In view of the difficult times the US and global economies are experiencing today, funds for the development of advanced fission reactors nuclear power systems for space propulsion and planetary surface applications are currently not available.

However, according to the Energy Policy Act of 2005 the U.S. needs to invest in developing fission reactor technology for ground based terrestrial power plants. Such plants would make a significant contribution toward drastic reduction of worldwide greenhouse gas emissions and associated global warming. To accomplish this goal the “Next Generation Nuclear Plant Project” (NGNP) has been established by DOE under the “Generation IV Nuclear Systems Initiative”. Idaho National Laboratory (INL) was designated as the lead in the development of VHTR (Very High Temperature Reactor) and HTGR (High Temperature Gas Reactor) technology to be integrated with MMW (multi-megawatt) helium gas turbine driven electric power AC generators. However, the advantages of transmitting power in high voltage DC form over large distances are also explored in the seminar lecture series.

As an attractive alternate heat source the “Liquid Fluoride Reactor” (LFR), pioneered at ORNL (Oak Ridge National Laboratory) in the mid 1960’s, would offer much higher energy yields than current nuclear plants by using an inherently safe energy conversion scheme based on the Thorium -> U233 fuel cycle and a fission process with a negative temperature coefficient of reactivity. The power plants are to be sized to meet electric power demand during peak periods and also for providing thermal energy for hydrogen (H2) production during "off peak" periods. This approach will both supply electric power by using environmentally clean nuclear heat which does not generate greenhouse gases, and also provide a clean fuel H2 for the future, when, due to increased global demand and the decline in discovering new deposits, our supply of liquid fossil fuels will have been used up. This is expected within the next 30 to 50 years, as predicted by the Hubbert model and confirmed by other global energy consumption prognoses.

Having invested national resources into the development of NGNP, the technology and experience accumulated during the project needs to be documented clearly and in sufficient detail for young engineers coming on-board at both DOE and NASA to acquire it. Hands on training on reactor operation, test rigs of turbomachinery, and heat exchanger components, as well as computational tools will be needed.

Senior scientist/engineers involved with the development of NGNP should also be encouraged to participate as lecturers, instructors, or adjunct professors at local universities having engineering (mechanical, electrical, nuclear/chemical, and/or materials) as one of their fields of study.
CSU Lecture on Thorium –LFR NUCLEAR POWER PLANTS

Space & Terrestrial Power System Integration

Optimization Code BRMAPS

for

Gas Turbine Space Power Plants with Nuclear Reactor Heat Sources

Dr. Albert J. Juhasz

February 13th, 2007
**INTRODUCTION**

- Focus of Talk on Numerical Methods (*BRMAPS* to analyze Power Systems composed of
  - Thermal Energy Source
    (ie. Fission Reactor, Solar Conc.& Heat Receiver, Chemical)
  - Energy Conversion (ECS) via Brayton cycle (Compressor, Turbine, Alternator/Generator, Electr. Controls)
  - Heat Source Heat Exchangers Coupled to Reactor & ECS
  - Heat Sink Heat Exchangers Connecting ECS to Heat Sink
  - Heat Rejection Subsystems (Radiator for Space, Bodies of Water for Ground Based Plants)
  - Pumps and Controls as Parasitic Loads
- Selected Output Results
Topical Outline – Power System Design Drivers

- **Space (Lunar) Power Systems**
  - Emphasis is on Minimum System Mass
  - High System Reliability, Autonomy and long Operational Life required to compensate for little or no maintenance
  - Need least complex systems w. minimum components
  - Thermal Efficiency can be traded to achieve Low Mass, i.e. non-regenerated and direct heated/cooled cycles eliminate heat exchanger (regenerator HX, HSHX, CSHX) mass

- **Terrestrial Nuclear Power Systems**
  - Emphasis is on Maximizing Thermal Efficiency and thus Power Output, Revenue, Profit & Return on Investment
  - System Maintenance during regularly scheduled Periods
  - High System Mass and Complexity are acceptable as long as high Power Plant Availability/Reliability is assured
**BRMAPS System Code Highlights**

