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

Session 11 – Advanced Terrestrial & Space Power Generation

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Session 11 Outline

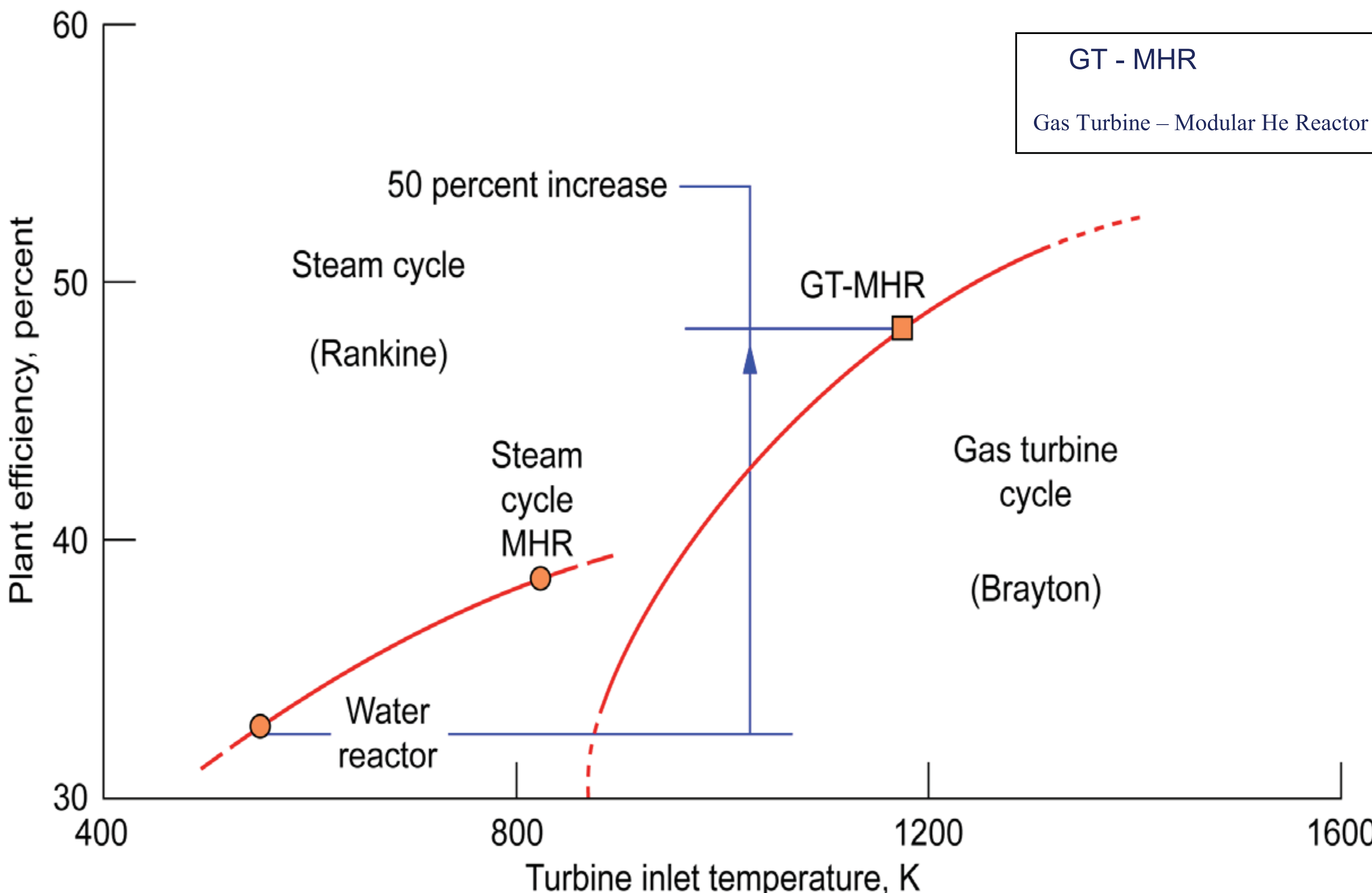
This panel plans to cover thermal energy and electric power production issues facing our nation and the world over the next decades, with relevant technologies ranging from near term to mid-and far term.

- 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

(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.

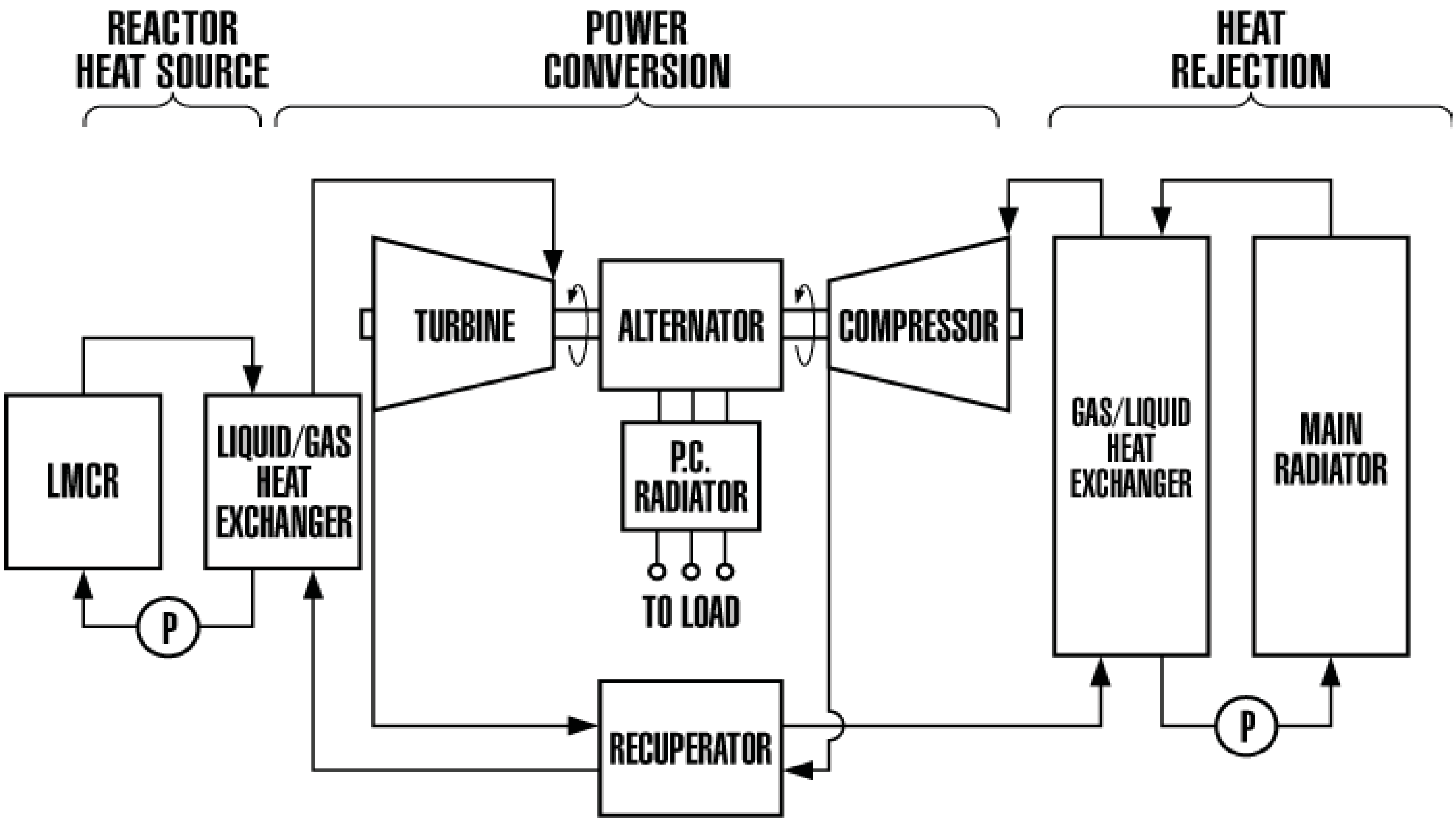
- Terrestrial Nuclear Power Systems –e.g. LFTR Power Plant
  - Emphasis is on maximizing Thermal Efficiency and thus Power Output, Revenue, Profit & Return on Investment
  - System Maintenance possible during regularly scheduled Periods
  - High System Mass and Complexity are acceptable as long as high Power Plant Availability/Reliability is assured

Space CBC Systems

and

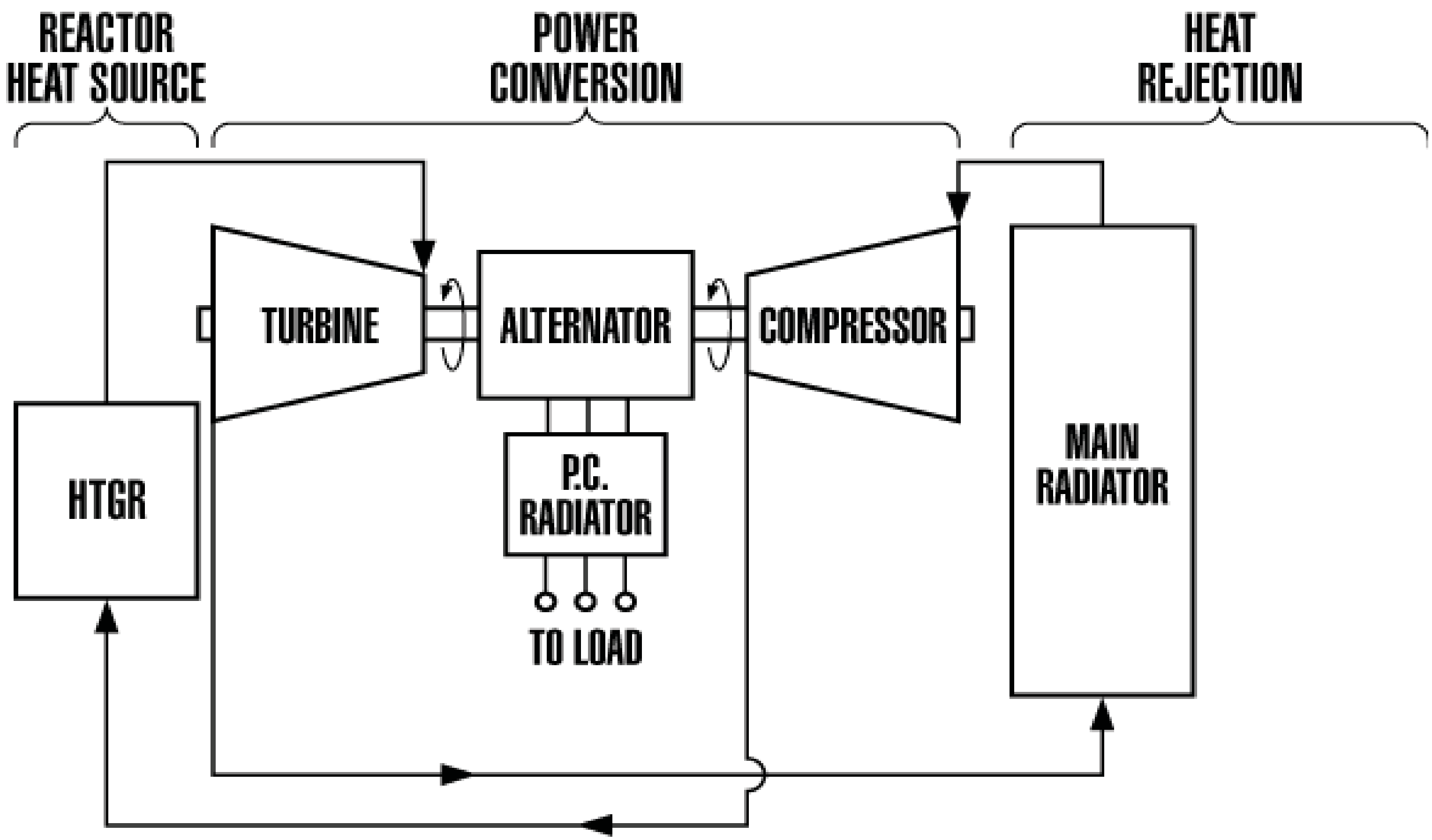
Analysis

In-direct Heat Input & Rejection via Radiator for Regenerated Closed Brayton Cycle (CBC) Power System



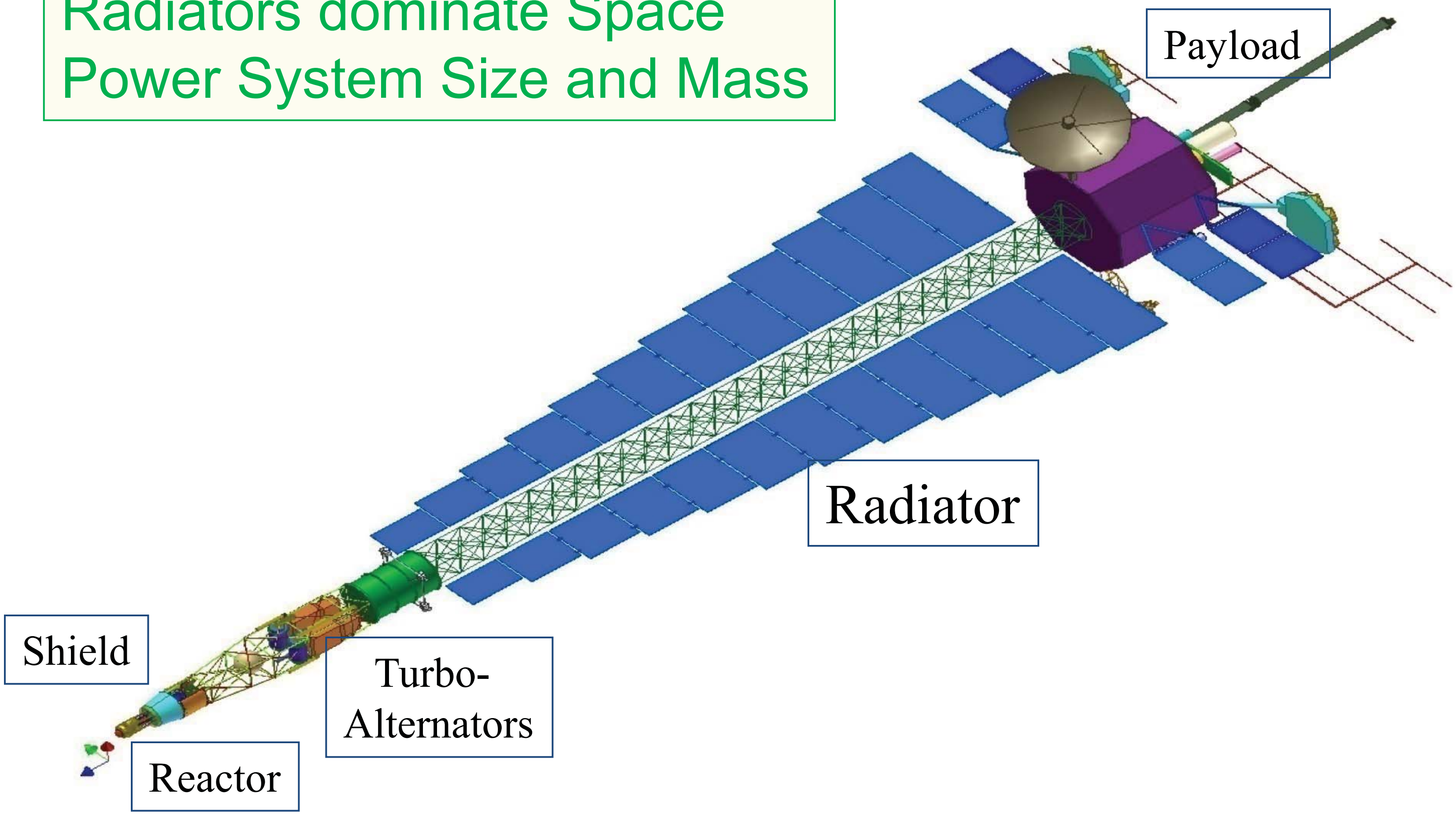
Direct Heat Input and Rejection via Radiator for Non-Regenerated Closed Brayton Cycle (CBC) Power System

(Simpler System eliminates 3 Heat Exchangers; - but lower η_{th})

