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 green house 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

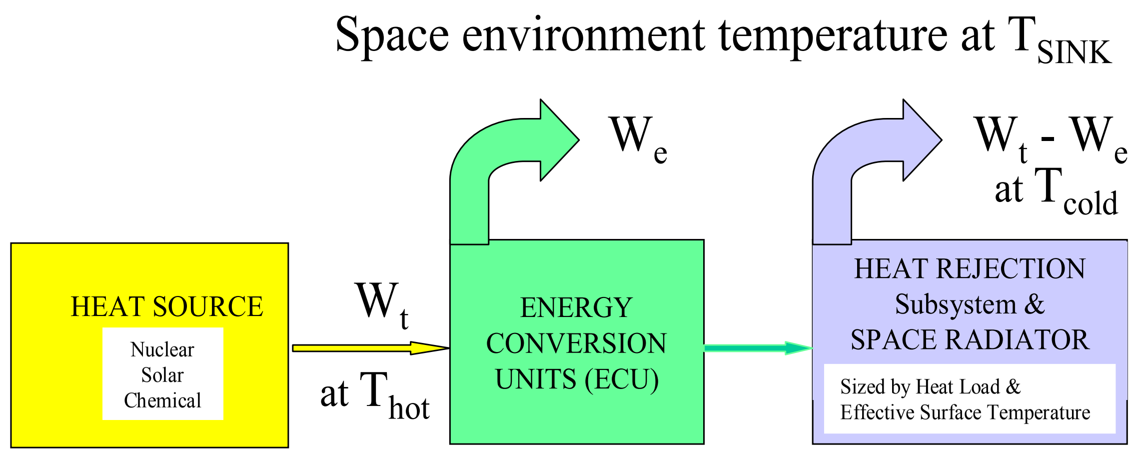
- Space (Lunar) Power Systems
  - Emphasis is on Minimum System Mass
  - High System Reliability, Autonomy and long Operational Life required to compensate for little or no maintenance
  - Need least complex systems w. minimum components
  - Thermal Efficiency can be traded to achieve Low Mass, i.e. 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

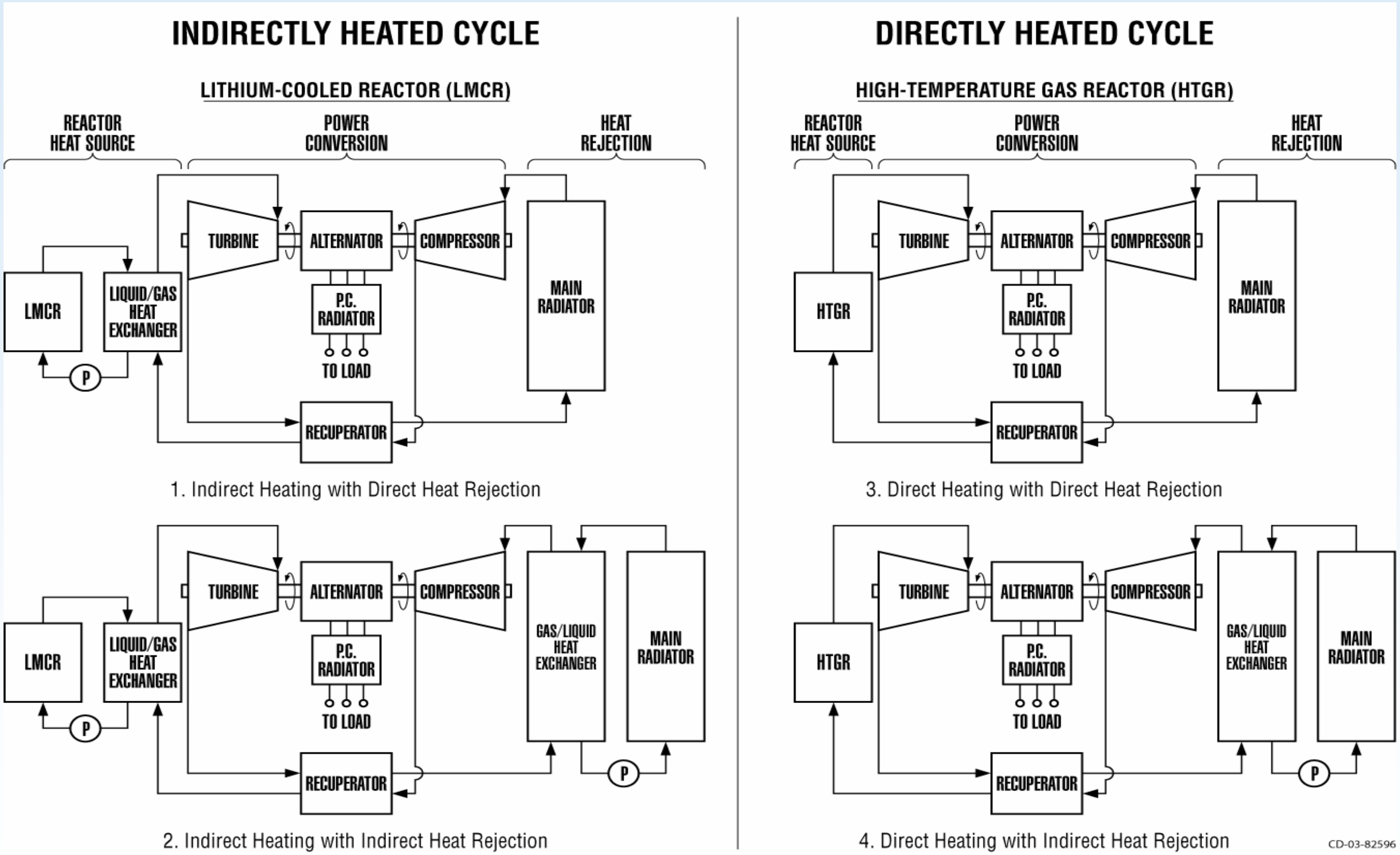
Synopsis of Closed Brayton Cycle Code - *BRMAPS*

