Gas Turbine Energy Conversion Systems for Nuclear Power Plants applicable to LiFTR “Liquid Fluoride Thorium Reactor” Technology

Session 11 – Advanced Terrestrial & Space Power Generation

Albert J. Juhasz – PhD
NASA - GRC, Cleveland, Ohio
Session 11 Outline

This panel plans to cover thermal energy and electric power production issues facing our nation and the world over the next decades, with relevant technologies ranging from near term to mid- and far term.

- Although the main focus will be on ground based plants to provide baseload electric power, energy conversion systems (ECS) for space are also included, with solar- or nuclear energy sources for output power levels ranging tens of Watts to kilo-Watts for unmanned spacecraft, and eventual mega-Watts for lunar outposts and planetary surface colonies. Implications of these technologies on future terrestrial energy systems, combined with advanced fracking, are touched upon.

- Thorium based reactors, and nuclear fusion along with suitable gas turbine energy conversion systems (ECS) will also be considered by the panelists. The characteristics of the above mentioned ECS will be described, both in terms of their overall energy utilization effectiveness and also with regard to climactic effects due to exhaust emissions.
Background & Motivation

• Advanced Nuclear Power named in Energy Policy Act of 2005 (Gen IV Nuclear Systems Initiative)
  – Gen. Baseload GW’s Power -> Solve Depletion of Earth’s HC (hydro-carbon) Resources
  – Ameliorate world climate problems by eliminating Greenhouse Gas Emissions

• Thorium Nuc. Power Plant Construction (100 GWe over next 25 yrs) would re-invigorate US and World economies

• Gen IV Candidate Advanced Nuclear Power Plants
  – Gas Turbine Modular He Reactor (GT-MHR) Systems - Space
  – Liquid Fluoride Thorium Reactor (LFTR) GT Systems - Terrestrial

• High Temperature Gas Turbine Power plants offer large Thermal Efficiency improvement over Steam plants
Energy Conversion Cycle Comparisons

GT - MHR

Gas Turbine – Modular He Reactor

50 percent increase

Steam cycle
(Rankine)

Steamp cycle
MHR

Gas turbine cycle
(Brayton)

Water reactor

Plant efficiency, percent

Turbine inlet temperature, K

(La Bar, 2002)
Requirements – i.e. Power System Design Drivers

- Space (Lunar-Mars) 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 at reduced Eff.

- Terrestrial Nuclear Power Systems – e.g. LFTR Power Plant
  - Emphasis is on maximizing Thermal Efficiency and thus Power Output, Revenue, Profit & Return on Investment
  - System Maintenance possible during regularly scheduled Periods
  - High System Mass and Complexity are acceptable as long as high Power Plant Availability/Reliability is assured
Space CBC Systems
and
Analysis
In-direct Heat Input & Rejection via Radiator for Regenerated Closed Brayton Cycle (CBC) Power System
Direct Heat Input and Rejection via Radiator for Non-Regenerated Closed Brayton Cycle (CBC) Power System
(Simpler System eliminates 3 Heat Exchangers; - but lower $\eta_{th}$)
Radiators dominate Space Power System Size and Mass
SP – 100 Radiator Panel/Cone Configuration

Radiator panel with 226 heat pipes

Evaporator

Heat pipe with end caps

Design features
- 12-panel, conical radiator
- Carbon-carbon heat pipes
- Integral fins
- Potassium working fluid
- Metal liner

Radiator configuration
GAS TURBINE (BRAYTON CYCLES)

Regenerated Cycle

Non-Regenerated Cycle

CD-04-82620
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 Heat Transfer Coefficient $U$ as a Parameter for He Working Fluid

$$U = 28.4 \text{ W/sq. m-K}$$
$$= 56.8 \text{ "}$$
$$= 113.6 \text{ "}$$
$$= 284.2 \text{ "}$$

Regenerator Effectiveness -- $\varepsilon$
Advanced Space Power System Applications

Lunar Base Power System

Interplanetary Fusion Propulsion Space Vehicle
Ground Based CBC Systems and Analysis
Recall GAS TURBINE (BRAYTON CYCLES)

Regenerated Cycle

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

Entropy – J/kg - K

Turbine Inlet Temp ➔
Heat Source Inlet Temp. ➔
Heat Input

Regenerated Thermal Energy

Compression Outlet Temp. ➜
Heat Rejection ➜
Compressor Inlet Temp.

