Energy Tech 2019 Conference

IX Center – Cleveland, OHIO

10/22 to 10/25, 2019

Gas Turbine Energy Conversion Systems for Lunar & Planetary Nuclear Power Plants including Ground Based Applications using LiFTR "Liquid Fluoride Thorium Reactor" Technology

Session 7 (10/22/19)

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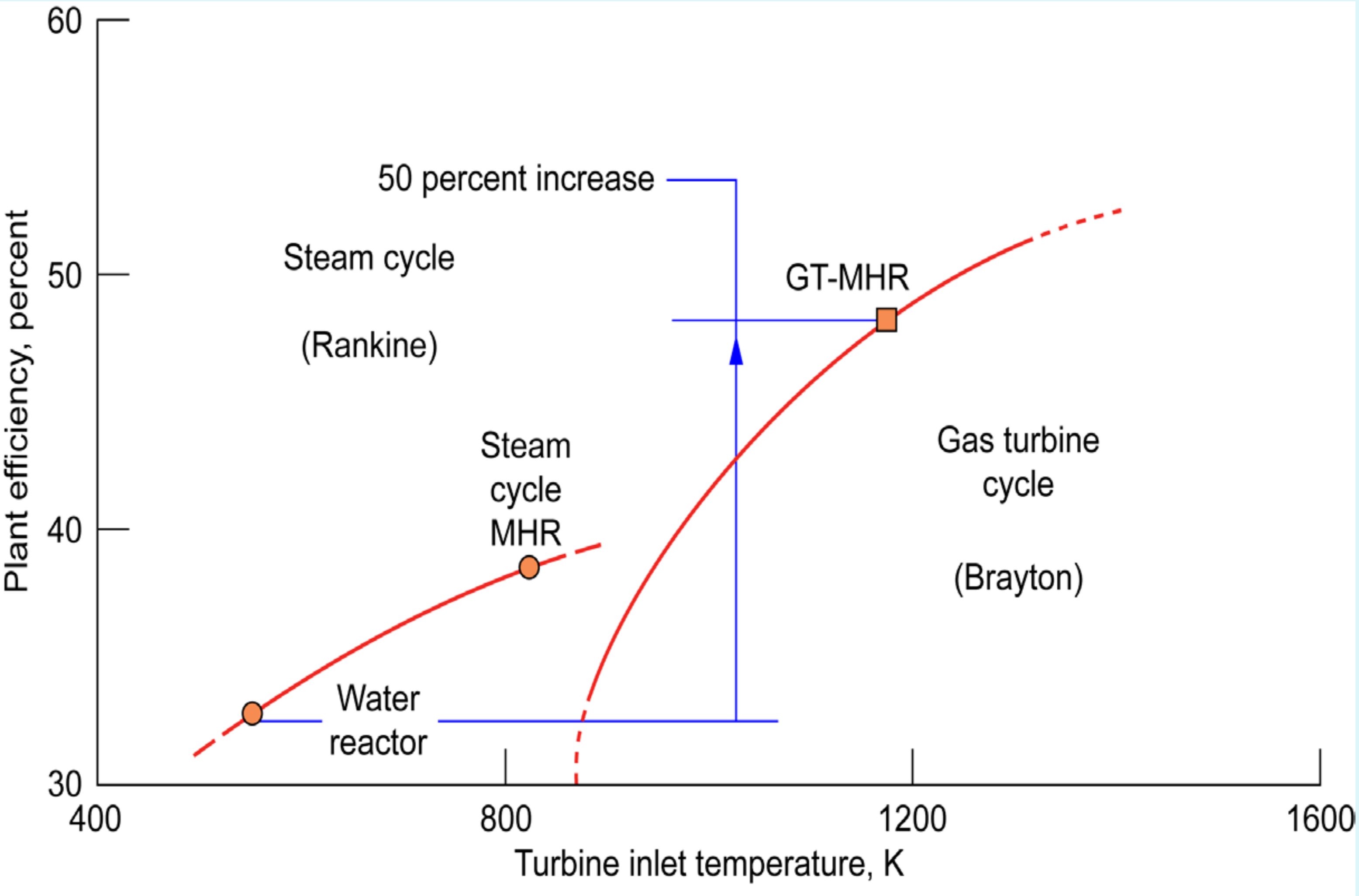
Background & Motivation

- 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 Energy Independence & Security Act of 2008 (S.3680)

  Thorium 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
  - Amenable to formation of nuclear micro-grid elements housed in off-shore submarine hulls

Energy Conversion Cycle Comparisons



(La Bar , 2002)

Requirements – i.e. Power System Design Drivers

- Space (Lunar-Mars) Power Systems
  - MWe Power Levels require CBC (Closed Brayton Cycle) Conversion
  - 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.
  - Location in permanently shadowed Lunar craters is ideal for CBC Nuclear Power systems, by enabling "Low Temperature Heat Rejection", i.e. (High Efficiency at low radiator area).

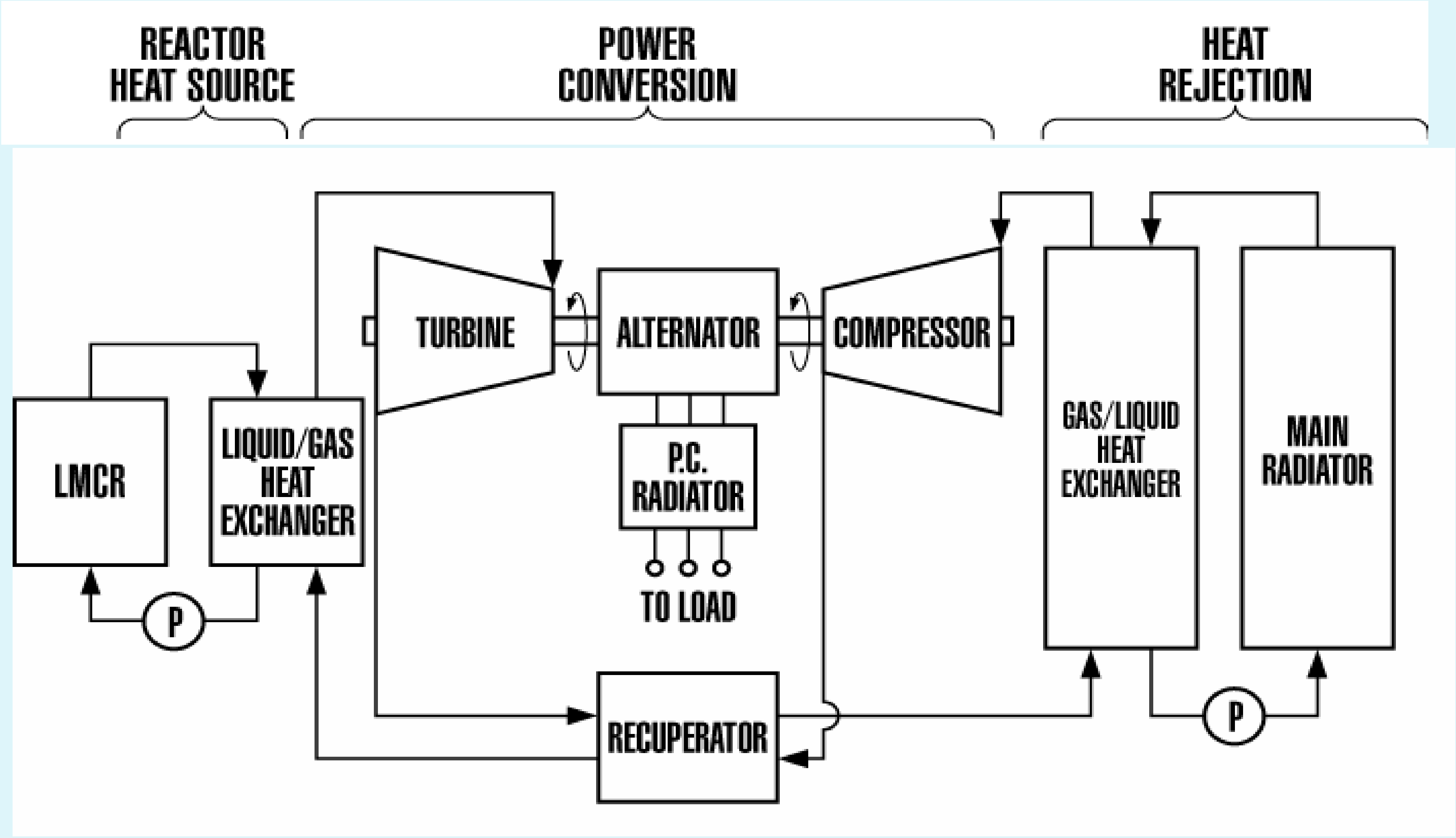
- Terrestrial Nuclear Power Systems – e.g. LFTR Power Plant
  - Emphasis is on maximizing Thermal Efficiency, η_t and thus Power Output, Revenue, Profit & Return on Investment
  - High Temp. Materials R&D enables high TIT, and thus high η_t
  - System Maintenance possible during regularly scheduled Periods
  - High System Mass and Complexity are acceptable as long as high Power Plant Availability/Reliability is assured
  - Ideal for Micro – Grid nuclei

