduled for FY05
  - Advanced aero design configurations
  - Advanced materials options (Si_3N_4, C-C)





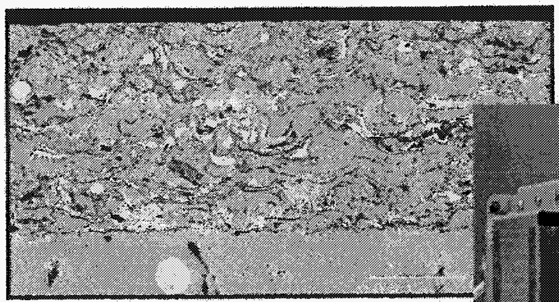


Ceramic (Kyocera) gasifier turbine in IR Powerworks machine

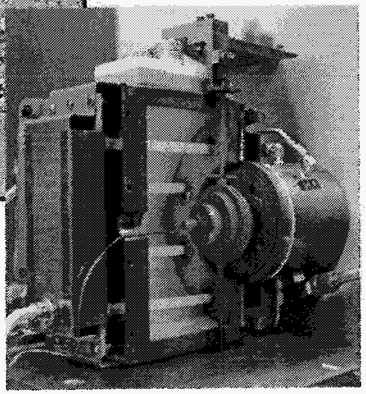
- **Integrated wheel/shaft/bearing design, development & test**
  - Use existing DD&T capability at GRC

Bearing Technology

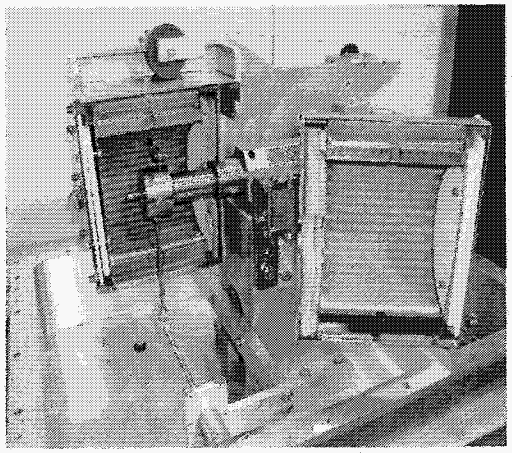
- **Material Selection**
  - Low/Moderate Temp: Graphite, Moly Disulfide, Teflon, Polyimides
  - High Temp: PS100 (NiCr-Glass), PS200 (NiCo-Cr_3O_2), PS304 (NiCr/CrO_3 + Ag, BaF_2/CaF_2)
  - Application Processes: Sprays, Power Metallurgy, Thin Films
- **Testing**
  - Friction & Wear Rigs (Pin on Disk, Pin on Plate)
  - Elevated Temperatures
  - Controlled Atmospheres (e.g. HeXe)
- **Post-test Analyses**
  - Wear Measurements
  - Optical Microscopy/Profilometry
  - Electron, X-ray Examination
- **Performance Characterization**
  - Start / Stop Torques
  - Bearing Preload
  - Power loss and Heat Generation
  - Load Capacity and Sizing
  - Durability and Life
  - Radiation Effects