Cycle Efficiency: 49.97%
Specific Net Work: 1895. KJ/kg
Mass Flow Rate: 555.5 kg/s
1000 MWe Power Plant 2 Salt Configuration
Thorium Molten Salt Reactor
He CBC w. Rht. & Intcl. - 1200 K Turbine Inlet Temp

Compressor Power = 1758 MW
Turbine Power = 333 MW

Temp Ratio = 4.0
Efficiency = 50.6 %

Specific Work = 2300 kJ / kg
m_{He} = 435 kg / s
m_{LiF} = 7860 kg / s

1976 MW_{th}

Complex System!
Three Stage Intercool Only Brayton Cycle
Temperature – Entropy Diagram

Entropy – J/kg-K

Regenerated Thermal Energy

T-K

TIT →

TIC →

Entropy – J/kg-K
100 MWe Power Plant – 2 Salt Configuration
Thorium Molten Salt Reactor with Intercooled He CBC
with 950 K Turbine Inlet Temperature (mHe = 189.2 kg/s)

Temp Ratio = 3.17
Efficiency = 41.3%
Turbine Power = 217.9 MW
Compressor Power = – 115.8 MW

Notation: 1 P = 1 MPa

Specific Work = 529 kJ / kg

Thorium Reactor
242 MWth

\( m_{LIF} = 480 \text{ kg/s} \)

\( m_{He} = 189 \text{ kg/s} \)
100 MWe Power Plant – 2 Salt Configuration
Thorium Molten Salt Reactor - Helium Brayton Cycle, 1200 K Turbine Inlet Temp

Temp Ratio = 4.0
Efficiency = 50.5 %
Turbine Power = 178.9 MW
Compressor Power = 76.9 MW

Notation: 1 P = 1 MPa
Gen-4 Liquid 2 Salt Configuration Reactor Concept – ORNL

LiF-BeF2 HT Loop

ThF4 – UF4 LiF-BeF2 Reactor Loop

He Gas Loop

Emergency Dump Tanks

Purified Salt

Fuel Salt

Control Rods

Coolant Salt

MSR Molten Salt Reactor

Generator

Turbine

Recuperator

Compressor

Heat Sink

Pre Cooler

Heat Exchanger #1

Heat Exchanger #2

Intercooler

02-GA50807-02

22
100 MWe Power Plant Efficiency w. Intercool & Reheat Cycles
(3 Inter-cooled Compressors in Series)
100 MWe Power Plant Flowrate w. Intercool & Reheat Cycles
(3 Inter-cooled Compressors in Series)
Typical Axial Radial Turbo-compressor
Axial/Radial Compressor with Axial Intake

Type AR 250-8-2 axial-centrifugal compressor with axial intake

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>Air</td>
</tr>
<tr>
<td>Flow volume</td>
<td>272,000 m³/h</td>
</tr>
<tr>
<td>Intake pressure</td>
<td>1.01 bar</td>
</tr>
<tr>
<td>Discharge pressure</td>
<td>6.4 bar</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>4,550 rpm</td>
</tr>
<tr>
<td>Drive rating</td>
<td>22,700 kW (turbine)</td>
</tr>
</tbody>
</table>
Flow Diagram for AR Compressor with Axial Intake