Space CBC Systems

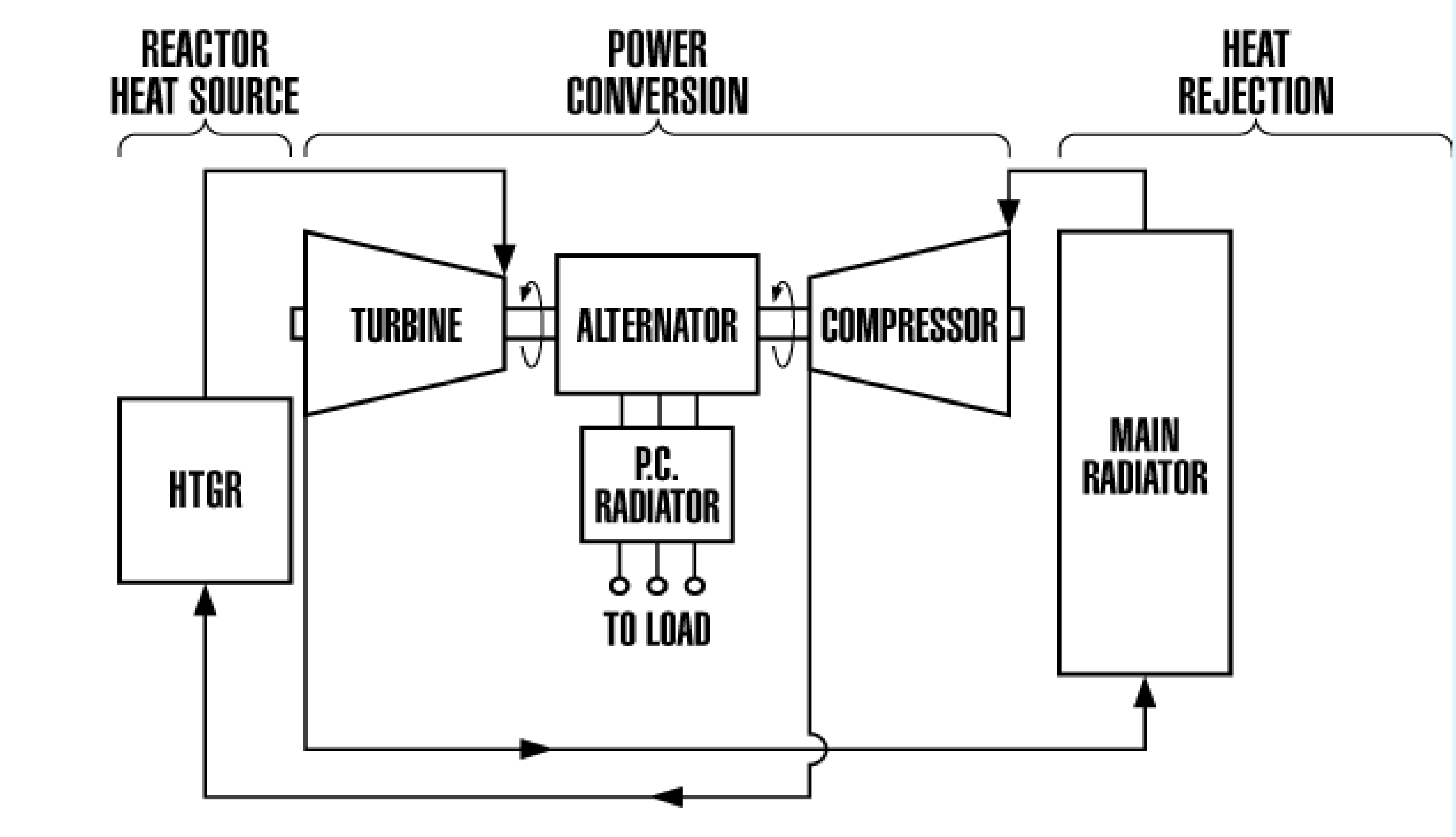
and

Analysis

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

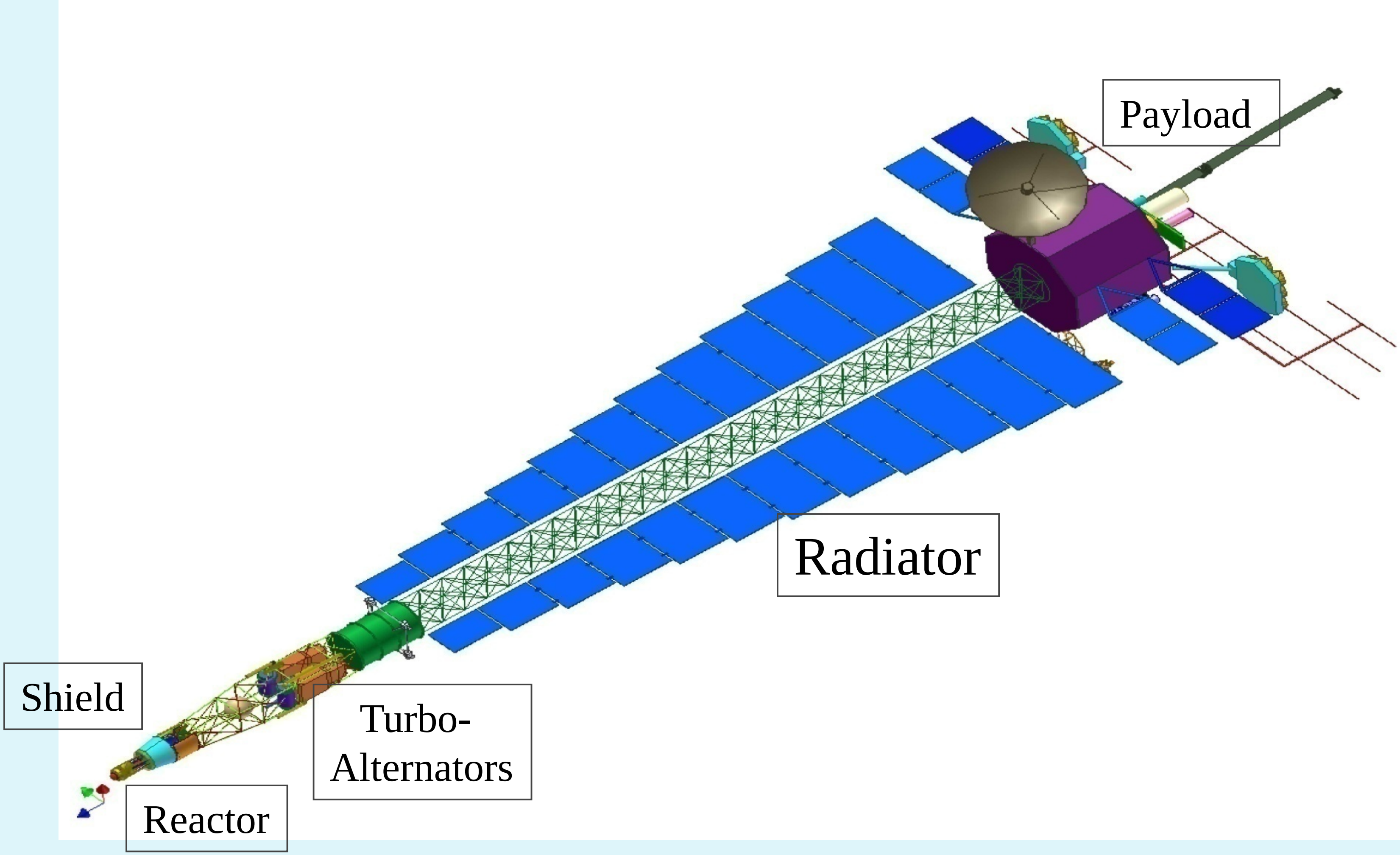


Direct Heat Input and Rejection via Radiator for Non-Regenerated Closed Brayton Cycle (CBC) Power System

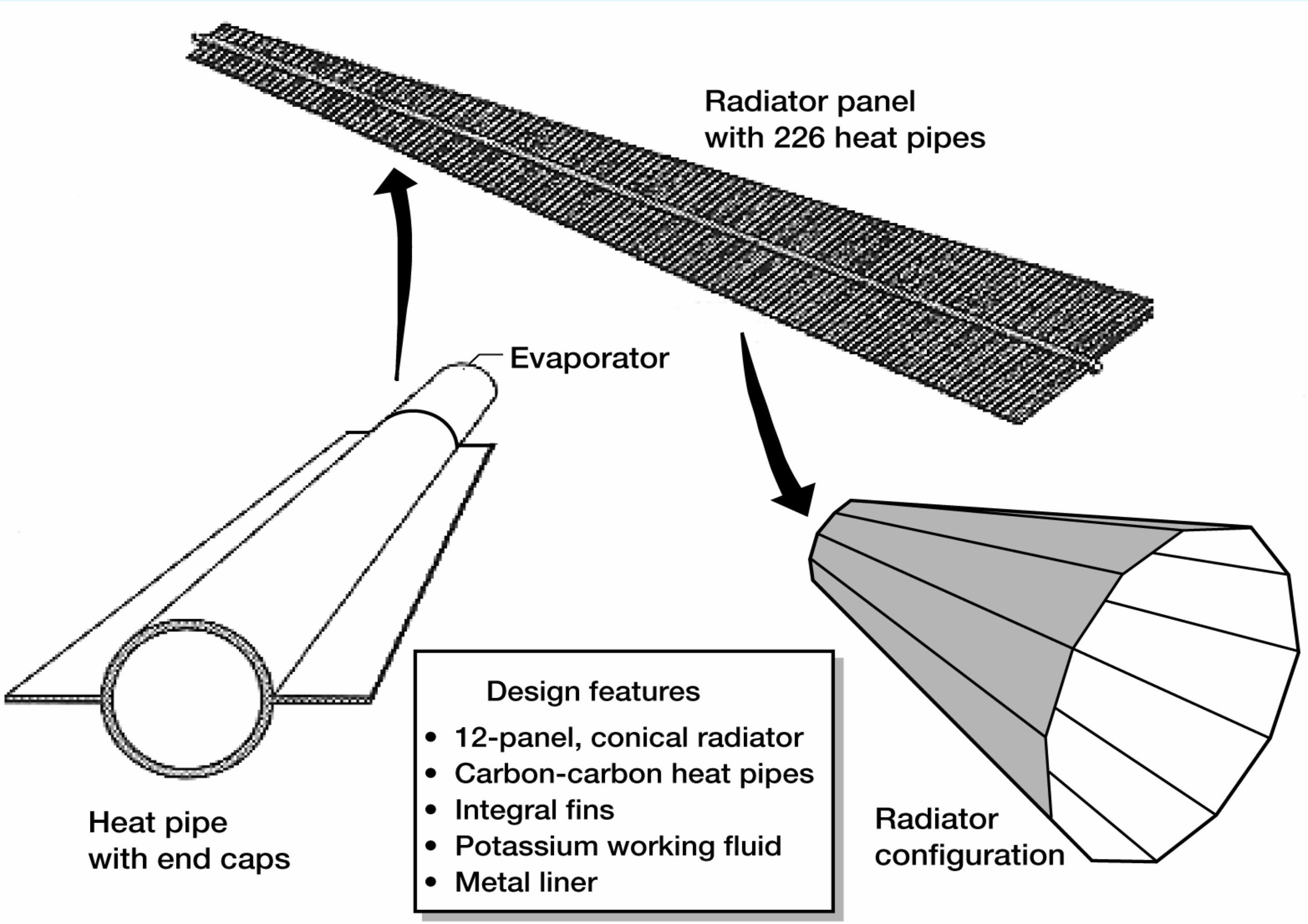


Spacecraft with Trapezoidal Heat Pipe Radiator

(Ref. SP-100 Program)



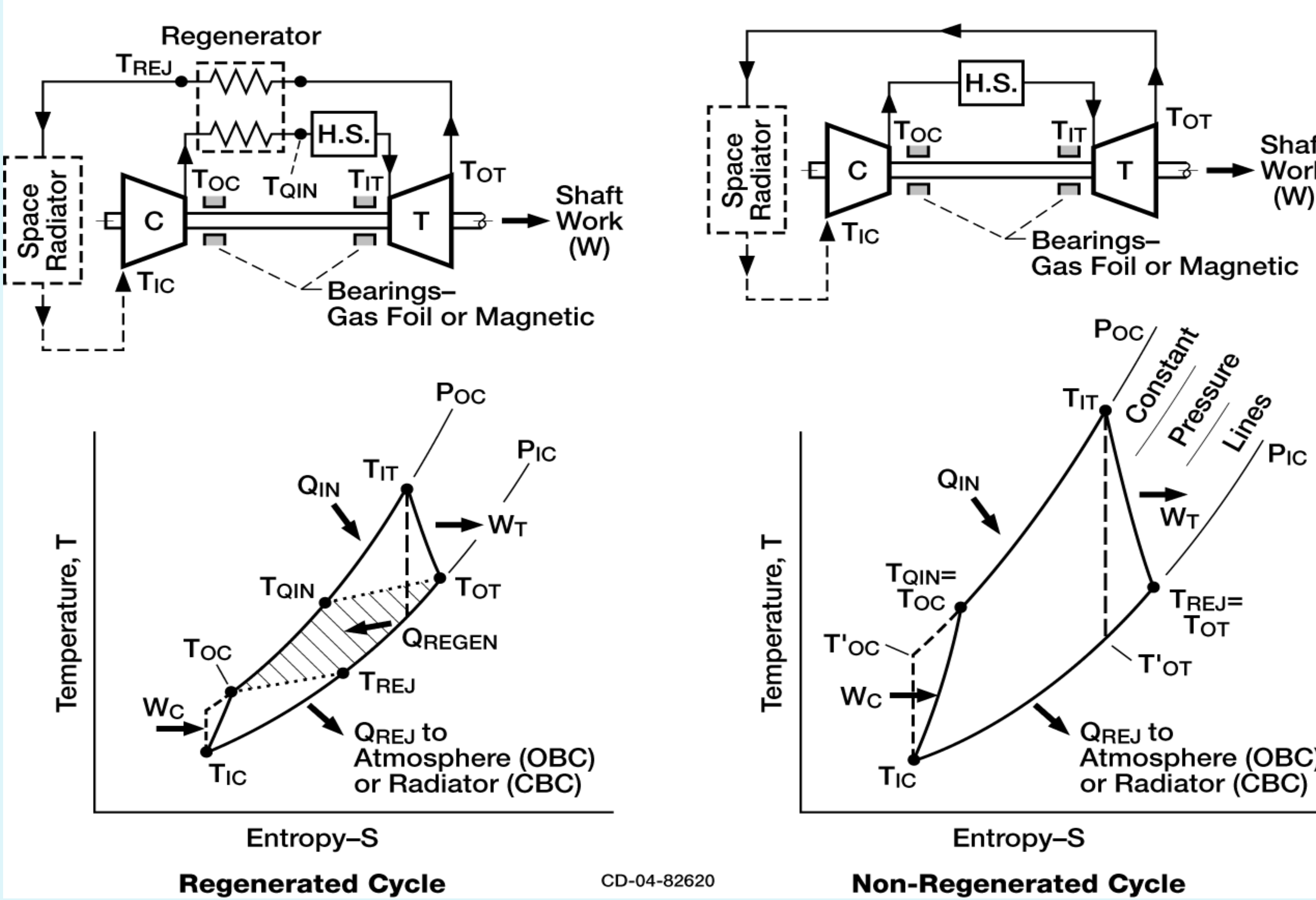
SP – 100 Radiator Panel/Cone Configuration