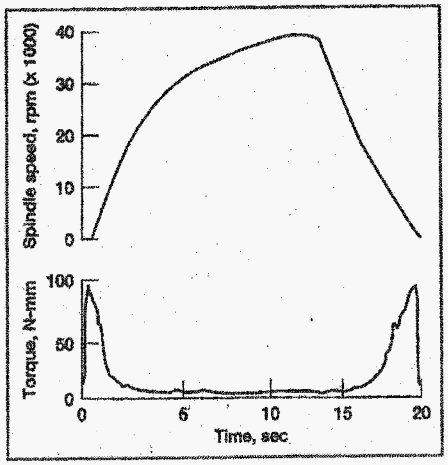
NASA PS304



Journal Test Rig



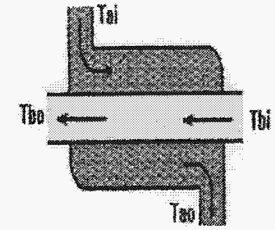
Controlled Atmos. Test Rig

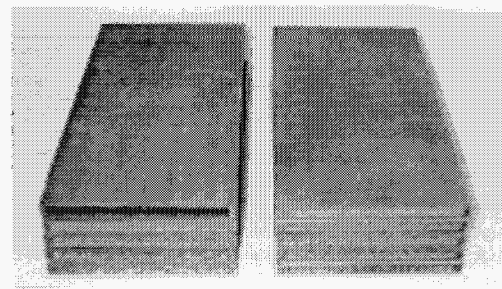


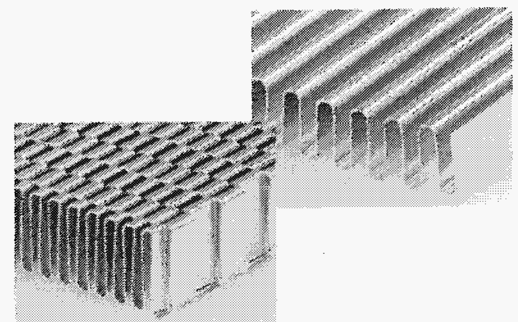
Speed and Torque Trace

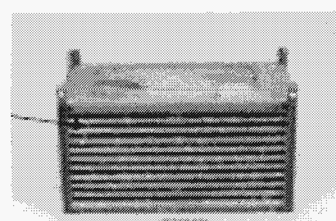
Heat Exchangers

- Heat exchanger modeling
  - In-house code upgrades completed
- Carbon-carbon recuperator study
  - IECEC 2004 Paper
- Hot side heat exchanger options
  - Study ongoing; report Sept 04
- Gas coolers
- University grant (Penn St/ARL)
  - Advanced materials
  - Constructal-formulation-based design
  - Integral design/CFD analysis capability
- Upgraded GRC HX test facility
  - Ambient & thermal-vac test capability
  - Mods ongoing; July 05 completion
- DoD technology leveraging
  - SBIR with Allcomp; C-C plate-fin HXs







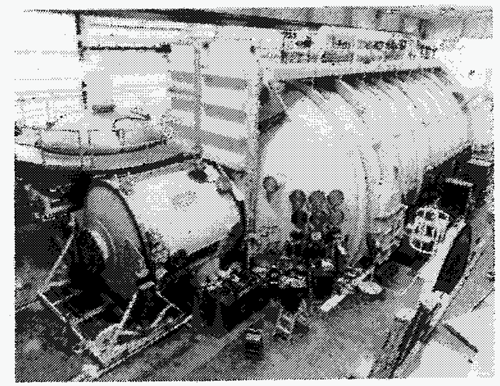


Radiator Demonstration Unit

Objective - Design, build, and test a radiator using advanced materials and heat spreading technology to characterize and demonstrate heat rejection performance over a range of temperatures applicable to dynamic power conversion options.

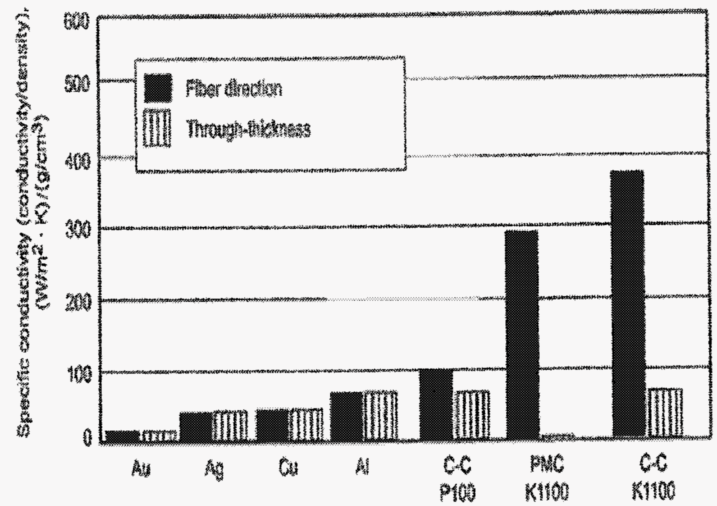
Design Parameter	Values
Heat Load, kWt	**200, 400, 800**
Radiator Outlet Temperature, K	**300, 350, 400**
Radiator Fluid ΔT, K	**100, 150**
Sink Temperature, K	**200**