- Wide operating range capability allows efficient narrowing of design space: Turb, Inlet Temp., Cycle Temp. Ratio, Press. Ratio
- Code Models Interacting Principal Sub-systems of Closed Cycle Gas Turbine (CCGT) Space Power Systems
  - Heat Source (Nuclear Reactor + Shield)
  - Thermal-to-Electric Energy Converter – *Turbo-Alternator*
  - Heat Rejection Subsystem – *Thermal Loop and Space Radiator*
- Code Incorporates new Triple Objective Optimization – PR Variable
  - Operating Conditions for *Maximum Cycle Efficiency, Minimum Radiator Area, Minimum Overall System Mass*
  - Global Optimization Loops for Systematic Variation of Cycle Temp. Ratio and Peak Cycle Temperature – TIT
  - Rapid Visualization of Sys. Mass trends with Turbine Inlet Temp. – TIT
- Code results validated against Aero and Ground Based Power Plants
- Sub-Codes for Space Environment and System Reliability Issues
  - Turbomachine Size & Speed; Compressor & Turbine Power; Recuperator & HX; Heat Rejection Subsystem
Thermodynamic System Block Diagram Comprising three major Subsystems

- **Heat Source** sends Thermal Energy (Heat) to **ECU**
- **ECU** Subsystem transforms part of Heat Source Thermal Energy, $W_t$, to Electric Work - $W_e$
- Unconverted “Low Grade” Heat, $W_t - W_e$, is Rejected to Space at $T_{SINK}$ by Thermal Radiation Heat Transfer

Space environment temperature at $T_{SINK}$
Regenerated Brayton Cycle Configurations w. Fission Reactor Heat Sources
Non-regenerated Brayton Cycle Configurations w. Fission Reactor Heat Sources

5. Indirect Heating Cycle with Direct Heat Rejection

6. Indirect Heating Cycle with Indirect Heat Rejection

7. Direct Heating Cycle with Direct Heat Rejection

8. Direct Heating Cycle with Indirect Heat Rejection
Traditional CBC Configuration for Space
(Contains 3 Heat Exchangers, 2 Pumps)

2. Indirect Heating with Indirect Heat Rejection
Non-regenerated Cycle Configuration
(No Heat Exchangers)
Closed Brayton Cycle with Solar Heat Source
Closed Cycle Gas Turbines
(a) 10 kWe Radial BRU; (b) 30 MWe Axial Machines

(a) 10 kWe BRU
(b) 30 MWe Axial Turbines
EFFECT OF MOLECULAR WEIGHT ON TURBOMACHINERY

TURBINE STAGES

MOLECULAR WEIGHT

RELATIVE SIZE

0 20 40 60 80 100 120 140

0 2 4 6 8 10

0 .4 .8 1.2 1.6

Glenn Research Center at Lewis Field
Turbine Materials Technology Map
GAS TURBINE (BRAYTON CYCLES)

Regenerated Cycle

Non-Regenerated Cycle
Isentropic and Polytropic Efficiency Relationships

**Isentropic Compressor Efficiency - \( \eta_c \)**

A function of pressure ratio, \( \gamma \), \( \eta_{pc} \)

\[
\eta_c = \left( \frac{P_{OC}}{P_{IC}} \right)^{\frac{\gamma - 1}{\gamma}} \left( \frac{P_{OC}}{P_{IC}} \right)^{\gamma} \eta_{pc}
\]

**Isentropic Turbine Efficiency - \( \eta_t \)**

A function of pressure ratio, \( \gamma \), \( \eta_{pt} \)

\[
\eta_t = 1 - \left( \frac{P_{IT}}{P_{OT}} \right)^{\gamma} \left( \frac{\eta_{pt} (1 - \gamma)}{1 - (\gamma \eta_{pt})} \right)
\]

\( \gamma \) Is specific heat ratio

\( \eta_{pc} \) is polytropic or infinitesimal compressor stage efficiency

\( \eta_{pt} \) is polytropic or infinitesimal compressor stage efficiency
Isentropic Efficiency for Compressors and Turbines as a Function of Pressure Ratio for various Infinitesimal Stage Efficiencies (ETAPC and ETAPT)

- ETAPC = 0.95
- ETAPT = 0.9

Graphs showing isentropic efficiency as a function of pressure ratio for different efficiency levels.
# Typical Code Output from Global Minimum Mass Scan

<table>
<thead>
<tr>
<th>TEMP RATIO</th>
<th>ETAAB</th>
<th>ETAFC</th>
<th>ETAFT</th>
<th>HSG</th>
<th>GAMMA</th>
<th>LPC</th>
<th>EFM</th>
<th>EPSIL</th>
<th>TIT-K</th>
<th>TSINK-K</th>
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<tbody>
<tr>
<td>2.90</td>
<td>.950</td>
<td>.950</td>
<td>.950</td>
<td>.950</td>
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<td>.940</td>
<td>.940</td>
<td>.960</td>
<td>1.600</td>
<td>200</td>
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</table>