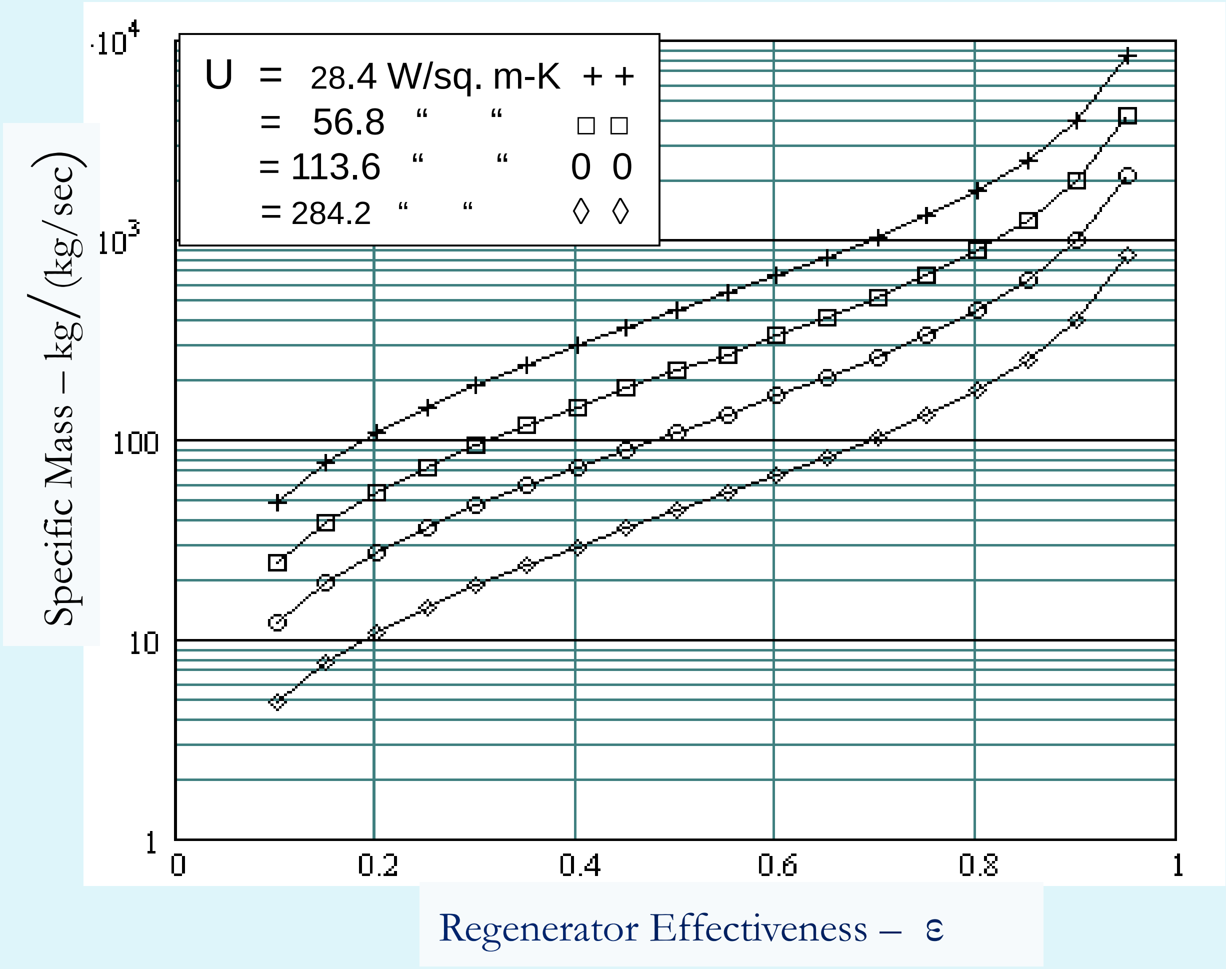
Design features

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

GAS TURBINE (BRAYTON CYCLES)

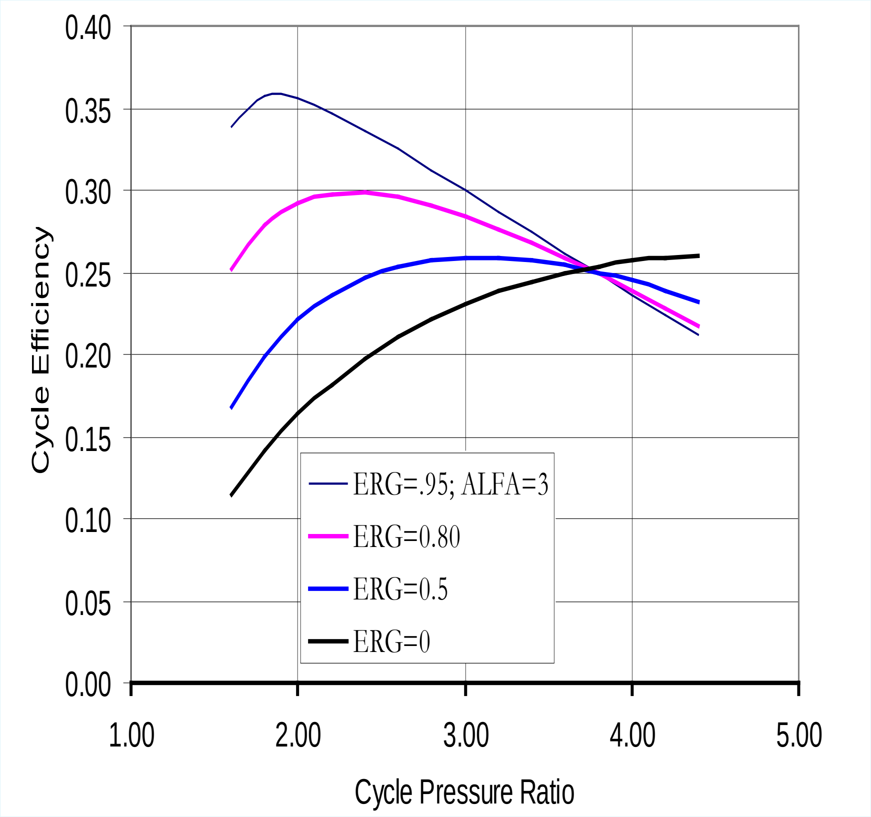


Regenerator Specific Mass vs. Effectiveness with Heat Transfer Coefficient U as a Parameter for He Working Fluid

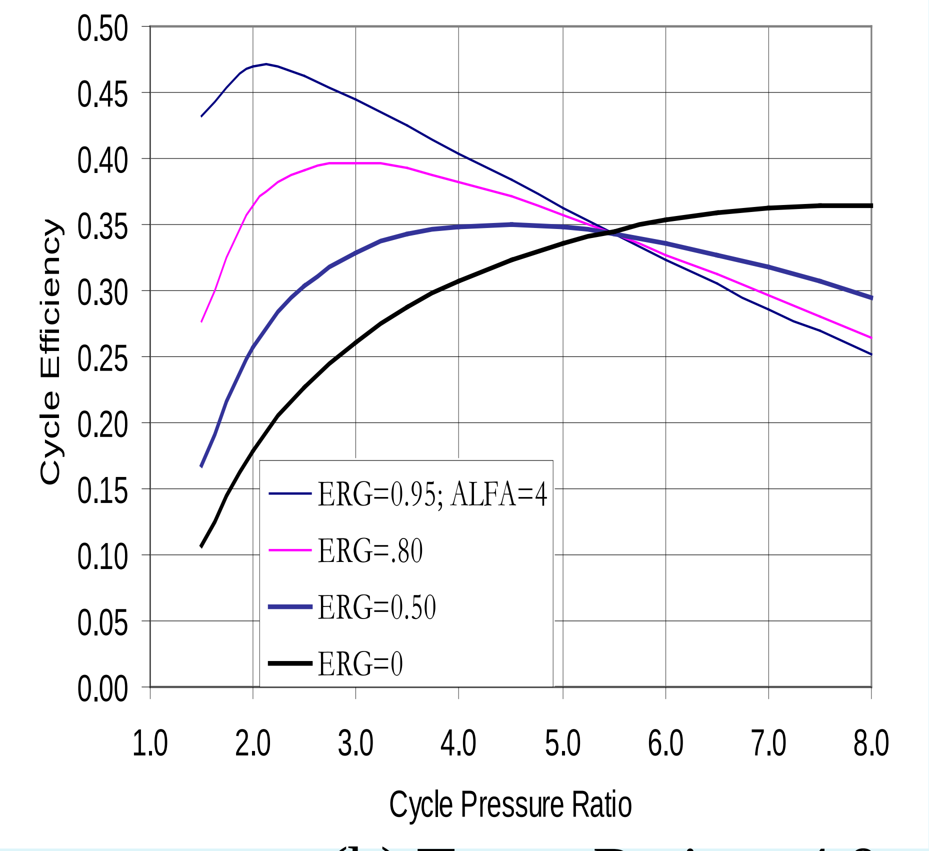


Influence of Regenerator Effectiveness (ERG) on Cycle Efficiency at Cycle Temp. Ratio of 3.0 and 4.0