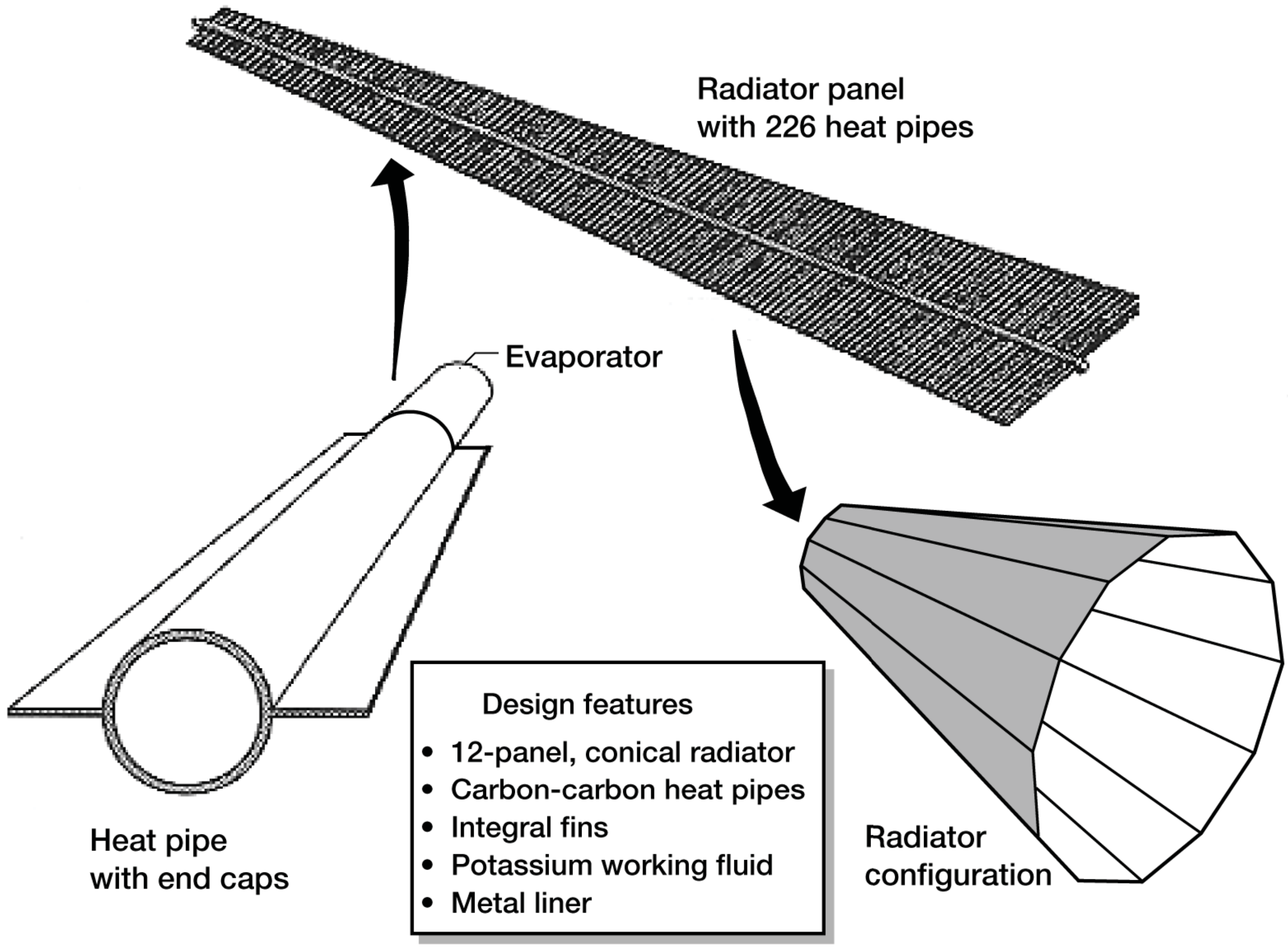


Spacecraft with Trapezoidal Heat Pipe Radiator

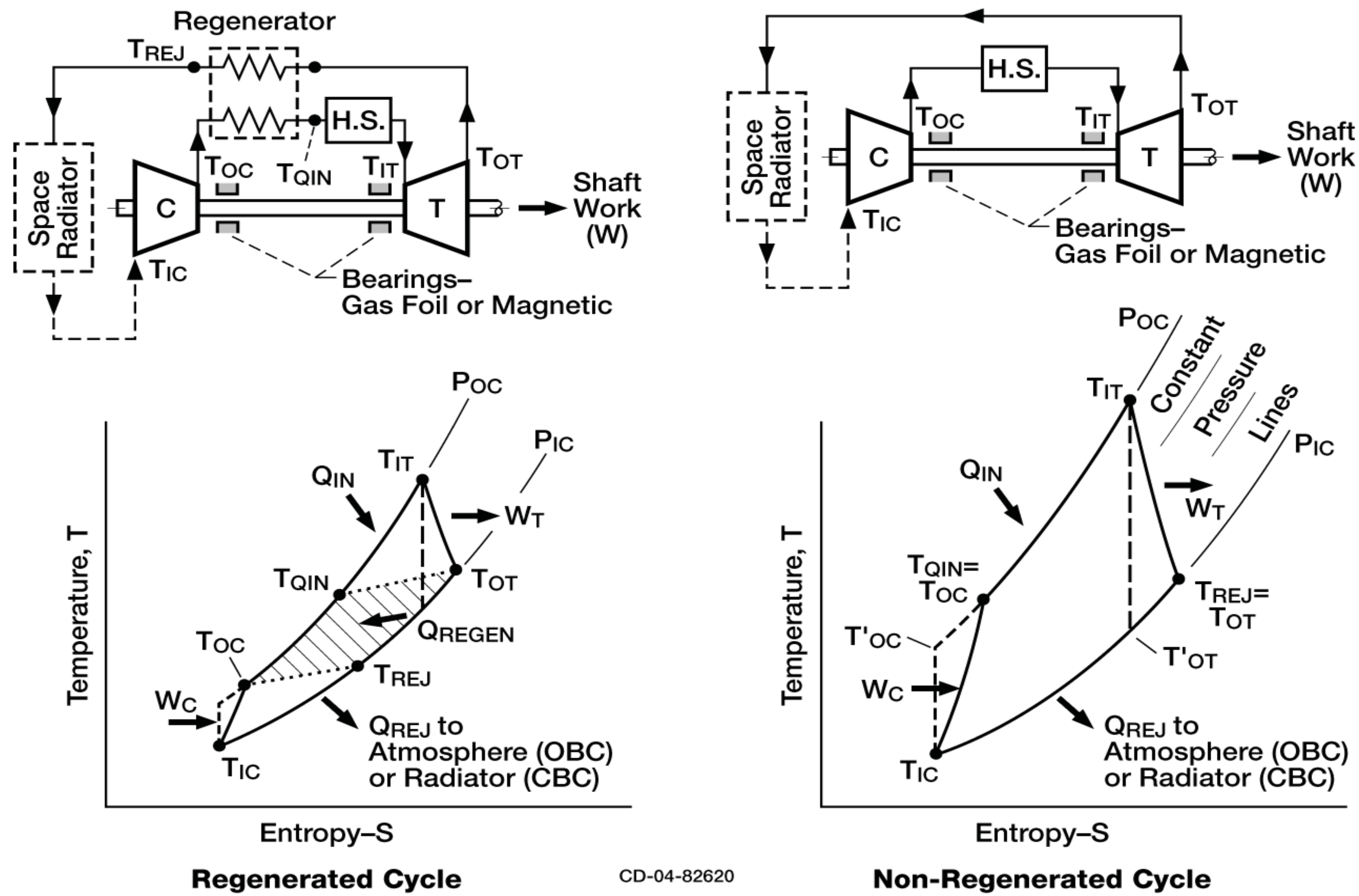
Radiators dominate Space Power System Size and Mass



SP – 100 Radiator Panel/Cone Configuration

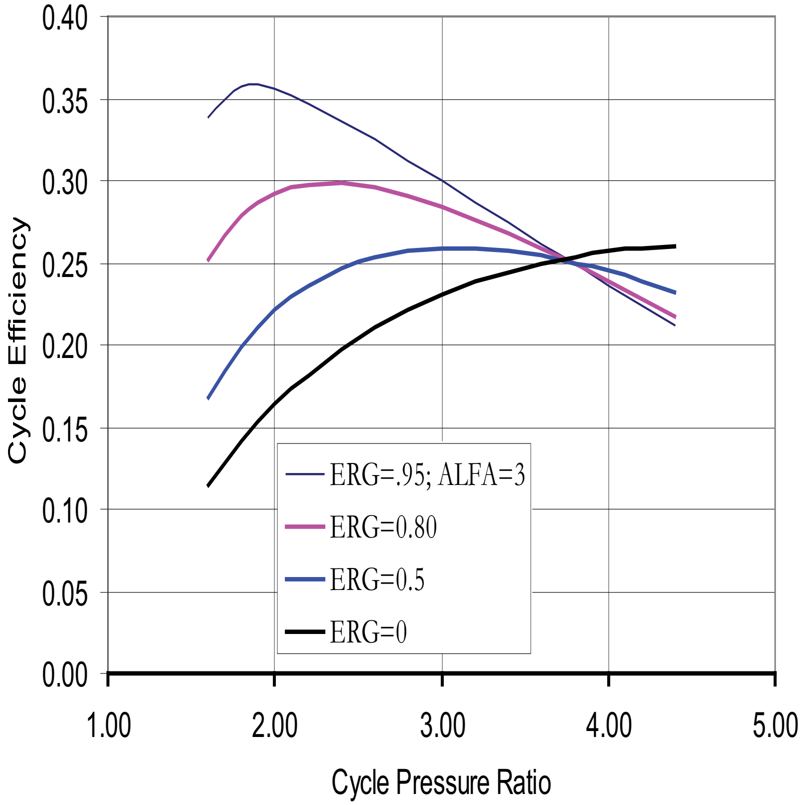


GAS TURBINE (BRAYTON CYCLES)



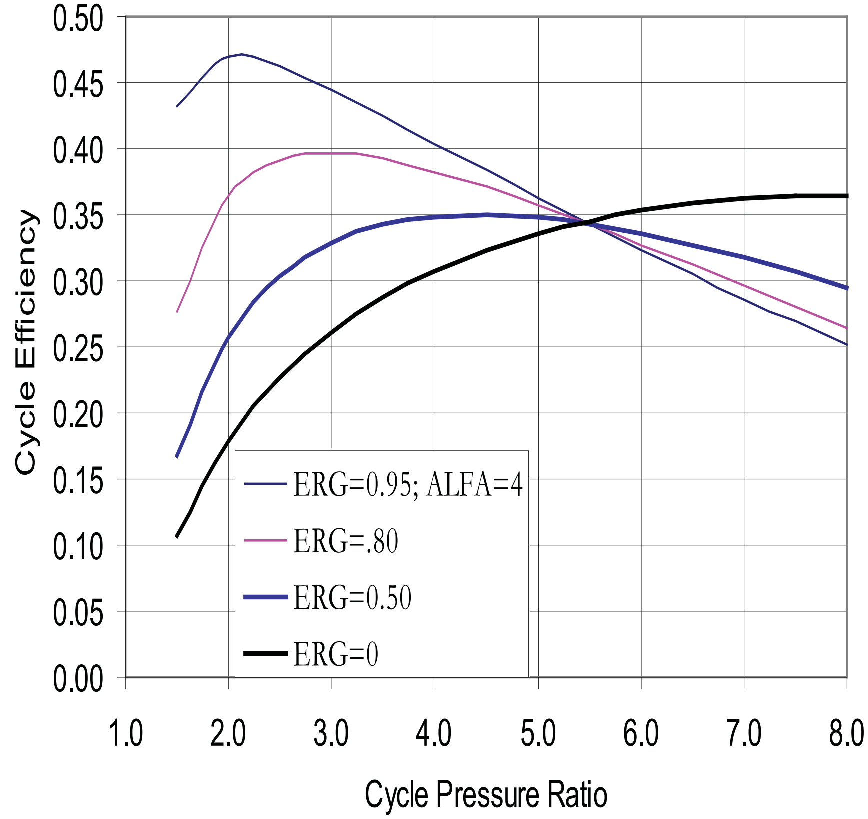
Influence of Regenerator Effectiveness (ERG) on Cycle Efficiency at Cycle Temp. Ratio of 3.0 and 4.0

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



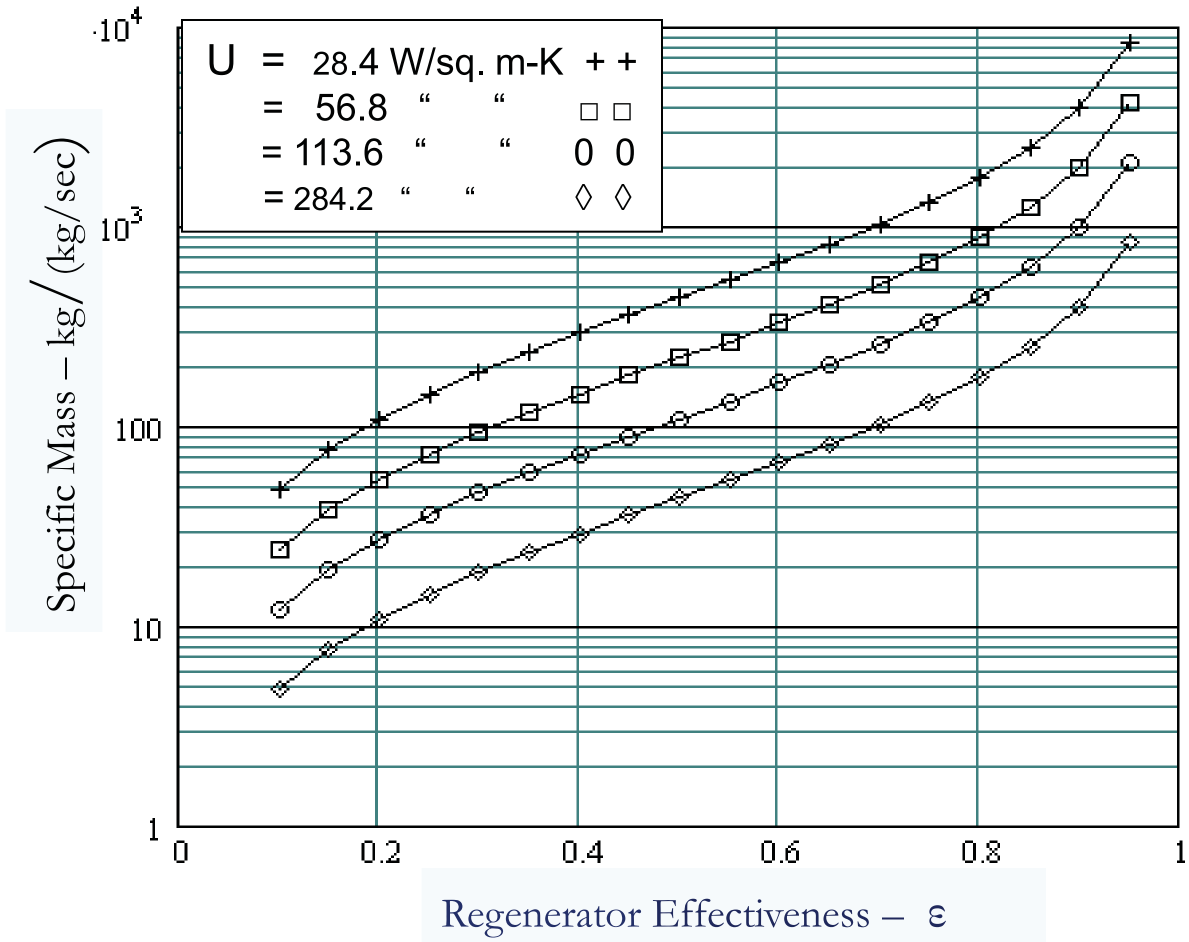
(a) Temp. Ratio = 3.0

= 0.9;

