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

(Theme for Advanced Nuclear Power Plant Lectures at CSU–Spring ’07)

by Dr. Albert J. Juhasz

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 --> U_{233} 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 (H_{2}) 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 H_{2} 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.
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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)
    (Solar Concentrator + Heat Receiver)
  - 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
Synopsis of Closed Brayton Cycle Code - \textit{BRMAPS}

Thermodynamic System Block Diagram
Comprising three major Subsystems

Space environment temperature at $T_{\text{SINK}}$

\begin{itemize}
  \item \textit{Heat Source} sends Thermal Energy (Heat) to \textit{ECU}
  \item \textit{ECU Subsystem} Transforms Part of Heat Source Thermal Energy, $W_t$, to Electric Work - $W_e$
  \item Unconverted “Low Grade” Heat, $W_t - W_e$, is Rejected to Space at $T_{\text{SINK}}$ by Thermal Radiation Heat Transfer
\end{itemize}
Regenerated Brayton Cycle Configurations w. Fission Reactor Heat Sources

**INDIRECTLY HEATED CYCLE**

**LITHIUM-COOLED REACTOR (LMCR)**

1. Indirect Heating with Direct Heat Rejection

2. Indirect Heating with Indirect Heat Rejection

**DIRECTLY HEATED CYCLE**

**HIGH-TEMPERATURE GAS REACTOR (HTGR)**

3. Direct Heating with Direct Heat Rejection

4. Direct Heating with Indirect Heat Rejection
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)
Non-regenerated Cycle Configuration
(No Heat Exchangers)

HIGH-TEMPERATURE GAS REACTOR (HTGR)

7. Direct Heating Cycle with Direct Heat Rejection

Gas Reactor

Gas Flows over Heat pipe Evaporators
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 .4 .8 1.2 1.6

10 8 6 4 2
EFFECT OF MOLECULAR WEIGHT ON HEAT-EXCHANGER SIZE

RELATIVE HEAT-EXCHANGER SIZE

MOLECULAR WEIGHT

HELUM
NEON
ARGON
HELIUM-XENON GAS MIXTURE
KRYPTON
XENON
GAS TURBINE (BRAYTON CYCLES)

Regenerated Cycle

Non-Regenerated Cycle

Entropy–S

CD-04-82620
Isentropic and Polytropic Efficiency Relationships

Isentropic Compressor Efficiency - $\eta_c$

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

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

Isentropic Turbine Efficiency - $\eta_t$

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

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

$\gamma$ 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

ETAPC = 0.9
<table>
<thead>
<tr>
<th>TEMP RATIO</th>
<th>ETAFS</th>
<th>ETAFC</th>
<th>ETAFT</th>
<th>KG</th>
<th>GAMMA</th>
<th>LPC</th>
<th>ETM</th>
<th>EPSIL</th>
<th>TIT-K</th>
<th>TSINK-K</th>
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<td>2.36</td>
<td>2.43</td>
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<td>3.50</td>
<td>2.42</td>
<td>3.97</td>
<td>495.9</td>
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<tr>
<td>4.00</td>
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<td>4.26</td>
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<td>5.03</td>
<td>200.91</td>
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</table>

**MINIMAL SYSTEM MASS AT ABOVE TEMP RATIOS:**

- 1800 kg

**MINIMUM SYSTEM MASS AT ALFA = 3.40**

**EXECUTION TIME = 5.438 SEC**

**MAP**

GLOBAL MINIMUM MASS CONDITIONS FOR TURBINE INLET TEMPERATURE (K) = 1500

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

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

- 2.100
- 2.200
- 2.300

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

| TURBINE INLET TEMPERATURE (K) | 1600 |
| REACTOR EX INLET TEMP. (K) | 244 |
| CYCLE TEMPERATURE RATIO | 3.400 |
| ACT. COMP. MASS FLOWRATE (MG/KS) | 13.325 MOLA= 4.0 |
| COMPRESSOR PRESSURE RATIO | 2.370 |
| PERCENT CANNOT EFFICIENCY (PCT) | 55.35 |
| SYSTEM THERMAL EFFICIENCY (PCT) | 37.86 |