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

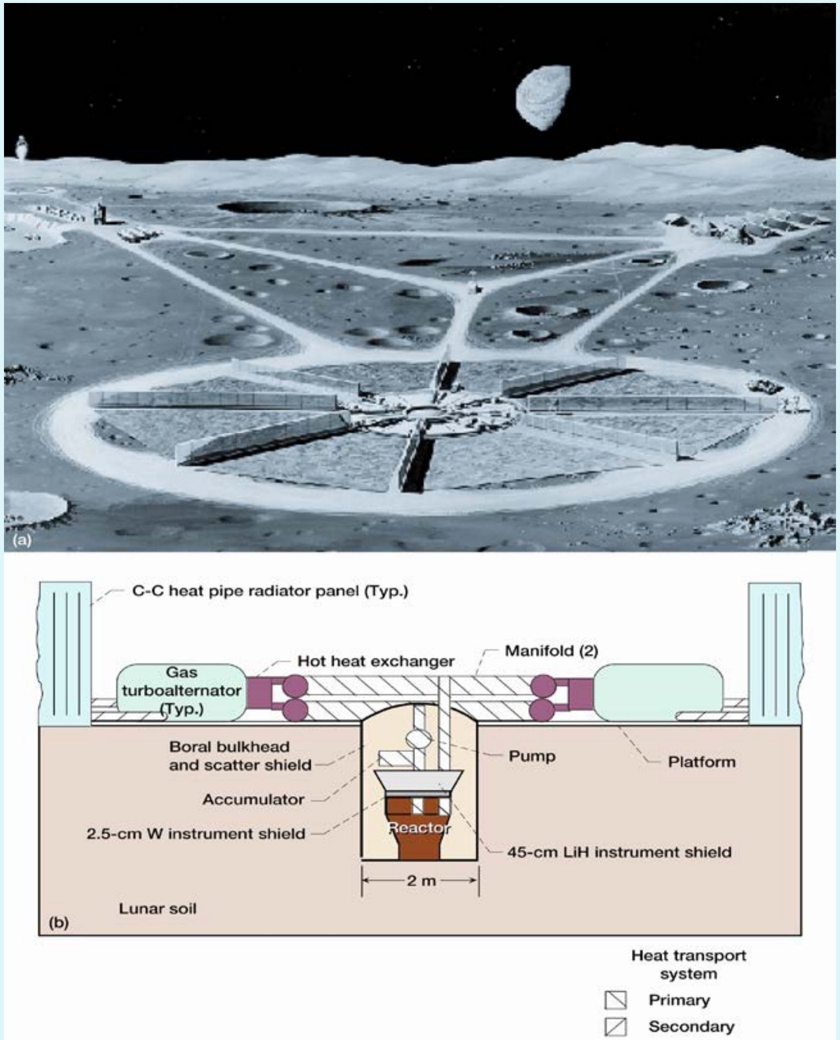


(a) Temp. Ratio = 3.0

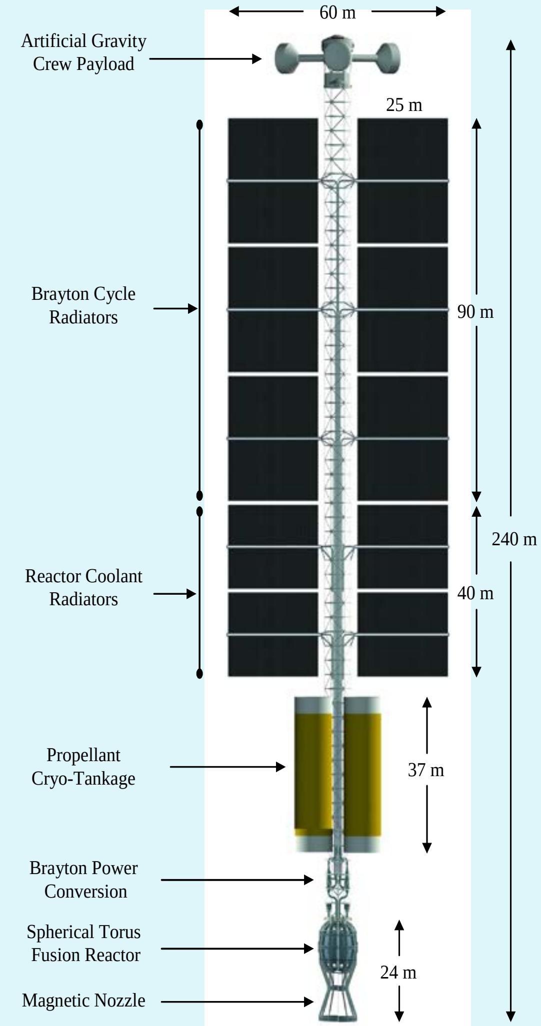


(b) Temp. Ratio = 4.0

Advanced Power System Applications



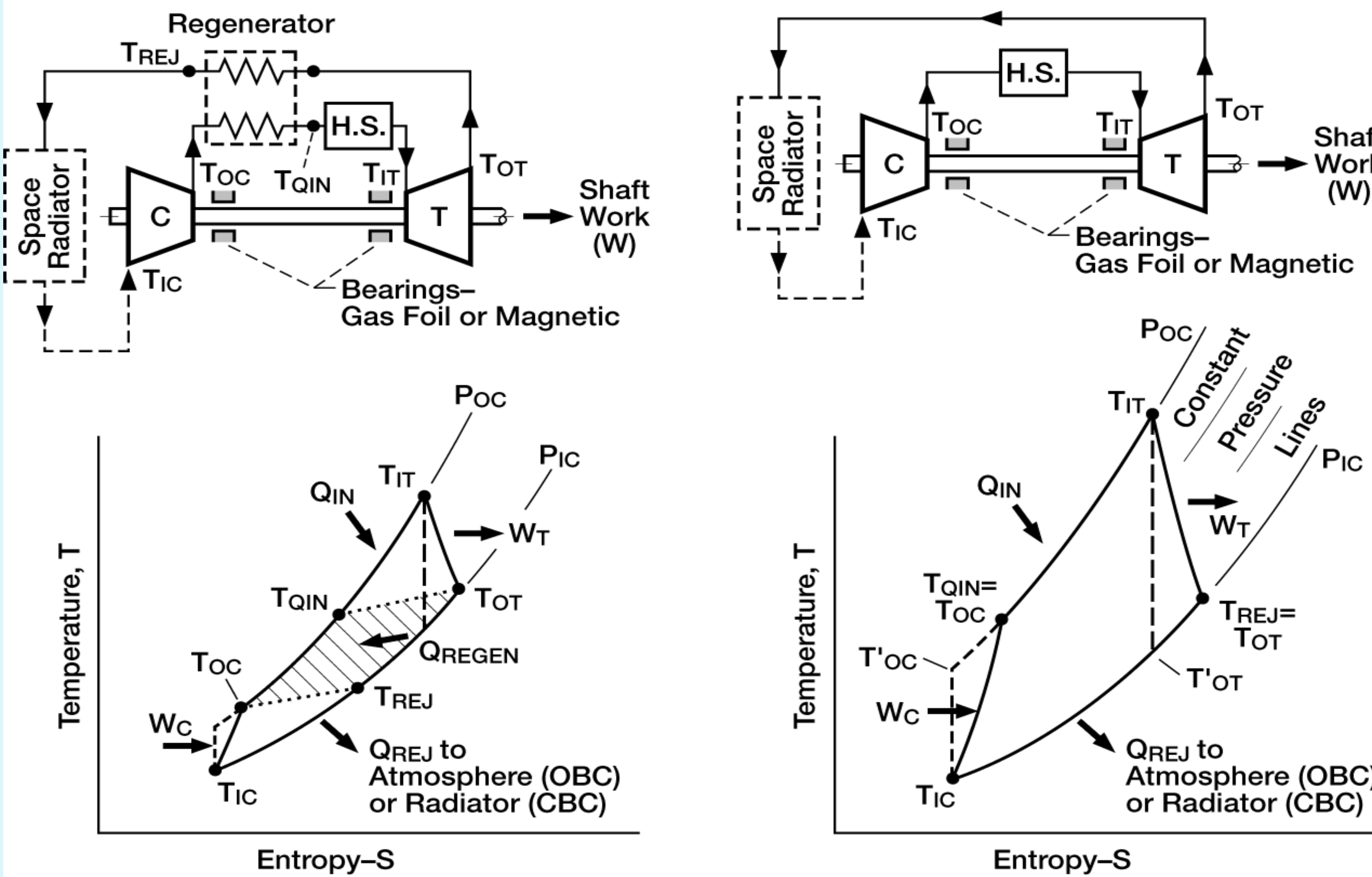
Lunar Base Power System



Interplanetary Fusion Propulsion Space Vehicle

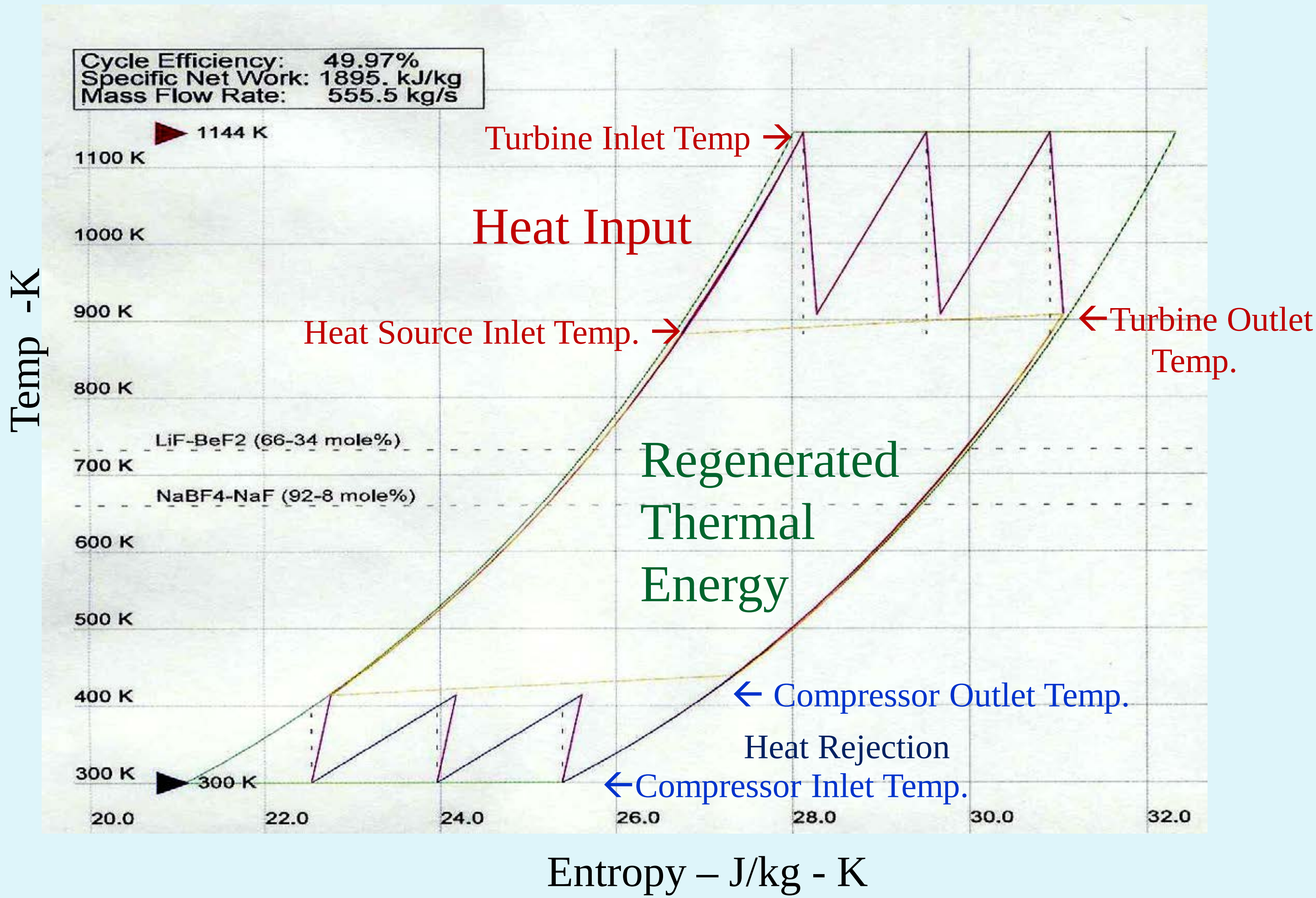
Ground Based CBC Systems

Recall GAS TURBINE (BRAYTON CYCLES) – w/o RH & IC

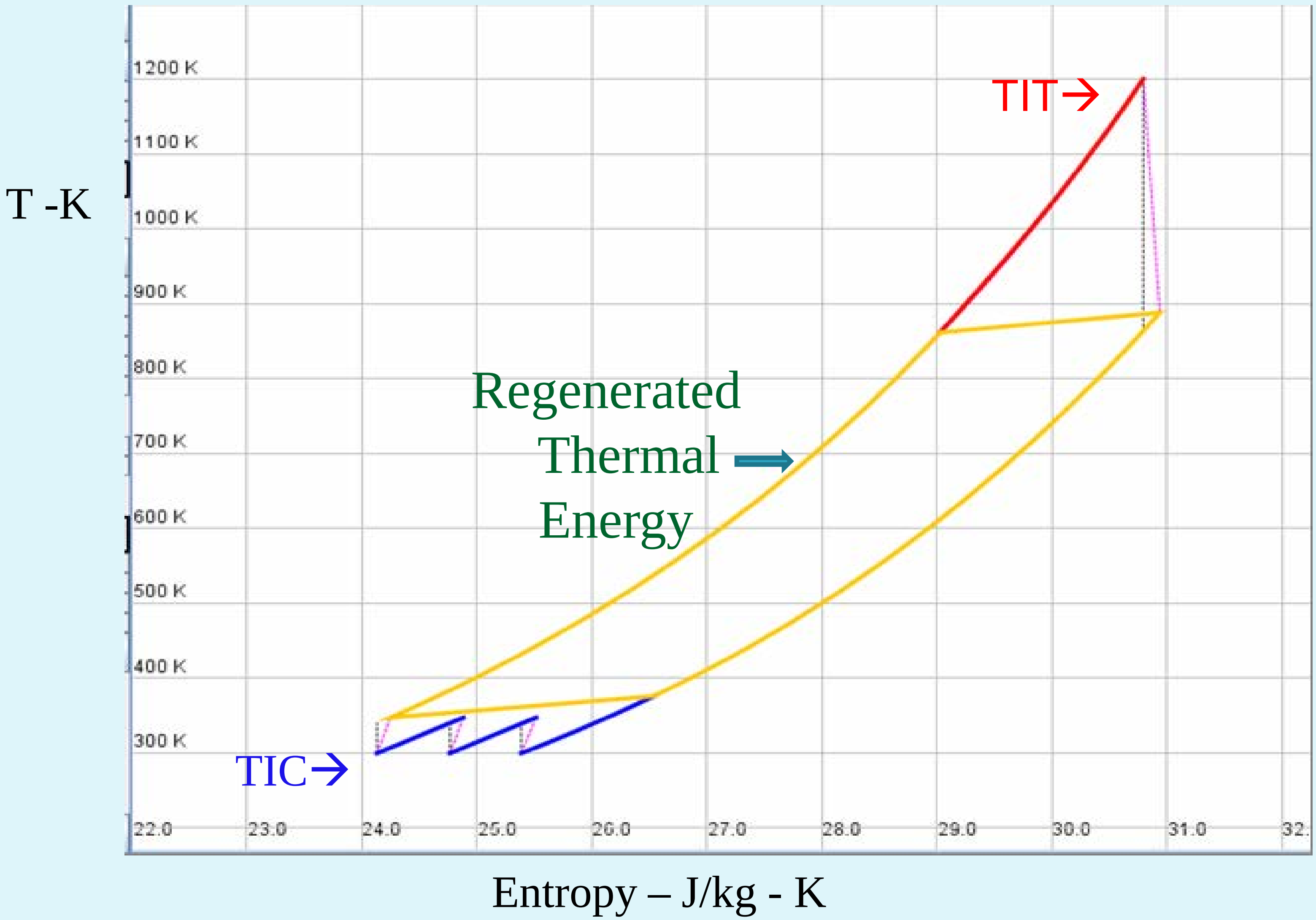