**BRAYTON GLOBAL MIN. MASS SEARCH FOR POWER LEVEL = 10,000 MW; TIT = 1600 K (RECOMMENDED) = .950**

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>TEMP</th>
<th>PRESSURE</th>
<th>THERMAL MAIN RADIANT</th>
<th>MIN SYS</th>
<th>MASS</th>
<th>SP ARAD</th>
<th>AREA</th>
<th>SPEC. SYS.</th>
<th>MA SS</th>
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<tr>
<td></td>
<td>RATIO</td>
<td>RATIO</td>
<td>EFFIC</td>
<td>AREA (M2)</td>
<td>(METRIC TONS)</td>
<td>(MN/KW)</td>
<td>(KJ/KW)</td>
<td>(KJ/KG)</td>
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<tr>
<td>2.90</td>
<td>2.14</td>
<td>3.325</td>
<td>2.959</td>
<td>54.274</td>
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<td>3.271</td>
<td>3.193</td>
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<td>4.97</td>
<td>204.31</td>
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<tr>
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<td>3.209</td>
<td>3.341</td>
<td>41.368</td>
<td>2.270</td>
<td>4.93</td>
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<td>3.134</td>
<td>4.050</td>
<td>46.950</td>
<td>2.94</td>
<td>4.91</td>
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<tr>
<td>3.30</td>
<td>2.32</td>
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<td>4.780</td>
<td>46.330</td>
<td>3.08</td>
<td>4.89</td>
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<tr>
<td>3.40</td>
<td>2.37</td>
<td>3.766</td>
<td>4.911</td>
<td>46.915</td>
<td>3.32</td>
<td>4.89</td>
<td>204.44</td>
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<td></td>
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</tbody>
</table>

**MIN GLOBAL SYSTEM MASS AT ABOVE TEMP RATIO:**

- **MIN. SYSTEM MASS AT 1600 K:** 400
- **MIN. SYSTEM MASS AT 1500 K:** 3.40

**EXECUTION TIME:** 5.438 SEC

**MAP**: GLOBAL MINIMUM MASS CONDITIONS FOR TURBINE INLET TEMPERATURE = 1500 K

**BRAYTON CYCLE CALCULATIONS**

- REGENERATED = 1600 K- POWER LEVEL = 10,000 MW, TSINK-K = 200

<table>
<thead>
<tr>
<th>TEMP RATIO</th>
<th>ETAAB</th>
<th>ETAFC</th>
<th>ETAFT</th>
<th>HSG</th>
<th>GAMMA</th>
<th>LPC</th>
<th>EFM</th>
<th>EPSIL</th>
<th>TIT-K</th>
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<td>.950</td>
<td>.950</td>
<td>1.687</td>
<td>.940</td>
<td>.940</td>
<td>.960</td>
<td>1.600</td>
</tr>
</tbody>
</table>

**OPTIMUM PRESSURE RATIOS (MAX THERM EFF; MIN ARP, MASS)**

- 2.180 = 2.820 = 2.370 = 471

<table>
<thead>
<tr>
<th>PK RATIO</th>
<th>THERM EFF.</th>
<th>ARP(M2/KW)</th>
<th>MSYS(M2)</th>
<th>W(KR/KW)</th>
<th>THERM-K</th>
<th>THERM-K</th>
<th>THERM-K</th>
<th>THERM-K</th>
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<td>49.085</td>
<td>.3078</td>
<td>51.875</td>
<td>57.070</td>
<td>59.731</td>
<td>191.31</td>
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<tr>
<td>2.370</td>
<td>.3786</td>
<td>.3346</td>
<td>49.085</td>
<td>.3078</td>
<td>51.875</td>
<td>57.070</td>
<td>59.731</td>
<td>191.31</td>
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<tr>
<td>2.820</td>
<td>.3786</td>
<td>.3346</td>
<td>49.085</td>
<td>.3078</td>
<td>51.875</td>
<td>57.070</td>
<td>59.731</td>
<td>191.31</td>
</tr>
</tbody>
</table>