Thermodynamic System Block Diagram Comprising three major Subsystems

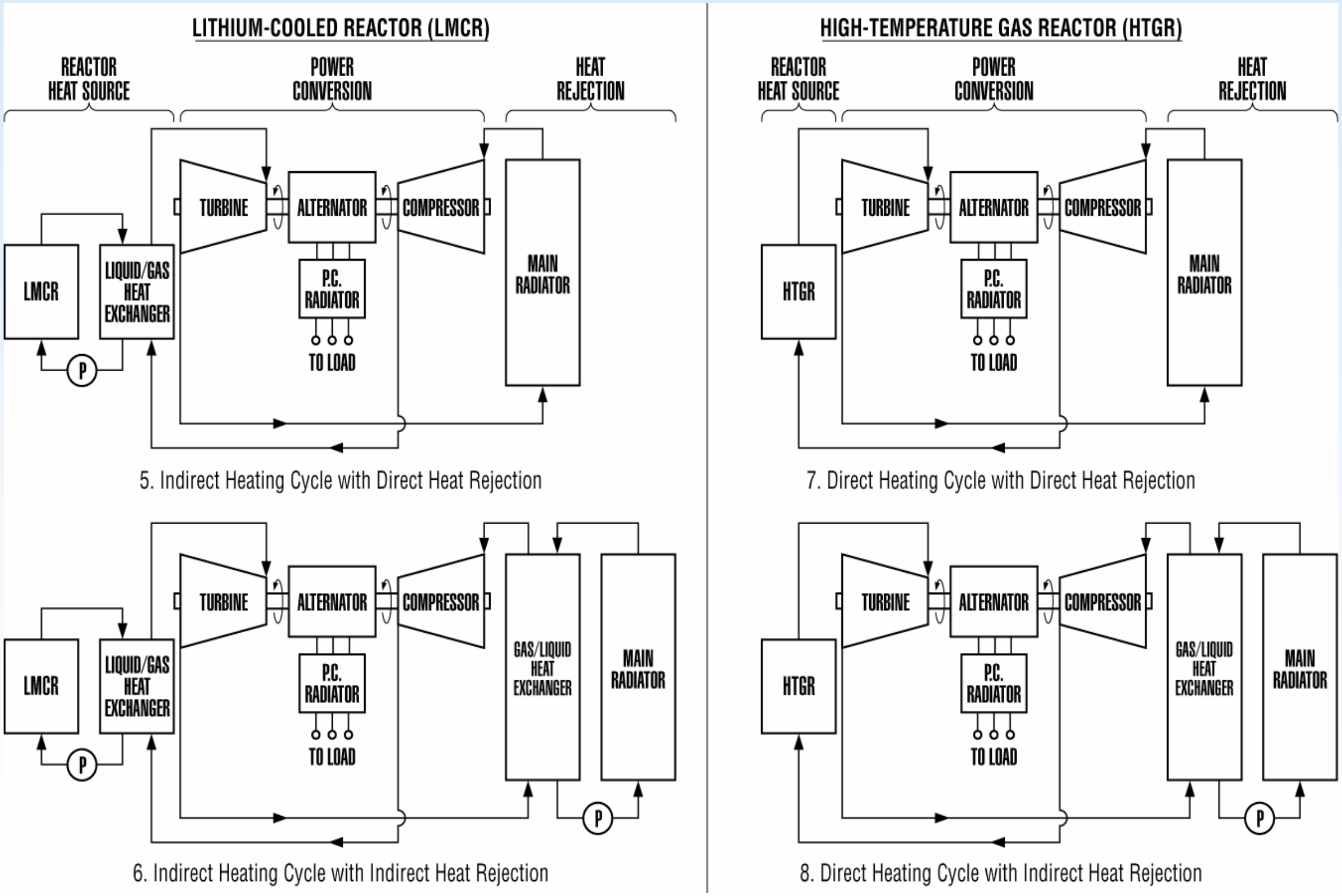


- *Heat Source sends Thermal Energy (Heat) to E C U*
- *E C U Subsystem Transforms Part of Heat Source Thermal Energy,* W_t *, to Electric Work -* W_e
- *Unconverted "Low Grade" Heat,* $W_t - W_e$ *, is Rejected to Space at* T_{SINK} *by Thermal Radiation Heat Transfer*

Regenerated Brayton Cycle Configurations w. Fission Reactor Heat Sources

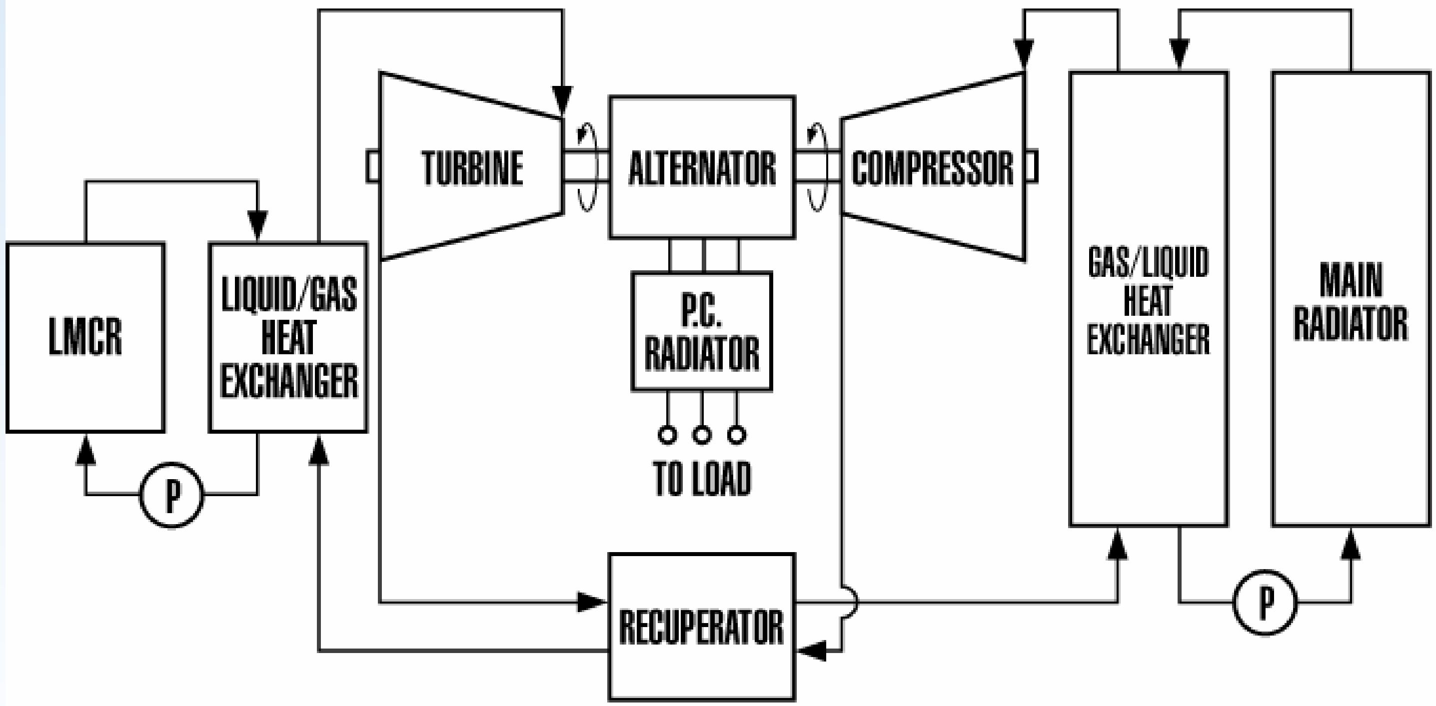


Non-regenerated Brayton Cycle Configurations w. Fission Reactor Heat Sources



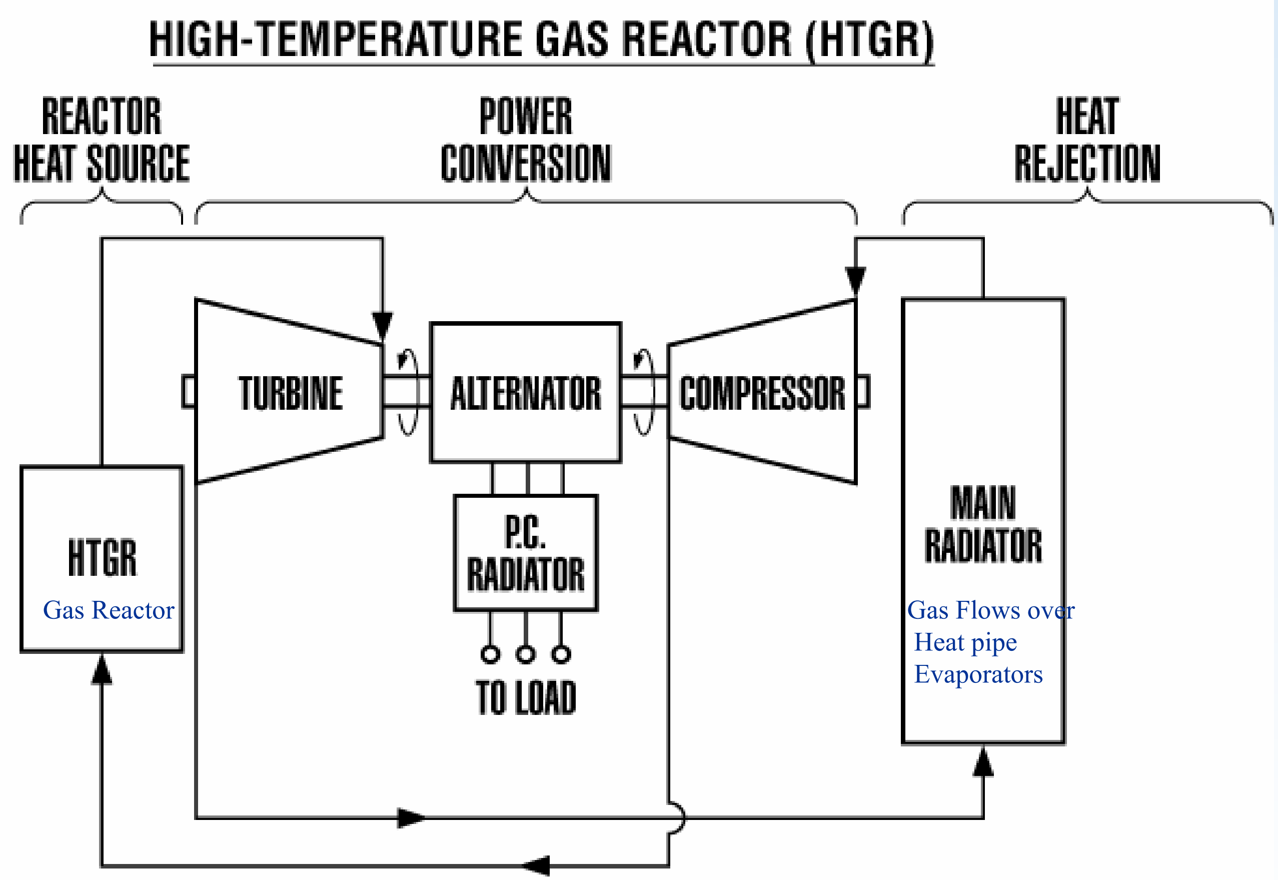
Traditional CBC Configuration for Space

(Contains 3 Heat Exchangers, 2 Pumps)



