Small Closed Brayton Cycle Engines for Space Applications

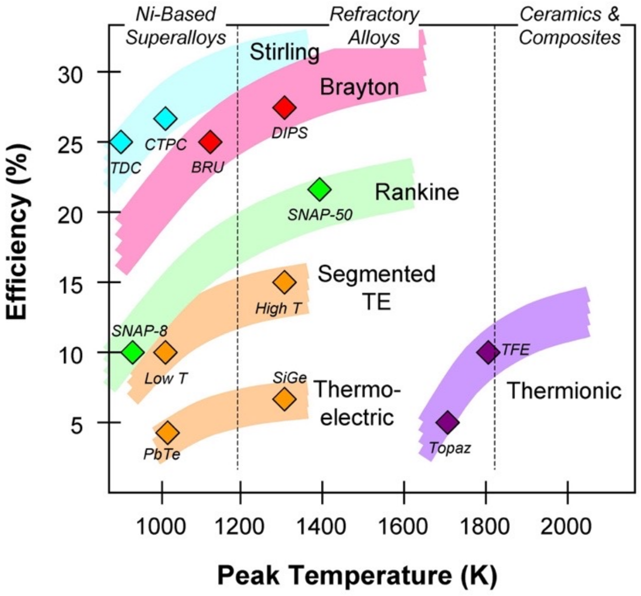
MIT Gas Turbine Workshop

Lee Mason

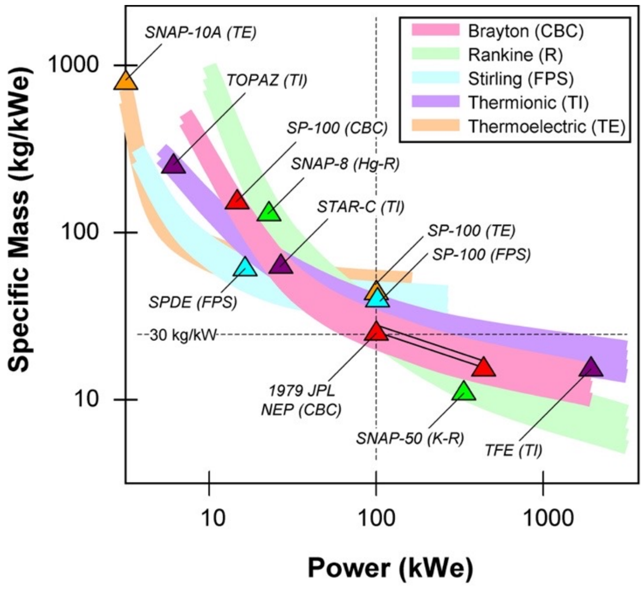
2 May 2023

System Trends & Discriminators

Efficiency vs Temperature

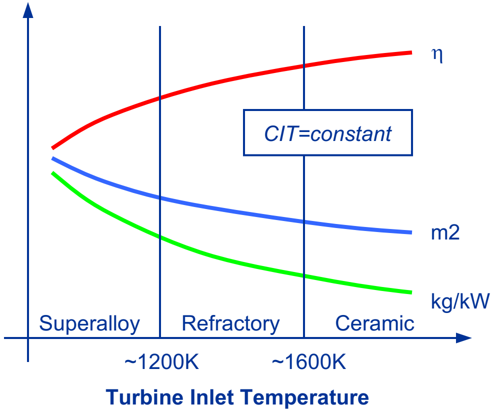


Specific Mass vs Power



Power Technology Options for Nuclear Electric Propulsion, IECEC 2002

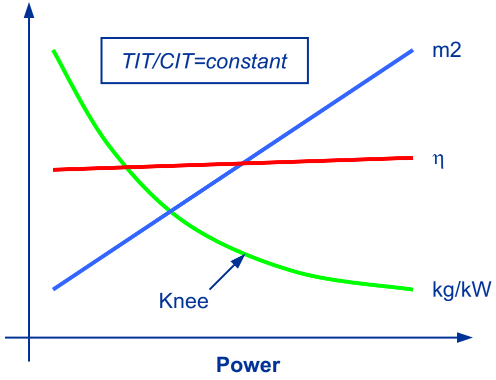
Brayton Systems Analysis Trends



<u>Increasing CIT:</u>
- Higher heat reject temp
- Smaller radiator ($\propto T^4$)

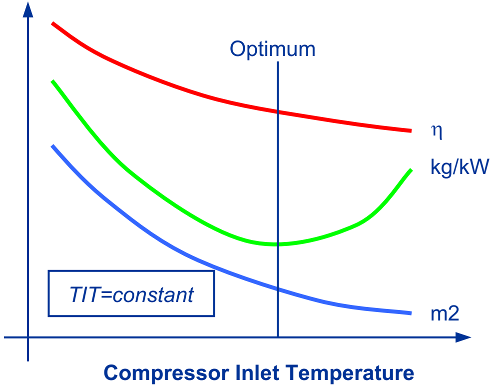
<u>But,</u>
- Smaller temp ratio
- Lower efficiency
- More Qin, larger heat source

Results in optimum mass



<u>Increasing TIT:</u>
- Larger temp ratio
- Greater efficiency
- Less Qin, smaller heat source
- Less Qrej, smaller radiator

<u>But,</u>
- TRL of advanced materials
- Greater thermal stress
- Possible life issues

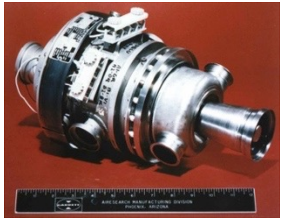
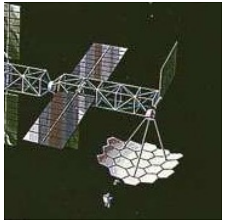


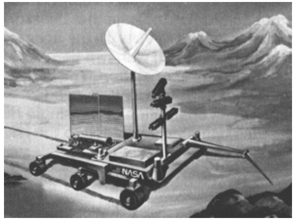
<u>Increasing Power:</u>
- Slight efficiency increase
- Linear area increase
- Large economy of scale benefits in Brayton

<u>But,</u>
- TRL issues at high power

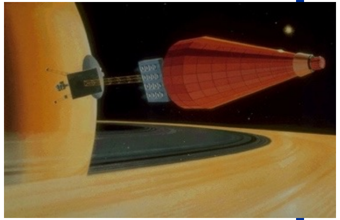
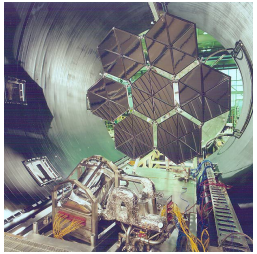
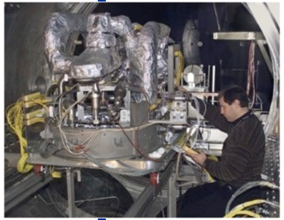
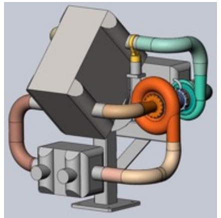
Mass curve has steep slope at low power & knee

Space Brayton Development 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 Nuclear Concepts

1980

- 25 kW Solar Dynamic (SD) Power Module for Space Station Freedom
- 20 to 500 kW SP-100 Brayton Designs
- 6 kW Dynamic Isotope Power System (DIPS)

1990

- 0.5 to 2.5 kW DIPS for Science & Exploration
- 2 kW SD Ground Test Demonstration
- 2 kW SD-Mir Flight Experiment
- 2 kW Brayton Testbed

2000

- 200 kW Brayton for Jupiter Icy Moons Orbiter (JIMO)
- 20 kW Dual Capstone Brayton Test Loop
- 12 kW Fission Surface Power (FSP) Brayton