**MASS BREAKDOWN FOR 10,000 MW POWER SYSTEM**

- TURBINE INLET TEMPERATURE = 1500 K
- REACTOR/EX INLET TEMP. = 500 K
- CYCLE TEMPERATURE RATIO = 3.400
- ACT COMP. MASS FLOWRATE = 13.35 MOL/KW 4.0
- COMPRESSOR PRESSURE RATIO = 2.370
- PERCENT CANNOT EFFICIENCY = 53.35
- SYSTEM THERMAL EFFICIENCY = 37.68
- TOTAL RADIATING AREA (M2) = 4491.10
- SYSTEM SPECIFIC MASS (KJ/KW) = 4.09
- SYSTEM SPECIFIC POWER (W/KG) = 204.44

**COMPONENT WEIGHTS IN KG**

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>WEIGHT</th>
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<tbody>
<tr>
<td>REACTOR</td>
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<tr>
<td>HSG</td>
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<tr>
<td>HT SOURCE HX, PUMP</td>
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<td>RECUPERATOR</td>
<td>4798</td>
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<tr>
<td>COMRESSOR (2/1)</td>
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<td>TURBINE (2/1)</td>
<td>2556</td>
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<td>ALTERRATOR (2/3)</td>
<td>6346</td>
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<tr>
<td>HT SINK EX, PUMP</td>
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<tr>
<td>POWER CONDITIONING</td>
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<td>MAIN RADIATOR</td>
<td>5900</td>
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<td>RADIATOR (2)</td>
<td>4947</td>
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<tr>
<td>TOTAL SYSTEM MASS</td>
<td>46915</td>
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</tbody>
</table>

Glenn Research Center at Lewis Field

NASA
Influence of Regenerator Effectiveness (ERG) on Cycle Efficiency at Cycle Temp. Ratio of 3.0 and 4.0

\[ \eta_{PC} = \eta_{PT} = 0.9; \quad \gamma = 1.666 \]

(a) Temp. Ratio = 3.0

(b) Temp. Ratio = 4.0
Regenerator Specific Mass vs. Effectiveness with Overall Heat Transfer Coefficient $U$ as a Parameter for He Working Fluid

$$U = 28.4 \text{ W/sq. m-K}$$
$$= 56.8$$
$$= 113.6$$
$$= 284.2$$
Space System Mass for 10 MWe CBC vs. Cycle Temperature Ratio with Turbine Inlet Temperature TIT as a Parameter
Space System Mass for 10 MWe CBC vs. Cycle Efficiency with Turbine Inlet Temperature TIT as a Parameter

- TIT = 1100 K
- TIT = 1200 K
- TIT = 1350 K
- TIT = 1600 K
- Min. Mass Locus
Carbon-Carbon Heat Pipe and SP-100 Radiator Assembly

- Evaporator Nb-1Zr foil liner extension
- C-C pressure shell with Ni and internal Nb-1Zr foil liner
- End cap
- Heat pipe with end caps
- Radiator panel with 226 heat pipes
- Evaporator
- Radiator configuration

Design features:
- 12-panel, conical radiator
- Carbon-carbon heat pipes
- Integral fins
- Potassium working fluid
- Metal liner
Segmented Radiator Characteristics for Survival Probability $S=0.999$

$$S = \sum_{n=N_s}^{N} \frac{N!}{n!(N-n)!} (1-p)^{N-n} p^n$$

Relative Weight

$$w \equiv \left( \frac{N}{N_s} \right) \left[ N_s \ln \left( \frac{1}{p} \right) \right]^{-1/3}$$

Relative Thickness

$$\tau = \left[ N_s \ln \left( \frac{1}{p} \right) \right]^{1/3}$$
Theoretical Basis for Space Sink Temperature Analysis Code 
*TSCALC* (developed by author)

A giant sphere, 1 AU in radius, would catch all the Sun's radiative energy.

Above Earth's atmosphere, 1 m² of detector catches 1370 W.
Solar Fusion Energy Generation via Proton-Proton Chain Reaction

1. $^{1}_1\text{H} + ^{1}_1\text{H} \rightarrow ^{2}_1\text{H} + e^+ + \nu(\text{neutrino}) \quad (0.42 \text{ MeV})$
2. $e^+ + e^- \rightarrow \gamma (\text{radiation}) \quad (1.02 \text{ MeV})$
3. $^{1}_1\text{H} + ^{2}_1\text{H} \rightarrow ^{3}_2\text{He} + \gamma \quad (5.49 \text{ MeV})$
4. $^3_2\text{He} + ^3_2\text{He} \rightarrow ^4_2\text{He} + ^1_1\text{H} + ^1_1\text{H} \quad (12.86 \text{ MeV})$