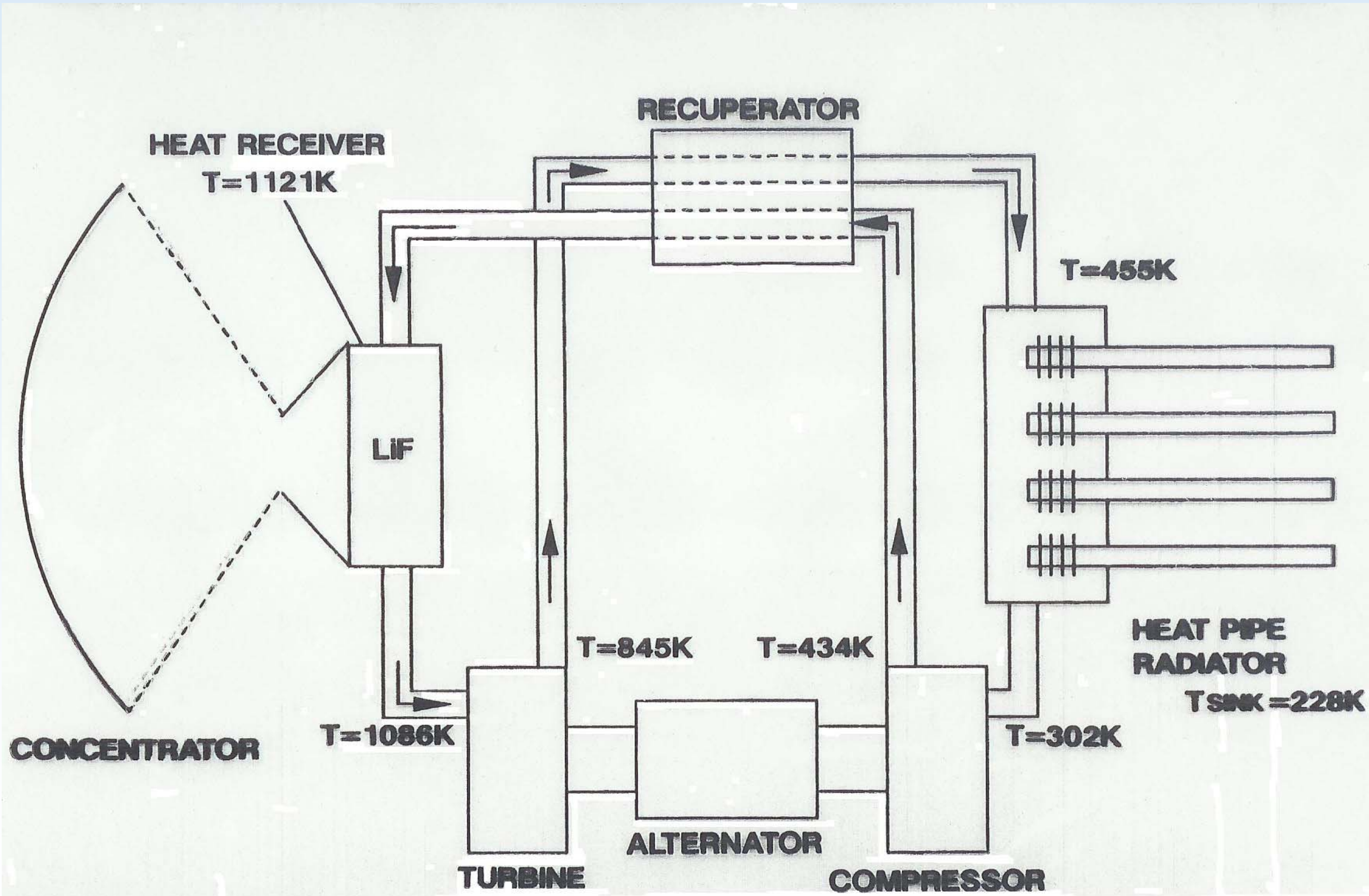
2. Indirect Heating with Indirect Heat Rejection

Non-regenerated Cycle Configuration (No Heat Exchangers)

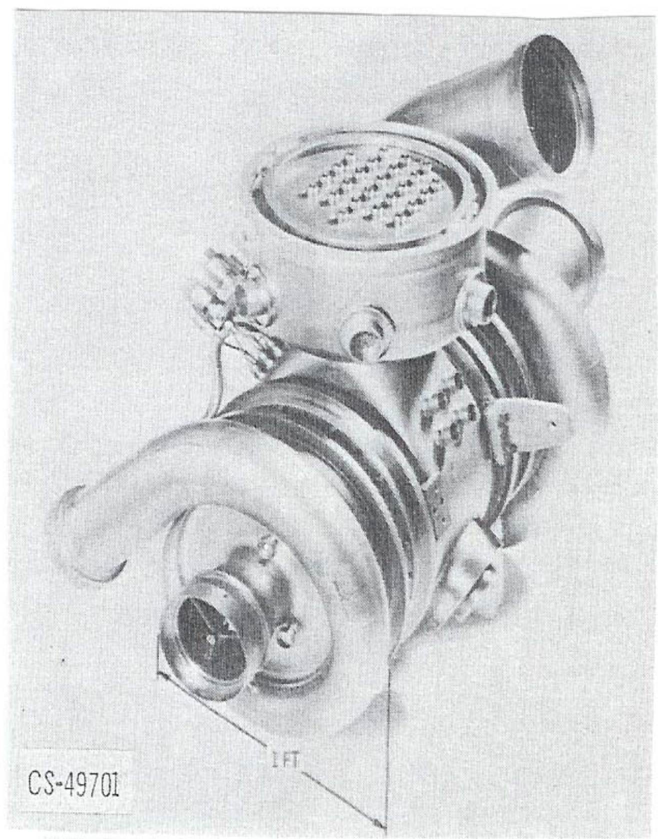


7. Direct Heating Cycle with Direct Heat Rejection

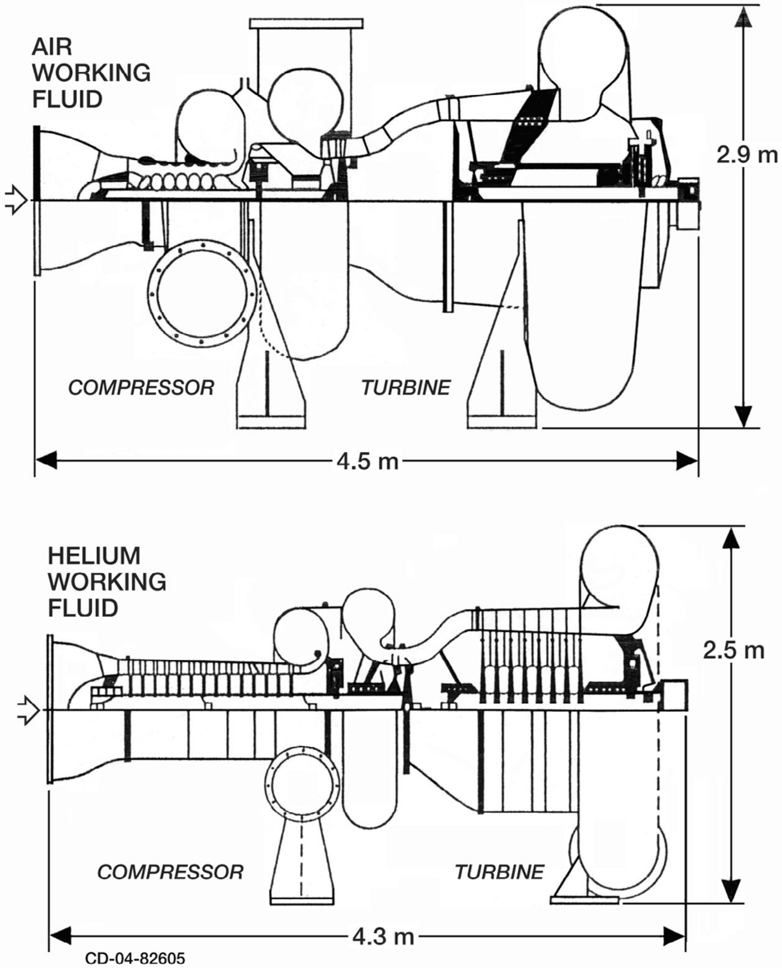
Closed Brayton Cycle with Solar Heat Source