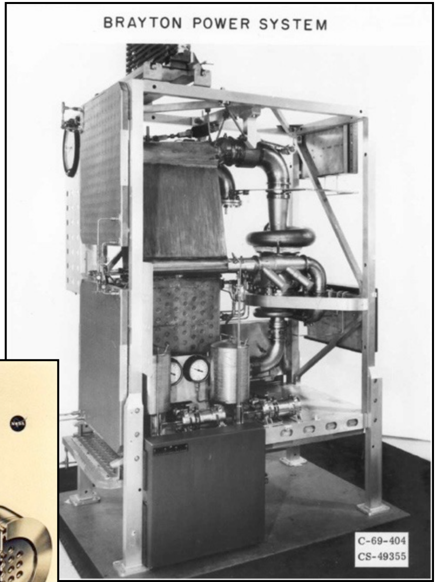
Brayton Rotating Unit

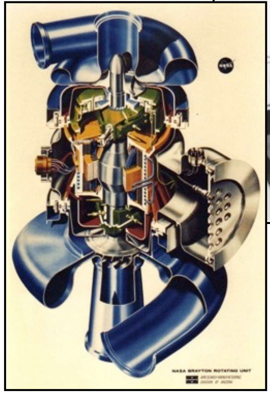
- **First-ever Closed Brayton Cycle (CBC) power conversion system for space (1968-76)**
  - 4 BRUs Fabricated by AiResearch and Tested at Lewis Research Center
  - Included Brayton Heat Exchanger Unit (BHXU) combined Recuperator and Cooler
  - 1 Unit (BRU-F) Modified with Foil Bearings

- **BRU Program Successfully Demonstrated:**
  - Manufacturing & Assembly
  - Jacking Gas Startup
  - High Conversion Efficiency (>25%)
  - Material Compatibility
  - Tilt-Pad Bearings
  - Extended Life: 38000 Hrs Operation on One Unit Without Degradation, Approx. 50000 Hrs Total on Four Units

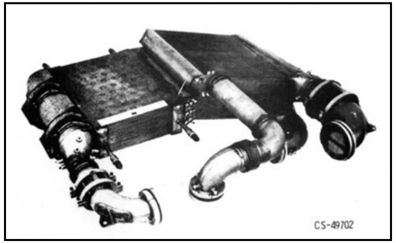
- **Performance Parameters:**
  - Alternator Output 2.25 to 15 kWe
  - Turbine Inlet Temp 1144 K (1600 F)
  - Compressor Inlet Temp 300 K (80 F)
  - Compressor Exit Pressure 310 kPa (45 psia)
  - 36000 RPM, 1200 Hz, 208 V
  - 65 kg BRU, 200 kg BHXU

BRU Life Test



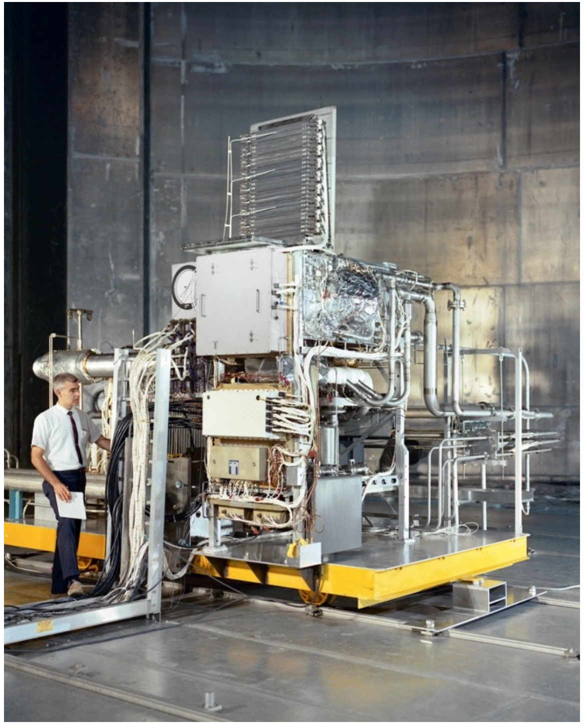


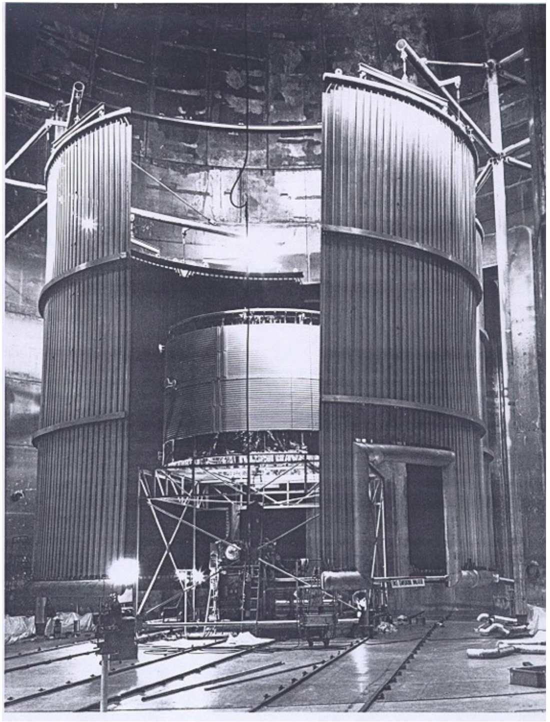
Turboalternator-Compressor



BHXU

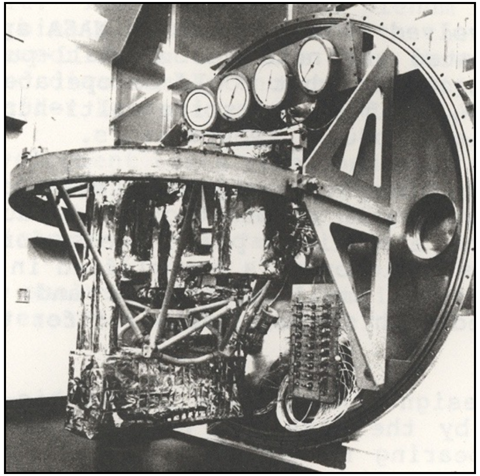
1972 BRU System Test at SPF



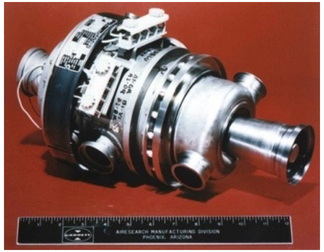


Mini-BRU

- **Mini-BRU and Recuperator developed for use with Modular Isotope Heat Source (1974-78)**
  - Built by AiResearch, Tested by Lewis
  - Major Differences from BRU: Lower Power, Foil Bearings, Internal Stator Cooling
  - Interchangeable Superalloy and Refractory Turbine Plenums Fabricated
- **Led to 1.3 kW Brayton Isotope Power System (BIPS) development (DOE)**
  - No Flight, but 1000 Hr Workhorse Loop Test
- **Mini-BRU Successfully Demonstrated:**
  - High Efficiency (>25%) at Lower Power
  - Foil Bearings
  - Alternator Motoring Startup
  - Leak-Free Recuperator Designs
- **Performance Parameters:**
  - Alternator Output 650 to 2100 watts
  - Turbine Inlet Temp 1144 K (1600 F)
  - Compressor Inlet Temp 300 K (80 F)
  - Compressor Exit Pressure 730 kPa (106 psia)
  - 52000 RPM, 1733 Hz, 67 V
  - 17 kg mini-BRU, 59 kg Recuperator

