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

Michael Barrett
NASA-GRC

Lee Mason, Tony Baez, Dave Hervol, Duane Beach, John Gayda, Cheryl Bowman, Frank Ritzert, Jay Singh, Chris Dellacorte, John Lucero

2nd International Energy Conversion Engineering Conference
Providence, Rhode Island USA
August 16, 2004
Acknowledgment

Project Prometheus, NASA's Nuclear Systems Program, supported the work described within this presentation, 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 NASA, Project Prometheus or the JIMO Project.

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Some Nuclear Electric Power Possibilities

Thermoelectric
Brayton
Stirling
Rankine

Converters

Surface Bases

Landers

Interplanetary Spacecraft

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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

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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

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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)

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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

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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

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Alternator Power, kWe</td>
<td>25, 50, 100</td>
</tr>
<tr>
<td>Line-to-Line Voltage, Vrms</td>
<td>400, 4000</td>
</tr>
<tr>
<td>Operating Speed, RPM</td>
<td>30000, 60000</td>
</tr>
<tr>
<td>Number of Magnetic Poles</td>
<td>2, 4, 6, 8</td>
</tr>
</tbody>
</table>

- **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

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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

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High Power PMAD Initial Capability Configuration

400Vac
1000Hz
Power Supply
90 kVA

Parallelic Load
Resistor (PLR)

Alternator
Controller

PMAD Controller

Control/Data
Bus

Main Power
Distribution Unit

3 Phase
400Vac
1000Hz

PPU Simulator

Load
20 kW

Science
5 kW

Load
5 kW

PPU Simulator

Load
5 kW

Telecom
5 kW

Load
5 kW

Other High Power
Loads
25 kW

Load
25 kW

AG/DC
Converter
10kW

Solar Array
Simulator

DC (120V) Power
Distribution Unit

DC/DC
Converter
5kW

DC (28V) Power
Distribution Unit

DC/DC
Converter
5kW

Aux
Load
5kW

Spacecraft 28
VDC Loads
(5 kW)

Note: Not the JIMO
Gov’t PMAD design

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NASA
Turbomachinery

- **Advanced rotor/wheel conceptual design studies**
  - Task scheduled for FY05
  - Advanced aero design configurations
  - Advanced materials options (Si$_3$N$_4$, C-C)

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

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Bearing Technology

- **Material Selection**
  - Low/Moderate Temp: Graphite, Moly Disulfide, Teflon, Polymides
  - High Temp: PS100 (NiCr-Glass), PS200 (NiCo-Cr₃O₆), PS304 (NiCr/CrO₃ + Ag, BaF₂/CaF₂)
  - 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

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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

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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.

- **Phase 1 - 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

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load, kWt</td>
<td>200, 400, 800</td>
</tr>
<tr>
<td>Radiator Outlet Temperature, K</td>
<td>300, 350, 400</td>
</tr>
<tr>
<td>Radiator Fluid ΔT, K</td>
<td>100, 150</td>
</tr>
<tr>
<td>Sink Temperature, K</td>
<td>200</td>
</tr>
</tbody>
</table>

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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)

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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**

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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} \text{ torr}) below Nb-1Zr Threshold (10^{-9} \text{ 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