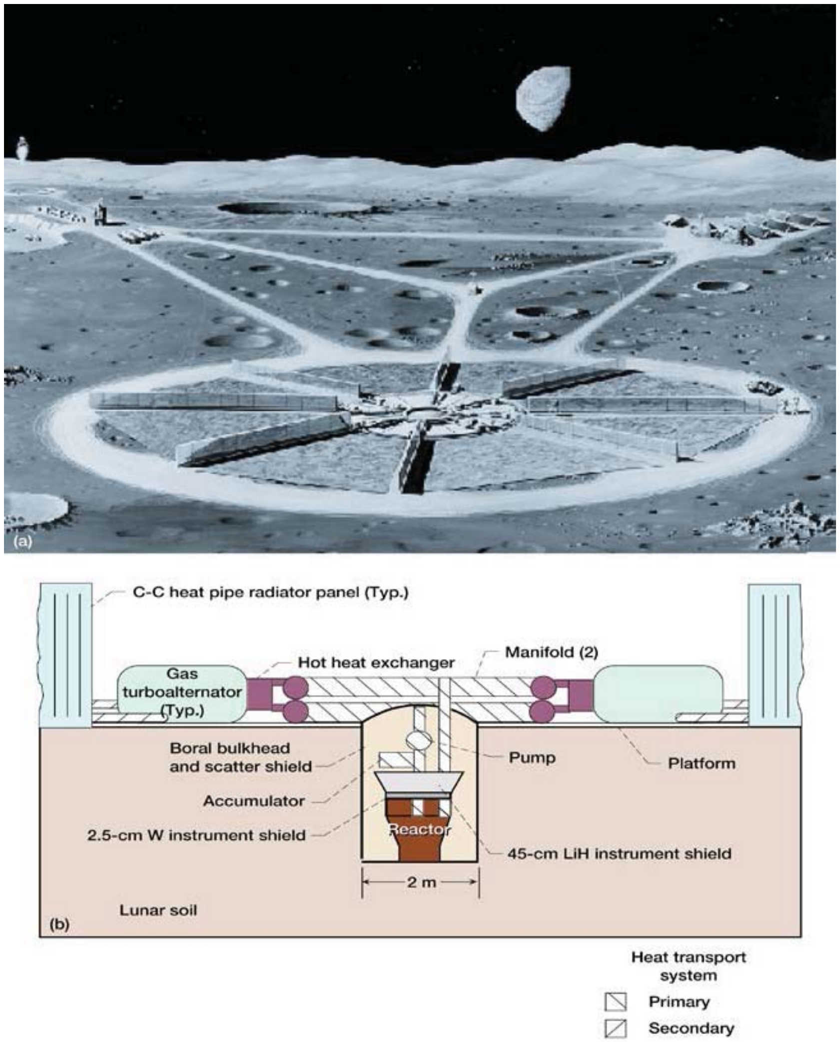


(b) Temp. Ratio = 4.0

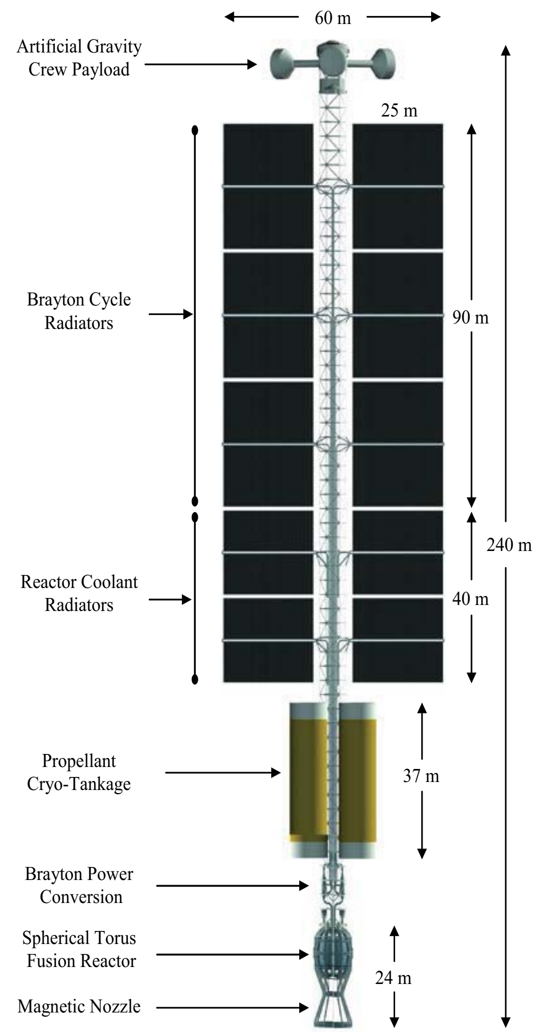
Regenerator Specific Mass vs. Effectiveness with Heat Transfer Coefficient U as a Parameter for He Working Fluid



Advanced Space Power System Applications



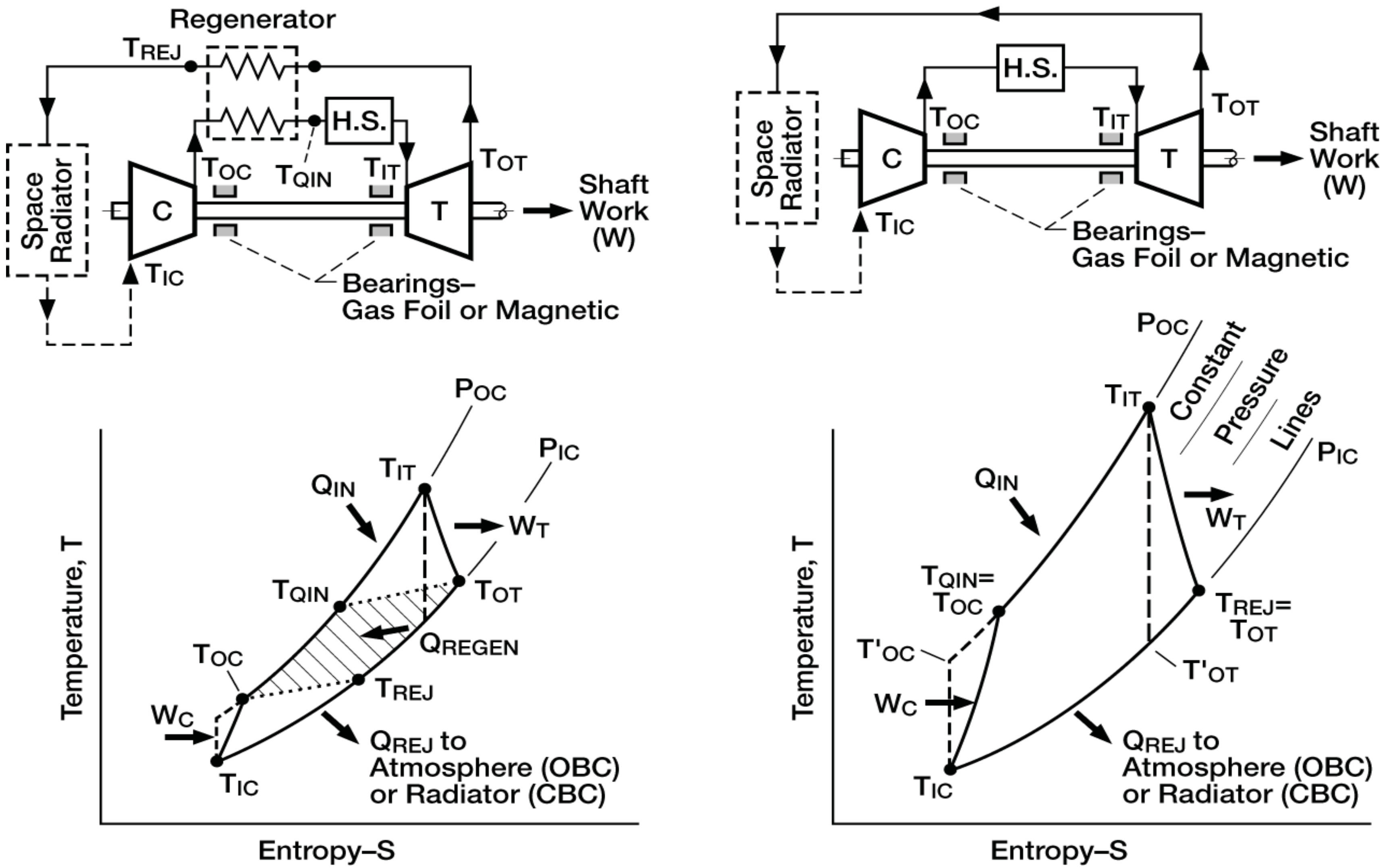
Lunar Base Power System



Interplanetary Fusion Propulsion Space Vehicle

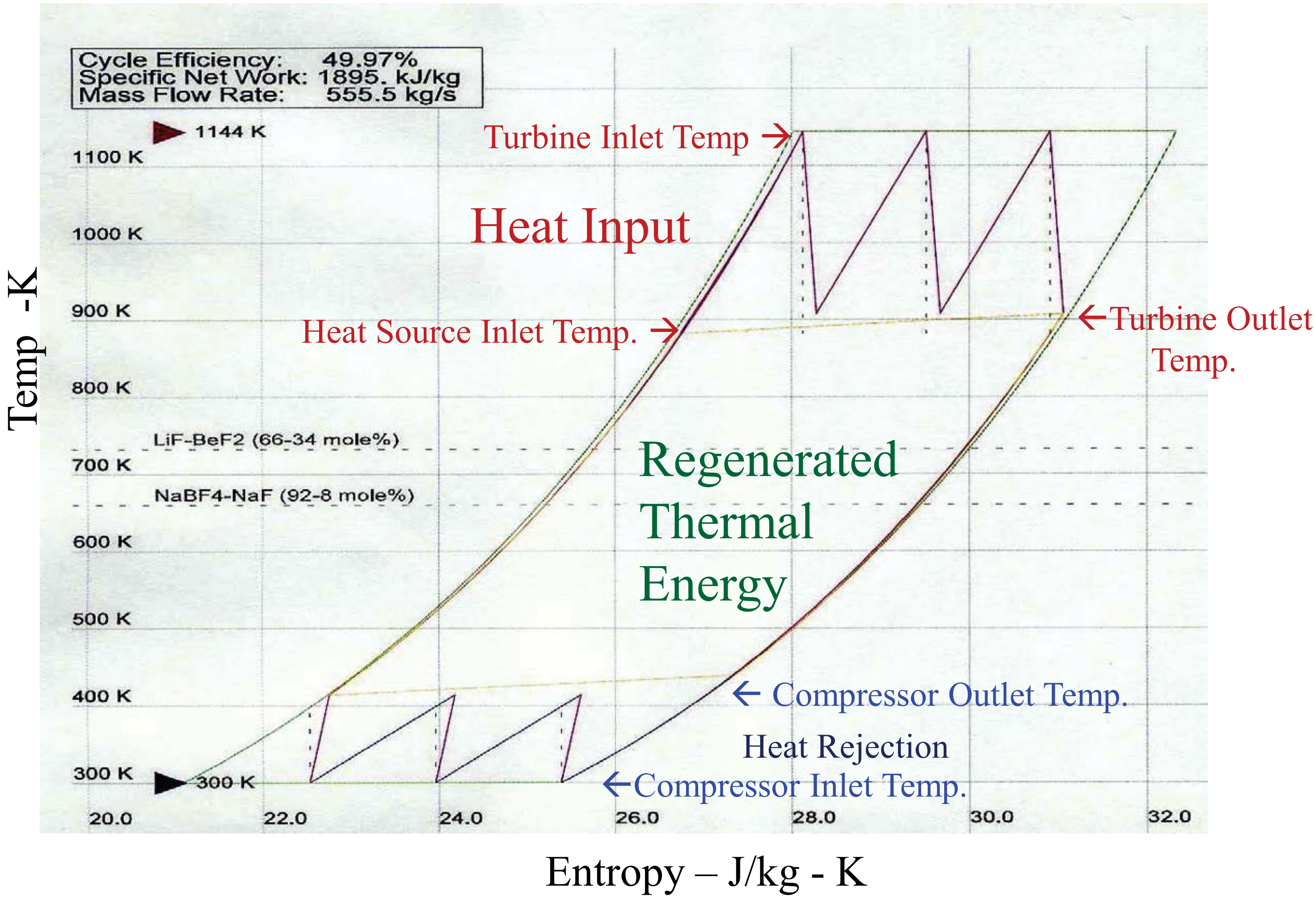
Ground Based CBC Systems and Analysis

Recall GAS TURBINE (BRAYTON CYCLES)