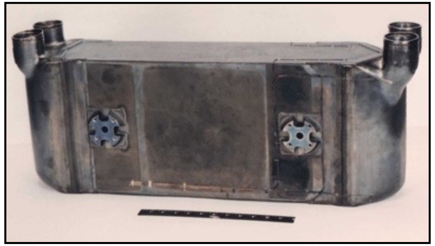


BIPS Workhorse Loop

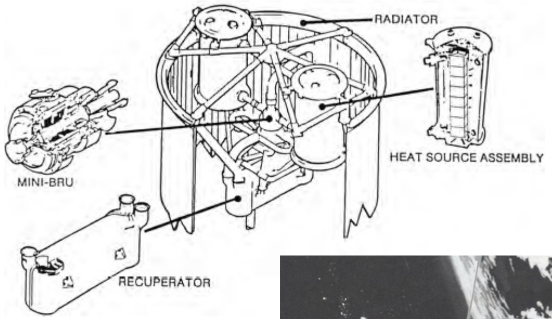


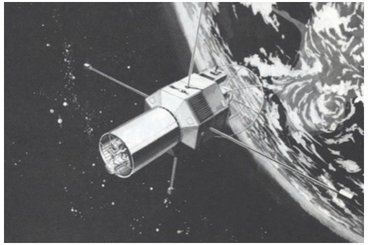
Turboalternator-Compressor

Mini-BRU Recuperator

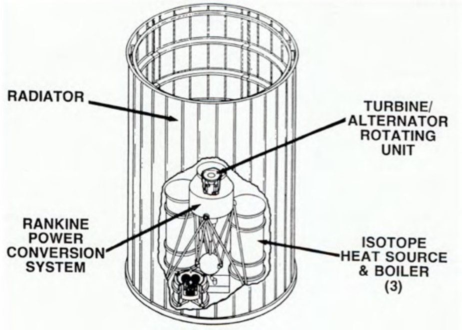


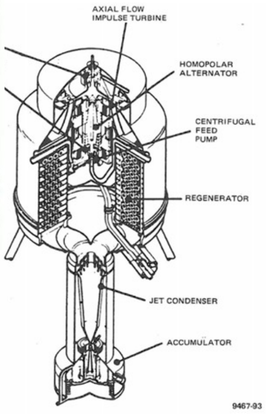
BIPS vs. KIPS (1978)





Closed Brayton Cycle





Organic Rankine Cycle

Brayton Isotope Power System

- AirResearch/Garrett Corp.
- 2 MHW Heat Sources (4.8 kWt input)
- 1144K Turbine Inlet, 263K Comp. Inlet (HeXe working fluid)
- 1.3 kWe net power (27% eff.)
- 210 kg, 12.4 m2 radiator

Kilowatt Isotope Power System

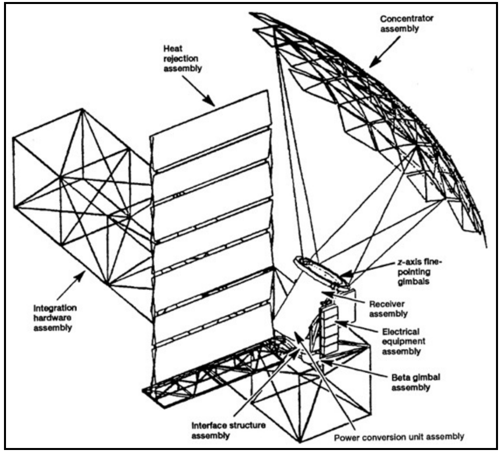
- Sundstrand Energy Systems
- 3 MHW Heat Sources (7.2 kWt input)
- 620K Turbine Inlet, 349K Cond. Inlet, (Dowtherm A working fluid)
- 1.3 kWe net power (18% eff.)
- 215 kg, 10.1 m2 radiator

A Brief History of Rankine

Years	Project	Power	Working Fluid	Status
1960s	ORC	6 kWe	645K Dowtherm	PCU test (3,000 hr)
1960s	K-Rankine	500 kWe	1400 K Potassium	Concept
1960s	SNAP-2	5 kWe	895 K Mercury	PCU test (30,000 hr)
1960s	SNAP-8	35 kWe	950 K Mercury	PCU test (10,000 hr)
1960s	SNAP-50	300 kWe	1365 K Potassium	Concept
1960s	MPRE	140 or 300 kWe	1100 K or 1365K Potassium	Material & loop tests
1970s	KIPS	1.3 kWe	620 K Dowtherm	PCU test (11,000 hr)
1980s	SSF SD	25 kWe	675 K Toluene	Design
1980s	AF DIPS	6 kWe	675 K Toluene	Concept

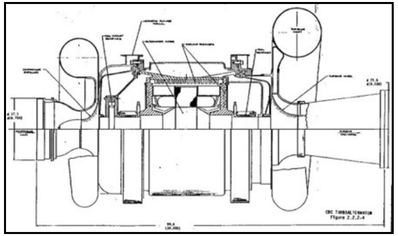
Solar Dynamic Brayton - Space Station Freedom

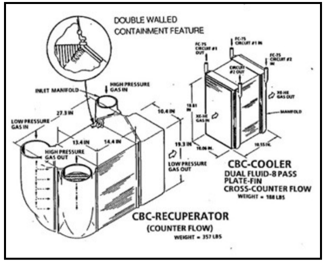
- **25 kW Solar Dynamic Power Module for Space Station Freedom (1986-91)**
  - Part of Hybrid PV/SD Power System
  - Reduced Life Cycle Costs Compared to PV/Battery System
  - 15 year On-Orbit Life
  - Human-Rated System
- **Phase C/D Design Completed**
  - Higher Risk Components Built & Tested (e.g., Concentrator, Heat Receiver)
  - Power Conversion Unit Considered Low Risk due to BRU Heritage
- **Performance Parameters:**
  - Alternator Output 36 kWe
  - Cycle Efficiency 27%
  - Turbine Inlet Temp 1034 K (1400 F)
  - Compressor Inlet Temp 338 K (148 F)
  - Compressor Exit Pressure 560 kPa (81 psia)
  - 32000 RPM, 120V
  - 104 kg Turboalternator-Compressor, 162 kg Recuperator, 85 kg Gas Cooler



SD Flight Configuration

Turboalternator-Compressor

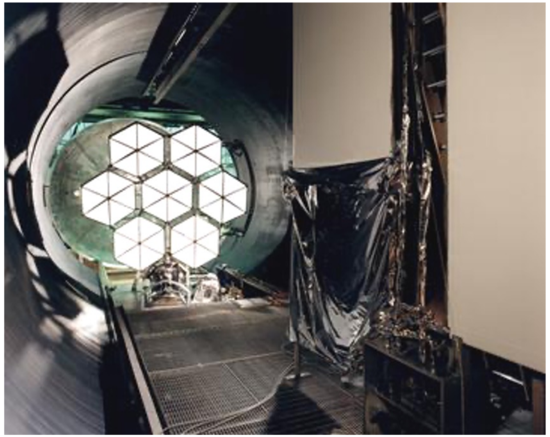




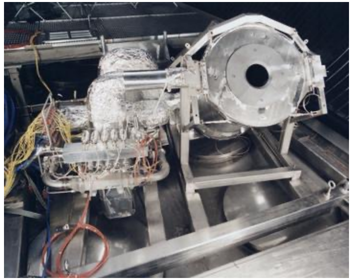
Recuperator/ Cooler

Solar Dynamic Ground Test Demonstration

- **2 kW Solar Dynamic Ground Test Demonstration (1994-98)**
  - Congressional Ear-Mark Following Cancellation of SD Option for SSF
  - Full End-to-End System Test in Solar-Thermal-Vacuum (TRL6)
  - Government/Industry Team: NASA Lewis, Allied Signal, Harris, Loral-Vought, Rocketdyne
- **Extensive Test Program:**
  - 33 Separate Tests, 372 LEO Orbit Cycles
  - 800 Hours of Operational Experience
  - No Performance Degradation
- **Led to US/Russian 2 kW Mir SD Flight Demo (1996-98)**
  - Shuttle Delivery Mission Redirected for Logistics Re-supply
- **Multiple Brayton Unit Configurations**
  - Mini-BRU with 120V Rice Alternator
  - SD Mir Development Unit with 28V Permanent Magnet (PM) Alternator
  - SD Mir Unit with Rewound 120V PM Alternator