1 – Intake Casing
2 – Discharge for Axial Section
3 – Intake for 1. Radial Section
4 – Discharge for 1. Radial S.
5 - Intake for 2. Radial Section
6 – Discharge for 2. Radial S.
7,8,9 – Stage Intercoolers
10 – Compressor Discharge Flow
11 – Start-up Valve
12 – Surge Control Valve
13 – Blow-off Line
14 – Start-up Relief Valve
Energy Extraction Comparison for $^{238}\text{U}$ and $^{232}\text{Th}$

**Uranium-fueled light-water reactor:** 
- 35 GW*hr/MT of natural uranium
- 1000 MW*yr of electricity
- 33% conversion efficiency (typical steam turbine)
- 3000 MW*yr of thermal energy

**Thorium-fueled liquid-fluoride reactor:** 
- 11,000 GW*hr/MT of natural thorium
- 1000 MW*yr of electricity
- 50% conversion efficiency (triple-reheat closed-cycle helium gas-turbine)

Conversion and fabrication of fuel:
- Uranium: 365 MT of natural UF$_6$ (247 MT $^{235}\text{U}$)
- Thorium: 0.8 MT of thorium metal

Conversion and fabrication of heavy metal:
- Uranium: 32,000 MW*days/MT heavy metal (typical LWR fuel burnup)
- Thorium: 914,000 MW*days/MT $^{233}\text{U}$ (complete burnup)

Thermal energy:
- Uranium: 3000 MW*yr
- Thorium: 2000 MW*yr

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html
Submarine Based Power Plants
Compact, Portable Thorium Reactors

Proposal to use US mothballed shipyards to produce hundreds of portable thorium nuclear gas turbine power plants.
Concluding Remarks

• Verified that Advanced Nuclear Power Plants with CCGT Conversion Technology can achieve > 50% Thermal Efficiency at TIT ~ 1200 K.
• Above result obtained for both ‘Intercool + Reheat’ and ‘Intercool Only’ Cycle Configurations
• ‘Intercool + Reheat’ Configurations have higher Complexity (number of ducts and heat exchangers) but lower Working Fluid Mass Flow (He) Requirements thus reducing Ducting and Heat Exchanger Size
• Liquid Fluoride Thorium Reactor Technology (LFTR) can meet the goals of the Gen IV Nuclear Energy Systems Initiative – Energy Policy Act ’05
  – Uses fertile Th232 breeding to fissile U233
  – Can meet world energy demands for tens of millennia
  – ~300 times Energy Density of current LWR Nuclear Power Plants with corresponding reduction in fission products. Decay <300 yrs.
  – Inherently Safe due to negative temp. coefficient of reactivity
  – Proliferation resistant
  – Load Leveling to produce H2, Desalination
• Submarine based Power Plants with HVDC distribution proposed
Backup Slides
Ref.: K. Sorensen and J. Bonometti
http://www.energyfromthorium.com
Energy from Thorium via Liquid Fluoride Thorium Reactor Technology
Thorium and Uranium Abundance in the Earth's Crust

Fig. 5.13. The chemical composition of the Earth's crust.
Thorium-232 - Uranium-233 Breeding Cycle

Thorium-232 absorbs a neutron from fission and becomes thorium-233.

Thorium-233 decays quickly (half-life of 22.3 min) to protactinium-233 by emitting a beta particle (i.e. an electron).

Protactinium-233 decays more slowly (half-life of 27 days) to uranium-233 by emitting a beta particle (an electron).

It is important that Pa-233 NOT absorb a neutron before it decays to U-233—it should be shielded from any neutrons until it decays.

Uranium-233 is fissile and will fission when struck by a neutron, releasing energy and 2 to 3 neutrons. One neutron is needed to sustain the chain-reaction, one neutron is needed for breeding, and any remainder can be used to breed additional fuel.
Thorium –Uranium Fuel Cycle

1. $^{90}\text{Th}^{232} + _{0}n^{1} \rightarrow ^{90}\text{Th}^{233} + \gamma$ (neutron absorption)

2. $^{90}\text{Th}^{233} \rightarrow -_{1}\beta^{0} + ^{91}\text{Pa}^{233}$ ($\beta$ decay – $\lambda = 22.3$ min)