**TOTAL RADIATING AREA (M2):**

- 4493.10

**SYSTEM SPECIFIC MASS (KG/KW):**

- 6.9

**SYSTEM SPECIFIC POWER (W/KG):**

- 204.44

**COMPONENT WEIGHTS IN KG (PERCENT):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (KG)</th>
<th>Percent</th>
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<tbody>
<tr>
<td>REACTOR</td>
<td>5735</td>
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<td>COOLING</td>
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<tr>
<td>HT SOURCE, PUMP</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>RECOVER PUMP</td>
<td>4779</td>
<td>9.8</td>
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<tr>
<td>COMPRESSOR (2/1)</td>
<td>5264</td>
<td>15.8</td>
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<tr>
<td>TURBINE (2/1)</td>
<td>2556</td>
<td>4.6</td>
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<tr>
<td>ALTERNATOR (2/1)</td>
<td>6846</td>
<td>13.9</td>
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<tr>
<td>HT SINK EX, PUMP</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>POWER CONDITIONING</td>
<td>5000</td>
<td>10.8</td>
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<td>MAIN RADIATOR</td>
<td>5930</td>
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<td>PWR RADIATOR, 4TH</td>
<td>828</td>
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<td>RADIATOR 4TH</td>
<td>3328</td>
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<tr>
<td>STRUCTURE</td>
<td>4447</td>
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</tr>
</tbody>
</table>

**TOTAL SYSTEM MASS: 49185 KG**
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

\[ U = 28.4 \text{ W/sq. m-K} + + \]
\[ = 56.8 \text{ “ “ } \square \square \]
\[ = 113.6 \text{ “ “ } 0 0 \]
\[ = 284.2 \text{ “ “ } \diamond \diamond \]
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 fin and internal Nb-1Zr foil liner
- End cap

**Radiator panel with 226 heat pipes**
- Design features:
  - 12-panel, conical radiator
  - Carbon-carbon heat pipes
  - Integral fins
  - Potassium working fluid
  - Metal liner

**Heat pipe with end caps**
- Evaporator
- Radiator configuration
Segmented Radiator Characteristics for Survival Probability $S=0.999$

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

Relative Weight

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

Relative Thickness

$$\tau = \left[ N_S \ln \left( \frac{1}{p} \right) \right]^{1/3}$$

(a) Relative weight, $w$

(b) Relative thickness, $\tau$

Proportion of segments surviving, $N_s/N$
Brayton Cycle Mapping Code - BRMAPS

Start

- Read input data arrays specifying major subsystems
- Select Routing Option

TIT Map Entry

- Vector of TIT values each with Vector of Temperature Ratio (ALFA) values

Fixed TIT Vector of ALFA Map Entry

- BRMAPM program
  - Read turbine temperature, TIT, values
  - Set up program routing

BRUNM1 – Subprogram

- Read starting temperature ratio (i/ivl) and set up ALFA Vector using DiIV
- Route calls to BRCYC21 and TST3

BRCYC21 – Subprogram

- Set up triple optimization scheme
- Compute theoretical efficiency
- Call BRCY1 for detailed computations

Local Optima Entry

- Fixed TIT Fixed ALFA

EXWT21

- Detailed local output for current ALFAS

RUNOUTPT

- Global output for range of ALFAS with range of TIT

No – Iterate Pressure Ratios using step sizes of LIM Vector

Yes

Local Optima Found?

Yes

Current TIT, ALFA

Processed all Temperature Ratios?

Yes

Current TIT, range of ALFA

Completed all Turbine Inlet Temperatures?

Yes

No – Process next Temperature Ratio of ALFA Vector

No – Process next TIT of TTV Vector

Global output
Optimization Code – TST3

Brayton Cycle Code BRCY1

Legend:
- ALFA - Alpha
- AFR - Alpha Range
- BR - Brayton
- ETH - Exhaust Temperature
- ETHL - Exhaust Temperature Limit
- ETHS - Exhaust Temperature Setpoint
- FLT - Flow
- FLTH - Flow Limit
- FLTS - Flow Setpoint
- HTRP - High Temperature
- HTP - High Temperature Setpoint
- LTP - Low Temperature Setpoint
- P - Pressure
- PR - Pressure Setpoint
- R - Ratio
- RR - Reverse Ratio
- RHP - Reduced High Pressure
- RLP - Reduced Low Pressure
- T - Temperature
- THT - Temperature High Limit
- TLT - Temperature Low Limit
- W - Work
- WRF - Work Reference
- WRP - Work Reference Point
- WRH - Work Reference High
- WRB - Work Reference Low
- X - Variable
- Y - Variable
- Z - Variable

TST3 - Optimization Program

BRCY1 - Core Subprogram

Compute local optimum pressure ratios, PR,

where ETH is maximized, PR is minimized when

BRCY1 - Subprogram

Compute cycle performance

Values at given ALFA and PR

WTCAL - Subroutine

Calculate subsystem and system

Masses.