Regenerated Cycle CD-04-82620 **Non-Regenerated Cycle**

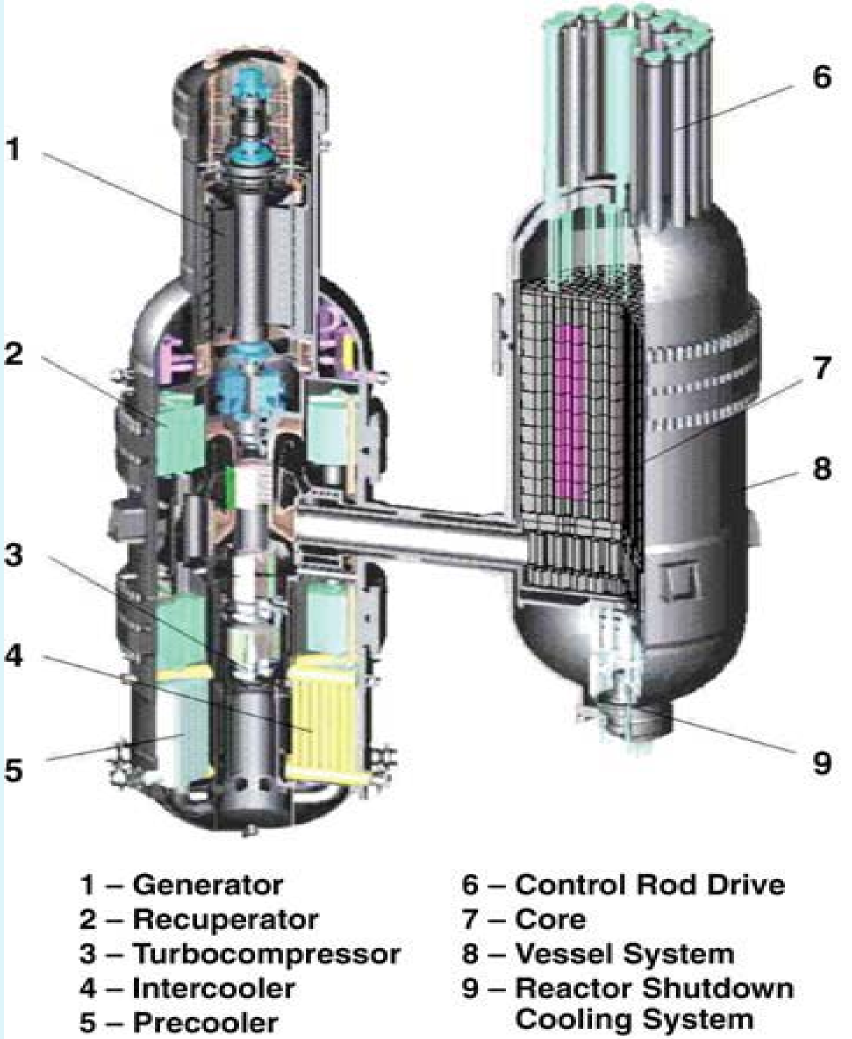
Three Stage Reheat & Intercool Brayton Cycle Temperature – Entropy Diagram



Three Stage Intercool Only Brayton Cycle Temperature – Entropy Diagram

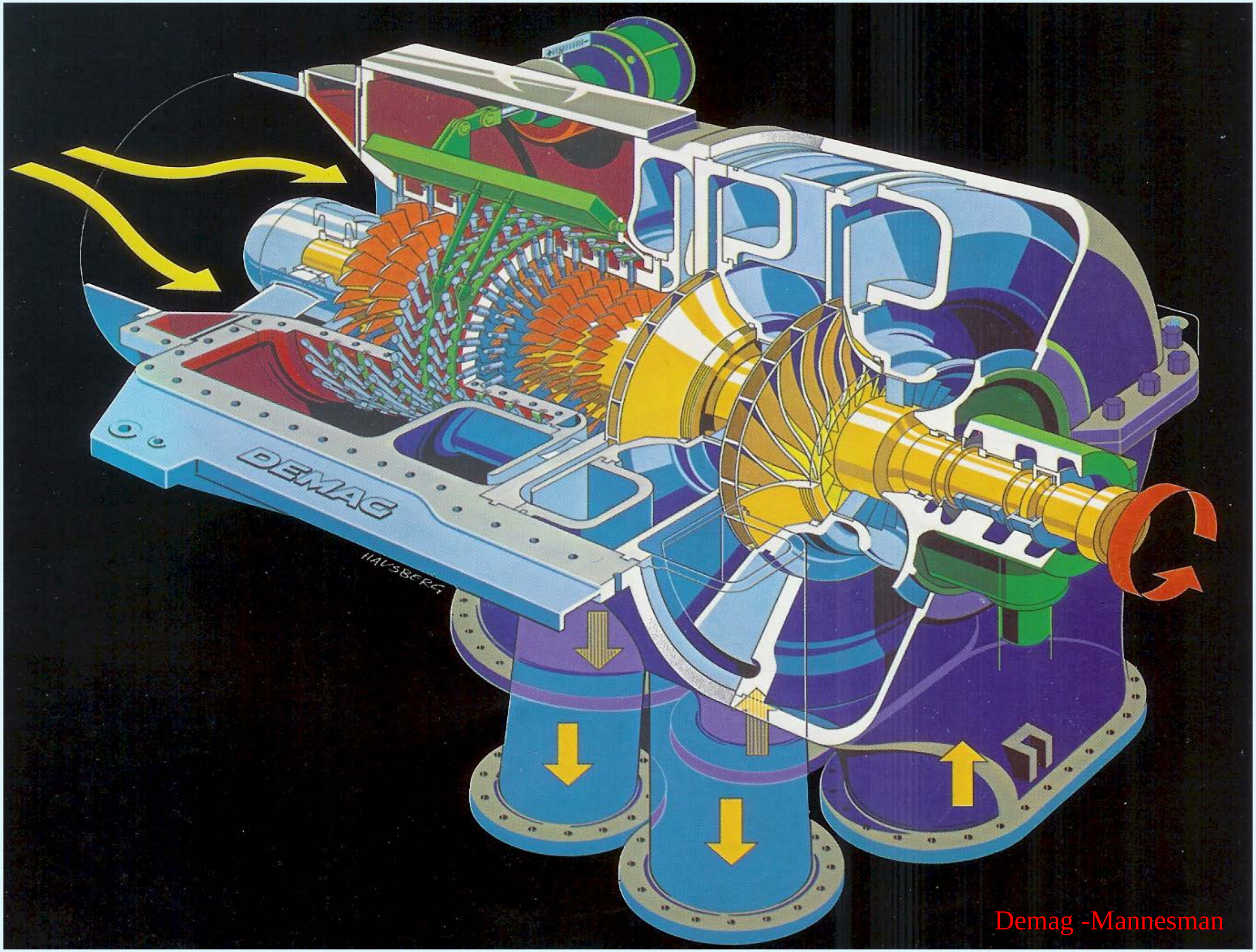


Proposed Vertical Orientation of GT-MHR* Turbomachinery



* Gas Turbine Modular Helium Reactor

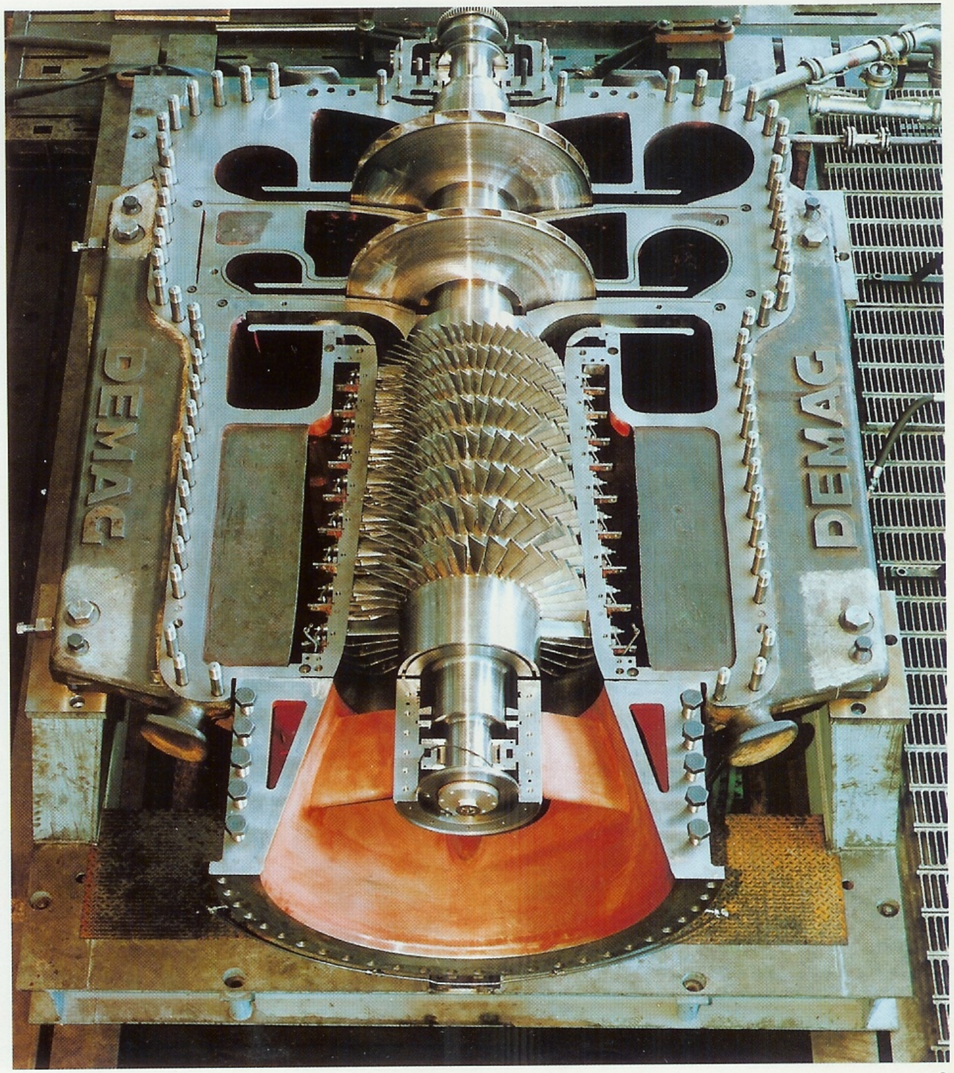
Typical Axial Radial Turbo-compressor



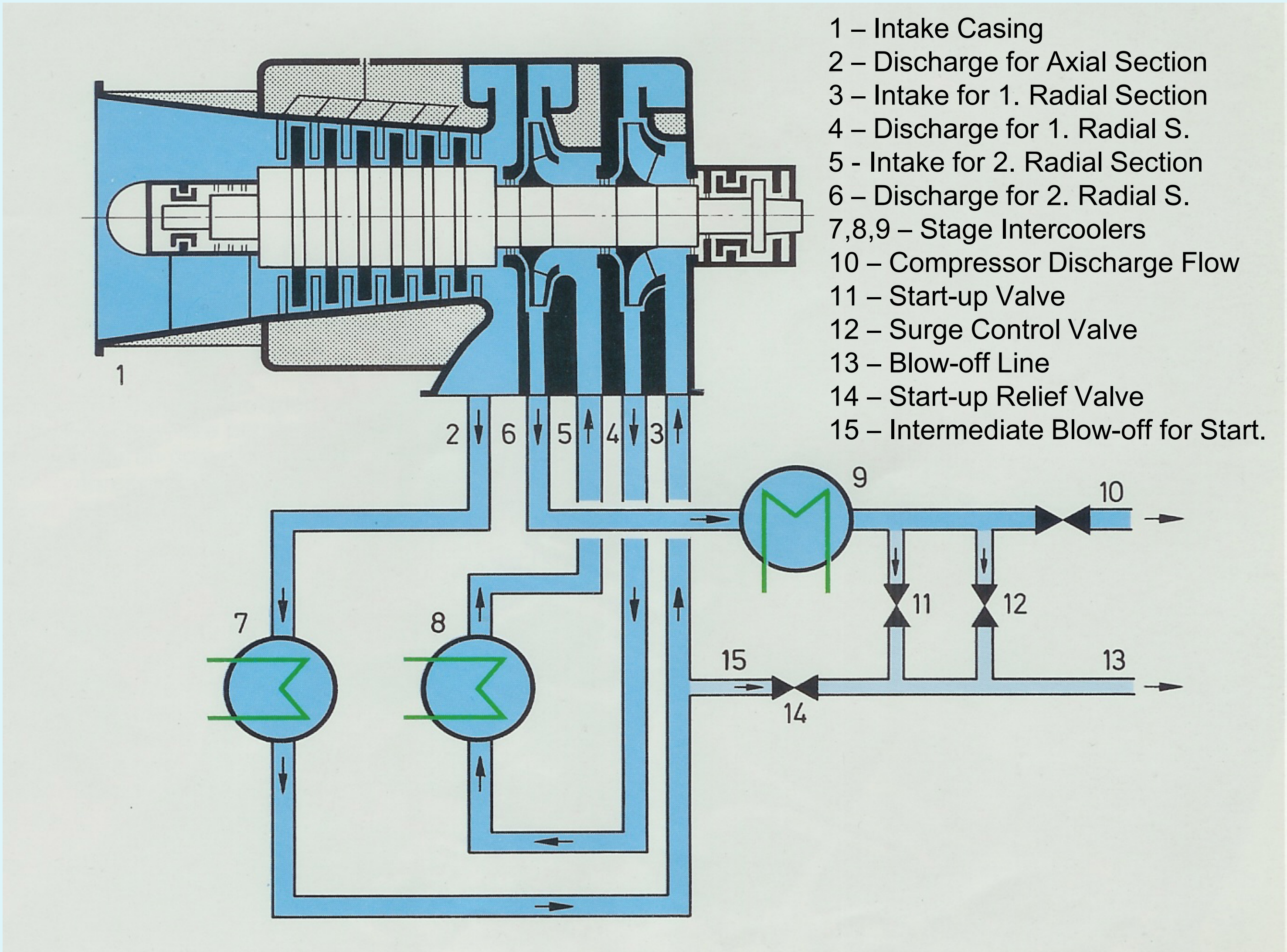
Axial/Radial Compressor with Axial Intake