3. $^{91}\text{Pa}^{233} \rightarrow -_{1}\beta^{0} + ^{92}\text{U}^{233}$ ($\beta$ decay – $\lambda = 27$ days)
Time for 99.9% Beta Decay of Protactinium to U-233

- **Looking at Step 3**, the time required for 99.9% of Pa$^{233}$ decaying to U$^{233}$ and 0.1% remaining Pa$^{233}$, let $N(t) = 0.1$ and $N_0 = 99.9$ in eq. (1)

  $$N(t) = N_0 e^{-\lambda t} \quad (1)$$

  where $\lambda$ is the *decay constant* computed from

  $$\lambda = (\ln .5)/T_{0.5} \ , \text{ with } T_{0.5} \text{ being the } \text{Half Life} = 27 \text{ days}$$

- So $\lambda = -0.693/27 = -0.02567 \text{ days}^{-1}$

  Substituting in (1) : $0.1 = 99.9 \ e^{-0.02567 \ast t} \quad (2)$

  Dividing (2) by 99.9 $\sim 100$, and taking the ln of both sides, we have

  $$\ln .001 = - .02567 \ t$$

  $$t = - 6.9077 / -.02567$$

  $$= 269 \text{ days, or } \sim 9 \text{ months for } 99.9\% \text{ of Pa } \rightarrow \text{ U}^{233}$$

- **Note that for 99% transmutation to U$^{233}$ only 179.5 days would be required**
Submarine Based Power Plants
Compact, Portable Thorium Reactors

Proposal to use US mothballed shipyards to produce hundreds of portable thorium nuclear gas turbine power plants
Key Cycle Input Parameters

- Compressor Inlet Temperature (TIC), K 300
- Cooling Water Temperature, K 288
- Reactor Heat Loss, percent 1.0
- Polytropic Efficiency—Compressor, percent 86
- Polytropic Efficiency—Turbine, percent 92
- Recuperator Effectiveness, percent 95
- Intercooler HX Pressure Loss, percent 0.5
- Reheat HX Pressure Loss, percent 0.8
- Turbine Pressure Ratio Fraction, percent 96
- Generator Efficiency, percent 98
Comparison to Space System - Direct Heat Input and Rejection via Radiator for Non-Regenerated Closed Brayton Cycle (CBC) Power System

CLOSED-CYCLE NONREGENERATED GAS TURBINE NUCLEAR POWER SYSTEM CONFIGURATIONS

INDIRECTLY HEATED CYCLE

DIRECTLY HEATED CYCLE

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
# Partial BRMAPS Code Output Results for 5 MWe Lunar Power Plant

**BRAYTON CYCLE CALCULATIONS - NON REGENERATED - 1500 K POWER LEVEL = 5.00 MWE TSTINK - K = 190**

<table>
<thead>
<tr>
<th>TEMP RATIO</th>
<th>ETA9</th>
<th>ETA9C</th>
<th>ETA9PT</th>
<th>ERG</th>
<th>GAMMA</th>
<th>LPC</th>
<th>EM</th>
<th>EPSIL</th>
<th>TIT-K</th>
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<tbody>
<tr>
<td>3.000</td>
<td>.990</td>
<td>.900</td>
<td>.900</td>
<td>.000</td>
<td>1.667</td>
<td>.969</td>
<td>.950</td>
<td>.900</td>
<td>1530</td>
</tr>
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</table>