Regenerated Cycle CD-04-82620 **Non-Regenerated Cycle**

Three Stage Reheat & Intercool Brayton Cycle
Temperature – Entropy Diagram

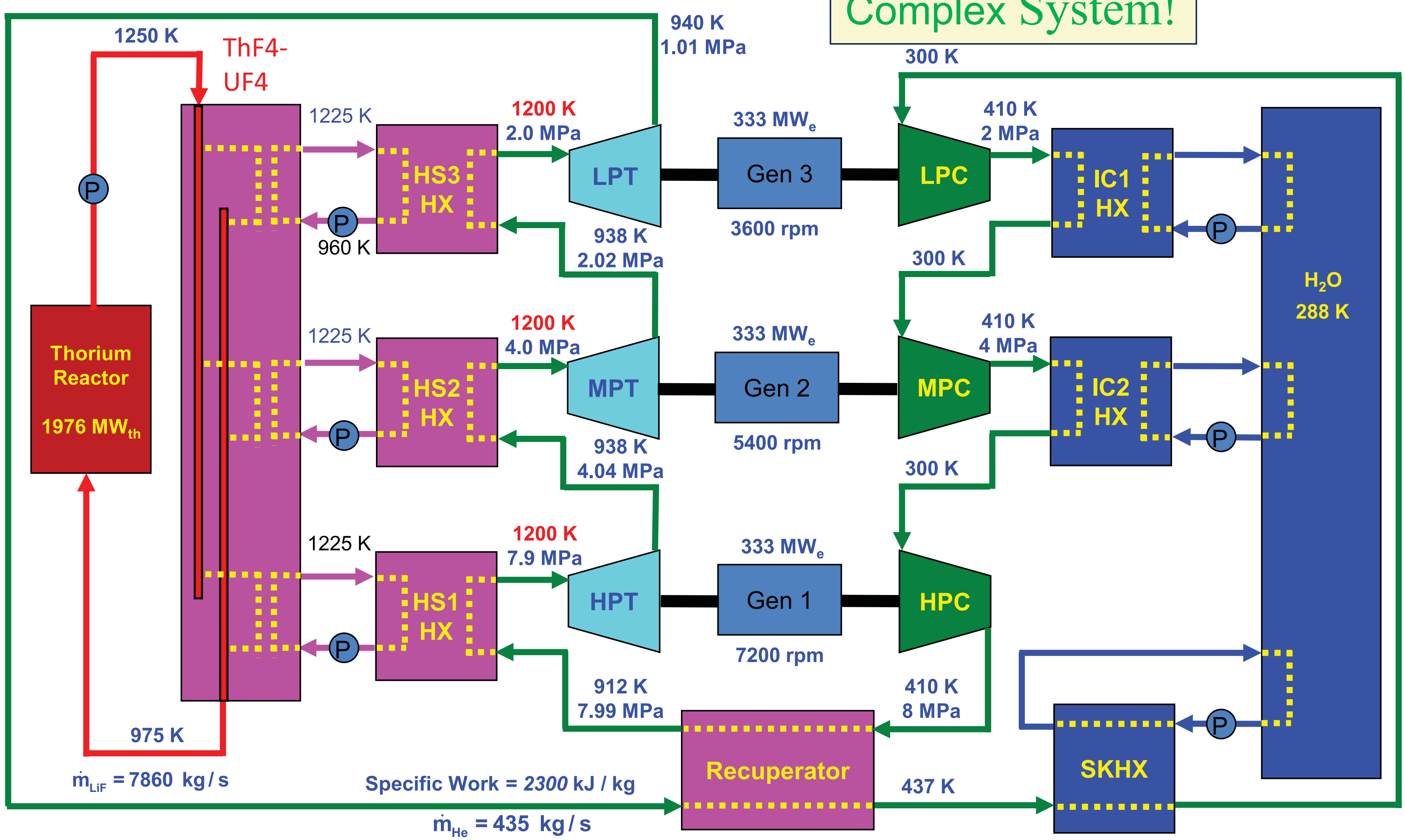


1000 MWe Power Plant 2 Salt Configuration
Thorium Molten Salt Reactor
He CBC w. Rht. & Intcl.- 1200 K Turbine Inlet Temp

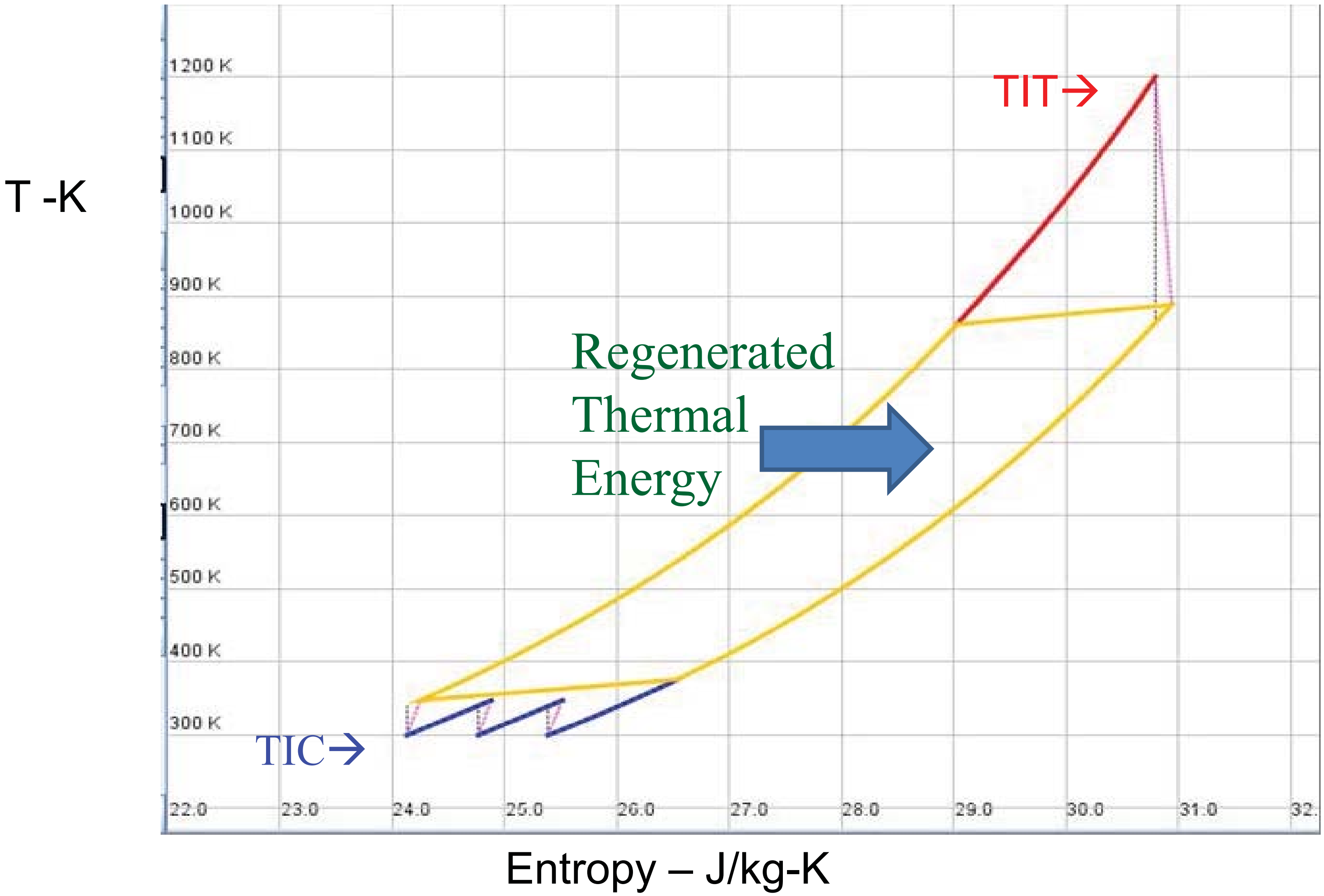
Temp Ratio = 4.0
Efficiency = 50.6 %
Turbine Power = 1758 MW
Compressor Power = –738 MW

He ---
LiF – BeF2
ThF4-UF4

Complex System!

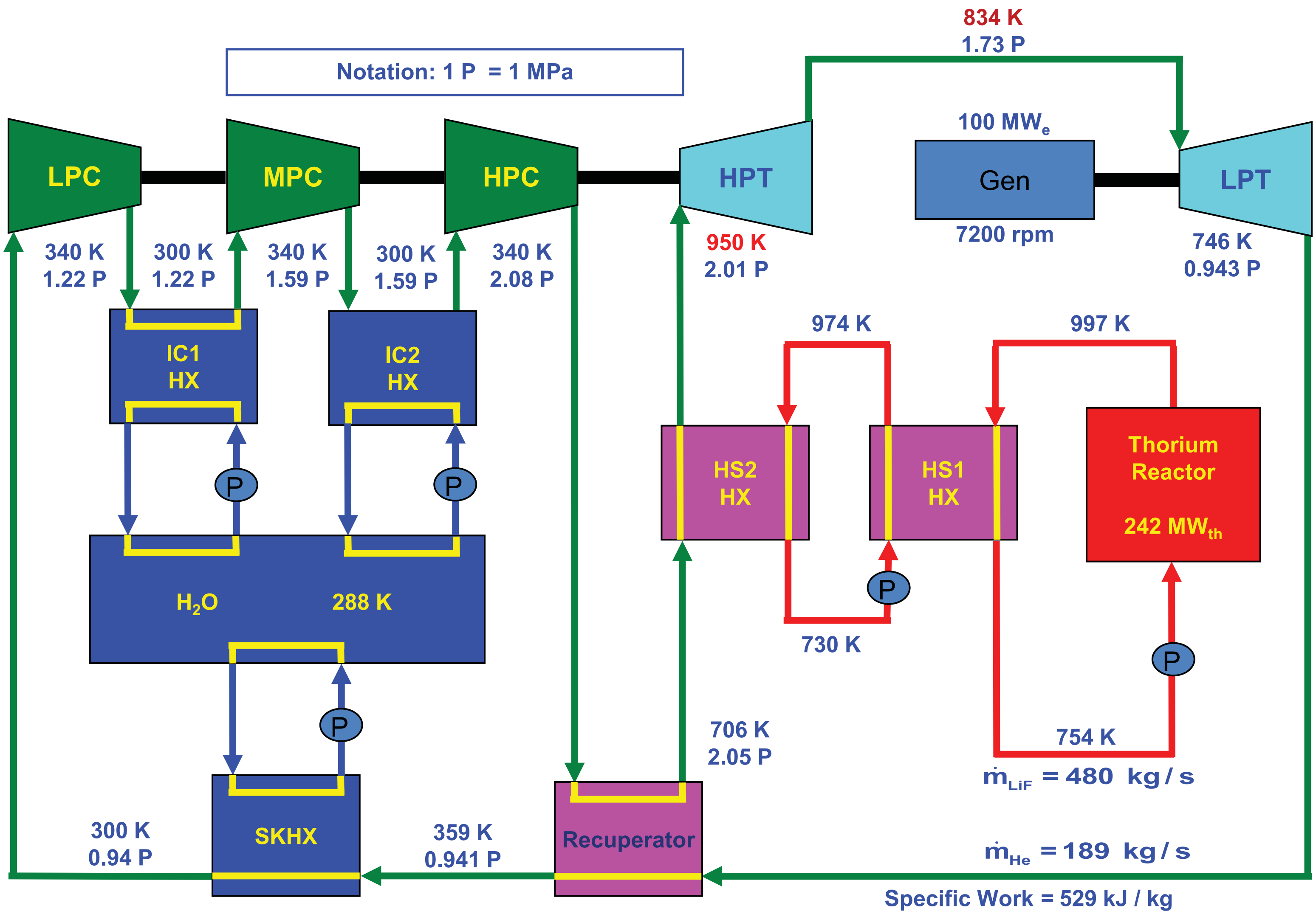


Three Stage Intercool Only Brayton Cycle Temperature – Entropy Diagram



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

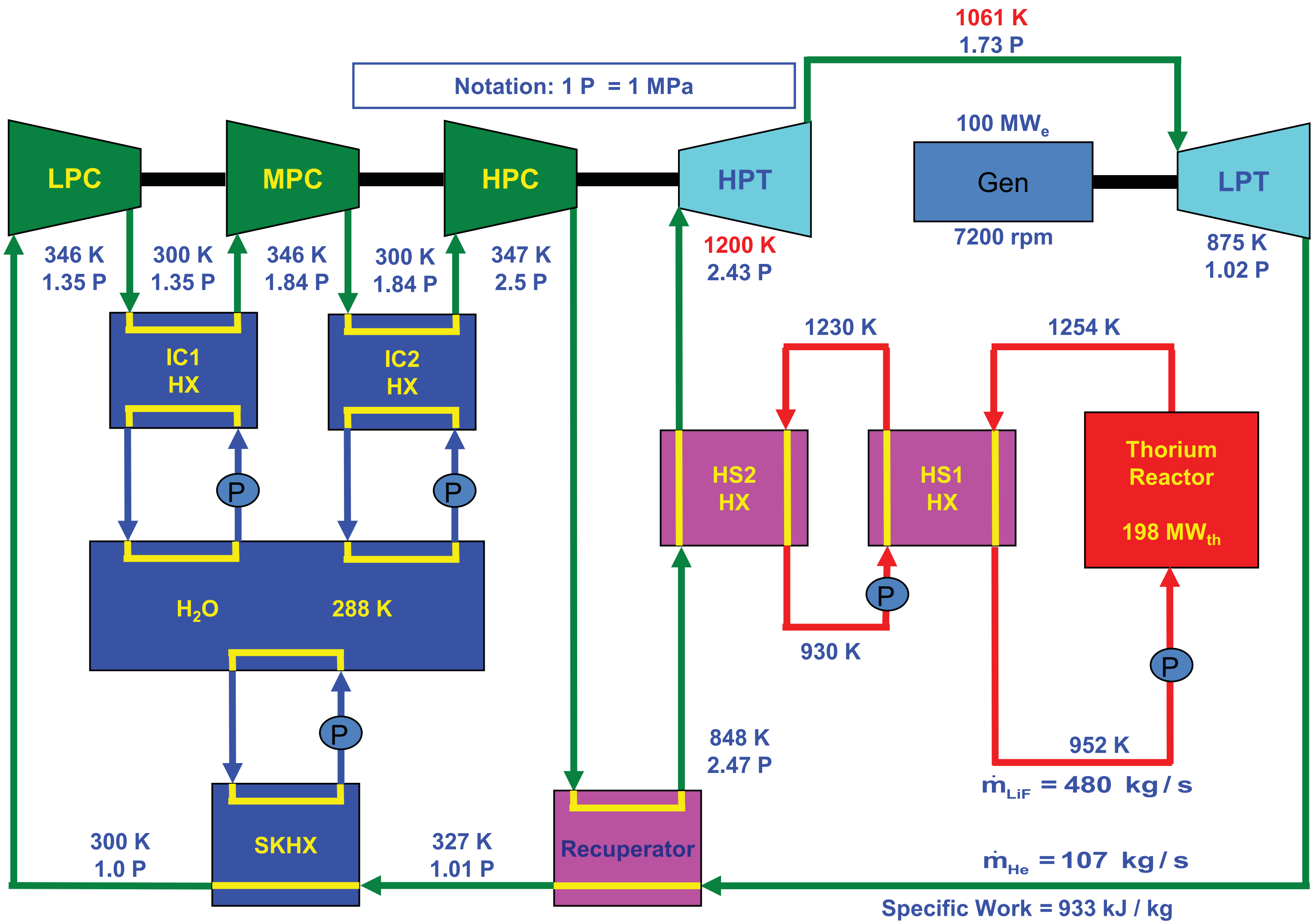
100 MWe Power Plant – 2 Salt Configuration
Thorium Molten Salt Reactor with Intercooled He CBC
with 950 K Turbine Inlet Temperature (mHe = 189.2 kg/s)



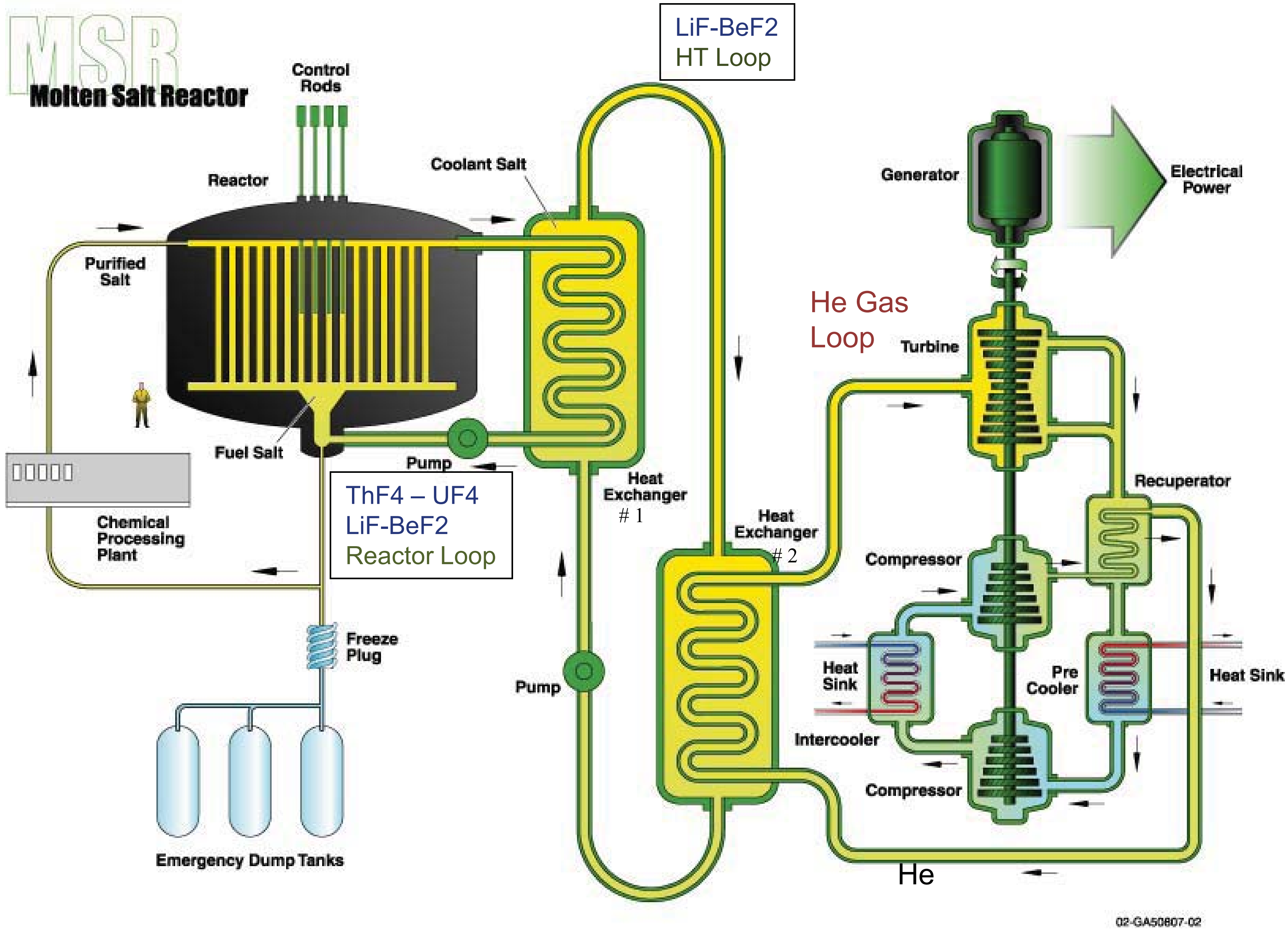
100 MWe Power Plant – 2 Salt Configuration Thorium Molten Salt Reactor - Helium Brayton Cycle, 1200 K Turbine Inlet Temp