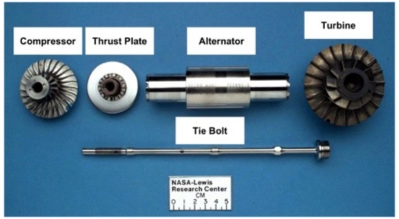


View from Solar Sim. Window Port

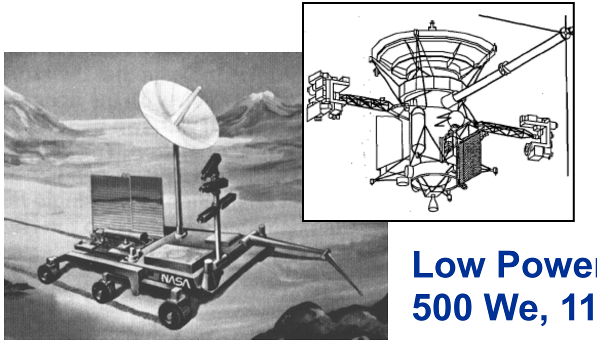


Heat Receiver & Power Conversion Unit

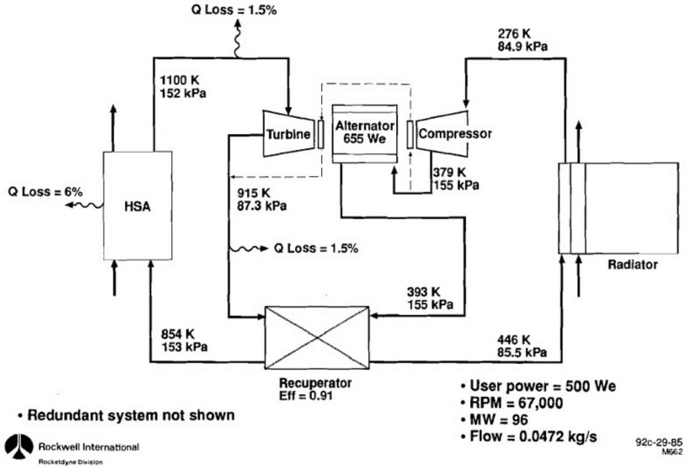
Rotor Components



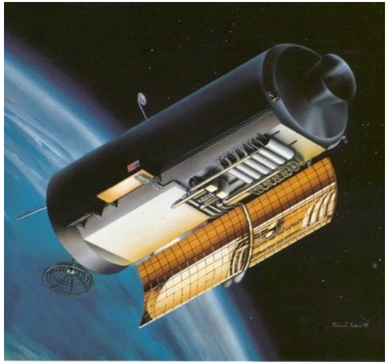
Brayton DIPS (early 1990s)

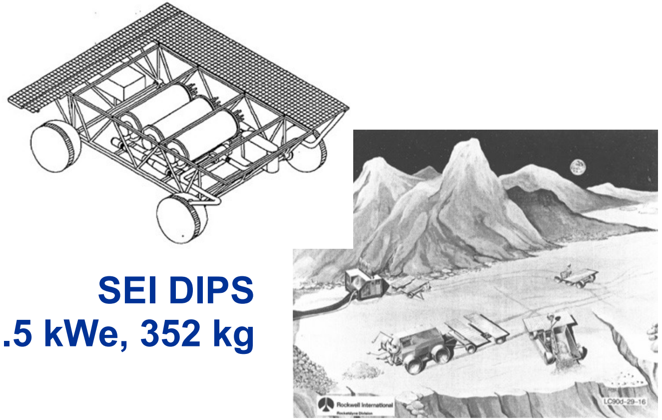


Low Power DIPS
500 We, 116 kg



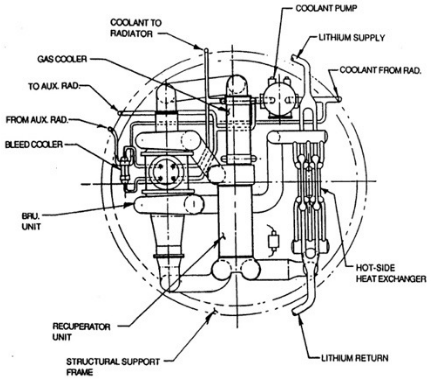
Air Force
BSTS DIPS
6 kWe, 675 kg





SEI DIPS
2.5 kWe, 352 kg

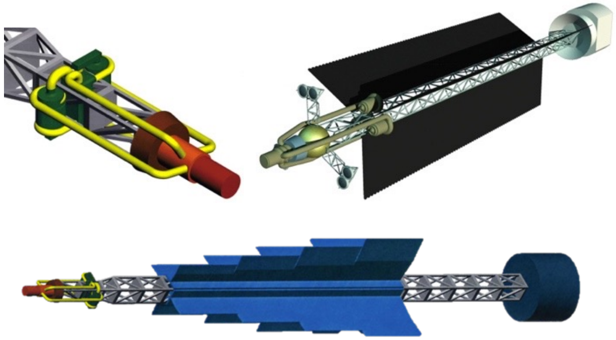
1990s Brayton Concepts & Studies

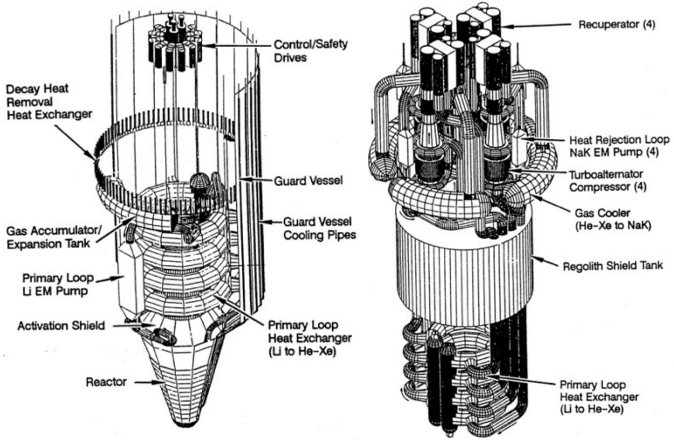


20 kW Brayton for Near-Term SP-100 Flight Demo

25 kW Brayton for Bi-Modal NTR

SP-100 Brayton for NEP

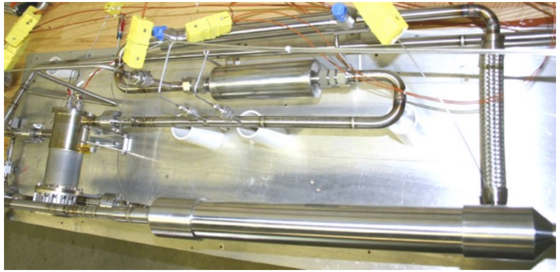


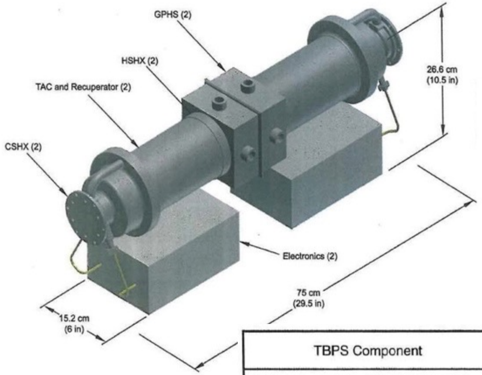


550 kW SP-100 Brayton for Lunar Surface

Creare Turbo-Brayton for RPS (2001)