Reciprocator

Heat Exchanger

Compressor, Turbine, Alt.

Radiators and Ducts

Start Results for Output

Optimisation Program

Stop

BRCC1 evaluates all local optimum

processing strategy

BRCY1
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. \( ^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu(\text{neutrino}) \) (0.42 MeV)
2. \( e^+ + e^- \rightarrow \gamma (\text{radiation}) \) (1.02 MeV)
3. \( ^1_1H + ^2_1H \rightarrow ^3_2He + \gamma \) (5.49 MeV)
4. \( ^3_2He + ^3_2He \rightarrow ^4_2He + ^1_1H + ^1_1H \) (12.86 MeV)

Net Effect: \( 4 ^1_1H \rightarrow ^4_2He + 2 e^+ + 2 \nu \)

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

**Total Energy Generated – \( E = m c^2 \)**

\[
E_t = (4.0313008 - 4.002603) \text{ u} \times 1.66 \times 10^{-27} \text{ kg/u} \times (3 \times 10^8 \text{ m/sec})^2
\]

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

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

**Solar Luminosity, \( L \), is due to \( 9 \times 10^{37} \text{ p-p cyc/sec} \)**

\[L = 26.76 \text{ MeV} \times 1.602 \times 10^{-13} \text{ J/MeV} \times 9 \times 10^{37} / \text{sec} = 3.86 \times 10^{26} \text{ Watts}\]

**Solar Mass Loss**

\[(4.0313008 - 4.002603) \text{ u} \times 1.66 \times 10^{-27} \text{ kg/u} \times 9 \times 10^{37} / \text{sec} = 4.3 \times 10^9 \text{ kg/sec}\]

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

Wavelength \( \mu \) - meters

Radiation Intensity - Watts/m² \( \mu \)

\[ I(\lambda, 5780) \]

\[ I(\lambda, 3500) \]

Solar Spectrum

Visible Range

Infrared Spectrum
### Equilibrium Temperatures, $TS(K)$, at Various AU Distances

<table>
<thead>
<tr>
<th>CONDITIONS FOR SPACECRAFT APPROACHING SUN</th>
<th>ORBIT</th>
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<tbody>
<tr>
<td>ILUMANG (DEG)</td>
<td>FV</td>
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<tr>
<td>-----------------</td>
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<tr>
<td>25.00</td>
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<td>1.0</td>
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<tr>
<td>90.0</td>
<td>1.0</td>
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</table>
Solar Heat Flux & Space Probe Temperatures At Various Orbital Distances (AU)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Heat Flux (W/m²)</th>
<th>Temperature (K)</th>
<th>AU</th>
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<tbody>
<tr>
<td>Earth</td>
<td>1371</td>
<td>279</td>
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<tr>
<td>Venus</td>
<td>2620</td>
<td>482</td>
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<tr>
<td>Mars</td>
<td>591</td>
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<td>161</td>
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Solar Heat Flux at Various Distances from the Sun:
- Sun: 9149 W/m²
- Mercury: 9149 (448K), 5149 (51K)
- Venus: 2620 (328K)
- Earth: 1371 (279K)
- Mars: 591 (226K)
- Jupiter: 51 (122K)
- Saturn: 15 (90K)
- Uranus: 3.7 (64K)
- Neptune: 1.5 (51K)
- Pluto: 0.9 (44K)
- Asteroids: 152 (161K)

A. Juhasz
NASA GRC.
10/31/03
Radiator Area Requirement for 300 kW$_t$ Heat Load 
at Avg. Radiator Surface Temperature = 390 K 
($\theta = 25^\circ$; FV = 1; $\alpha/\varepsilon$ ranging 0.1 to 1.0)
Spacecraft with Trapezoidal Heat Pipe Radiator

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

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

Brayton Cycle Thermal Efficiency

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

where

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

\[ \Theta_T = \left( \frac{P_{\text{IT}}}{P_{\text{OT}}} \right)^{(\gamma - 1)/\gamma} \] 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
Advanced Power System Applications

Lunar Base Power System

Interplanetary Fusion Propulsion Space Vehicle

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

Dimensions:
- 60 m
- 25 m
- 90 m
- 240 m
- 37 m
- 24 m
- 37 m
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

P = 1.08 MPa; 1045 K

433 kg/sec – He flow

325 K; P = 1 MPa

Body of water heat sink

CD-06-82887-2
GAS TURBINE (BRAYTON CYCLES)

Regenerated Cycle

Non-Regenerated Cycle
Three Stage Reheat & Intercool Brayton Cycle
Temperature – Entropy Diagram

Cycle Efficiency: 49.97%
Specific Net Work: 1895 kJ/kg
Mass Flow Rate: 595.5 kg/s

Turbine Inlet Temp ➔
Turbine Outlet Temp.
Compressor Outlet Temp.
Compressor Inlet Temp.