Net Effect: $4\ ^{1}_1\text{H} \rightarrow ^{4}_2\text{He} + 2\ e^+ + 2\ \nu$

$4 \times 1.0078265 \text{ u} = 4.002603 \text{ u} + (2\ e^+ + 2\ \nu + 2\ \gamma + 12.86 \text{ MeV})$

Total Energy Generated – $E = m*c^2$

$E_t = (4.0313008 - 4.002603) \text{ u} \times 1.66\times10^{-27} \text{ kg/u} \times (3\times10^8 \text{ m/sec})^2$

$= 26.76 \text{ MeV/p-p cycle} \quad \text{which checks } \Sigma \text{ reaction step energies, } E_{RS}$

$E_{RS} = 2 \times (0.42 \text{ MeV} + 1.02 \text{ MeV} + 5.49 \text{ MeV}) + 12.86 \text{ MeV} = 26.76 \text{ MeV/p-p}$

Solar Luminosity, $L$, is due to $9\times10^{37} \text{ p-p cyc/sec}$

$L = 26.76 \text{ MeV} \times 1.602\times10^{-13} \text{ J/MeV} \times 9\times10^{37} \text{ /sec} = 3.86\times10^{26} \text{ Watts}$

Solar Mass Loss

$(4.0313008 - 4.002603) \text{ u} \times 1.66\times10^{-27} \text{ kg/u} \times 9\times10^{37} \text{ /sec} = 4.3\times10^{9} \text{ kg/sec}$

$= 4.3 \text{ Million tonnes/sec}$
Solar and Arbitrary Infrared Spectra

Solar Spectrum

Visible Range

Infrared Spectrum

Radiation Intensity - Watts/m² μm

Wavelength μm - meters

I(λ, 5780)
I(λ, 3500)
### Equilibrium Temperatures, TS(K), at Various AU Distances

#### Conditions for Spacecraft Approaching Sun

<table>
<thead>
<tr>
<th>LUMANG (Deg)</th>
<th>FV</th>
<th>EPS</th>
<th>AE</th>
<th>AU</th>
<th>Q/A (W/m²) (at 90 deg)</th>
<th>TS(K)</th>
<th>ORBIT</th>
</tr>
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<tr>
<td>25.00</td>
<td>1.0</td>
<td>.90</td>
<td>.60</td>
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<td>.03</td>
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<td>.60</td>
<td>39.438</td>
<td>.88</td>
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<td>.90</td>
<td>.60</td>
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<td>279.9</td>
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<td>.005</td>
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<td>5800.2</td>
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Solar Heat Flux & Space Probe Temperatures At Various Orbital Distances (AU)

- **SUN**
  - **Mercury**: 9149 W/m², 48K, 0.387 AU
  - **Venus**: 2620 W/m², 78K, 0.723 AU
  - **Earth**: 1371 W/m², 279K, 1 AU
  - **Mars**: 591 W/m², 226K, 1.53 AU
  - **Asteroids**: 152 W/m², 161K, ~3 AU
  - **Jupiter**: 37 W/m², 122K, 5.2 AU
  - **Saturn**: 15 W/m², 90K, 8.94 AU
  - **Uranus**: 3.7 W/m², 64K, 19.2 AU
  - **Neptune**: 1.5 W/m², 51K, 30.1 AU
  - **Pluto**: 0.9 W/m², 44K, 39.44 AU

- **Solar Probe Temperatures**
  - **Mercury**: 510 K
  - **Venus**: 328 K
  - **Earth**: 328 K
  - **Mars**: 328 K
  - **Asteroids**: 161 K
  - **Jupiter**: 122 K
  - **Saturn**: 90 K
  - **Uranus**: 64 K
  - **Neptune**: 51 K
  - **Pluto**: 44 K
Radiator Area Requirement for 300 kW\textsubscript{t} Heat Load at Avg. Radiator Surface Temperature = 390 K 
(θ = 25°; FV = 1; α/ε ranging 0.1 to 1.0)
Spacecraft with Trapezoidal Heat Pipe Radiator

- Payload
- Turbo-Alternators
- Reactor
- Shield
- Radiator
Thermal Energy Transfer in a Heat Pipe Radiator