- **Started as SBIR in 2001**
  - Phase I preliminary design and rotor testing to 3500 rev/s
  - Phase II breadboard converter test unit with commercial recuperator (not successful – thrust bearing issues)
- **Transitioned to NASA Radioisotope Power Conversion Technology NRA Contract in 2004 (Goal ~ TRL5)**
  - Partners included Boeing/Rocketdyne, Ball Aerospace, Jackson & Tull
  - Year 1 converter design and thermo-mechanical analysis
  - Year 2 component fabrication and test
  - Year 3 system integration and thermal-vac test
  - Contract cancelled after first year due to NRA budget constraints
- **100 W Flight System with redundant Brayton units (2 GPHS) 26 kg**
  - 200 W Flight System (4 GPHS) 33 kg

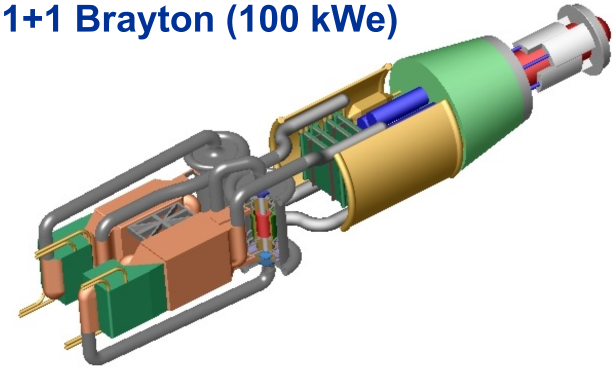




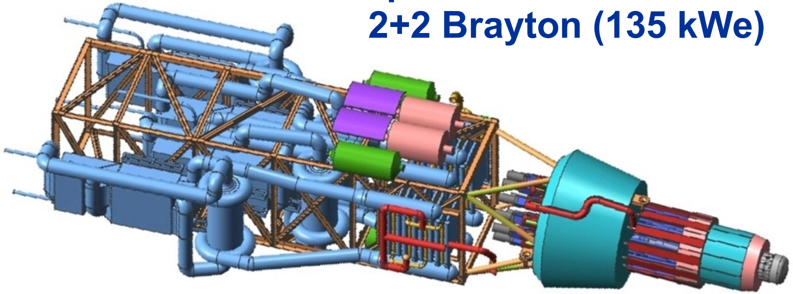
TBPS Component	Mass (kg)
TAC, recuperator, CSHX, HSHX (2)	13.4
Electronics (2)	4
GPHS (2)	3.2
Hot-Side Structural Support, Insulation & Enclosure	3
Radiator (1)	2.7
Total	26

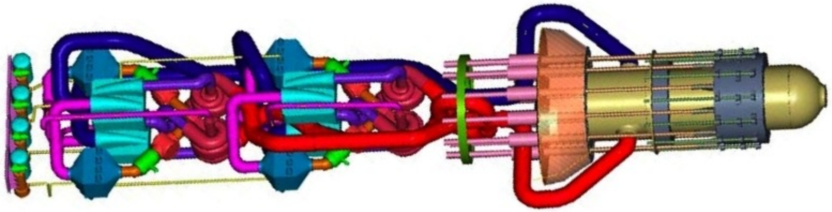
Jupiter Icy Moons Orbiter Concepts (2002-2005)

Liquid-Metal Reactor with
1+1 Brayton (100 kWe)



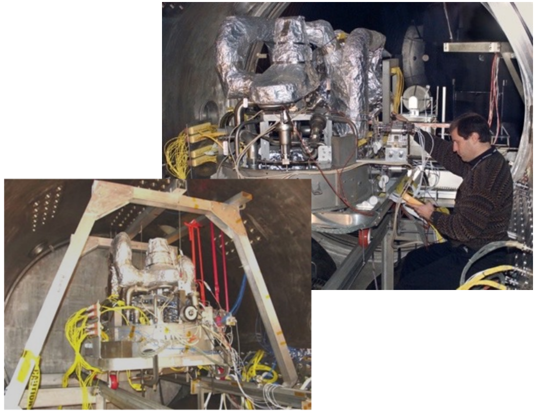
Liquid-Metal Reactor with
2+2 Brayton (135 kWe)



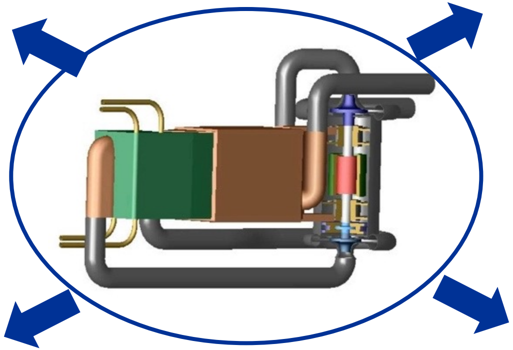


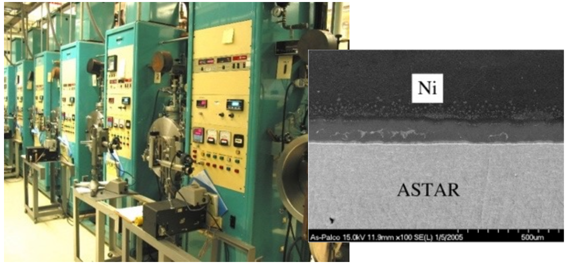
Gas-Cooled Reactor with
2+2 Brayton (200 kWe)

JIMO-era Brayton Technology Advancements



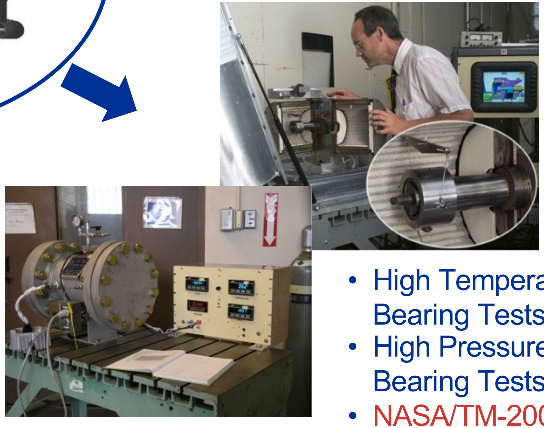
- 2 kW Brayton-Ion Demo
  NASA/TM-2004-212960
- 2 kW Mechanical-Dynamic Vibration Test
  NASA/TM-2005-213880





- Superalloy Material Creep Testing
  NASA/TM-2006-214110
- Dissimilar Metallic Joining STAIF 2007
- HeXe/Superalloy Compatibility IECEC 2004

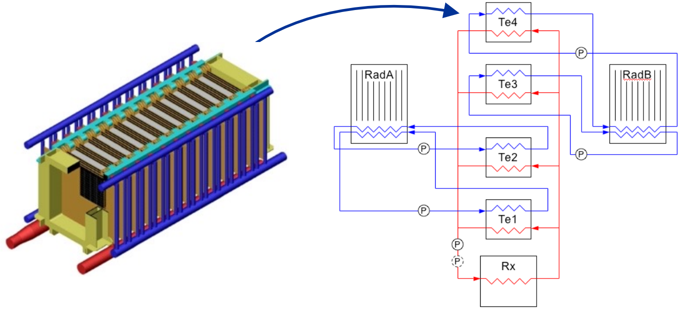
- 50 kW Alternator Test Unit
- Alternator-Thruster Integration Lab
- NASA/TM-2005-213895



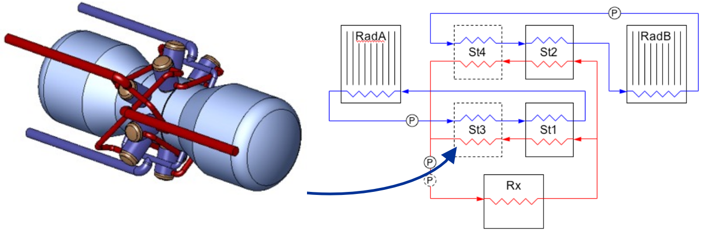
- High Temperature Journal Bearing Tests
- High Pressure Gas Foil Bearing Tests
- NASA/TM-2007-214470