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



Energy from Thorium

via

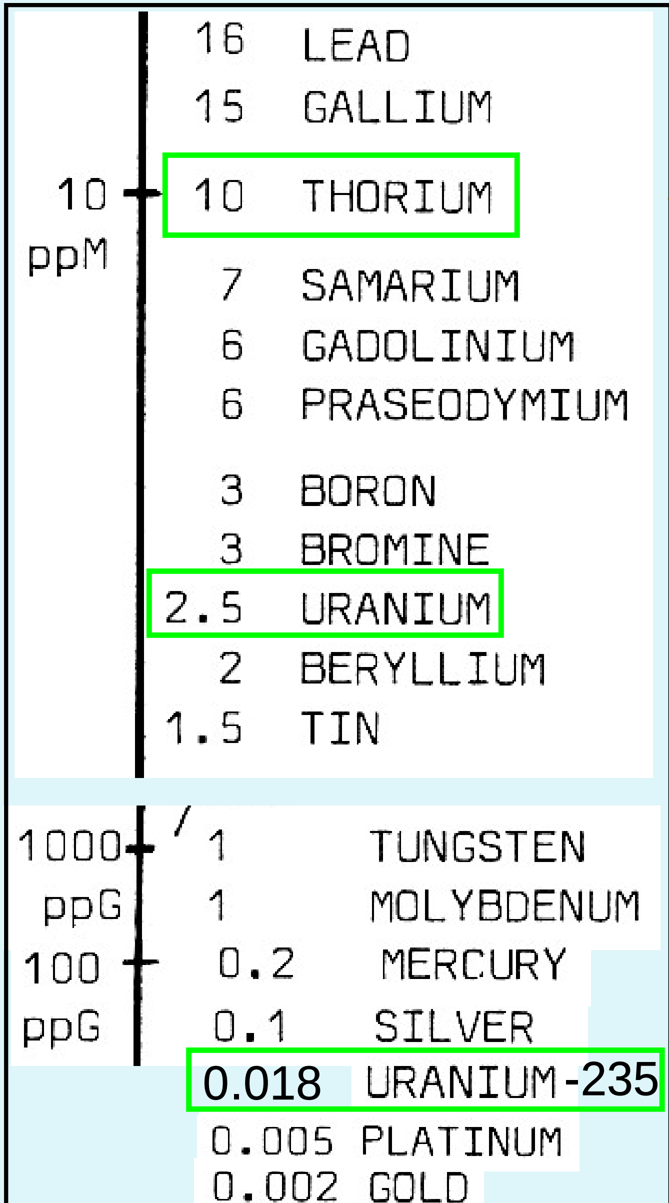
Liquid Fluoride Thorium Reactor- LFTR

for Terrestrial Power

References: Kirk Sorensen, W. Thesling

R. Hargraves – "Thorium energy cheaper than coal"

Thorium and Uranium Abundance in the Earth's Crust



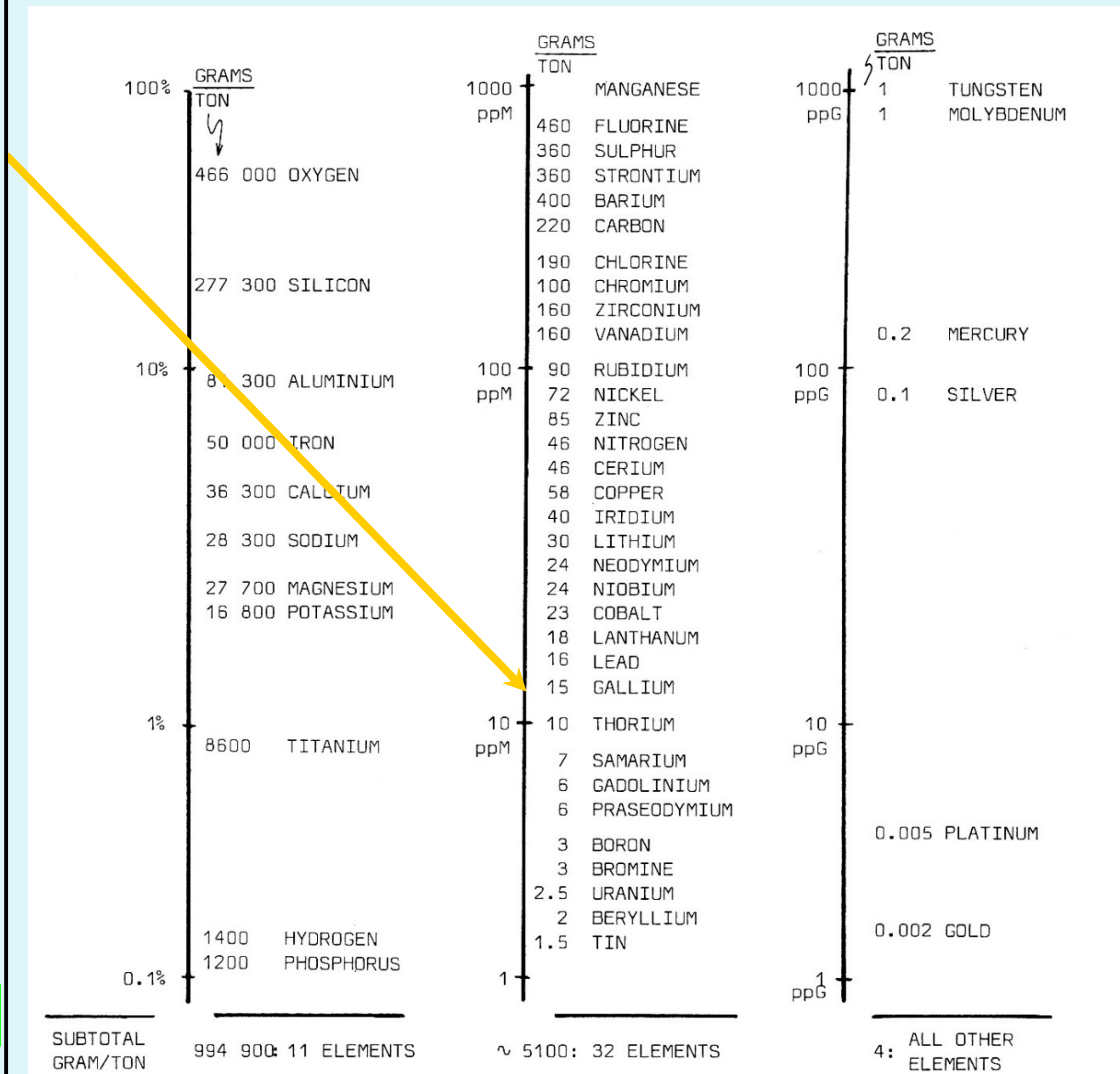


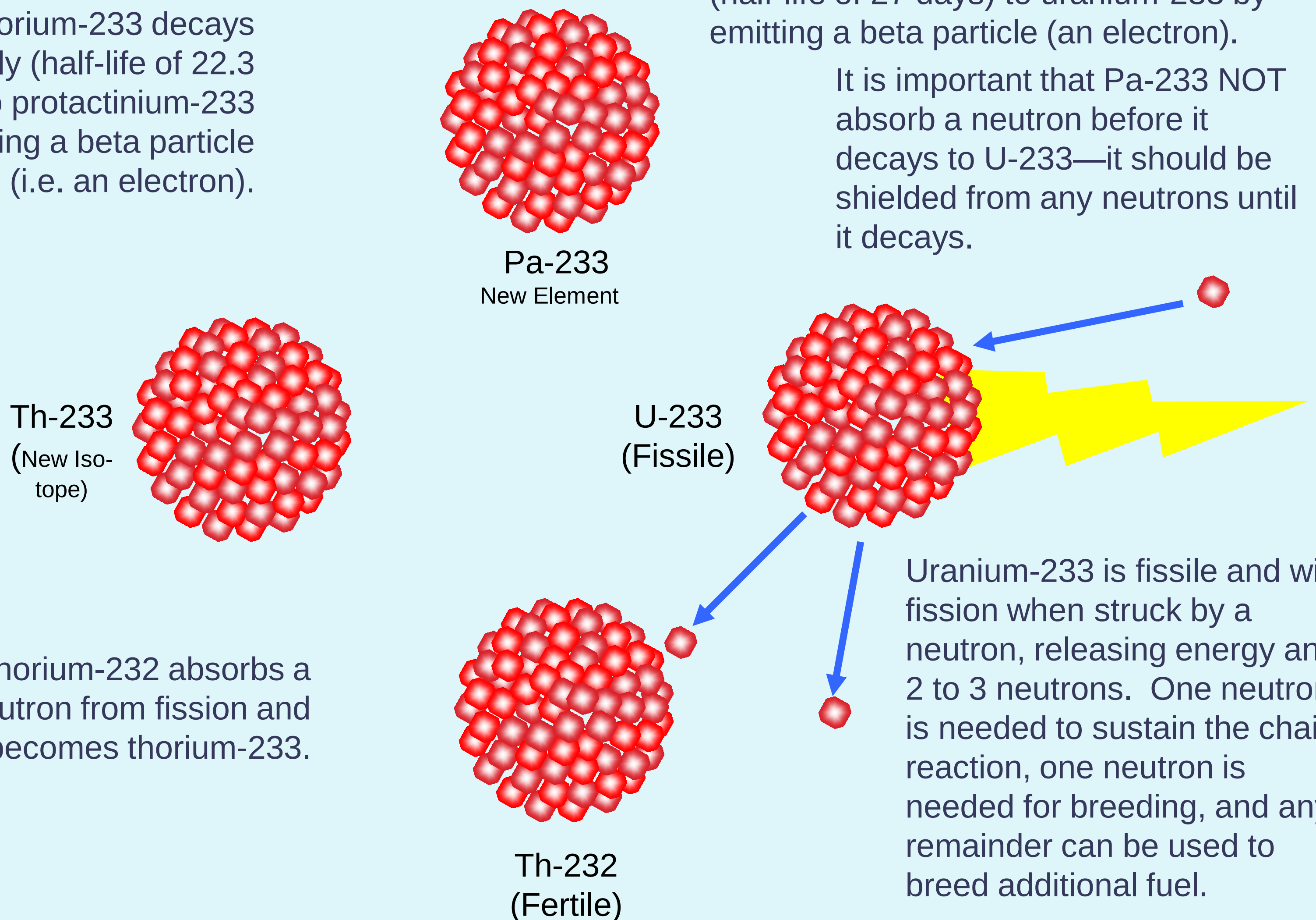
Fig. 5.13. The chemical composition of the Earth's crust.

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

Thorium-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.