Closed Cycle Gas Turbines
(a)10 kWe Radial BRU; (b) 30 MWe Axial Machines



(a) 10 kWe BRU

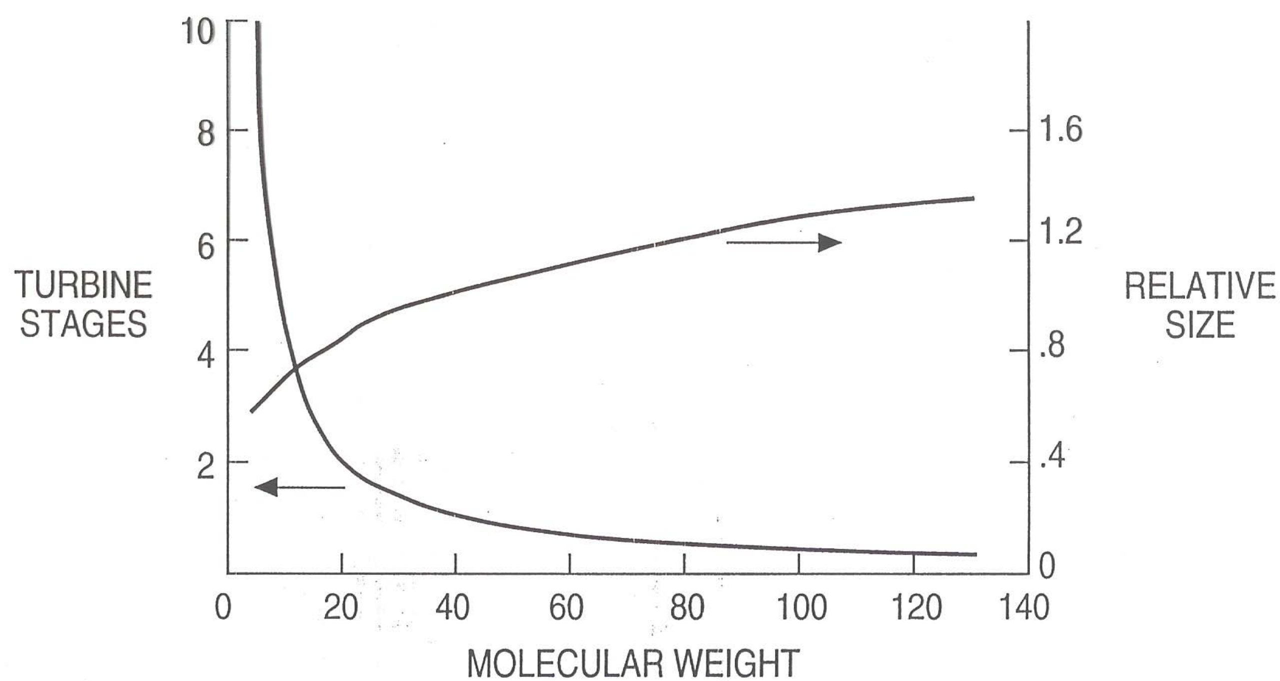


(b) 30 MWe Axial Turbines

National Aeronautics and
Space Administration
Lewis Research Center

EFFECT OF MOLECULAR WEIGHT ON TURBOMACHINERY

POWER TECHNOLOGY DIVISION



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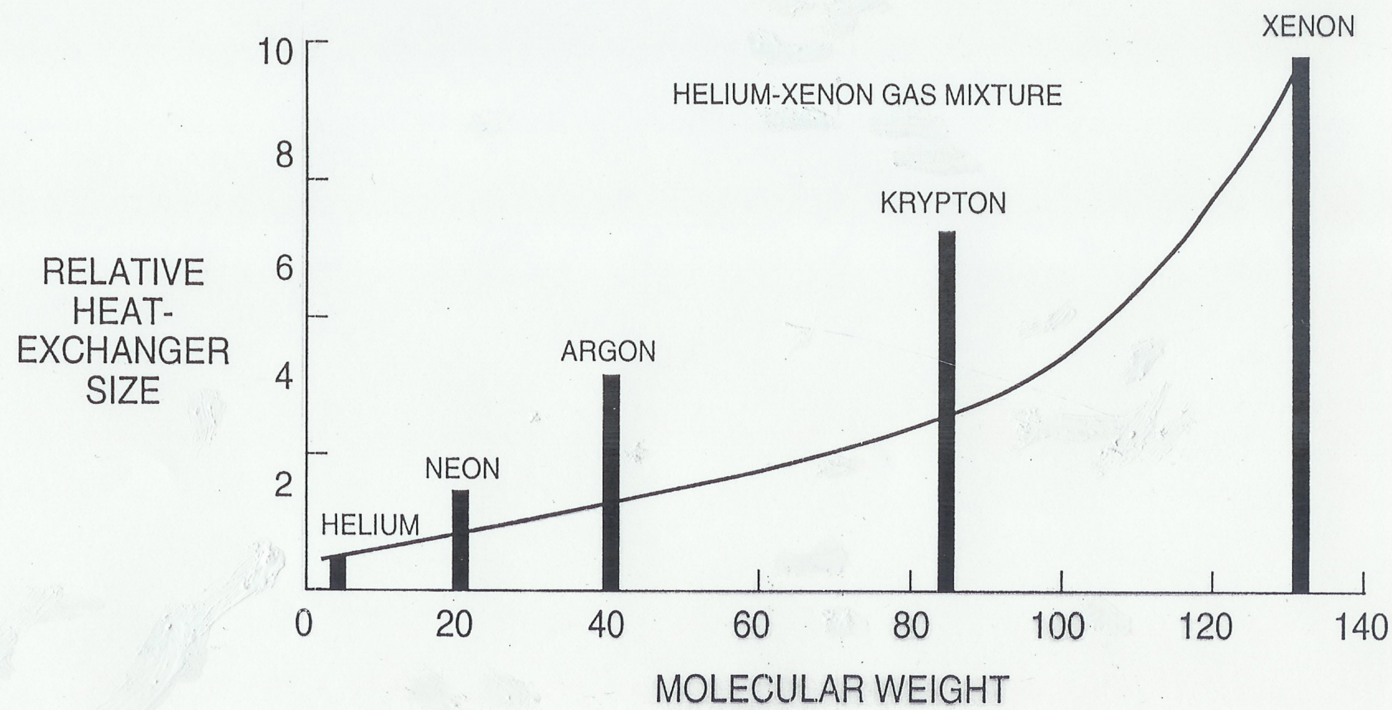
National Aeronautics and Space Administration
Lewis Research Center