Fission Surface Power Studies (2006)

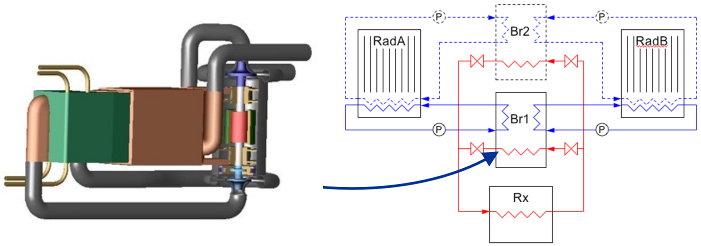
- **Liquid Metal Reactor & PbTe/TAGS Thermoelectrics**
  - NaK primary, 900K exit, 100K ΔT, 15% ALIP
  - 850K hot-shoe, 500K cold-shoe
  - Conductively-coupled TE modules in compact HXs
  - 4 converters, 4 required for full power
  - NaK secondary, 100K ΔT, 20% ALIP
  - 200 Vdc PMAD interface



- **Liquid Metal Reactor & Free-Piston Stirling**
  - NaK primary, 900K exit, 50K ΔT, 15% ALIP
  - 850K heater head, 450K cooler
  - Dual-opposed piston converters in serial pairs
  - 4 converters, 2 required for full power
  - H_2O secondary, 25K ΔT, 20% mech. pump
  - 300 Vac, 1Ø, 100 Hz PMAD interface



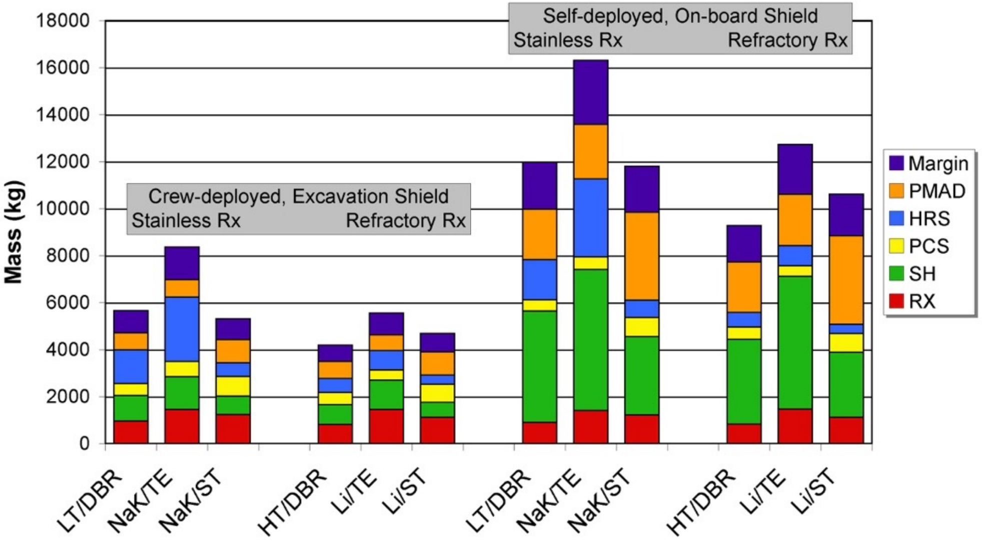
- **Gas Cooled Reactor & Direct Brayton**
  - HeXe primary, 900K exit, ~200K ΔT
  - 900K turbine inlet, 370K compressor inlet
  - Recuperated-turboalternator with gas cooler
  - 2 converters, 1 required for full power
  - H_2O secondary, ~100K ΔT, 20% mech. pump
  - 440 Vac, 3Ø, 2000 Hz PMAD interface

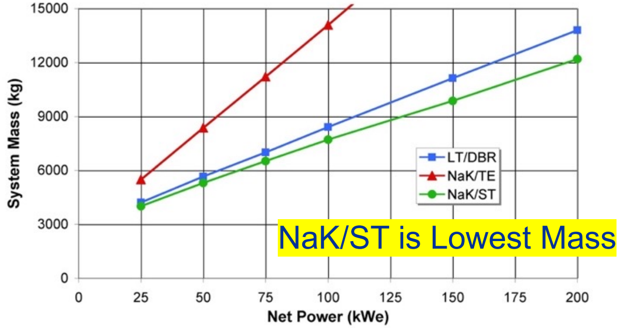


Fission Surface Power Studies (2006)

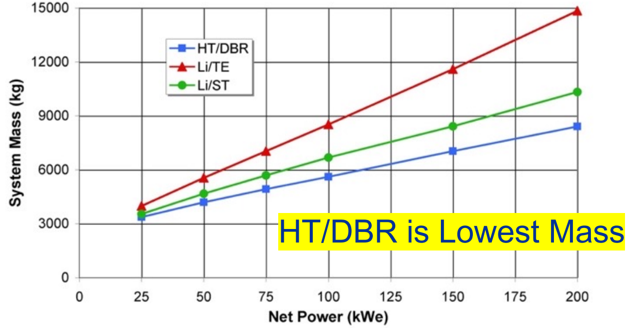
50 kWe Lunar Surface Reactor Power Systems

- 900K Direct HeXe Brayton
- 900K NaK Thermoelectric
- 900K NaK Stirling
- 1150K Direct HeXe Brayton
- 1300K Li Thermoelectric
- 1100K Li Stirling





Low Temp Reactors with Excavation Shielding

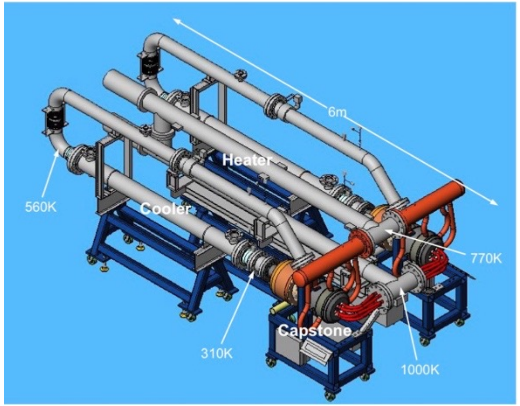


High Temp Reactors with Excavation Shielding

A Comparison of Fission Power System Options for Lunar and Mars Surface Applications NASA/TM-2006-214120

Dual Capstone Brayton Test Loop (2008)

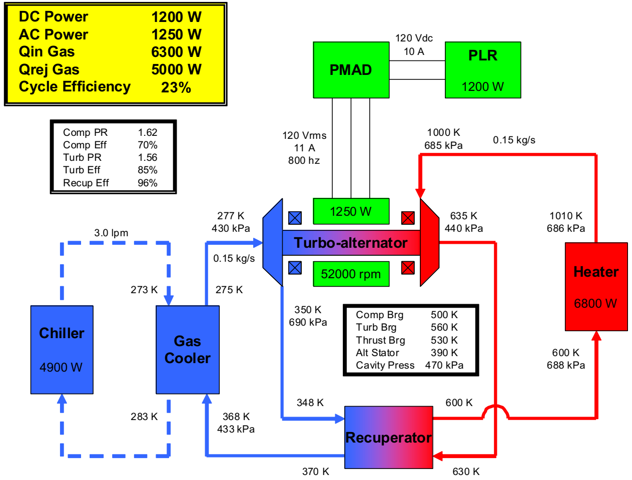
- **Designed and Built by Barber Nichols**
  - Uses two commercial Capstone micro-turbine generators modified for closed-loop operation
  - Common nitrogen gas loop; no isolation valves
  - Shared (180 kW) electrical resistance heater; water cooling
- **First-of-a-Kind Test System**
  - Based on Naval Reactor JIMO concept with direct-gas reactor and redundant Brayton power conversion units
  - Permits evaluation of operational interactions and transients
- **GRC Testing Completed May 2008**
  - Operated up to 22 kW total output power, 950K turbine inlet, 90000 rpm
  - Equal & unequal shaft speeds
  - Single and dual unit operation
  - Staggered & simultaneous startup
  - Analytical model validation