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

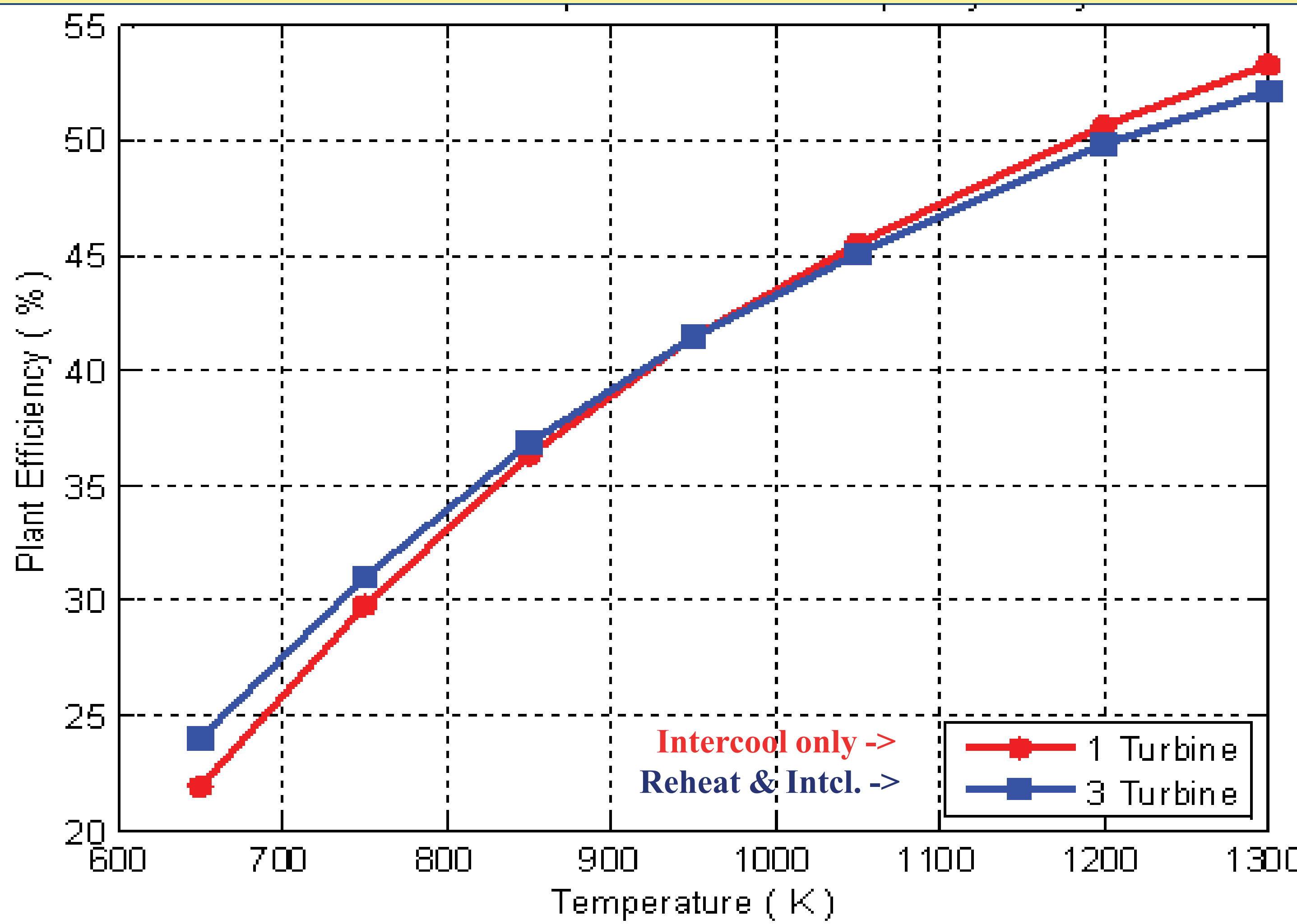
He ---
ThF4-UF4 ----
& BeF2 -------



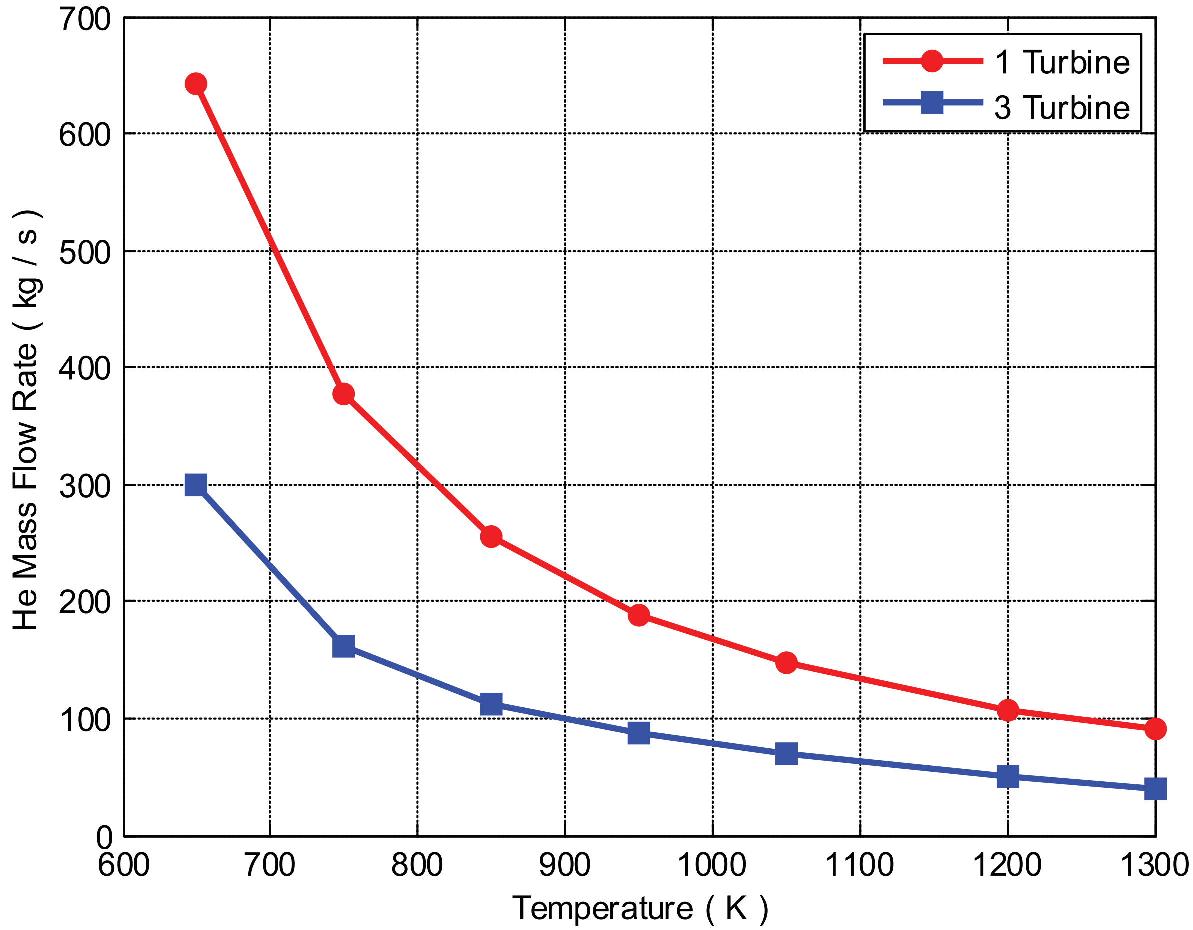
Gen-4 Liquid 2 Salt Configuration Reactor Concept – ORNL



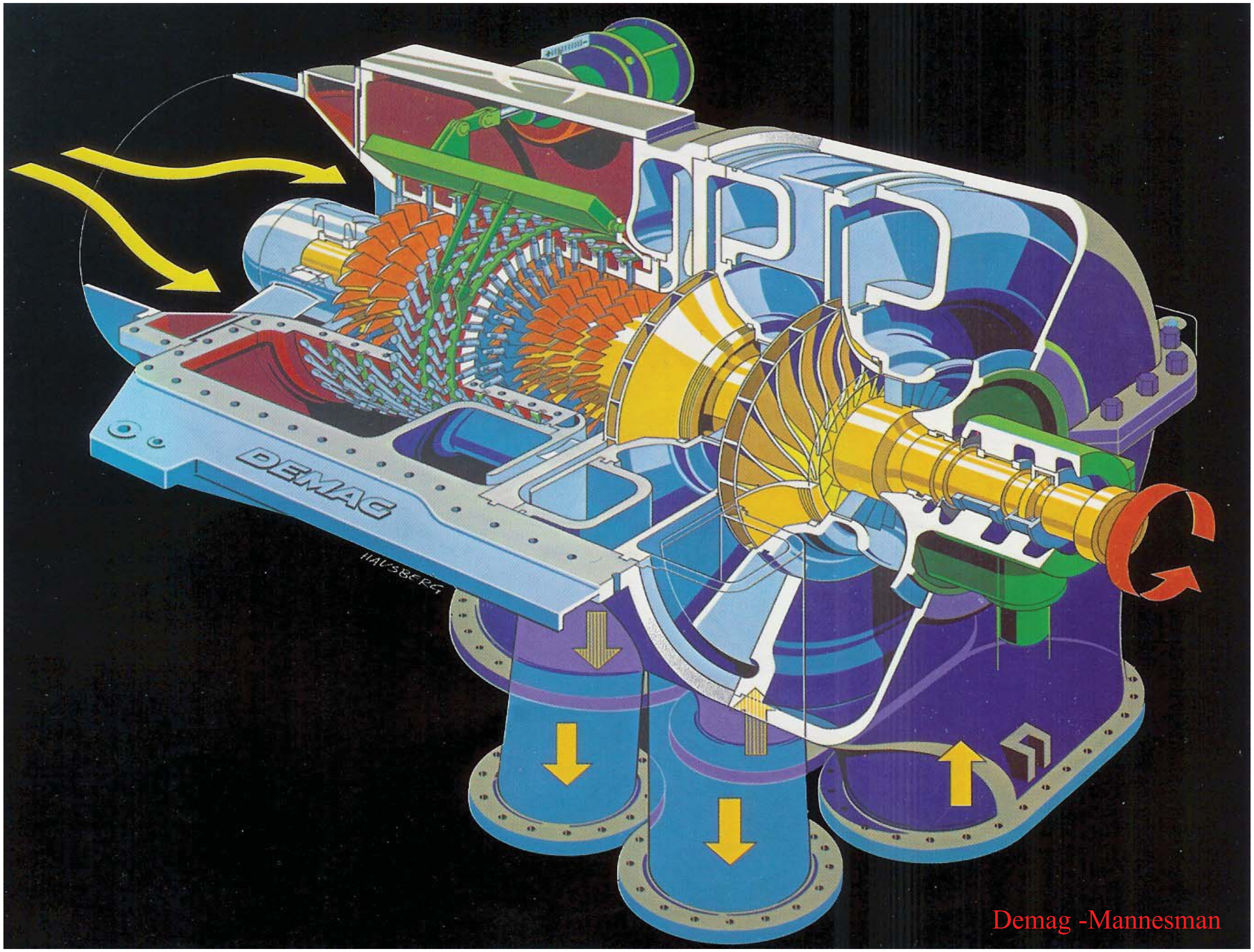
100 MWe Power Plant Efficiency w. Intercool & Reheat Cycles
(3 Inter-cooled Compressors in Series)



100 MWe Power Plant Flowrate w. Intercool & Reheat Cycles
(3 Inter-cooled Compressors in Series)



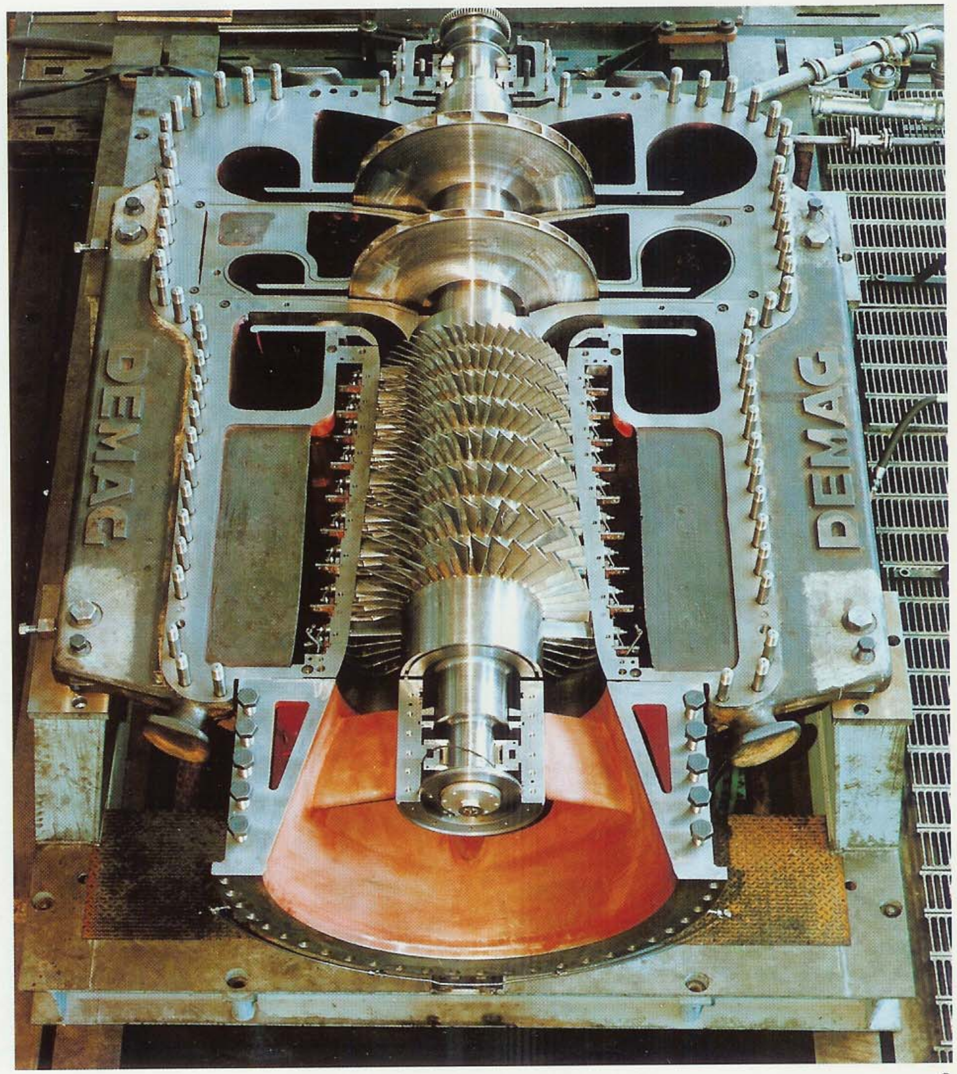
Typical Axial Radial Turbo-compressor



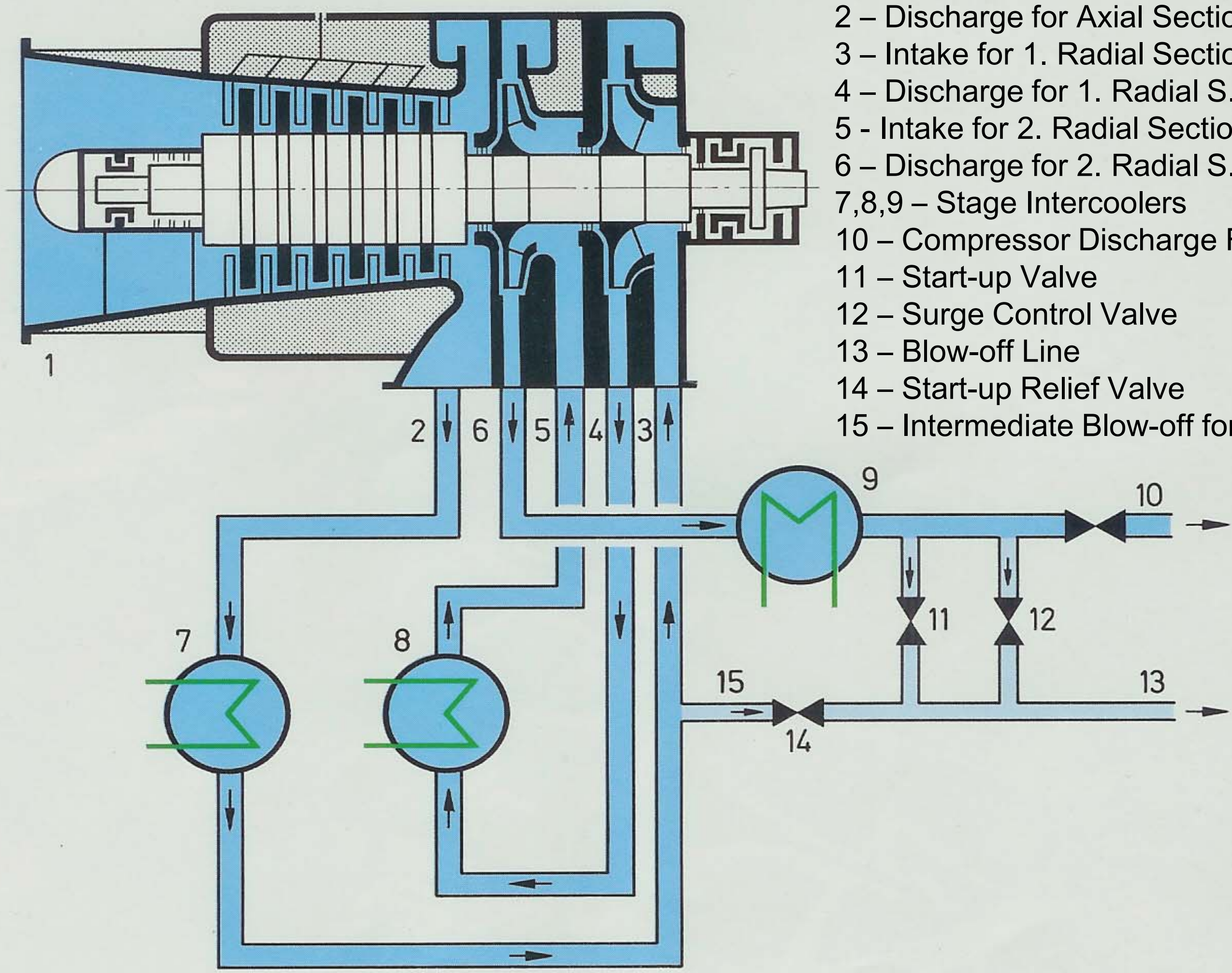
Axial/Radial Compressor with Axial Intake