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

Three Step process

Step 1 **-** Change **of Atomic Mass (Isotope)** via **neutron** absorption

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

Steps 2 & 3 **-** Change of **Atomic Number (Element)** via **β decay**

2. $_{90}Th^{233} \rightarrow {}_{-1}\beta^{0} + {}_{91}Pa^{233}$ **(β decay – λ = (**ln 0.5**)/(**HL= 22.3 min**)***

3. $_{91}Pa^{233} \rightarrow {}_{-1}\beta^{0} + {}_{92}U^{233}$ **(β decay – λ = (**ln 0.5**)/(**HL= 27 days**) ***

***(where λ** is Decay Constant

HL is Half Life)

)

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

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

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

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

= **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**

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

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

293 MT of natural U_3O_8 (248 MT U)

Conversion to UF6

365 MT of natural UF_6 (247 MT U_N)

Conversion and fabrication

39 MT of enriched (3.2%) UO_2 (35 MT U_{235})

1,120,000 MW*days/35 MT U235 at 3.2% enrichment (typical LWR fuel burnup)

3000 MW*yr of thermal energy

33% conversion efficiency (typical steam turbine)

1000 MW*yr of electricity

(1012 MW*yr)

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

0.9 MT of natural ThO2

Conversion to metal

0.8 MT of thorium metal

Thorium metal added to blanket salt through exchange with protactinium

0.8 MT of ^{233}Pa formed in reactor blanket from thorium (decays to ^{233}U)

765,000 MW*days/.8 MT ^{233}U (complete burnup)

2000 MW*yr of thermal energy

50% conversion efficiency (triple-reheat closed-cycle helium gas-turbine)

1000 MW*yr of electricity

(1048 MW*yr)

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

Thorium: Virtually Limitless Energy

World Thorium Resources

Country	**Reserve Base (tons)**
Australia	340,000
India	300,000
USA	**300,000**
Norway ("Thorcon" in Oslo)	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

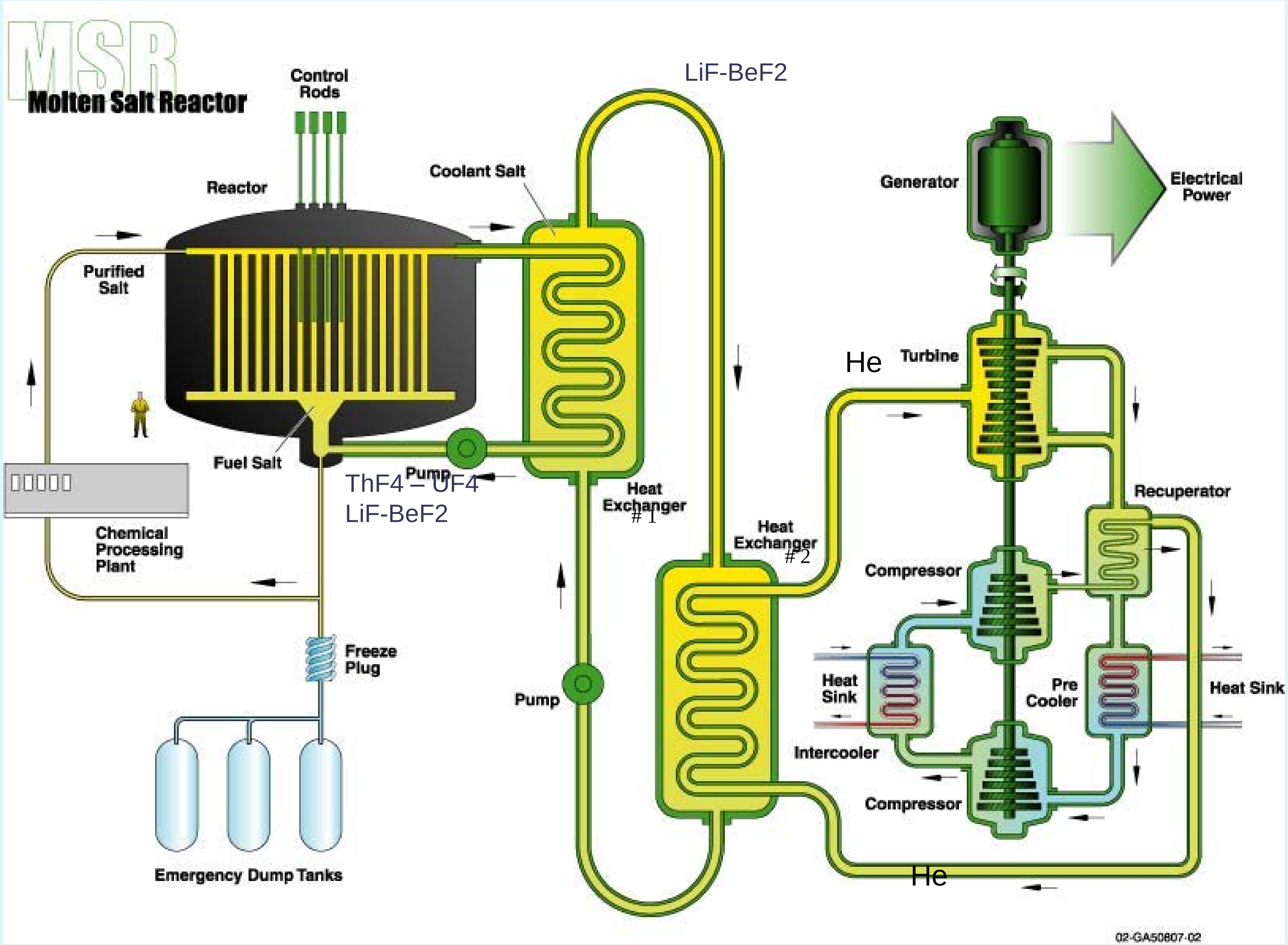
- Thorium is abundant around the world:
  - Found in trace amounts in most rocks and soils
  - India, Australia, Canada, US have large minable concentrations. (Main Ore "Monazite")
  - US has about 20% of the world reserve base
- No need to hoard or fight over this resource:
  - A single mine site in 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!

Gen-4 Liquid 2 Salt Configuration Reactor Concept – ORNL

Developers : Jerome Wigner and Saul Weinberg



CBC Energy Conversion System Analysis

(with Comp. IC & Turbine Re-Ht)

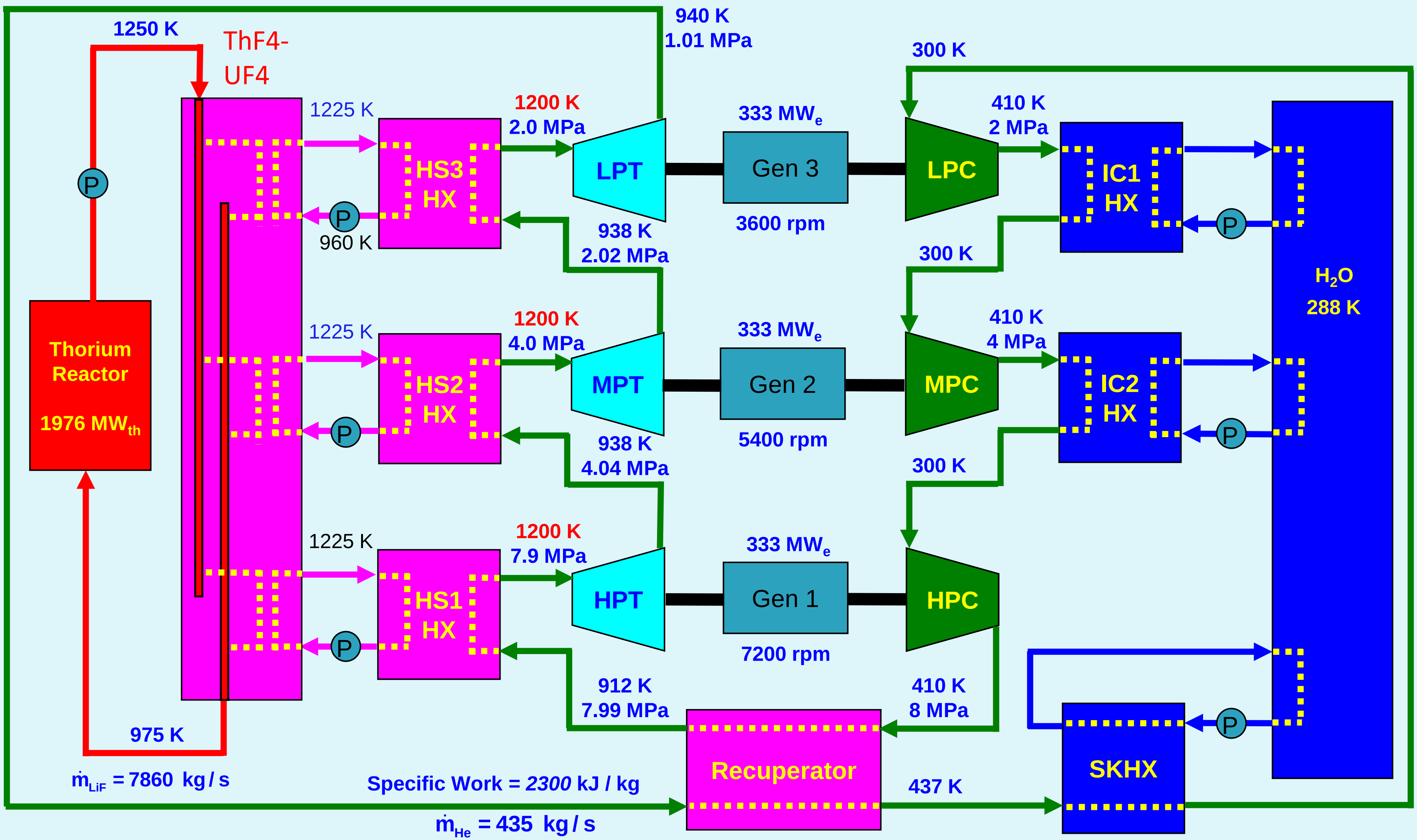
Key Cycle Input Parameters

• 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

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

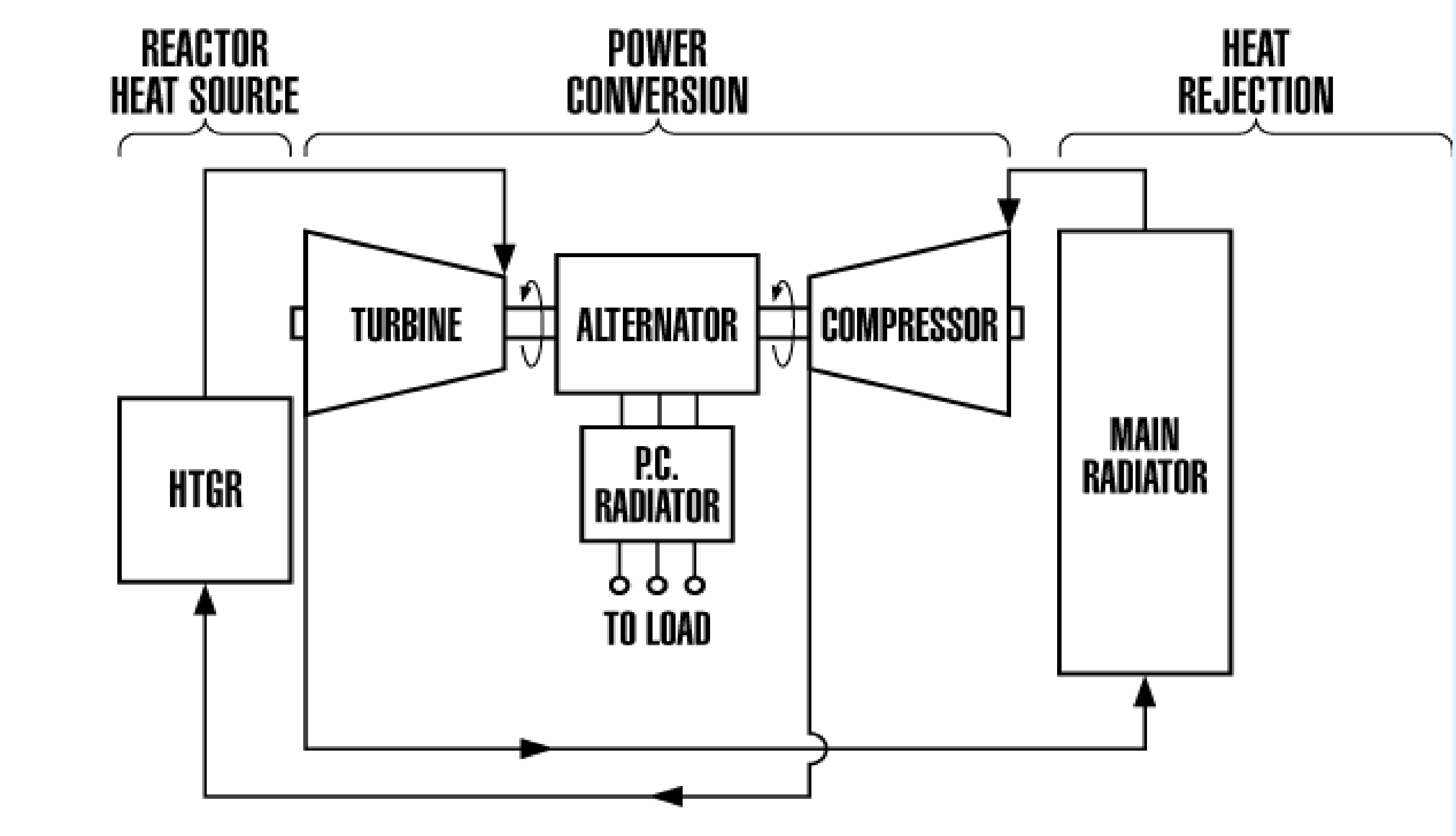
1000 MWe Power Plant 2 Salt Configuration
Thorium Molten Salt Reactor
He CBC w. Rht. & Intcl.- 1200 K Turbine Inlet Temp