EFFECT OF MOLECULAR WEIGHT ON HEAT-EXCHANGER SIZE

POWER TECHNOLOGY DIVISION



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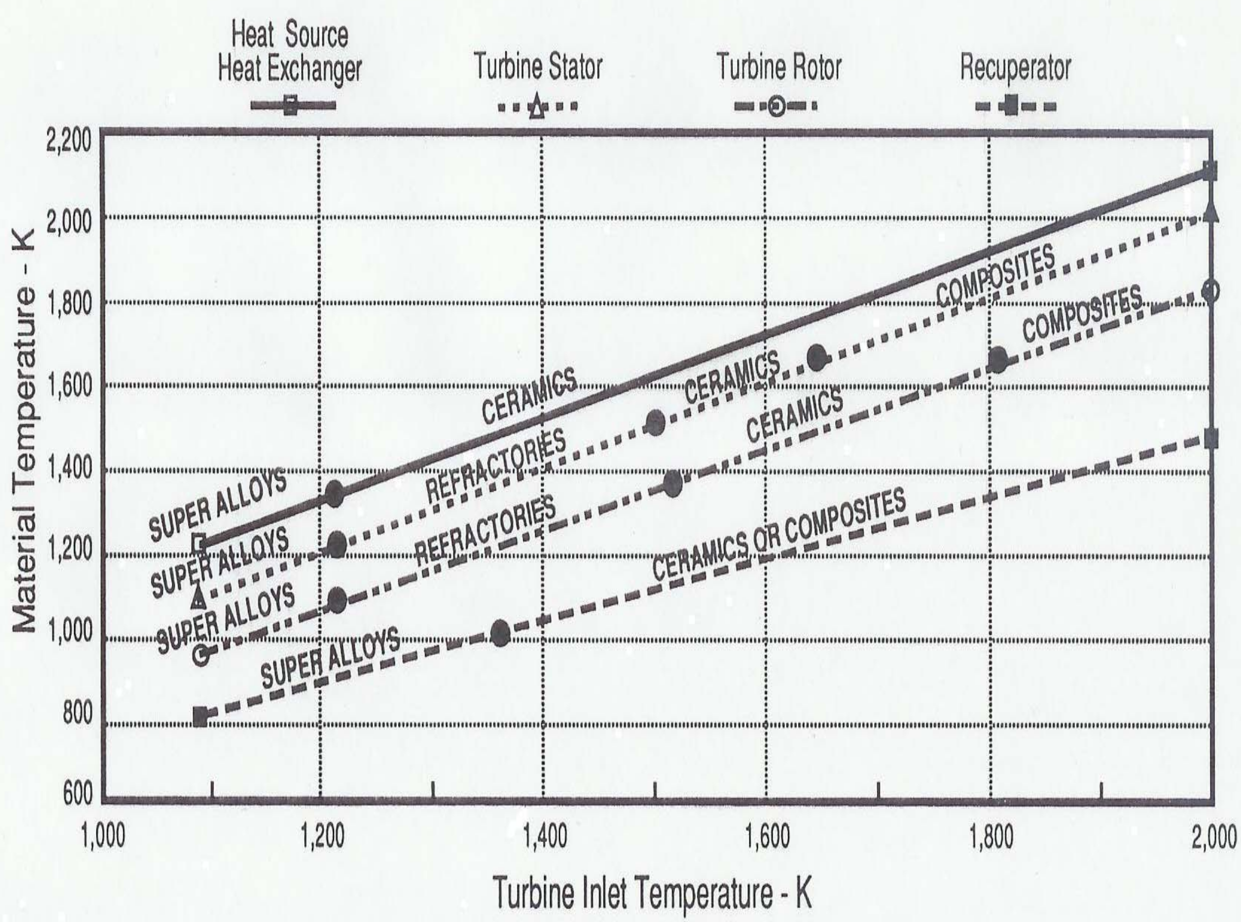
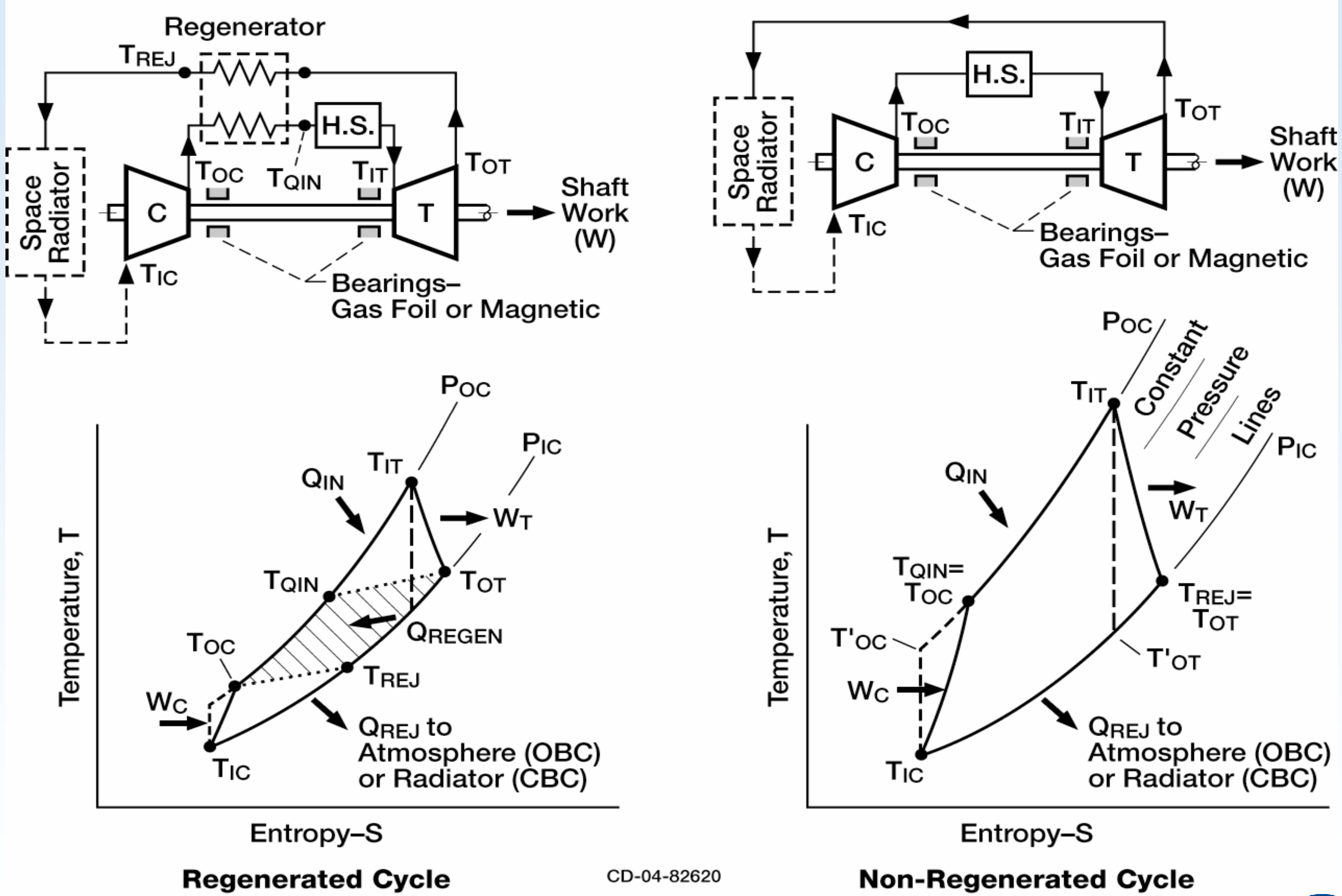
Turbine Materials Technology Map



GAS TURBINE (BRAYTON CYCLES)



Isentropic and Polytropic Efficiency Relationships

Isentropic Compressor Efficiency - η_c

A function of pressure ratio, γ, η_{pc}

$$\eta_C = \frac{\left(\frac{P_{OC}}{P_{IC}}\right)^{\frac{(\gamma - 1)}{\gamma}}}{\left(\frac{P_{OC}}{P_{IC}}\right)^{\frac{(\gamma - 1)}{\gamma \; \eta_{PC}}}}$$

Isentropic Turbine Efficiency - η_t

A function of pressure ratio, γ, η_{pt}

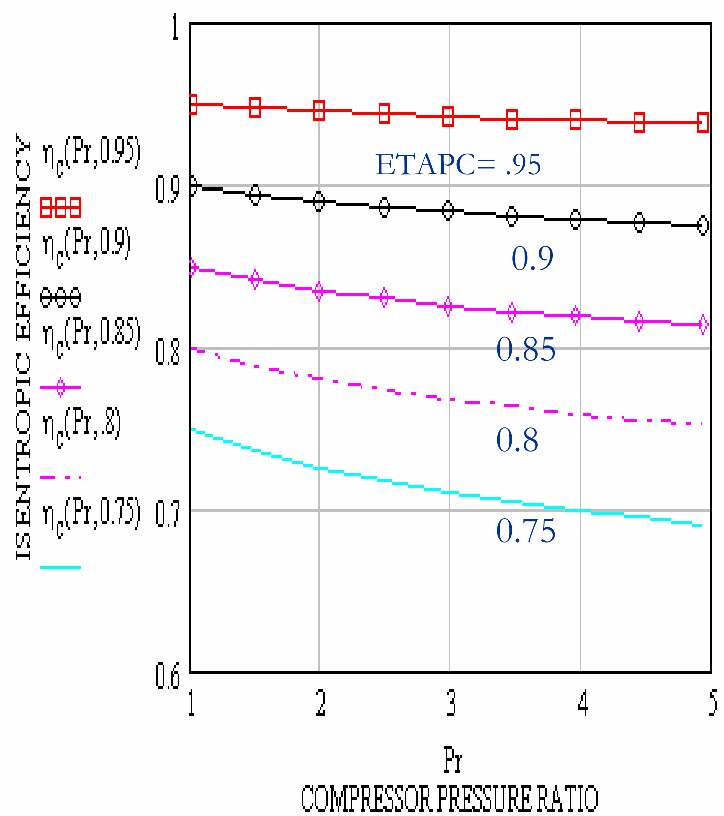
$$\eta_t = \frac{1 - \left(\frac{P_{IT}}{P_{OT}}\right)^{\frac{\eta_{pt}(1-\gamma)}{\gamma}}}{1 - \left(\frac{P_{IT}}{P_{OT}}\right)^{\frac{(1-\gamma)}{\gamma}}}$$