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

Medium	Air
Flow volume	272 000 m³/h
Intake pressure	1.01 bar
Discharge pressure	6.4 bar
Rotational speed	4 550 rpm
Drive rating	22 700 kW (turbine)



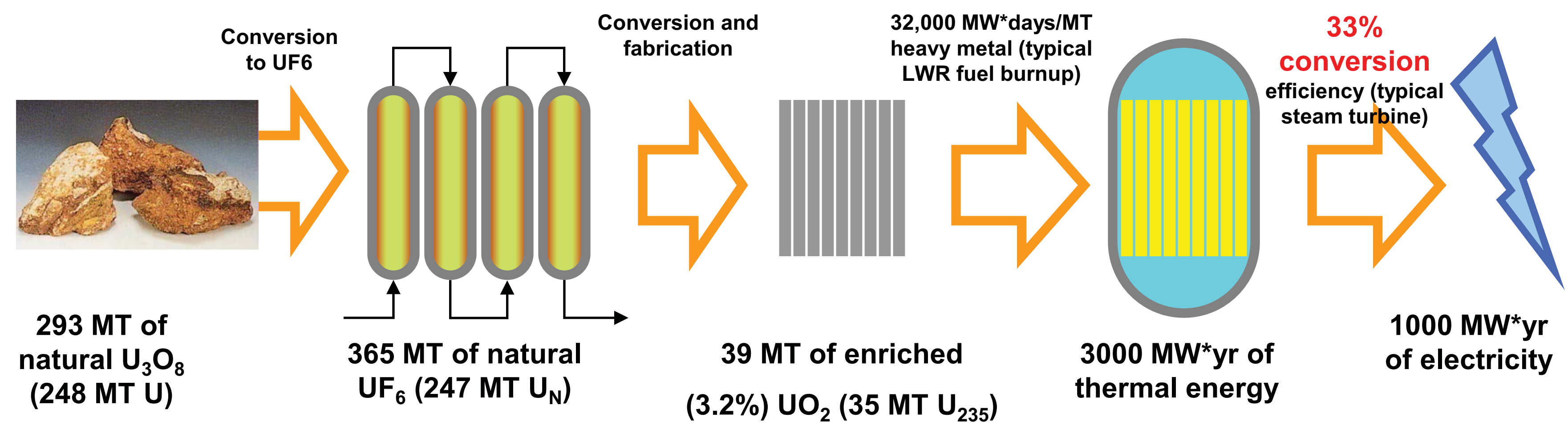
Flow Diagram for AR Compressor with Axial Intake



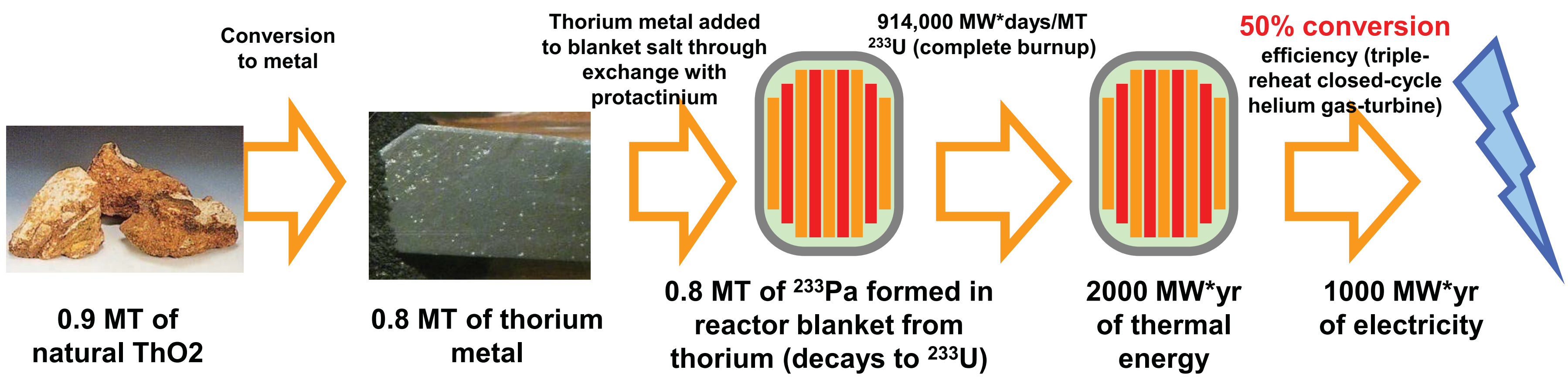
1 – Intake Casing
2 – Discharge for Axial Section
3 – Intake for 1. Radial Section
4 – Discharge for 1. Radial S.
5 - Intake for 2. Radial Section
6 – Discharge for 2. Radial S.
7,8,9 – Stage Intercoolers
10 – Compressor Discharge Flow
11 – Start-up Valve
12 – Surge Control Valve
13 – Blow-off Line
14 – Start-up Relief Valve
15 – Intermediate Blow-off for Start.

Energy Extraction Comparison for U_{238} and Th_{232}

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



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



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

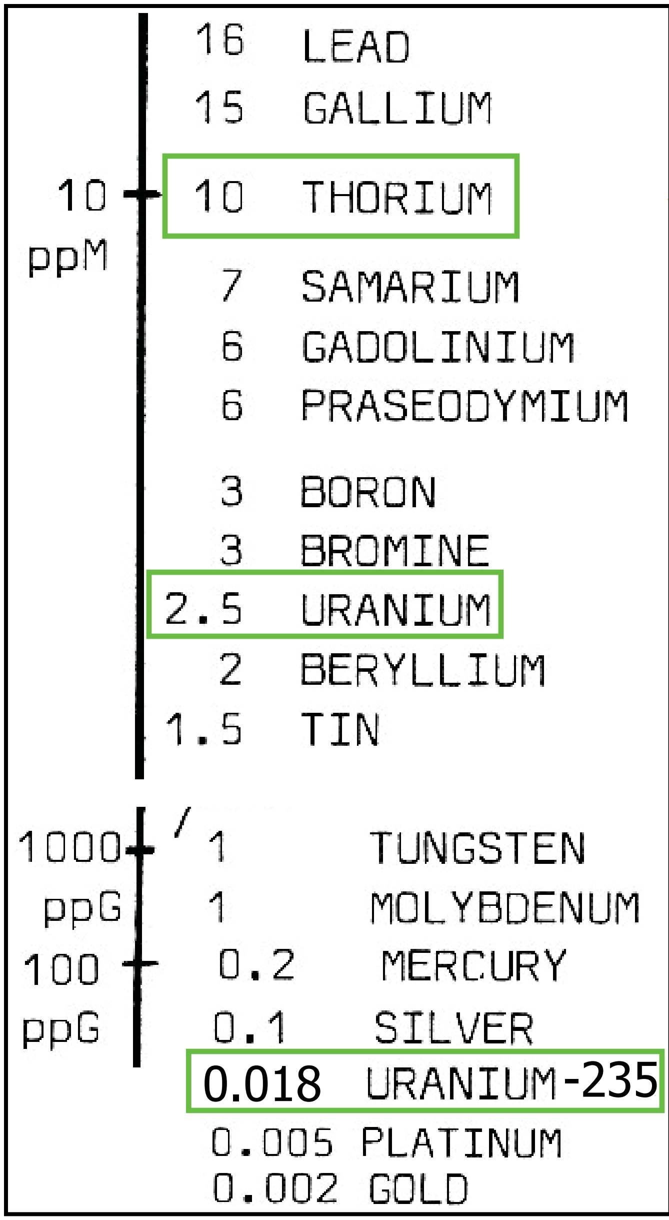
http://www.energyfromthorium.com

Energy from Thorium

via

Liquid Fluoride Thorium Reactor Technology

Thorium and Uranium Abundance in the Earth's Crust



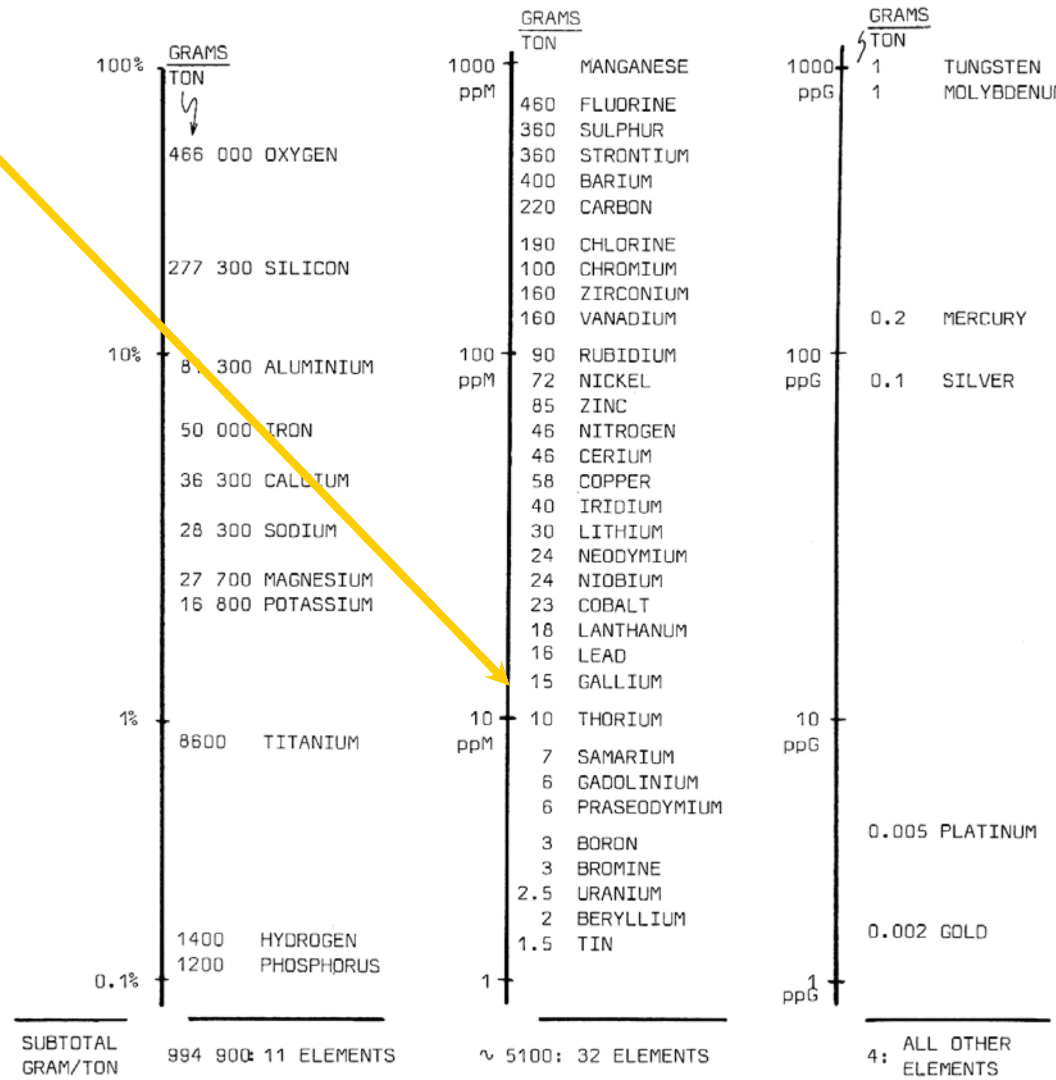


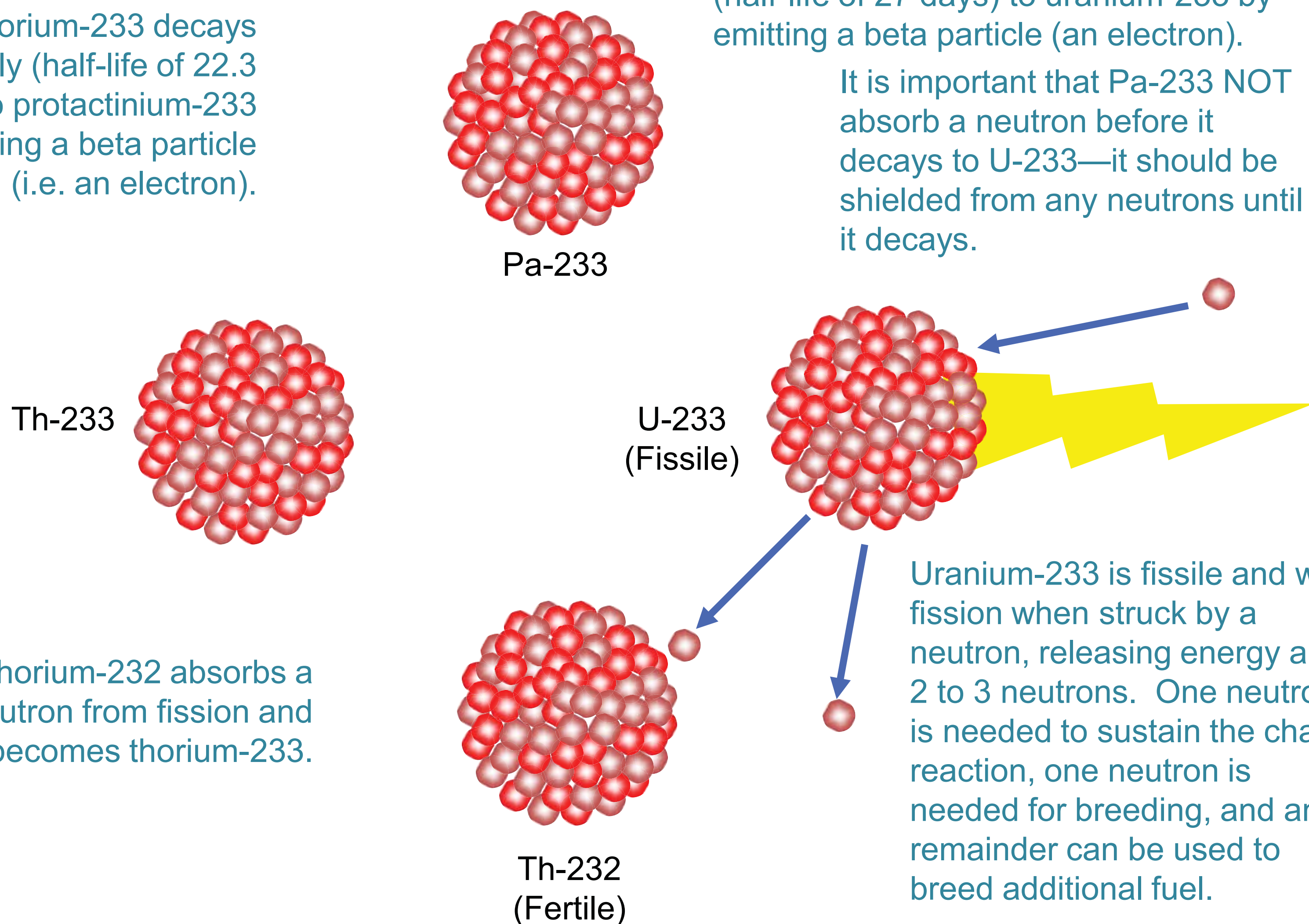
Fig. 5.13. The chemical composition of the Earth's crust.