### Radiator Area

\[ A_r = \dot{m} \cdot C_p \left[ \frac{1}{h_r} \cdot \ln \left( \frac{T_{\text{win}}^4 - T_s^4}{T_{\text{wex}}^4 - T_s^4} \right) + \frac{1}{4 \cdot \sigma \cdot \varepsilon \cdot T_s^3} \cdot \ln \left( \frac{T_{\text{win}} - T_s}{T_{\text{wex}} - T_s} \cdot \frac{T_{\text{wex}} + T_s}{T_{\text{win}} + T_s} \right) - 2 \left( \tan^{-1} \left( \frac{T_{\text{win}}}{T_s} \right) - \tan^{-1} \left( \frac{T_{\text{wex}}}{T_s} \right) \right) \right] \]

### Brayton Cycle Thermal Efficiency

\[ \eta_{th} = \frac{\eta_b \left( \frac{\Theta_T - 1}{\Theta_C} \right) \left( \alpha \eta_t - \frac{\Theta_C}{\eta_C} \right)}{\alpha (1 - \varepsilon_R) + \varepsilon_R \eta_t \alpha \left( 1 - \frac{1}{\Theta_T} \right) + \varepsilon_R - 1 + \frac{1}{\eta_C} \left( 1 - \Theta_C + \Theta_C \varepsilon_R - \varepsilon_R \right)} \]

where

- \( \Theta_C = \left( \frac{P_{OC}}{P_{IC}} \right)^{(\gamma - 1)/\gamma} \) is the compressor pressure ratio parameter

- \( \Theta_T = \left( \frac{P_{IT}}{P_{OT}} \right)^{(\gamma - 1)/\gamma} \) is the turbine pressure ratio parameter
Sample Power Plant Analyzed for Large Inter-planetary Spacecraft

Dual Loop 200 MWe Closed Cycle (He) Gas Turbine (CCGT) Power System with Nuclear Fusion Reactor Heat Source
Interplanetary Crew Transport Vehicle

- Artificial Gravity CrewPayload
- Brayton Cycle Radiators
- Reactor Coolant Radiators
- Propellant Cryo-Tankage
- Brayton Power Conversion
- Spherical Torus Fusion Reactor
- Magnetic Nozzle

Dimensions:
- 60 m
- 90 m
- 240 m
- 37 m
- 24 m
- 25 m
- 40 m
- 37 m
- 25 m
- 40 m
Advanced Power System Applications

Lunar Base Power System

Interplanetary Fusion Propulsion Space Vehicle
For Space Nuclear Powered Multi-Megawatt Closed Cycle Gas Turbine (CCGT) Systems with Nuclear can achieve Specific Mass (SPM) < 5 kg/kw

- By utilizing aircraft engine axial compressor/turbine technology
  - Higher pressure ratios allow removing heavy regenerator
  - Axial turbo-machinery has higher efficiency than radial
  - Turbine Inlet temperatures (TIT) can be increased to ~1600 K using He working fluid and ceramic turbine technology
- Using High Temperature Gas Reactors (HTGR-VHTR)
  - Direct heating of He working fluid makes heavy heat source liquid/gas heat exchanger and liquid circulating pump unnecessary
  - High TIT permits high cycle efficiency while permitting elevated heat rejection temperatures, thus reducing radiator area
- By direct cooling of turbine exhaust gas via Heat Pipe (HP) Radiator
  - Direct cooling of He working fluid makes heavy heat sink gas/liquid heat exchanger and liquid circulating pump unnecessary
  - Inherent redundancy of HP radiator permits reducing radiator specific mass while increasing overall system reliability
- Use of aircraft engine technology (modified for He working fluid as per CFD codes) lowers development costs.
Terrestrial Nuclear Power Plant w. LFR and HP, MP, LP Heat Exchangers for Reheat/Intercool Brayton Cycle
Ground Based Nuclear Power System (1000-MWe Helium Plant) With Turbine Reheat and Compressor Intercooling

Legend:
- Gen – Generator
- HSHX 1 – Heat Source Heat Exchanger 1
- HSHX 2 – Heat Source Heat Exchanger 2
- HSHX 3 – Heat Source Heat Exchanger 3
- LPT – Low Pressure Turbine
- MPT – Medium Pressure Turbine
- LFR – Liquid Fluoride Reactor
- HPT – High Pressure Turbine
- LPC – Low Pressure Compressor
- MPC – Medium Pressure Compressor
- HPC – High Pressure Compressor
- ICHX 1 – Intercooling Heat Exchanger 1
- ICHX 2 – Intercooling Heat Exchanger 2
- SKHX – Sink Heat Exchanger