**OPTIMUM PRESSURE RATIOS (MAX THERM EFF, MIN ARP, MASS) = 4.550 3.200 3.400 TIC-K = 500**

<table>
<thead>
<tr>
<th>PR RATIO THERM EFF, ARP (M2/KW)</th>
<th>MSTS (M2)</th>
<th>W (M2/S-MW)</th>
<th>TREJ-K</th>
<th>TREFF-K</th>
<th>TOC-K</th>
<th>TOT-K</th>
<th>ETPAC</th>
<th>ETAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5500</td>
<td>.2604</td>
<td>.4076</td>
<td>20.8794</td>
<td>.3897</td>
<td>862.88</td>
<td>630.73</td>
<td>1005.81</td>
<td>.867</td>
</tr>
<tr>
<td>3.2000</td>
<td>.2382</td>
<td>.3554</td>
<td>19.6747</td>
<td>.3122</td>
<td>985.29</td>
<td>663.87</td>
<td>850.84</td>
<td>.875</td>
</tr>
<tr>
<td>3.4000</td>
<td>.2446</td>
<td>.3566</td>
<td>19.6355</td>
<td>.3170</td>
<td>963.13</td>
<td>658.18</td>
<td>875.51</td>
<td>.974</td>
</tr>
</tbody>
</table>

**THEORETICAL OPTIMUM PRESSURE RATIO (PROPTI) = 4.579**

**NUMBER OF ITERATIONS (ICT8, ICTA, ICTM) = 7 9 6**

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**TURBO - ALTERNATOR POWER DISTRIBUTION**

- **GAS MOLECULAR WEIGHT (KG/MOL) = 4.000**
- **MASS FLOWRATE (KG/SBC) = 6.178**
- **COMPR. PRESSURE RATIO = 3.200**
- **NO. INTC. COMP. STAGES = 1**
- **NO. REHEAT TURB. STAGES = 1**
- **COMPR. BLEED PCT. = .500**
- **COMPRESSOR POWER (MW) = -10.921**
- **TURBINE POWER (MW) = 16.190**
- **POWER LOSSES (MW) = -.269**
- **POWER SUM BALANCE (MW) = 5.000**

(= GENERATOR TERMINAL ELECTRICAL POWER-(MW))
Isotope Production from LFTR

1000 kg of Th-232

- 90% fission 9000 GWe*hr $540-630M^*$
- 85% fission 900 GWe*hr $54-63M^*$

250 kCi of Pu-238 8400 watts-thermal $75-150M^{**}$

1000 kg U-233

- 100 kg U-234
- 100 kg U-235
- 15 kg U-236
- 15 kg Np-237
- 15 kg Pu-238

- ~20 kg of medical molybdenum-99
- ~5 g (1 Ci) of thorium-229 used in targeted alpha therapy cancer treatments
- ~20 kg (3300 watts-thermal) of radiostrontium (>90% $^{90}$Sr, heating value)
- ~150 kg of stable xenon and ~125 kg of stable neodymium
LFTR is passively safe in case of accident or sabotage

- The reactor is equipped with a “freeze plug”—an open line where a frozen plug of salt is blocking the flow.
- The plug is kept frozen by an external cooling fan.

- In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear energy can be safely released.

Freeze Plug

Drain Tank
"Ac-225 and Bi-213 are currently derived from purified Th-229 extracted from U-233 at ORNL. The only practical way at present is to derive these isotopes from the natural decay of Th-229. Th-229 is produced by the natural decay of U-233. Ac-225 is the product being shipped to medical facilities. Bi-213 is separated from the Ac-225 at the hospital and combined with the targeting agent.

"Bi-213 appears to be very potent, so only a very minute quantity may be needed to treat a patient... on the order of a billionth of a gram."
Power Generation Resource Inputs

• Nuclear: 1970’s vintage PWR, 90% capacity factor, 60 year life [1]
  - 40 MT steel / MW(average)
  - 190 m³ concrete / MW(average)

• Wind: 1990’s vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
  - 460 MT steel / MW (average)
  - 870 m³ concrete / MW(average)

• Coal: 78% capacity factor, 30 year life [2]
  - 98 MT steel / MW(average)
  - 160 m³ concrete / MW(average)

• Natural Gas Combined Cycle: 75% capacity factor, 30 year life [3]
  - 3.3 MT steel / MW(average)
  - 27 m³ concrete / MW(average)