Thorium$_{232}$ - Uranium$_{233}$ Breeding Cycle

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.

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



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

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.

Glasstone & Sesonske

Thorium –Uranium Fuel Cycle

1. $_{90}Th^{232} + {_0}n^1 \rightarrow {_{90}}Th^{233} + \gamma$ **(neutron absorption)**

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

3. $_{91}Pa^{233} \rightarrow {_{-1}}\beta^0 + {_{92}}U^{233}$ **(β decay – λ = 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)

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

where λ is the *decay constant* computed from

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

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

Substituting in (1) : $0.1 = 99.9\, e^{-0.02567 * t} \qquad (2)$

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

$$\text{Ln } .001 = -.02567\, t$$

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

$= \mathbf{269}$ **days, or ~ 9 months for 99.9% of Pa -> 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

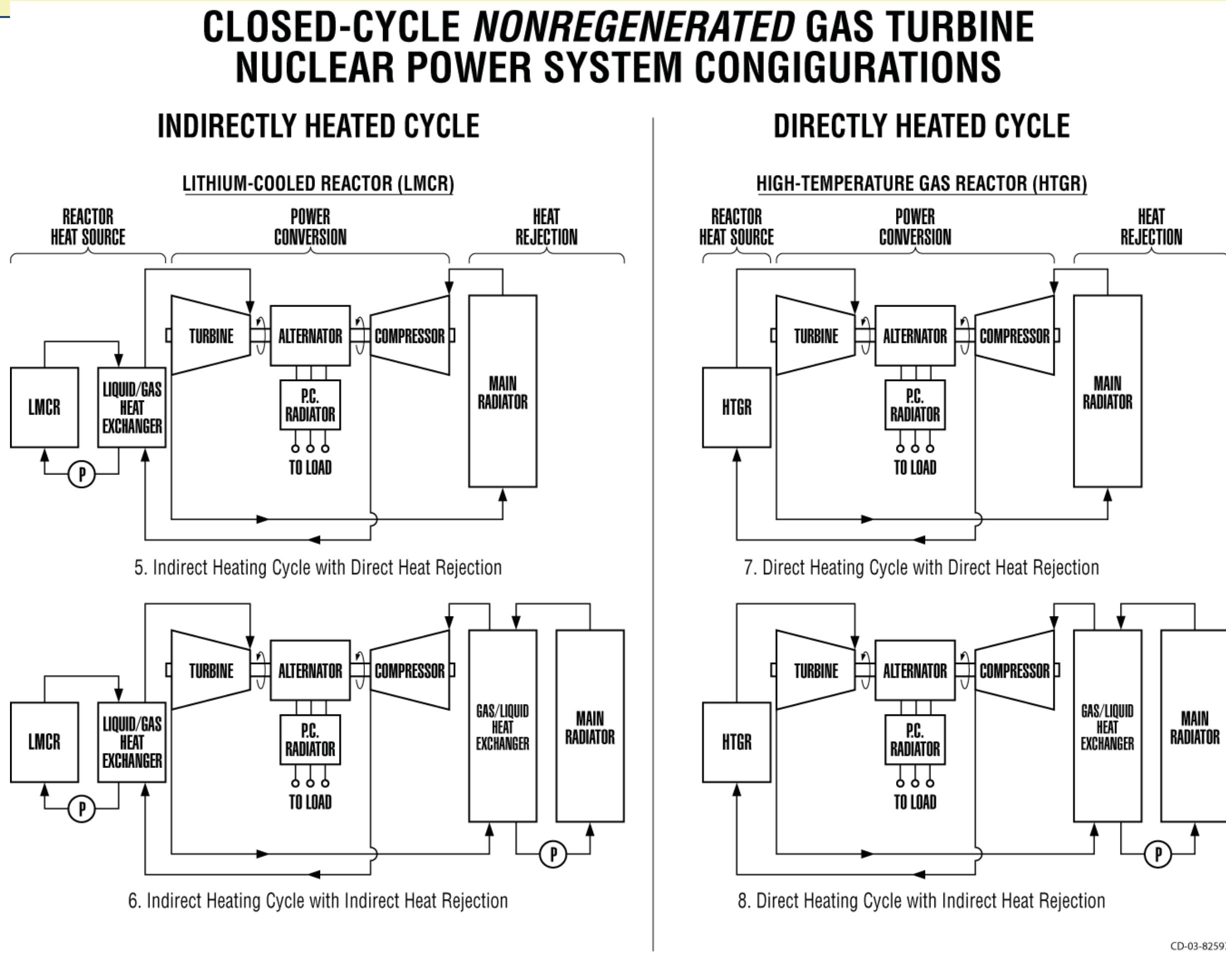
Proposal to use US mothballed shipyards to produce hundreds of portable thorium nuclear gas turbine power plants

Key Cycle Input Parameters

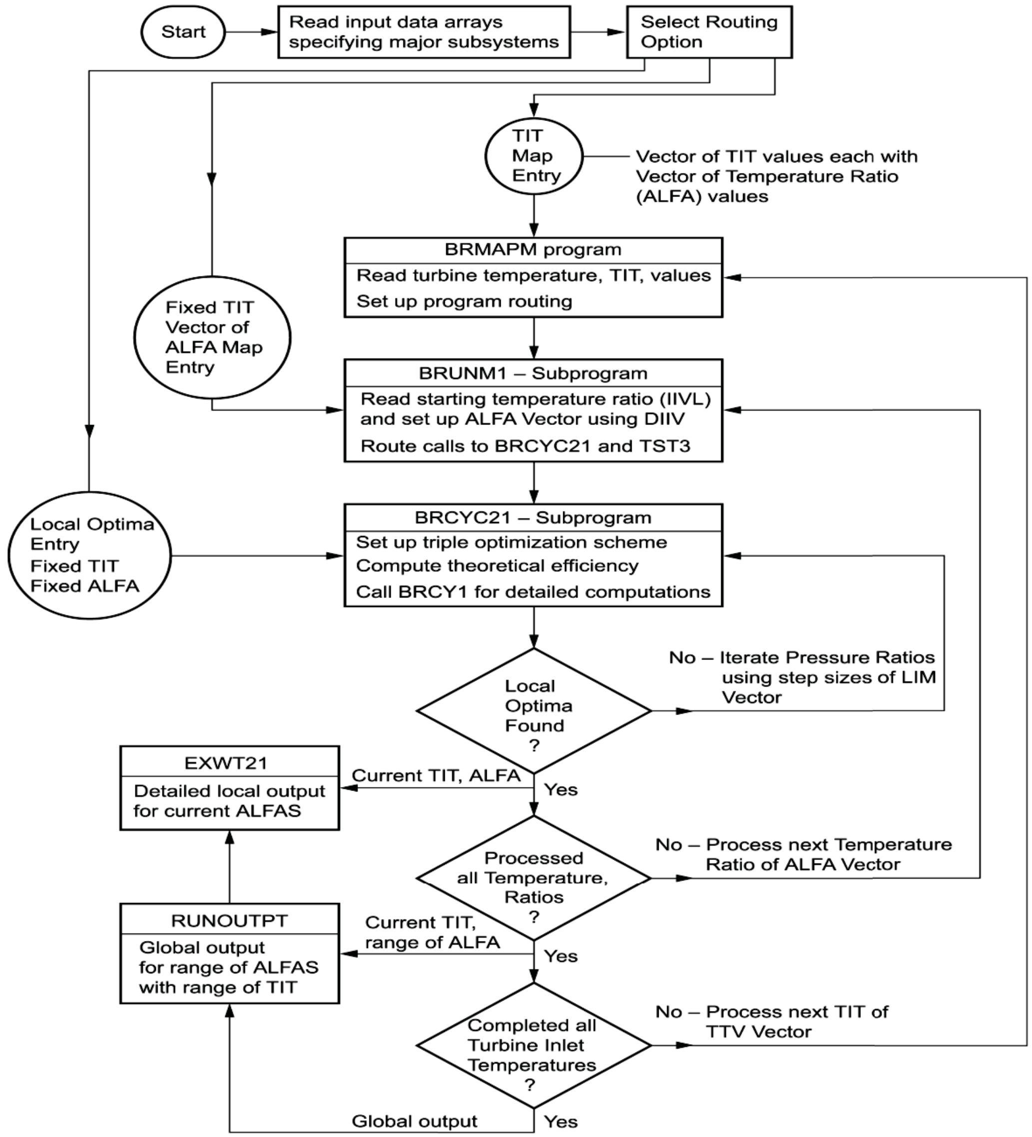
Compressor Inlet Temperature (TIC), K	300
Cooling Water Temperature, K	288
Reactor Heat Loss, percent	1.0
Polytropic Efficiency—Compressor, percent	86
Polytropic Efficiency—Turbine, percent	92
Recuperator Effectiveness, percent	95
Intercooler HX Pressure Loss, percent	0.5
Reheat HX Pressure Loss, percent	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



Brayton Cycle Mapping Code - BRMAPS



Partial BRMAPS Code Output Results for 5 MWe Lunar Power Plant

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

TEMP RATIO        ETAB      ETAPC      ETAPT       ERG      GAMMA       LPC       ETM      EPSIL      TIT-K

     3.000        .990       .900       .900       .000     1.667       .980      .950      .900       1500

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

  PR RATIO THERM EFF. ARP(M2/KW) MSYS(MG) W(KM/S-MW)  TREJ-K    TREFF-K    TOC-K     TOT-K    ETAC    ETAT

    4.5500      .2604      .4076    20.8974     .3895    862.88     630.73  1005.81    862.88    .867    .925
    3.2000      .2382      .3554    19.6747     .3122    985.29     663.87   850.84    985.29    .875    .919
    3.4000      .2446      .3566    19.6355     .3170    963.13     658.18   875.51    963.13    .874    .920

    3.2000      .2382      .3554    19.6747     .3122    985.29     663.87   850.84    985.29    .875    .919

THEORETICAL OPTIMUM PRESSURE RATIO (PROPTIM) =      4.579

NUMBER OF ITERATIONS (ICTE,ICTA,ICTM) =     7    9    9


                       TURBO - ALTERNATOR POWER DISTRIBUTION

                      GAS MOLECULAR WEIGHT (KG/MOL) =   4.000

                      MASS FLOWRATE (KG/SEC) =        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))
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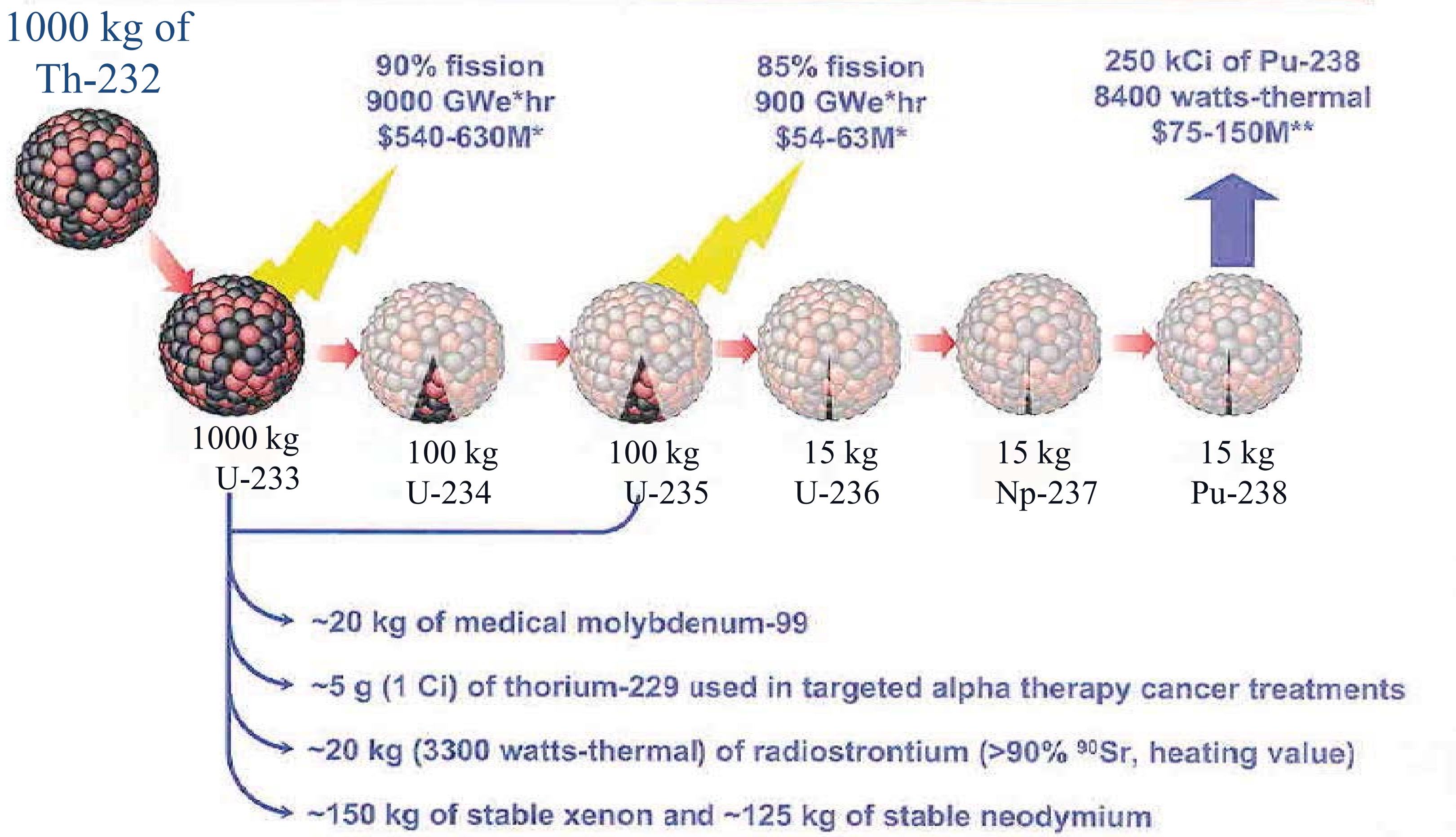
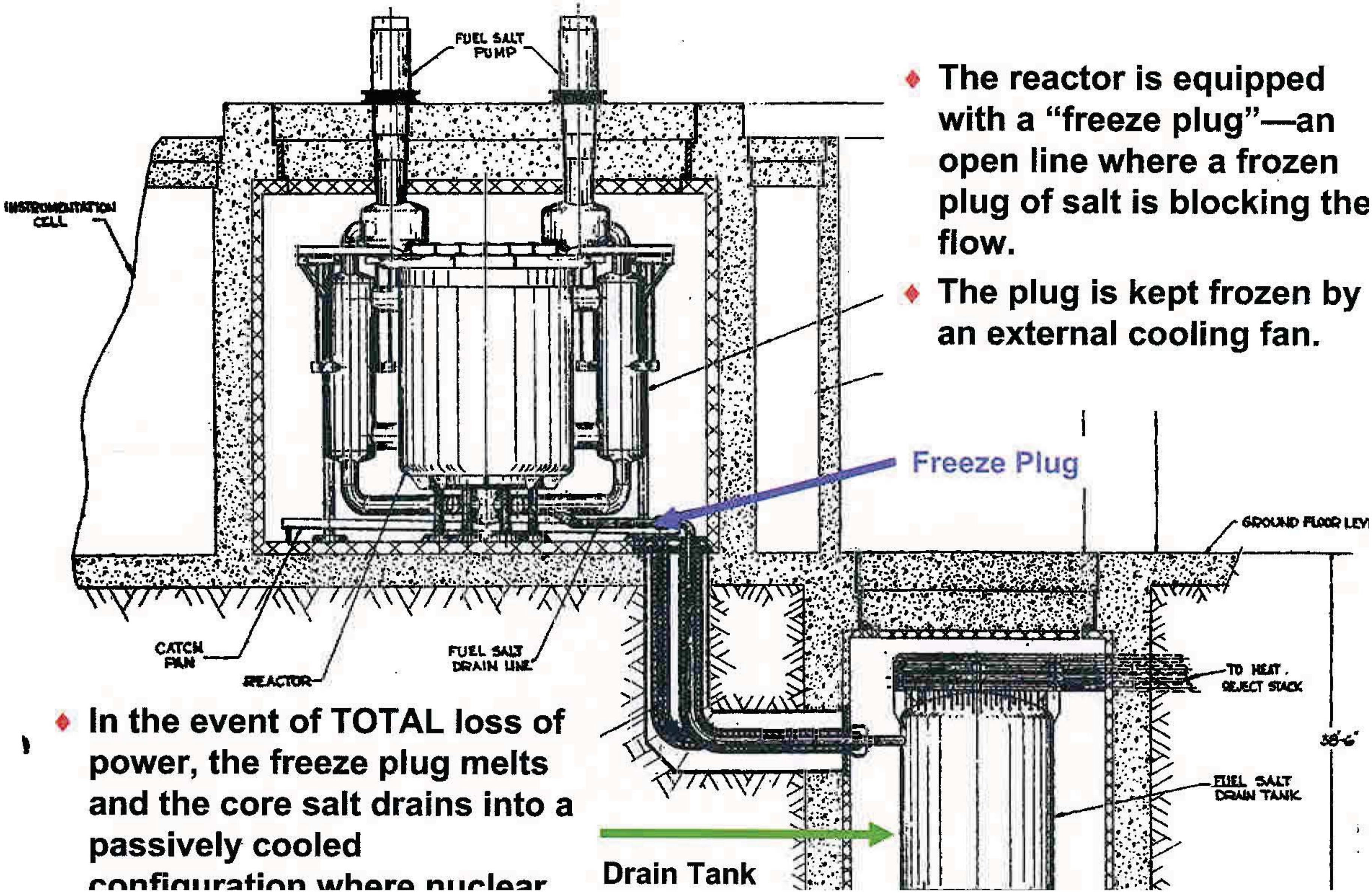
Isotope Production from LFTR