Entropy – J/kg - K

Temp - K

1100 K
1000 K
900 K
800 K
700 K
600 K
500 K
400 K
300 K

20.0
22.0
24.0
26.0
28.0
30.0
32.0
Power Cycle Schematic and T-S Diagram for Single Expansion Inter-Cooled Triple Compression System

(Frutschi)
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 m$^3$
  - Thermal Eff. = 48%

- **Three Reheat/Intercooled Turbo-Alt’s**
  - 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 m$^3$
  - Thermal Eff. = 51.5%
Typical Machine Sizes for 300 MWe He Plant

- **Single Turbo-Alt at 10 MPa and Pr=2; \((TIT=\text{1200K}; \ TR=4)\)**
  - Mass Flowrate \(\sim 434\, \text{kg/sec}\) (One 300 MWe Turbo-Gen.)
  - Dia. = 3.8 m; \(L = \sim 8.8\) m; Speed = 3600 rpm
  - Recuperator Volume \(\sim 96\, \text{m}^3\)
  - Thermal Eff. = 48%

- **Three Reheat/Intercooled Turbo-Alts (\(TIT=\text{1200K}; \ TR=4)\)**
  - Mass Flowrate \(\sim 142\, \text{kg/sec}\) (Three 100 MWe Turbo-Gens.)
  - \(P=20\, \text{Mpa}\) (Pr=2); Dia = 1.4 m, \(L = 3.3\) m, Speed = 8700 rpm
  - \(P=10\, \text{Mpa}\) (Pr=2); Dia = 1.9 m, \(L = 4.4\) m, Speed = 6200 rpm
  - \(P=5\, \text{Mpa}\) (Pr=2); Dia = 2.7 m, \(L = 6.3\) m, Speed = 4360 rpm
  - Recuperator Volume \(\sim 34\, \text{m}^3\)
  - 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

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mass Flowrate (kg/sec)</th>
<th>Diameter (m)</th>
<th>Length (m)</th>
<th>Speed (rpm)</th>
<th>Recuperator Volume (m³)</th>
<th>Thermal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Turbo-Alt at 10 MPa and Pr=2</strong></td>
<td>~ 178</td>
<td>2.2</td>
<td>~5.1</td>
<td>5240</td>
<td>~ 38</td>
<td>51.4</td>
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<tr>
<td><strong>Three Reheat/Intercooled Turbo-Alt’s</strong></td>
<td>~ 59.5</td>
<td>0.87</td>
<td>2.0</td>
<td>13,150</td>
<td>~ 13.5</td>
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<td>1.74</td>
<td>4.0</td>
<td>6600</td>
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</tbody>
</table>

Other details:
- TIT = 1300K; TR = 4.333
Energy Extraction Comparison for U$^{238}$ and Th$^{232}$

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

- Conversion to UF6
- 293 MT of natural U$_3$O$_8$ (248 MT U)
- Conversion and fabrication
- 365 MT of natural UF$_6$ (247 MT U)
- 39 MT of enriched (14.2%) UO$_2$ (35 MT U)
- 32,000 MW*days/MT heavy metal (typical LWR fuel burnup)
- 33% conversion efficiency (typical steam turbine)
- 3000 MW*yr of thermal energy
- 1000 MW*yr of electricity

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

- Conversion to metal
- 0.9 MT of natural ThO$_2$
- Thorium metal added to blanket salt through exchange with protactinium
- 0.8 MT of thorium metal
- 0.8 MT of $^{233}$Pa formed in reactor blanket from thorium (decays to $^{233}$U)
- 914,000 MW*days/MT $^{233}$U (complete burnup)
- 50% conversion efficiency (triple-reheat closed-cycle helium gas-turbine)
- 2000 MW*yr of thermal energy
- 1000 MW*yr of electricity

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html
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.