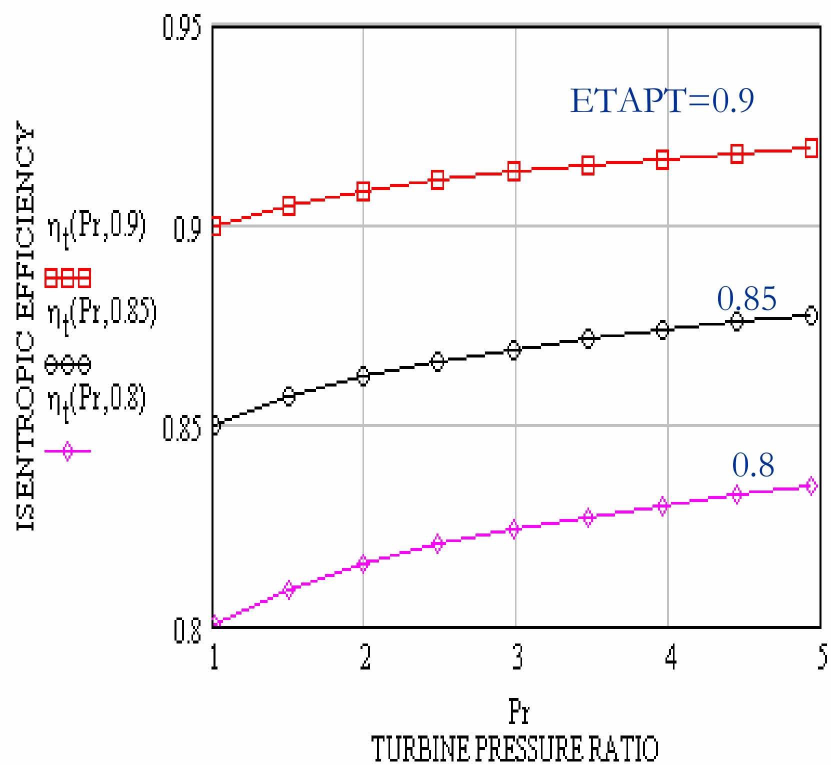
γ *Is specific heat ratio*

η_{pc} *is polytropic or infinitesimal compressor stage efficiency*

η_{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)





Typical Code Output from Global Minimum Mass Scan

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

   2.900      .990     .900     .900     .900    1.667     .940     .950     .900      1600     200

BRAYTON GLOBAL MIN. MASS SEARCH FOR POWER LEVEL = 10.000 MW; TIT = 1600 K  (REGEN EFF, = .900)

 CYCLE TEMP.PRESSURE THERMAL MAIN RADIATOR  MIN SYS. MASS SP.RAD.AREA SPEC. SYS. MASS
   RATIO       RATIO   EFFIC       AREA (M2)   (METRIC TONS)    (M2/KW)    (KG/KW)  (W/KG)

    2.90        2.14   .3126        3559.5         50.274        .256        5.03   198.91
    3.00        2.18   .3271        3719.4         49.699        .268        4.97   201.21
    3.10        2.23   .3406        3889.6         49.302        .280        4.93   202.83
    3.20        2.27   .3534        4080.1         49.053        .294        4.91   203.86
    3.30        2.32   .3653        4278.8         48.930        .308        4.89   204.37
    3.40        2.37   .3766        4491.1         48.915        .323        4.89   204.44

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

    3.50        2.42   .3872        4716.8         48.995        .340        4.90   204.10
    3.60        2.47   .3974        4955.9         49.159        .357        4.92   203.42
    3.70        2.52   .4070        5208.5         49.400        .375        4.94   202.43
    3.80        2.57   .4162        5474.7         49.711        .394        4.97   201.16

    3.90        2.63   .4248        5747.8         50.087        .414        5.01   199.65
    4.00        2.69   .4330        6034.9         50.524        .435        5.05   197.92

  BRUNM1 COMPLETED FOR TIT(K) = 1600

     MIN. SYSTEM MASS AT ALFA =       3.40

 EXECUTION TIME = 5.438 SEC

    MAP
          GLOBAL MINIMUM MASS CONDITIONS FOR TURBINE INLET TEMPERATURE-(K) =       1600

BRAYTON CYCLE CALCULATIONS        - REGENERATED - 1600 K- POWER LEVEL =  10.000 MWE,    TSINK-K =   200

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

     3.400       .990       .900       .900       .900      1.667       .940       .950       .900       1600

OPTIMUM PRESSURE RATIOS (MAX THERM EFF; MIN ARP,MASS ) =      2.180     2.890     2.370      TIC-K =   471

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

    2.1800     .3782     .3346   49.0082     .3018    725.87    570.30   669.71  1231.31   .884   .912
    2.8900     .3616     .3135   49.7861     .2581    798.03    592.93   763.49  1108.84   .877   .917
    2.3700     .3766     .3234   48.9150     .2832    745.87    576.78   696.10  1193.79   .882   .914

  MASS BREAKDOWN FOR    10.000 MW POWER SYSTEM

TURBINE INLET TEMPERATURE- K        1600
REACTOR/HX INLET TEMP.   - K        1144
CYCLE TEMPERATURE RATIO            3.400
ACT. COMP. MASS FLOWRATE- KG/S    11.326 MOLW= 4.0
COMPRESSOR PRESSURE RATIO          2.370
PERCENT CARNOT EFFICIENCY- PCT     53.35
SYSTEM THERMAL EFFICIENCY- PCT     37.66

TOTAL RADIATING  AREA (M2)       4491.10
 (KG/M2 =      2.0      2.0)
 SYSTEM SPECIFIC MASS (KG/KW)       4.89

 SYSTEM SPECIFIC POWER (W/KG)     204.44

    COMPONENT WEIGHTS IN KG      PERCENT

REACTOR                    5735    11.7
SHIELD                     5502    11.2
HT SOURCE HX, PUMP            0      .0
RECUPERATOR                4778     9.8
COMPRESSOR ( 2/ 1)         5264    10.8
TURBINE    ( 2/ 1)         2256     4.6
ALTERNATOR ( 2/ 1)         6016    12.3
HT SINK HX, PUMP              0      .0
POWER CONDITIONING         5000    10.2
  MAIN RADIATOR            5988    12.2
PC RADIATOR-473 K           562     1.1
 RADIATOR DUCT             3368     6.9
STRUCTURE                  4447     9.1