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.

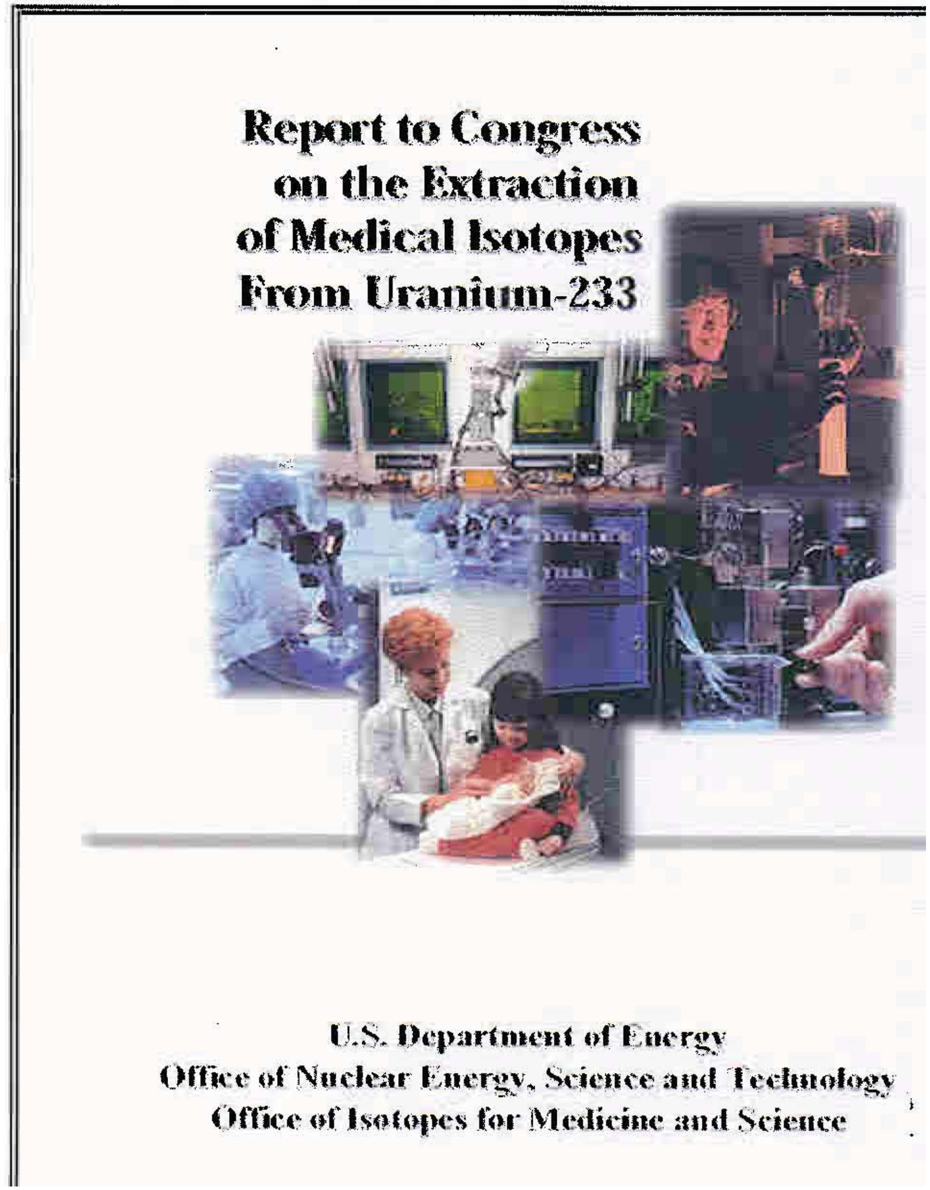


- In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear

Congressional Report Emphasizes Need for Th-229

"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

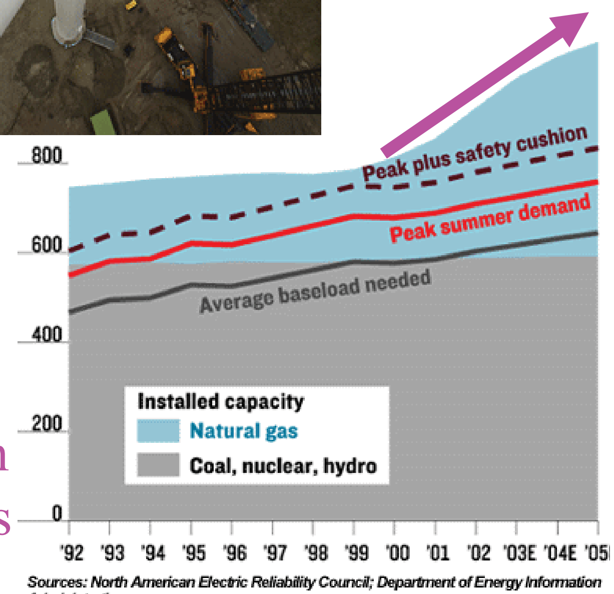
- Nuclear: 1970's vintage PWR, 90% capacity factor, 60 year life [1]
  - 40 MT steel / MW(average)
  - 190 m3 concrete / MW(average)
- Wind: 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
  - 460 MT steel / MW (average)
  - 870 m3 concrete / MW(average)
- Coal: 78% 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)

Distance from end user, prime real estate, energy intensity, etc…

Cost of:

- **materials**
- **labor**
- **land**
- **tools**
- **etc…**

Recent increase in natural gas plants



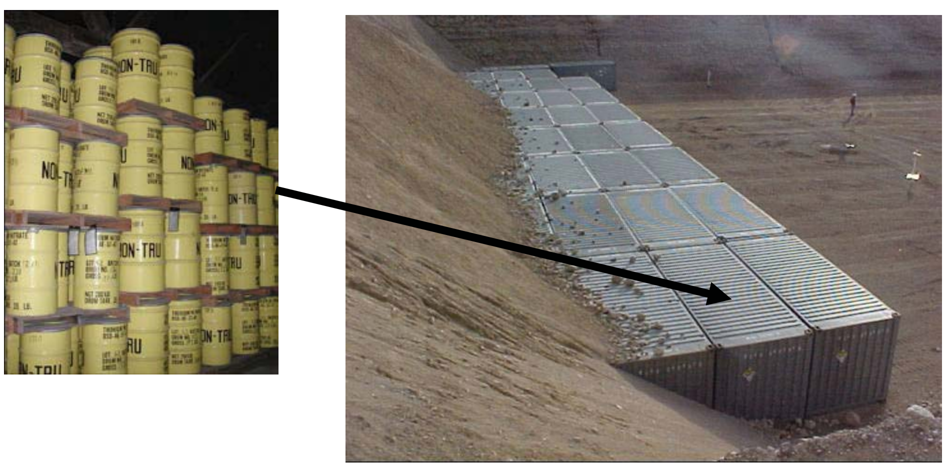
Thorium: Virtually Limitless Energy

World Thorium Resources

Country	**Reserve Base (tons)**
Australia	340,000
India	300,000
USA	**300,000**
Norway	180,000
Canada	100,000
South Africa	39,000
Brazil	18,000
Other countries	100,000
World total	1,400,000

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

- 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!

Relative Comparison: Uranium vs Thorium Based Nuclear Power

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

Source: http://www.energyfromthorium.com/ppt/thoriumEnergyGeneration.ppt

U-232 Formation in the Thorium Fuel Cycle

$$^{232}\mathrm{Th} \xrightarrow{n,2n} {}^{231}\mathrm{Th} \xrightarrow[25.5\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

$$^{233}\mathrm{U} \xrightarrow{n,2n} {}^{232}\mathrm{U}$$

$$^{230}\mathrm{Th} \xrightarrow{n,\gamma} {}^{231}\mathrm{Th} \xrightarrow[25.52\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

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)

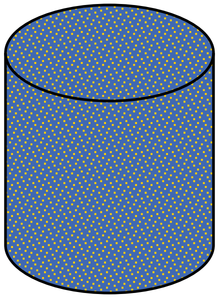
Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

Return

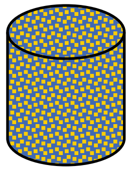
Typical Machine Sizes for 1000 MWe He Plant

- Single Turbo-Alt at 10 MP a 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 = 72000 rpm
  - P=10 Mpa (Pr=2); Dia = 2.7 m, L = 6.3m, Speed = 5400 rpm
  - P= 5 Mpa (Pr=2); Dia = 3.8 m, L = 8.5m, Speed = 3600 rpm
  - Recuperator Volume ~ 120 m^3
  - Thermal Eff. = 51.5%

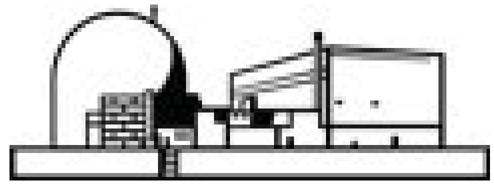
Today's approach to nuclear energy



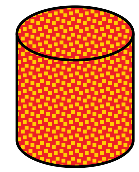
250 t of natural uranium containing 1.75 t U-235



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

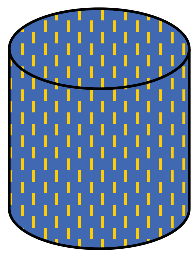


Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned



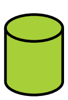
35 t of spent fuel stored on-site until disposal at Yucca Mountain. It contains:

- 33.4 t uranium-238
- 0.3 t uranium-235
- 0.3 t plutonium
- 1.0 t fission products.



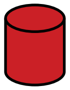
215 t of depleted uranium containing 0.6 t U-235—disposal plans uncertain.

Energy from thorium

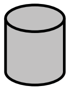


One tonne of natural thorium

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.

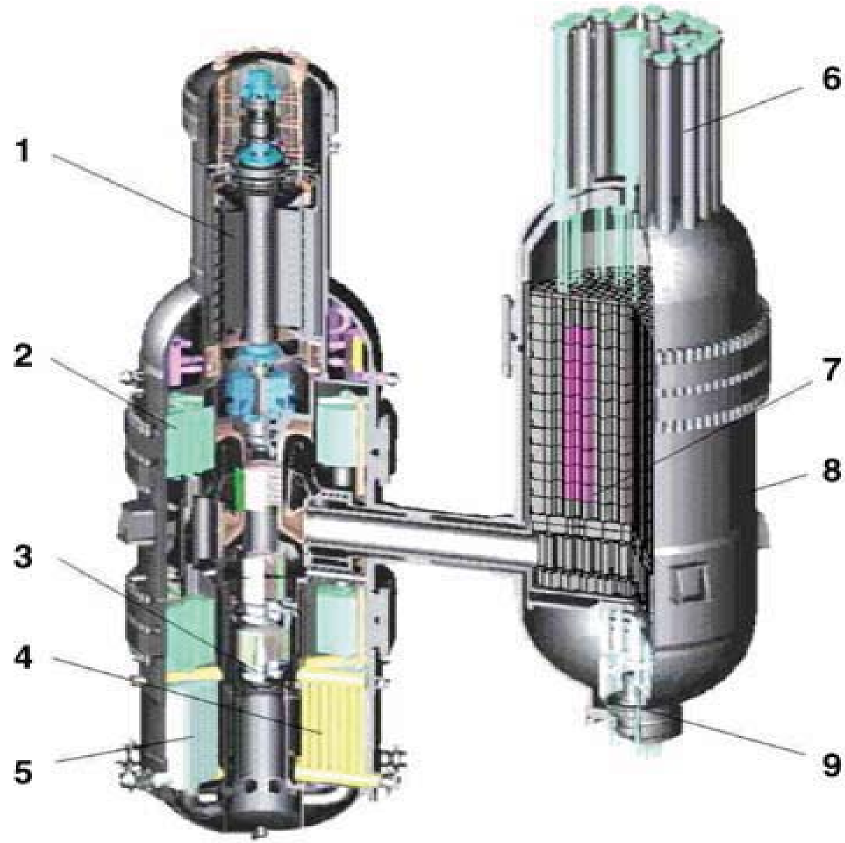
The remaining 17% fission products go to geologic isolation for ~300 years.

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

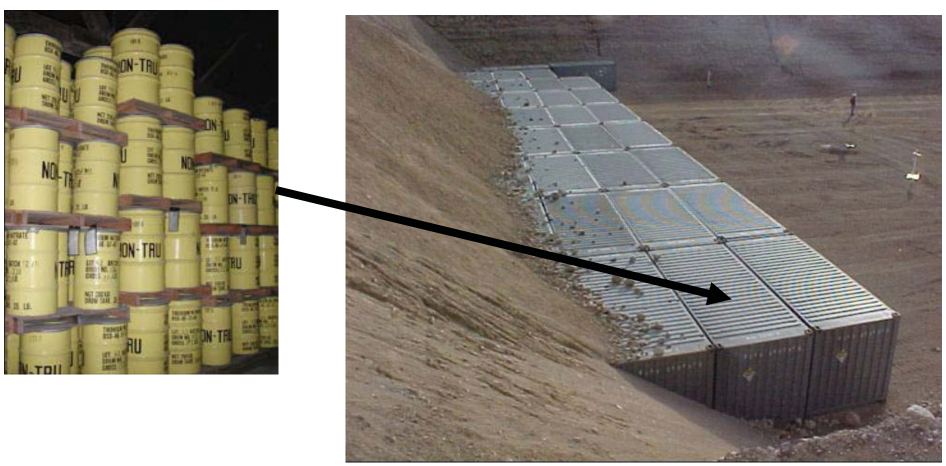
Thorium: Virtually Limitless Energy

World Thorium Resources

Country	Reserve Base (tons)
Australia	340,000
India	300,000
USA	**300,000**
Norway	180,000
Canada	100,000
South Africa	39,000
Brazil	18,000
Other countries	100,000
World total	1,400,000

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

- 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



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