Experimental and Analytical Performance of a Dual Brayton Power Conversion System NASA/TM-2009-215511

Direct Drive Gas – Brayton Test (2009)

- Glenn supplied 2 kW Brayton Power Conversion Unit
- Marshall supplied Direct Drive Gas (DDG) Reactor Simulator
- Testing at GRC Vacuum Facility #6
- Collaboration with Texas A&M and DOE/INL to validate reactor transient analytical models
  - Heater output power control tests
  - Heater exit temperature control tests
  - Simulated reactivity control tests

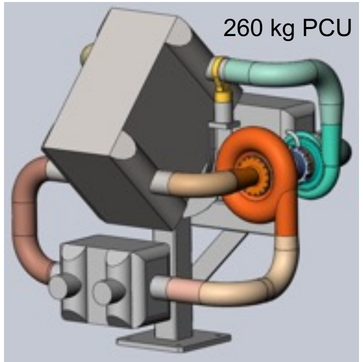


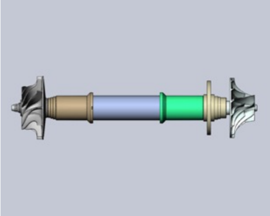
Test Results From a Direct Drive Gas Reactor Simulator Coupled to a Brayton Power Conversion Unit NASA/TM-2010-215843

12 kWe Brayton Power Conversion Unit (2010)

Barber Nichols - Closed Brayton Cycle Power Conversion Unit for Fission Surface Power (NASA Contract NNC08CA64C)

- 12 kWe generator output at 400 Vac
- NaK heating at 850 K +/-25 K
- H2O cooling at 375 K +/-25 K
- Parasitic load control with regulated 120 Vdc power bus
- Thermal-vac test environment of 10-6 torr and 200 K

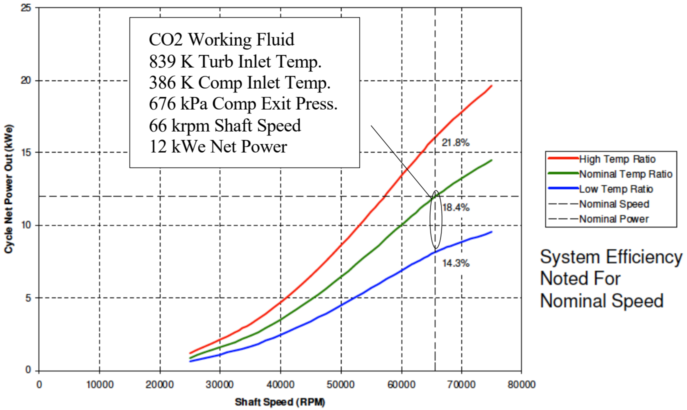




30 kg Rotating Unit
30 kg NaK Plate-Fin HX
110 kg CO2 Recuperator
35 kg H2O Gas Cooler

Prioritized Development Goals:

- Close relevance to future flight designs, including the potential for 8 yr service life
- Credible development path and maturation approach to achieve TRL6 in less than 3 yrs
- Low development cost and risk
- Extensible to Mars (materials and design strategies)
- High thermal-to-electric efficiency
- Minimum complexity
- Low mass and volume

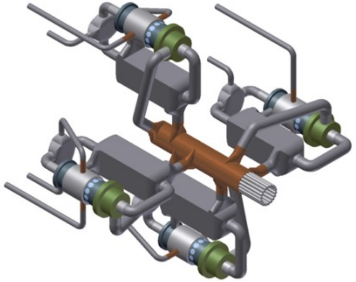


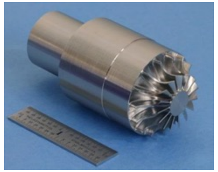
Closed Brayton Cycle Power Conversion Unit for Fission Surface Power Phase I Final Report NASA/CR-2010-215673

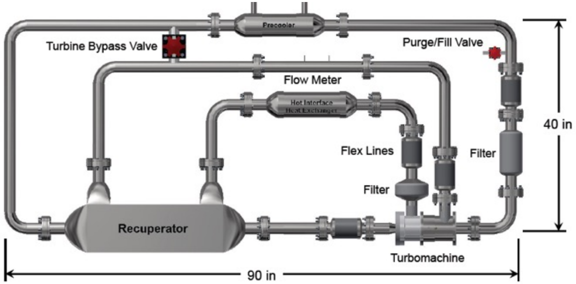
Creare Turbo-Brayton for Fission (2011-13)

- **2011 SBIR**
  - 1 kWe Brayton Design for Small Fission Systems (Kilopower)
  - Compressor (Ti6Al4V) & Turbine (Rene 41) fabrication trials
  - 1050 K Turbine Inlet with Mar-M247
  - Phase II not selected

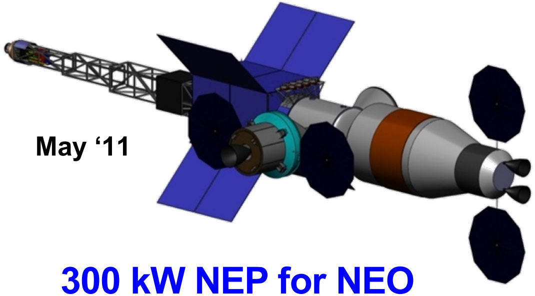
- **2013 SBIR**
  - 12 kWe Brayton Design for Fission Surface Power (TDU)
  - Scale-up from 1 kWe
  - 875 K Turbine Inlet, 375 K Compressor Inlet
  - Phase II selected to build 1 kWe breadboard test system
  - Design and component fabrication completed; testing to begin soon
  - Oct 2016 Phase II contract conclusion with possible Phase IIE







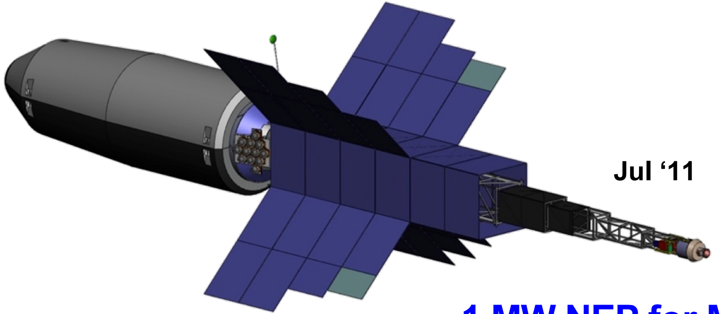
High-Power NEP Vehicle Studies (2011-12)



May '11

300 kW NEP for NEO Piloted Mission

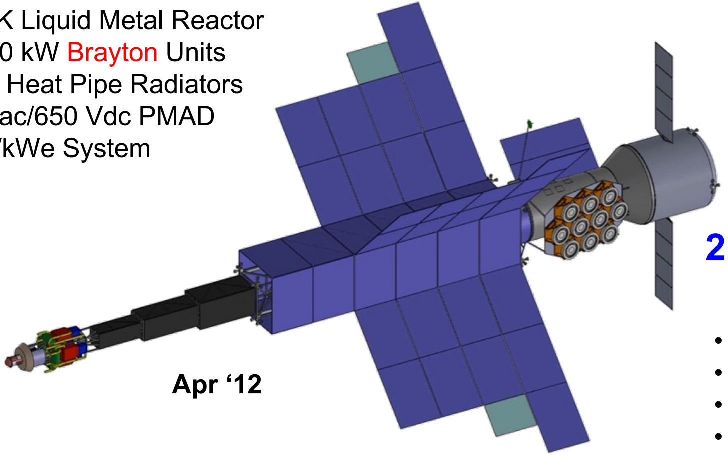
- 1200 K Liquid Metal Reactor
- 2X 300 kW Brayton Units
- 450 K Heat Pipe Radiators
- 480 Vac/650 Vdc PMAD
- 27 kg/kWe System