He ---
LiF – BeF2
ThF4-UF4



- Comparison to Space System-

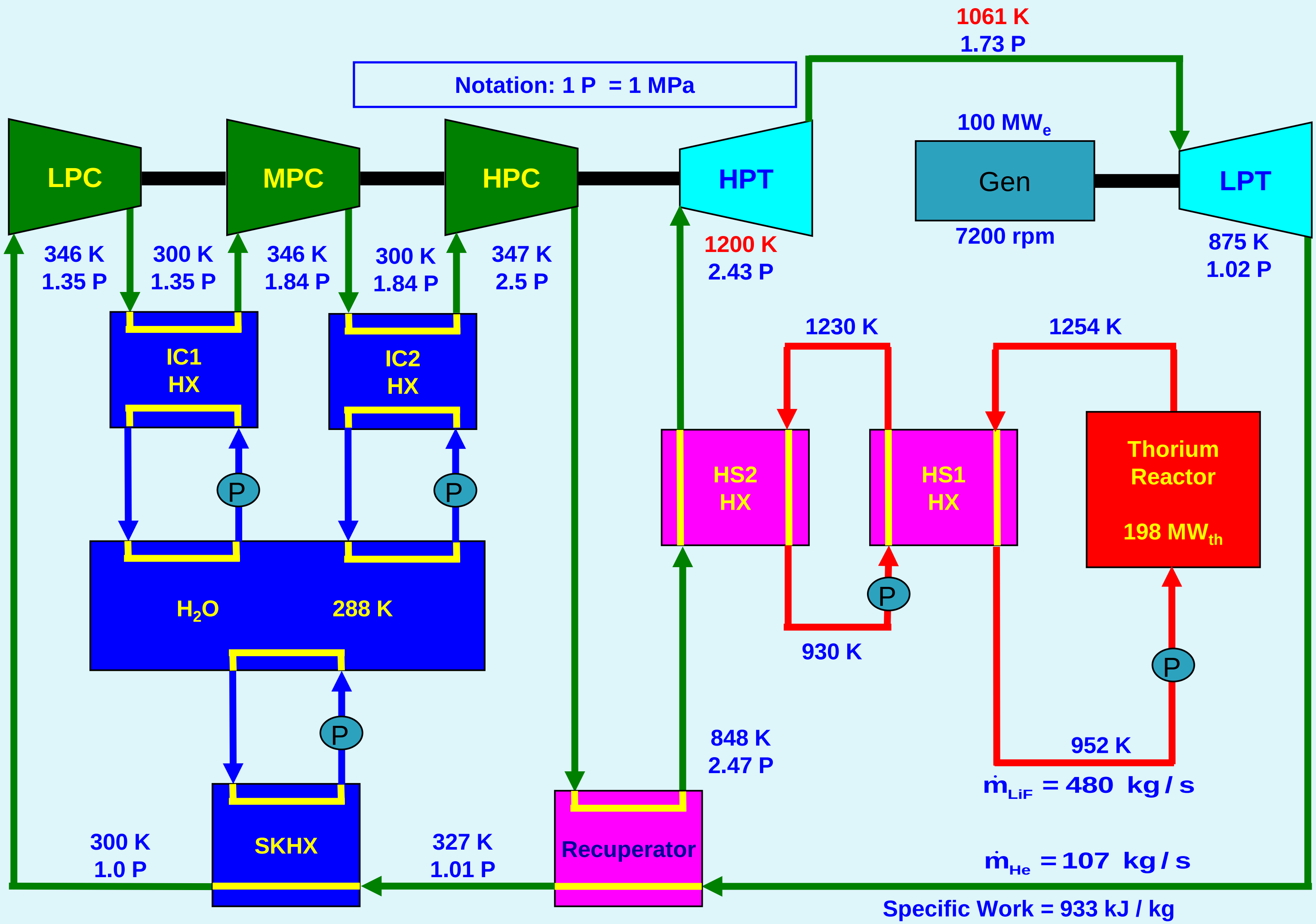
Direct Heat Input and Rejection via Radiator for Non-Regenerated Closed Brayton Cycle (CBC) Power System



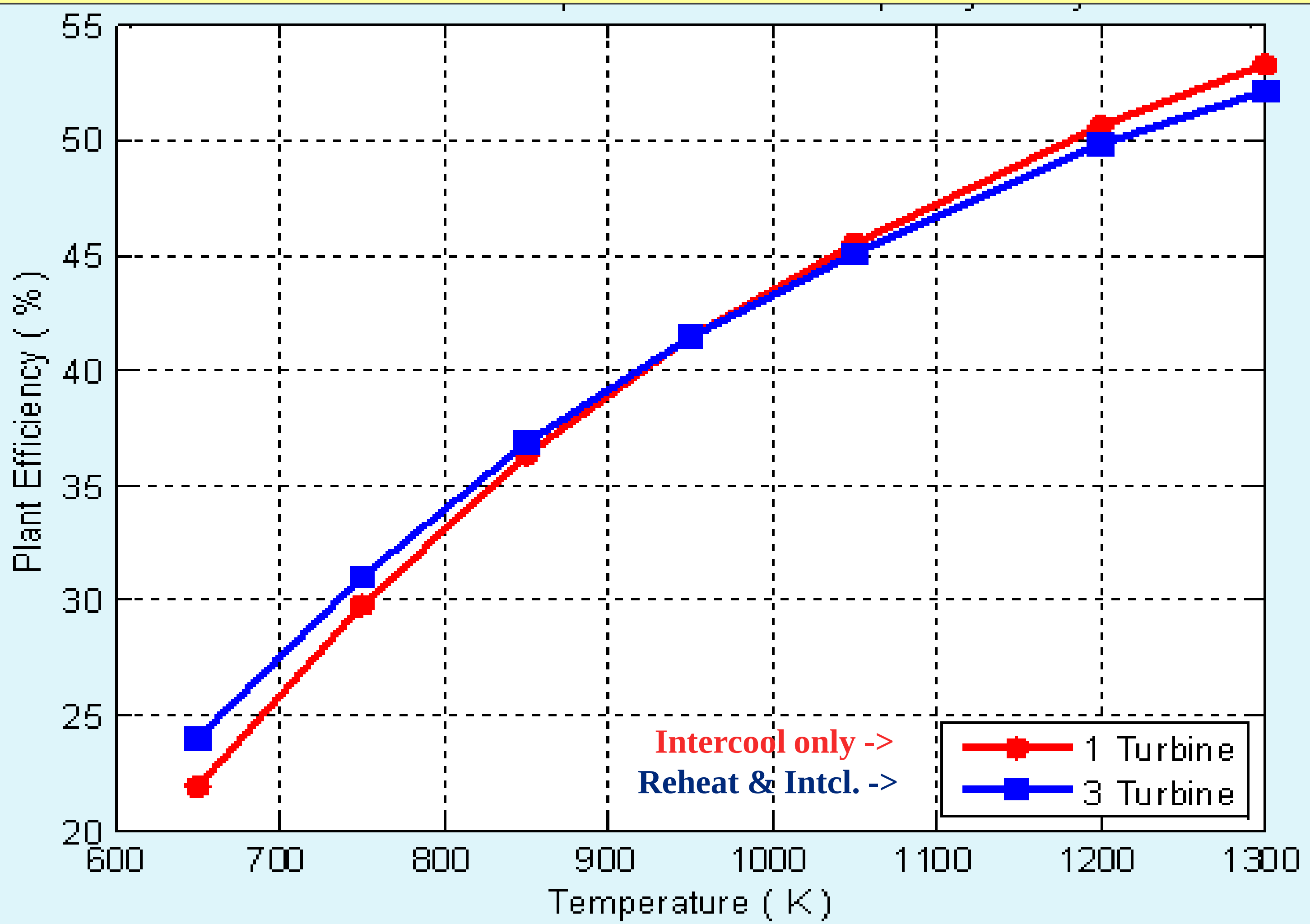
Temp Ratio = 4.0
Efficiency = 50.5 %
Turbine Power = 178.9 MW
Compressor Power = – 76.9 MW

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

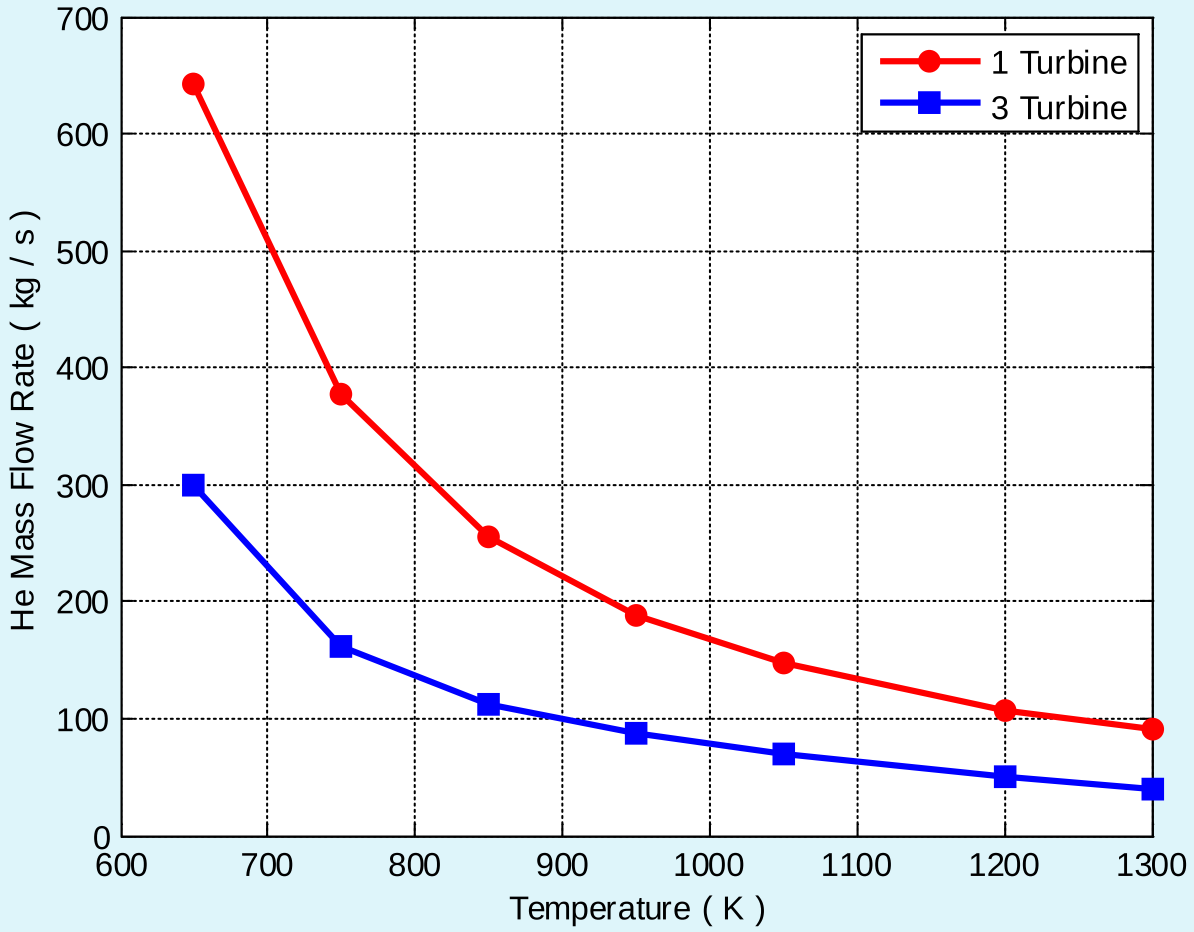
He ---
ThF_4-UF_4 ----
& BeF_2 -------



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)



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

- Numerically confirmed that 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 ’005
  - 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
  - Load Leveling operation to produce H2, & Sea Water Desalination
- Submarine based Power Plants located “off-shore” could serve as de-centralized micro-grid elements, hardened against cyber threats (EMP).

Backup Slides

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%

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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