 TOTAL SYSTEM MASS        48915   100.0
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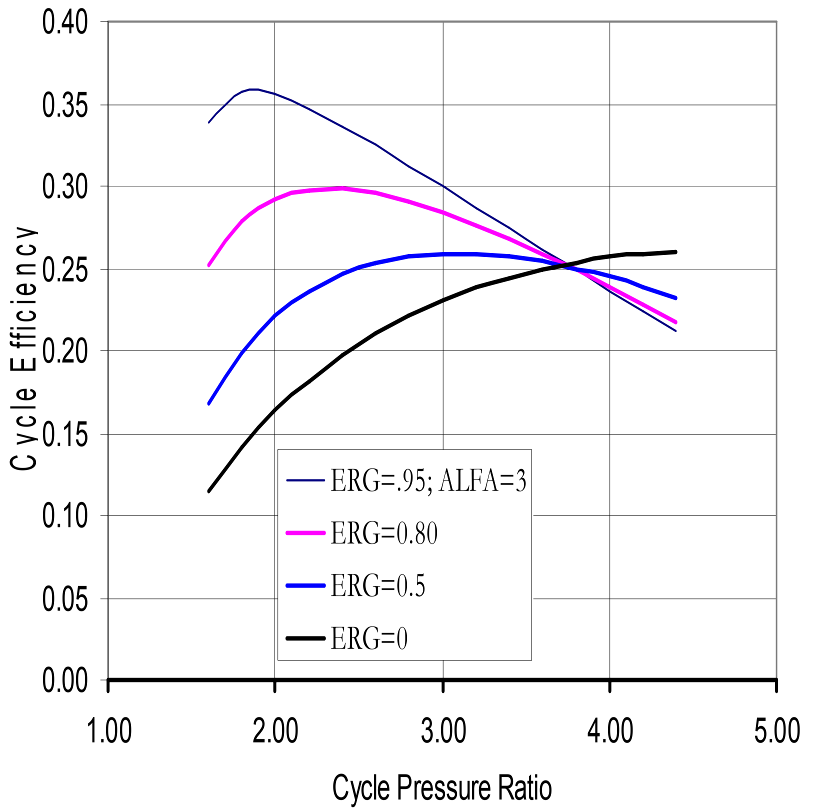
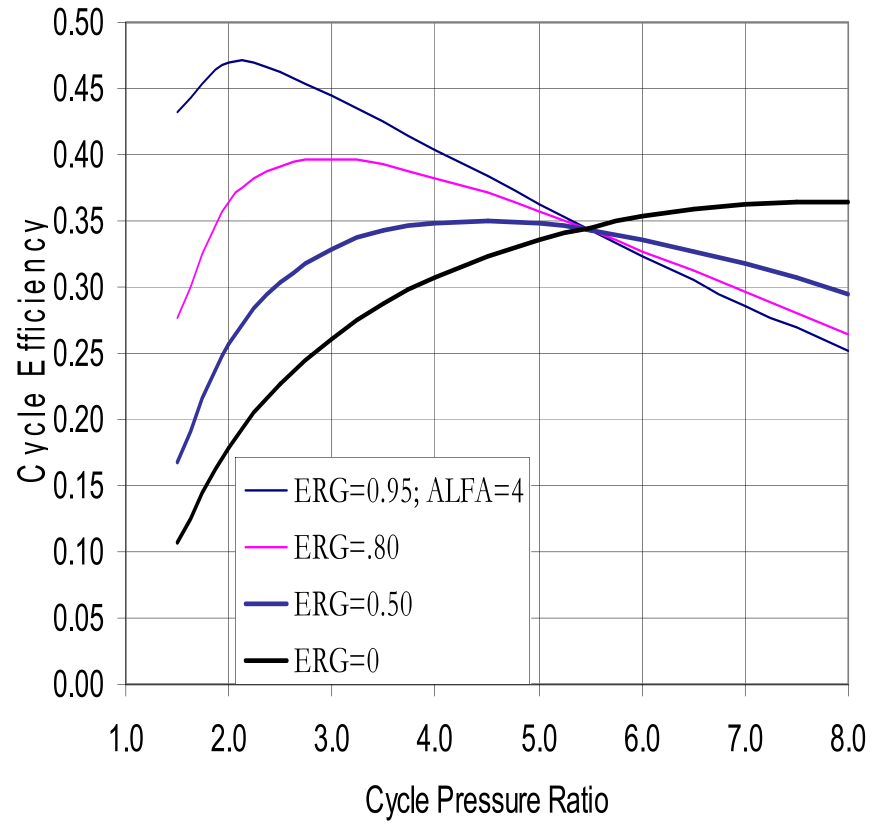
Influence of Regenerator Effectiveness (ERG) on Cycle Efficiency at Cycle Temp. Ratio of 3.0 and 4.0