Jul '11

1 MW NEP for Mars Cargo Mission

- 1200 K Liquid Metal Reactor
- 4X 300 kW Brayton Units
- 450 K Heat Pipe Radiators
- 560 Vac/750 Vdc PMAD
- 17 kg/kWe System



Apr '12

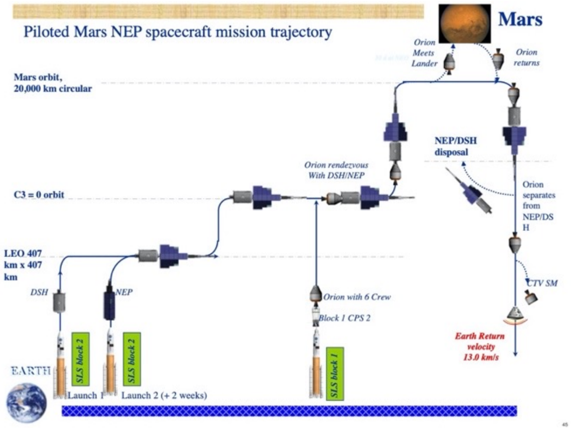
2.5 MW NEP for Mars Piloted Mission

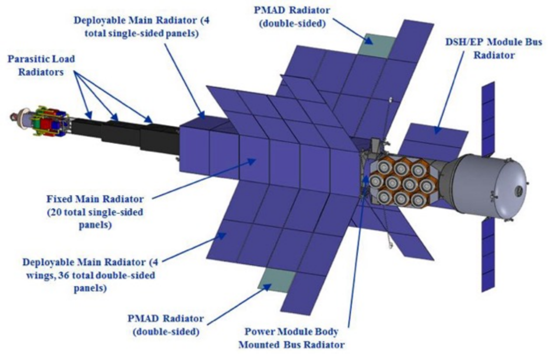
- 1500 K Liquid Metal Reactor
- 4X 900 kW Brayton Units
- 500 K Heat Pipe Radiators
- 1630 Vac/2200 Vdc PMAD
- 11 kg/kWe System

Mars Design Reference Architecture 5.0 (2014)

- **Piloted NEP Propulsion Option**
  - 2.5 MW reactor power system with Brayton conversion
  - Large deployable radiator with stowed package sized for SLS fairing
  - Ten 280 kW Xenon gridded annular ion thrusters
  - 1630 Vac to 2200 Vdc Direct Drive (5000s Isp)

- **Conjunction-class Mission**
  - Two SLS launches (2037)
  - Un-crewed spiral from 407 km LEO
  - Rendezvous with 6-person Deep Space Hab and Orion at earth escape
  - Mars capture at 20,000 km circular
  - 980-day total mission
  - 400-day Mars surface stay





NASA/SP–2009-566-ADD2 (Addendum #2, March 2014) https://www.nasa.gov/sites/default/files/files/NASA-SP-2009-566-ADD2.pdf

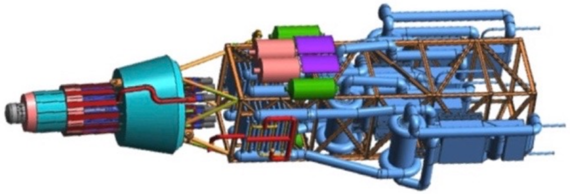
Mars Transportation Assessment Study (2020-21)

Nuclear Power Subsystem

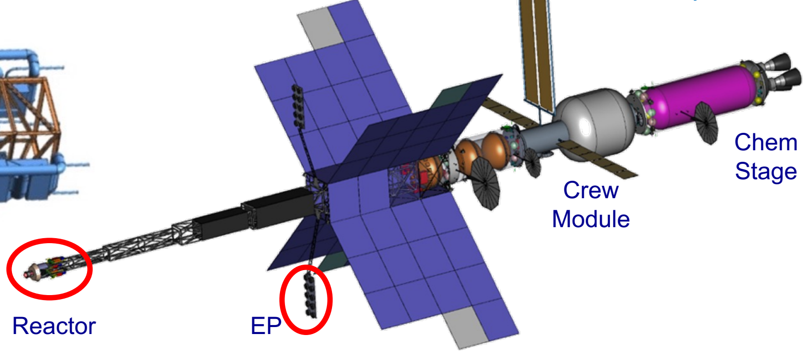
- Reference 1.9 MWe, 25t (13 kg/kWe) NEP power system includes:
  - 1200 K Lithium-cooled HA-LEU TRISO reactor with YH moderator
  - Four 500 kWe Supercritical gas Brayton converters
  - One 2500 m^2 deployable radiator module designed to fit within SLS launch fairing
  - 960 Vac, 2.5 kHz PMAD architecture delivers 650 Vdc to Hall thrusters and 120 Vdc to spacecraft
- Alternative fast-spectrum HEU reactor based on SP-100 technology increases TRL and reduces system mass to 21.5t (11 kg/kWe)

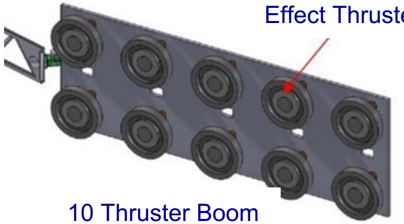
EP Subsystem

- High-power Hall Thrusters
  - Twenty 100 kW thrusters (18+2 config), 600 V/167A operating point, 2.5 kg/kW sp mass
  - 2600 seconds Isp, ~60% string efficiency
  - Advanced magnetic shielding supports 13t Xe throughput and 22,000 hr thruster lifetime
- High-efficiency Direct Drive Units (DDUs)
  - Primary plasma discharge direct drive from Brayton units
  - Auxiliary supplies for magnets, cathode heater, keeper, filtering and communications
- Commercial-derived Xenon Flow Controller
  - With supercritical Xe storage in COPV tanks



Li-cooled Reactor
& Brayton Assembly





10 Thruster Boom
(1 of 2 on Vehicle)

Nuclear Power Concepts and Development Strategies for High-Power Electric Propulsion Missions to Mars, NASA/TM-20210016968

Space Brayton Technology Challenges

- **Biggest challenge is to finally get a Brayton converter into space!**

- **Other key challenges include:**
  - Limited supplier base for niche design requirements
  - Life and reliability demonstration (with modern test unit)
  - Thermal interfaces at the heat source and heat sink
  - Ground test complications due to thermal requirements
  - Transient, off-nominal operations
  - Achieving competitive mass (with Stirling) at low power level
  - Space-rated electronics to process the electric power

Summary

- **Long history for Brayton space power systems with significant hardware development and testing**
  - Glory days were 1960s and 1970s
  - Technologies are well-suited for power levels from kilowatts to Multi-megawatts

- **Brayton technology experienced revivals for Space Station Freedom (late 1980s) and Prometheus (early 2000s)**
  - 25 kW SD system pursued, and 2 kW ground test demo completed
  - 200 kW NEP system pursued, and variety of ground demos from 2 to 50 kW completed

- **Current NASA interests in Brayton are focused on low-power RPS (<1 kW), mid-power FSP (40 kW), and high-power NEP (>1 MW)**
  - RPS Program built and tested a 300 W Brayton prototype with Creare
  - Two contractor teams are pursuing Brayton options for FSP
  - Brayton is the preferred technology for large-scale NEP systems

- **Continued NASA investments in turbine-based energy conversion technologies provides increased flexibility for future space systems**

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