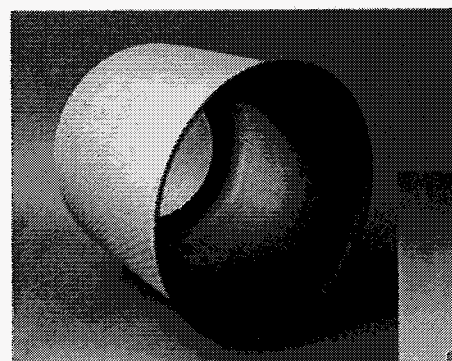
- **Phase I - RDU Design Trade (6 mo.)**
  - Two six-month RDU contracts awarded to conduct trade studies evaluating advanced radiator designs and develop a conceptual design
    - Advanced Cooling Technologies
    - Lockheed Martin Space Systems Company
  - Design Reviews: Apr/Jun '04
  - Trade Studies Complete: Jun/Aug '04
  - High Temperature (500/550 K) water heat pipe life tests underway at ACT.
- **Phase 2 - RDU Fabrication and Test (16 mo.)**
  - Validate manufacturing and design approach through development and test of RDU
  - Deliver RDU to NASA GRC for stand-alone and integrated thermal vacuum tests with 2kWe CBC test-bed
  - Design Reviews: Jan '05
  - Final Design Reports: Oct '05
  - Thermal/Vacuum Tests at GRC Tank 6 : Feb '06



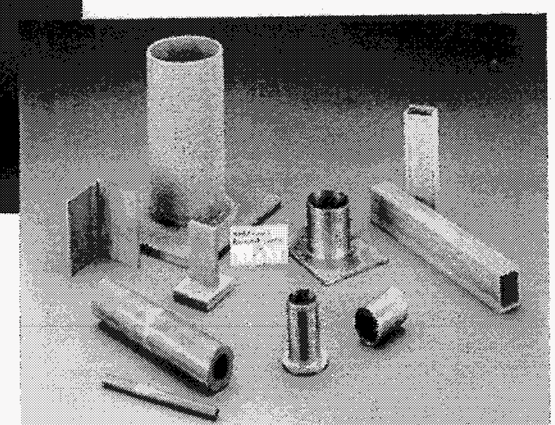
Carbon-Carbon Composites

- **Carbon-Carbon provides low density, high conductivity, high strength material for various uses:**
  - Radiator Panels
  - Heat Exchangers
  - Structures and Armoring
- **GRC Addressing Two Key Areas for Carbon-Carbon Implementation**
  - C-C to Metallic Brazing and CTE Mismatch Resolution (req'd for fluid system integration)
  - C-C Manufacturing Processes Using Melt Infiltration and Fiber Reinforcement
- **Expected Deliverables**
  - C-C Manufacturing Survey
  - Experimental Brazing Trials & Evaluation
  - C-C Materials with Tailored Properties
  - Transfer of Brazing and Assembly Technology to Vendors
- **Leverage Current Aero Programs**
  - Affordable Fiber Reinforced Ceramic Composites (AFReCC)
  - Affordable, Robust Ceramic Joining Technology (ARCJoinT)





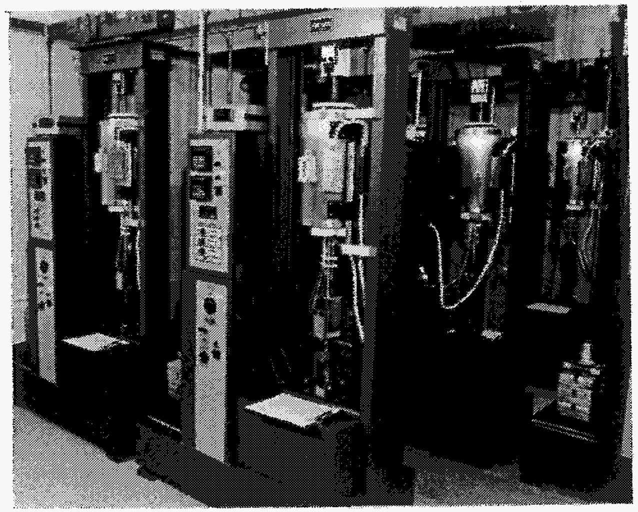
Ceramic Composites with Silicon Melt Infiltration