Reactor (LFR)

P = 1.08 MPa; 1045 K

HSHX 3
1300 K
1045 K
P = 2.1

HSHX 2
1300 K
1045 K
P = 4.2

HSHX 1
1300 K
1015 K

433 kg/sec – He flow

Recuperator
470 K

Gen 3
333 MWe

LPT

3φ AC – 10 kV

Gen 2
333 MWe

MPT

3φ AC – 10 kV

Gen 1
333 MWe

HPT

3φ AC – 10 kV

445 K; P = 8 MPa

HPC

325 K; P = 1 MPa

325 K

LPC

445 K; P = 2 MPa

ICHX 1

445 K; P = 4 MPa

ICHX 2

Body of water heat sink

H2O

CD-06-82887-2
Three Stage Reheat & Intercool Brayton Cycle
Temperature – Entropy Diagram

Entropy – J/kg - K

Turbine Inlet Temp ➔

Turbine Outlet Temp. ➖

Compressor Outlet Temp. ➖

Compressor Inlet Temp. ➖

Turbine Inlet Temp ➔

Compressor Outlet Temp. ➖

Compressor Inlet Temp. ➖
Power Cycle Schematic and T-S Diagram for Single Expansion Inter-Cooled Triple Compression System

Fig. 2 Cycle and entropy diagram of the first closed-cycle gas turbine plant AK 36, Escher Wyss 1939.
V Compressors, T Turbines, E Air Heater (Heat Input), R Recuperator, K Coolers (Heat Rejection), A Usable Work, G Generator.
Typical Machine Sizes for 1000 MWe He Plant

- Single Turbo-Alt at 10 MPa and Pr=2; (TIT=1200K; TR=4)
  - Mass Flowrate ~ 1420 kg/sec
  - Dia. = 6.5 m; L = ~20 m; Speed = 1800 rpm
  - Recuperator Volume ~ 360 m³
  - Thermal Eff. = 48%

- Three Reheat/Intercooled Turbo-Alts
  - Mass Flowrate ~ 474 kg/sec
  - P=20 Mpa (Pr=2); Dia = 1.9 m, L = 4.5m, Speed = 8000 rpm
  - P=10 Mpa (Pr=2); Dia = 2.7 m, L = 6.3m, Speed = 5670 rpm
  - P= 5 Mpa (Pr=2); Dia = 3.8 m, L = 8.5m, Speed = 4000 rpm
  - Recuperator Volume ~ 120 m³
  - Thermal Eff. = 51.5%
Typical Machine Sizes for 300 MWe He Plant

- Single Turbo-Alt at 10 MPa and Pr=2; (TIT=1200K; TR=4)
  - Mass Flowrate ~ 434 kg/sec (One 300 MWe Turbo-Gen.)
  - Dia. = 3.8 m; L = ~8.8 m; Speed = 3600 rpm
  - Recuperator Volume ~ 96 m³
  - Thermal Eff. = 48%

- Three Reheat/Intercooled Turbo-Alt’s (TIT=1200K; TR=4)
  - Mass Flowrate ~ 142 kg/sec (Three 100 MWe Turbo-Gens.)
  - P=20 Mpa (Pr=2); Dia = 1.4 m, L = 3.3 m, Speed = 8700 rpm
  - P=10 Mpa (Pr=2); Dia = 1.9 m, L = 4.4 m, Speed = 6200 rpm
  - P= 5 Mpa (Pr=2); Dia = 2.7 m, L = 6.3 m, Speed = 4360 rpm
  - Recuperator Volume ~ 34 m³
  - Thermal Eff. = 51.6%
Typical Machine Sizes for 150 MWe He Plant

- **Single Turbo-Alt at 10 MPa and Pr=2; (TIT=1200K; TR=4)**
  - Mass Flowrate ~ 217 kg/sec (One 150 MWe Turbo-Gen.)
  - Dia. = 2.3 m; L = ~5.3 m; Speed = 5040 rpm
  - Recuperator Volume ~ 48 m³
  - Thermal Eff. = 48.4%