Recent increase in natural gas plants

Cost of:
  • materials
  • labor
  • land
  • tools
  • etc…

Distance from end user, prime real estate, energy intensity, etc…
Thorium: Virtually **Limitless** Energy

- Thorium is abundant around the world:
  - Found in trace amounts in most rocks and soils
  - India, Australia, Canada, US have large minable concentrations
  - US has about 20% of the world reserve base

- No need to hoard or fight over this resource:
  - A single mine site in Idaho could produce 4500 MT of thorium per year
  - Replacing the total US electrical energy consumption would require ~400 MT of thorium

### World Thorium Resources

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserve Base (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>340,000</td>
</tr>
<tr>
<td>India</td>
<td>300,000</td>
</tr>
<tr>
<td>USA</td>
<td>300,000</td>
</tr>
<tr>
<td>Norway</td>
<td>180,000</td>
</tr>
<tr>
<td>Canada</td>
<td>100,000</td>
</tr>
<tr>
<td>South Africa</td>
<td>39,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>18,000</td>
</tr>
<tr>
<td>Other countries</td>
<td>100,000</td>
</tr>
<tr>
<td>World total</td>
<td>1,400,000</td>
</tr>
</tbody>
</table>

*Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2008*

The United States has buried 3200 metric tonnes of thorium nitrate in the Nevada desert.

There are 160,000 tonnes of economically extractable thorium in the US, even at today’s “worthless” prices!
## Relative Comparison: Uranium vs Thorium Based Nuclear Power

<table>
<thead>
<tr>
<th></th>
<th>Uranium LWR (light water reactor, high pressure low temp)</th>
<th>Thorium LFTR (liquid fluoride thorium reactor, low pressure high temp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Safety</td>
<td>Good (high pressure)</td>
<td>Very Good (low pressure, passive containment)</td>
</tr>
<tr>
<td>Burn Existing Nuclear Waste</td>
<td>Limited</td>
<td>Yes</td>
</tr>
<tr>
<td>Radioactive Waste Volume</td>
<td>1</td>
<td>1/30th</td>
</tr>
<tr>
<td>Storage Requirements</td>
<td>10,000+ yrs.</td>
<td>~300 yrs.</td>
</tr>
<tr>
<td>Produce Weapon Suitable Fuel</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>High Value By-Products</td>
<td>Limited</td>
<td>Extensive</td>
</tr>
<tr>
<td>Fuel Burning Efficiency</td>
<td>&lt;1%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>Fuel Mining Waste Vol.</td>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>Fuel Reserves (relative)</td>
<td>1</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Solid</td>
<td>Liquid</td>
</tr>
<tr>
<td>- Fuel Fabrication/Qualification</td>
<td>Expensive/Long</td>
<td>Cheap/Short</td>
</tr>
<tr>
<td>Plant Cost (relative)</td>
<td>1 (high pressure)</td>
<td>&lt;1 (low pressure)</td>
</tr>
<tr>
<td>Plant Thermal Efficiency</td>
<td>~35% (low temp)</td>
<td>~50% (high temp)</td>
</tr>
<tr>
<td>Cooling Requirements</td>
<td>Water</td>
<td>Water or Air</td>
</tr>
<tr>
<td>Development Status</td>
<td>Commercial Now</td>
<td>ORNL Demonstrated 1950-1970</td>
</tr>
</tbody>
</table>

Source: http://www.energyfromthorium.com/ppt/thoriumEnergyGeneration.ppt
U-232 Formation in the Thorium Fuel Cycle

\[
\begin{align*}
^{232}\text{Th} & \xrightarrow{n, 2n} ^{231}\text{Th} \xrightarrow{\beta^-} ^{231}\text{Pa} \xrightarrow{n, \gamma} ^{232}\text{Pa} \xrightarrow{\beta^-} ^{232}\text{U} \\
^{233}\text{U} & \xrightarrow{n, 2n} ^{232}\text{U} \\
^{230}\text{Th} & \xrightarrow{n, \gamma} ^{231}\text{Th} \xrightarrow{\beta^-} ^{231}\text{Pa} \xrightarrow{n, \gamma} ^{232}\text{Pa} \xrightarrow{\beta^-} ^{232}\text{U}
\end{align*}
\]

Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Dose Rate (rem/hr)</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weapon-grade plutonium</td>
<td>0.0013</td>
<td>3800</td>
</tr>
<tr>
<td>Reactor-grade plutonium</td>
<td>0.0082</td>
<td>610</td>
</tr>
<tr>
<td>U-233 containing 1 ppm U-232</td>
<td>0.013</td>
<td>380</td>
</tr>
<tr>
<td>U-233 containing 5 ppm U-232</td>
<td>0.059</td>
<td>80</td>
</tr>
<tr>
<td>U-233 containing 100 ppm U-232</td>
<td>1.27</td>
<td>4</td>
</tr>
<tr>
<td>U-233 containing 1 percent U-232</td>
<td>127</td>
<td>0.04</td>
</tr>
</tbody>
</table>
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-Alt’s
  – Mass Flowrate ~ 474 kg/sec
  – P=20 Mpa (Pr=2); Dia = 1.9 m, L = 4.5 m, Speed = 72000 rpm
  – P=10 Mpa (Pr=2); Dia = 2.7 m, L = 6.3 m, Speed = 5400 rpm
  – P= 5 Mpa (Pr=2); Dia = 3.8 m, L = 8.5 m, Speed = 3600 rpm
  – Recuperator Volume ~ 120 m³
  – Thermal Eff. = 51.5%
Today's approach to nuclear energy

250 t of natural uranium containing 1.75 t U-235

35 t of enriched uranium (1.15 t U-235)

Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

215 t of depleted uranium containing 0.6 t U-235—disposal plans uncertain.

35 t of spent fuel stored on-site until disposal at Yucca Mountain. It contains:
- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products.

Energy from thorium

One tonne of natural thorium

Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned".

One tonne of fission products; no uranium, plutonium, or other actinides.

Within 10 years, 83% of fission products are stable and can be partitioned and sold.

The remaining 17% fission products go to geologic isolation for ~300 years.
Acknowledgments & Disclaimer

The information contained in this presentation was generated at NASA Glenn Research Center and Cleveland State University.

Any opinions, findings, results, conclusions, or recommendations expressed in this presentation are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.
Proposed Vertical Orientation of GT-MHR* Turbomachinery

1 – Generator
2 – Recuperator
3 – Turbocompressor
4 – Intercooler
5 – Precooler
6 – Control Rod Drive
7 – Core
8 – Vessel System
9 – Reactor Shutdown Cooling System

* Gas Turbine Modular Helium Reactor
Thorium: Virtually **Limitless** Energy

**World Thorium Resources**

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserve Base (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>340,000</td>
</tr>
<tr>
<td>India</td>
<td>300,000</td>
</tr>
<tr>
<td>USA</td>
<td>300,000</td>
</tr>
<tr>
<td>Norway</td>
<td>180,000</td>
</tr>
<tr>
<td>Canada</td>
<td>100,000</td>
</tr>
<tr>
<td>South Africa</td>
<td>39,000</td>
</tr>
<tr>
<td>Brazil</td>
<td>18,000</td>
</tr>
<tr>
<td>Other countries</td>
<td>100,000</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>1,400,000</strong></td>
</tr>
</tbody>
</table>


- Thorium is abundant around the world:
  - Found in trace amounts in most rocks and soils
  - India, Australia, Canada, US have large minable concentrations
  - US has about 20% of the world reserve base
- No need to hoard or fight over this resource:
  - A single mine site in Idaho could produce 4500 MT of thorium per year
  - Replacing the total US electrical energy consumption would require ~400 MT of thorium

The United States has buried 3200 metric tonnes of thorium nitrate in the Nevada desert.

There are 160,000 tonnes of economically extractable thorium in the US, even at today’s “worthless” prices!