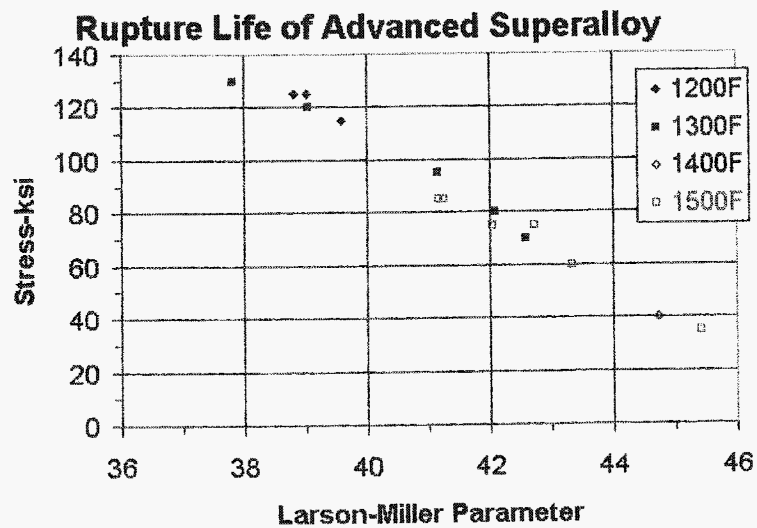


Ceramic Joining Examples

Creep Testing

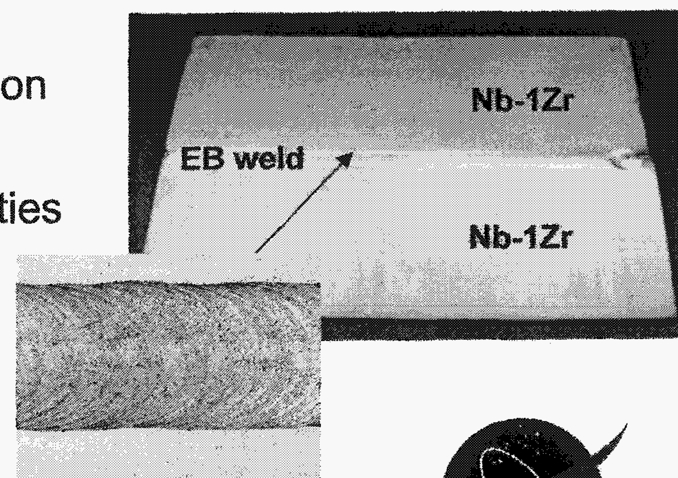
- **Conduct Broad Test Series of Potential Materials in Air Creep Rigs**
  - Cast Superalloys (e.g. MAR-M247)
  - Wrought Superalloys (e.g. LSHR Alloy)
  - Alternatives (e.g. TiAl, Silicon Nitride)
- **Selected Testing in new State-of-the Art Inert Gas Test Rigs**
  - 273 To 1300 K
  - 200 kg To 4,500 kg
  - Dual Strain Transducers with >100 Microstrain Resolution
  - Scheduled for FY04 Operation
- **Extrapolation Of Creep Data**
  - Test Candidate Materials Over a Wide Range of Temperatures and Stresses
  - Utilize Larson-Miller Parameter to Extrapolate Creep Data to Potential Mission Durations
- **Possible Testing of Bi-metallic Joints and Irradiated Material Samples**





Refractory Metal Interface

- Two Primary Concerns:
  - Contaminant Transport from Superalloy to Refractory via HeXe Working Fluid
  - Superalloy-to-Refractory Joints
- Contaminant Transport (e.g. O, N, C) Addressed through Superalloy Processing
  - Formation of Alumina on Surface Provides Protection Against Constituent Transport
  - Analysis Shows Partial Pressures of O_2 (10^{-38} torr) below Nb-1Zr Threshold (10^{-9} torr)
  - Experimental Verification in Work
- Electron Beam (EB) Welding Identified as Joining Approach
  - Solid-Solution Strengthened Hastelloy X + Nb-1Zr Initial Candidates
  - Others to be considered (e.g., INCO 617 + Nb-1Zr)
- Critical Process Elements include:
  - Long-term Stability And Deleterious Phase Formation
  - Working Fluid Exposure
  - Post-Weld Heat Treatment and Mechanical Properties



Technology Summary

Brayton Technology Efforts are Addressing Risk Areas

- Historical space system development and contemporary terrestrial systems inform current Brayton technology efforts
- 2-kWe test bed provides valuable tool for assessing power control, distribution and overall system integration issues
- Alternator Test Unit and Radiator Demonstration Unit address critical component technologies
- Turbomachinery, Bearing, and Heat Exchanger tasks complement potential industry development activities
- Materials Research will guide conversion system design, manufacturing, assembly, and life validation