- **Three Reheat/Intercooled Turbo-Alt’s (TIT=1200K; TR=4)**
  - Mass Flowrate ~ 72 kg/sec (Three 50 MWe Turbo-Gens.)
  - P=20 Mpa (Pr=2); Dia = 0.92 m, L = 2.2 m, Speed = 12,500 rpm
  - P=10 Mpa (Pr=2); Dia = 1.30 m, L = 3.0 m, Speed = 8800 rpm
  - P=  5 Mpa (Pr=2); Dia = 1.80 m, L = 4.2 m, Speed = 6200 rpm
  - Recuperator Volume ~ 16 m³
  - Thermal Eff. = 51.6%
Typical Machine Sizes for 150 MWe He Plant

- Single Turbo-Alt at 10 MPa and Pr=2; \(T_{IT}=1300K; \ TR=4.333\)
  - Mass Flowrate ~ 178 kg/sec (One 150 MWe Turbo-Gen.)
  - Dia. = 2.2 m; L = ~5.1 m; Speed = 5240 rpm
  - Recuperator Volume ~ 38 m\(^3\)
  - Thermal Eff. = 51.4%

- Three Reheat/Intercooled Turbo-Alt’s \(T_{IT}=1300K; \ TR=4.333\)
  - Mass Flowrate ~ 59.5 kg/sec (Three 50 MWe Turbo-Gens.)
  - P=20 Mpa (Pr=2); Dia = 0.87 m, L = 2.0 m, Speed = 13,150 rpm
  - P=10 Mpa (Pr=2); Dia = 1.23 m, L = 2.9 m, Speed = 9300 rpm
  - P=5 Mpa (Pr=2); Dia = 1.74 m, L = 4.0 m, Speed = 6600 rpm
  - Recuperator Volume ~ 13.5 m\(^3\)
  - Thermal Eff. = 53.7%
Energy Extraction Comparison for $^{238}\text{U}$ and $^{232}\text{Th}$

**Uranium-fueled light-water reactor:** 35 GW*hr/MT of natural uranium

- Conversion to UF$_6$
- 365 MT of natural UF$_6$ (247 MT U)
- 32,000 MW*days/MT heavy metal (typical LWR fuel burnup)
- 33% conversion efficiency (typical steam turbine)
- 39 MT of enriched (14.2%) UO$_2$ (35 MT U)
- 3000 MW*yr of thermal energy
- 1000 MW*yr of electricity

- 293 MT of natural U$_3$O$_8$ (248 MT U)
- Conversion and fabrication
- 3000 MW*yr of thermal energy
- Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

**Thorium-fueled liquid-fluoride reactor:** 11,000 GW*hr/MT of natural thorium

- Conversion to metal
- 0.8 MT of thorium metal
- 0.8 MT of $^{233}\text{Pa}$ formed in reactor blanket from thorium (decays to $^{233}\text{U}$)
- 2000 MW*yr of thermal energy
- 1000 MW*yr of electricity
- Thorium metal added to blanket salt through exchange with protactinium
- 914,000 MW*days/MT $^{233}\text{U}$ (complete burnup)
- 50% conversion efficiency (triple-reheat closed-cycle helium gas-turbine)

- 0.9 MT of natural ThO$_2$
Summary of MMW - CCGT Power Systems & BRMAPS Potential

• Code can be used for analysis and optimization of minimum mass space power systems (10 MWe) and also ~ 1000 MWe ground based power plants.
• Utilizing aircraft power plant technology leads to light weight and high efficiency turbo-machinery.
• Use of He working fluid reduces Heat exchanger size & turbo-machinery diameter, but increases number of axial stages for a specified pressure ratio.

For Space Applications
• High Temperature Gas Reactor (HTGR) allows a relatively high cycle temperature ratio, but indirect heating as with LFR and several HS heat exchangers is needed to permit turbine reheat cycle of ~50% thermal efficiency at low mass flow rate.
• For space applications higher heat rejection temperatures and direct cooling of turbine gas stream permits lowering of radiator area and mass requirement.
• Heat Pipe Radiator with high inherent redundancy permits reduction of radiator specific mass with increased radiator survivability to micro-meteoroid punctures, thus enhancing overall system reliability.
• BRMAPS Code Enables Power System Optimization Studies to be Conducted Orders of Magnitude Faster than with Case by Case Codes.

For Ground Based Applications
• Liquid Fluoride Reactor can transfer heat to several CBC connected in series (Turbine Reheat configuration) via HSHX (Heat Source heat Exchangers). Thermodynamic performance can be analyzed via BRMAPS (but not NPSS) Code. Alternator windage and bearing cooling losses at specified operating conditions can be added as computational refinements.