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

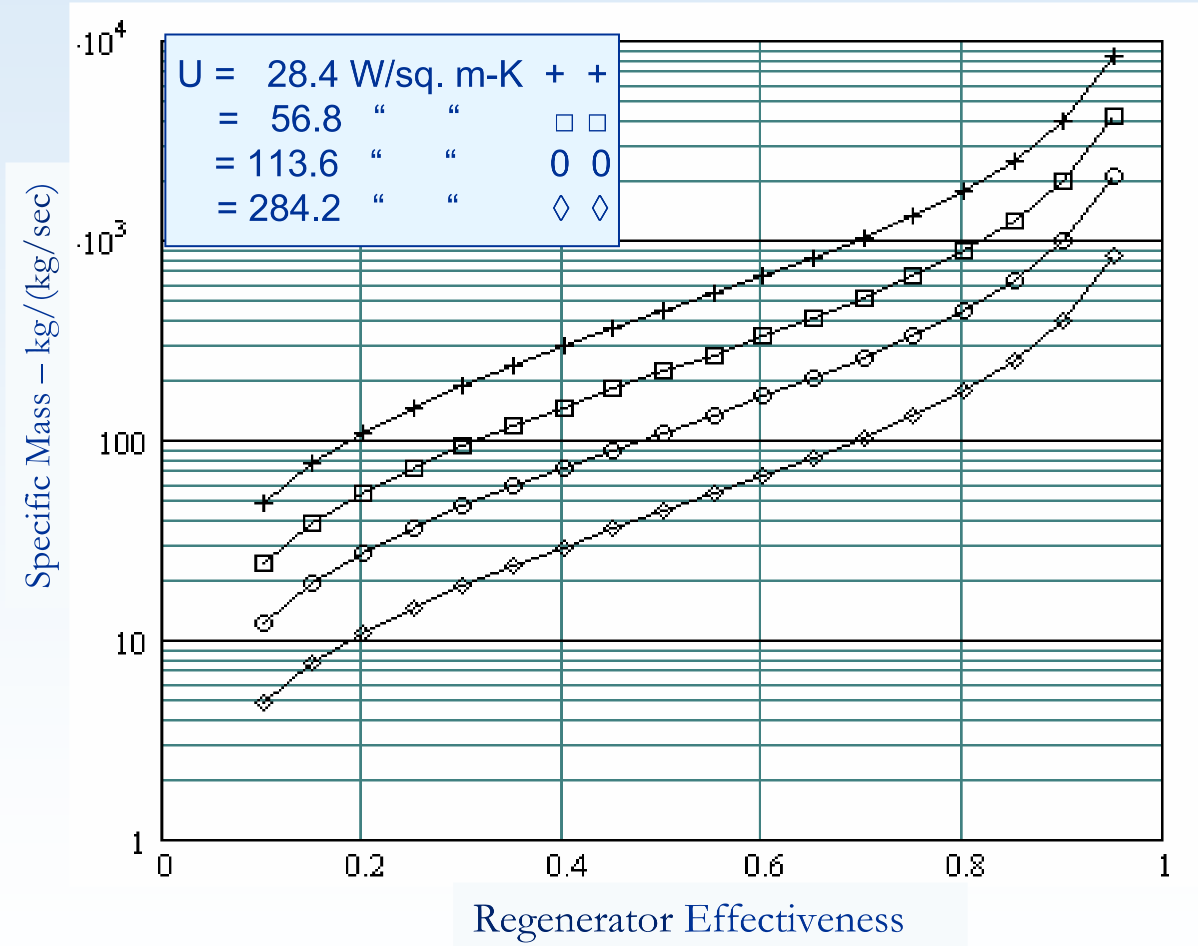


(a) Temp. Ratio = 3.0

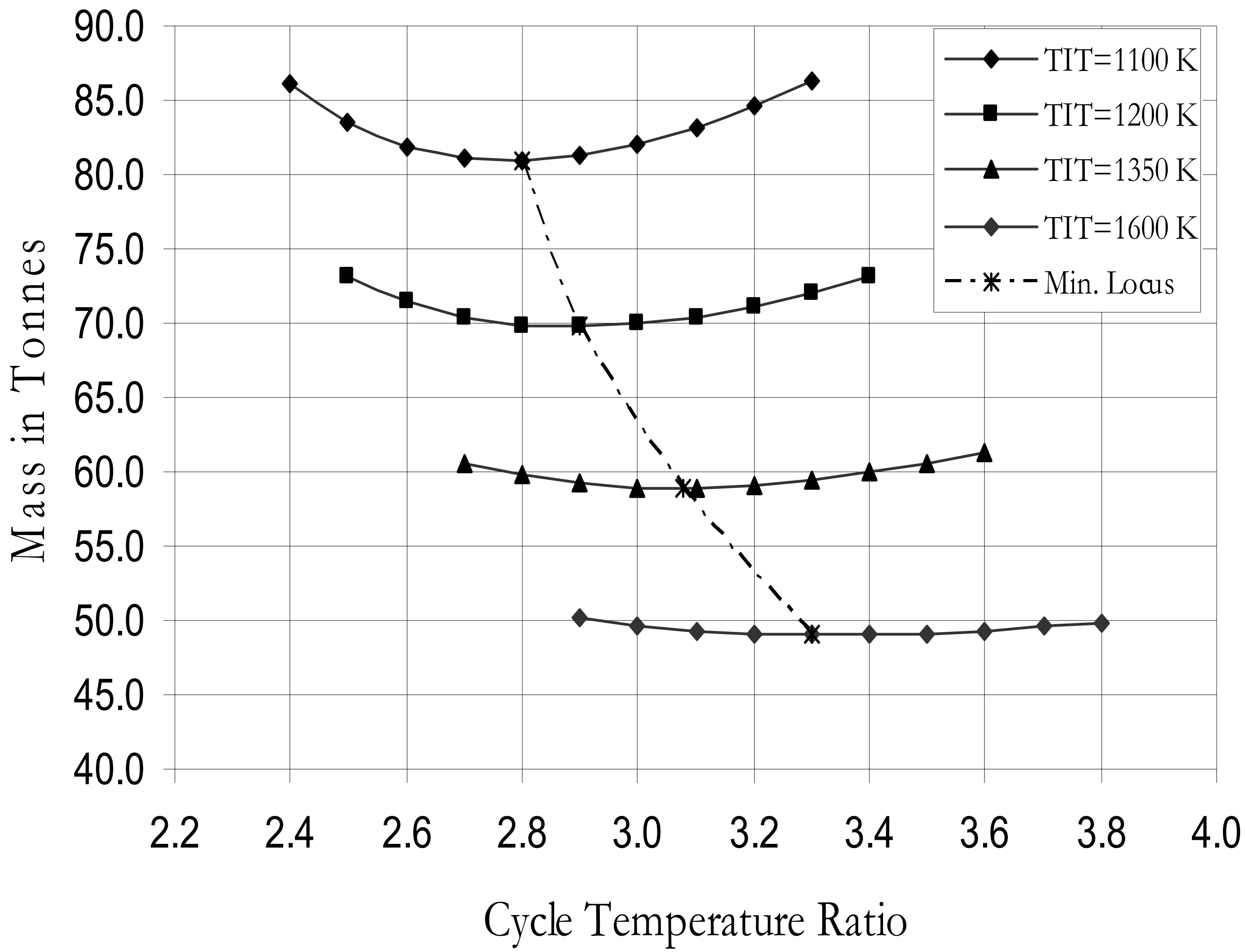


(b) Temp. Ratio = 4.0

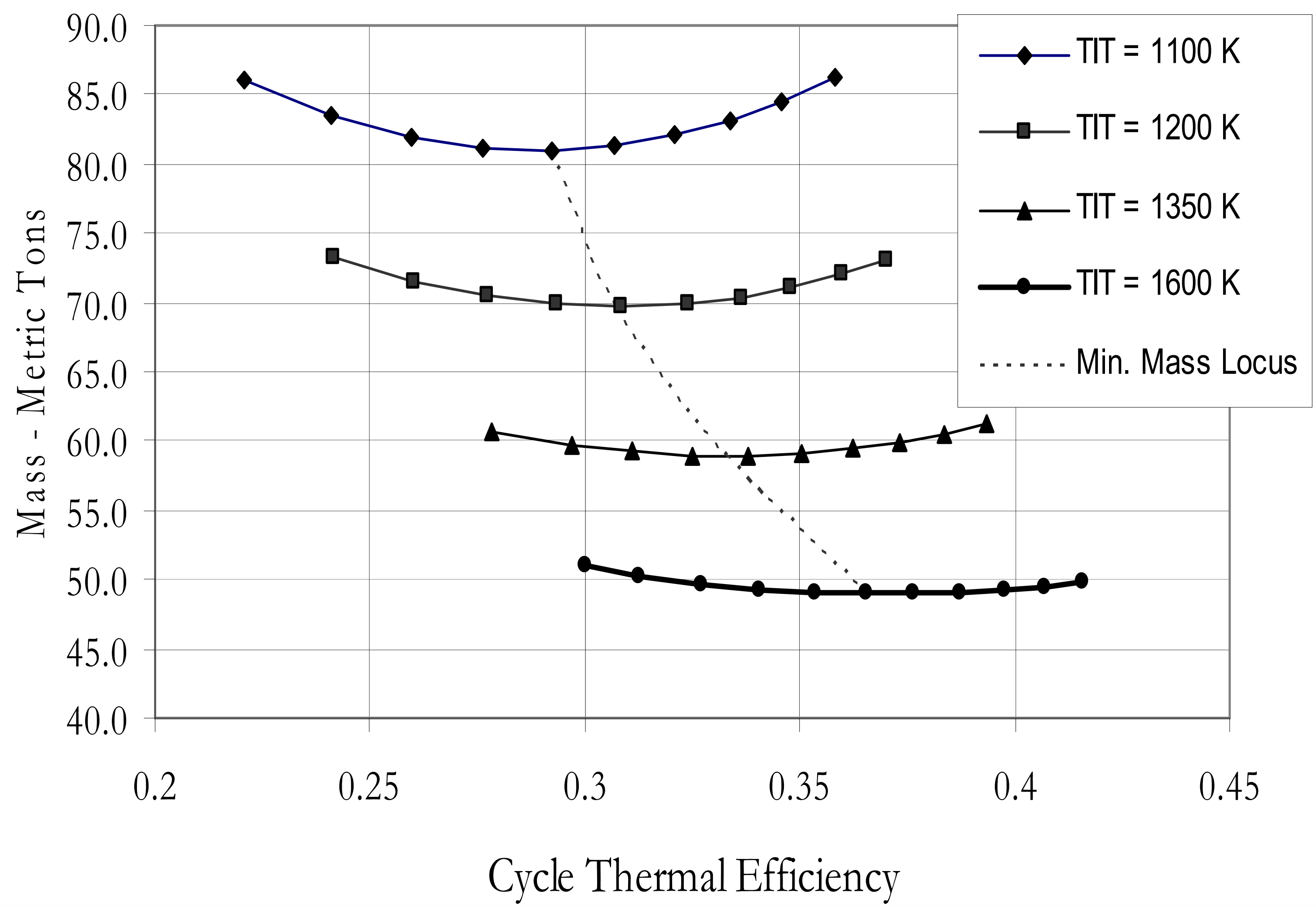
Regenerator Specific Mass vs. Effectiveness with Overall Heat Transfer Coefficient U as a Parameter for He Working Fluid



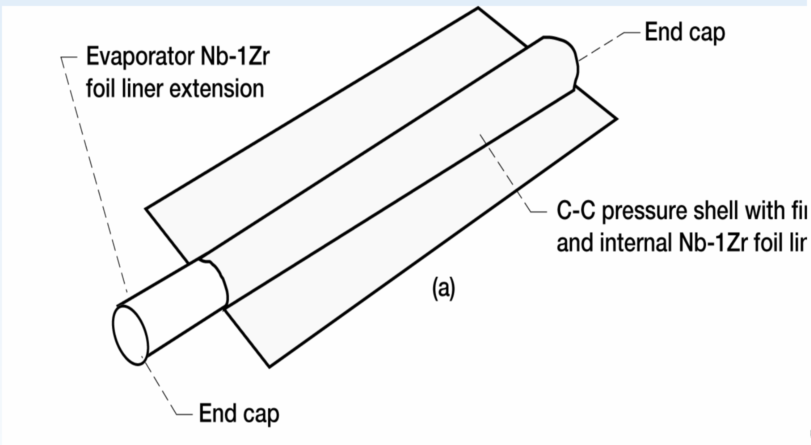
Space System Mass for 10 MWe CBC vs. Cycle Temperature Ratio with Turbine Inlet Temperature TIT as a Parameter

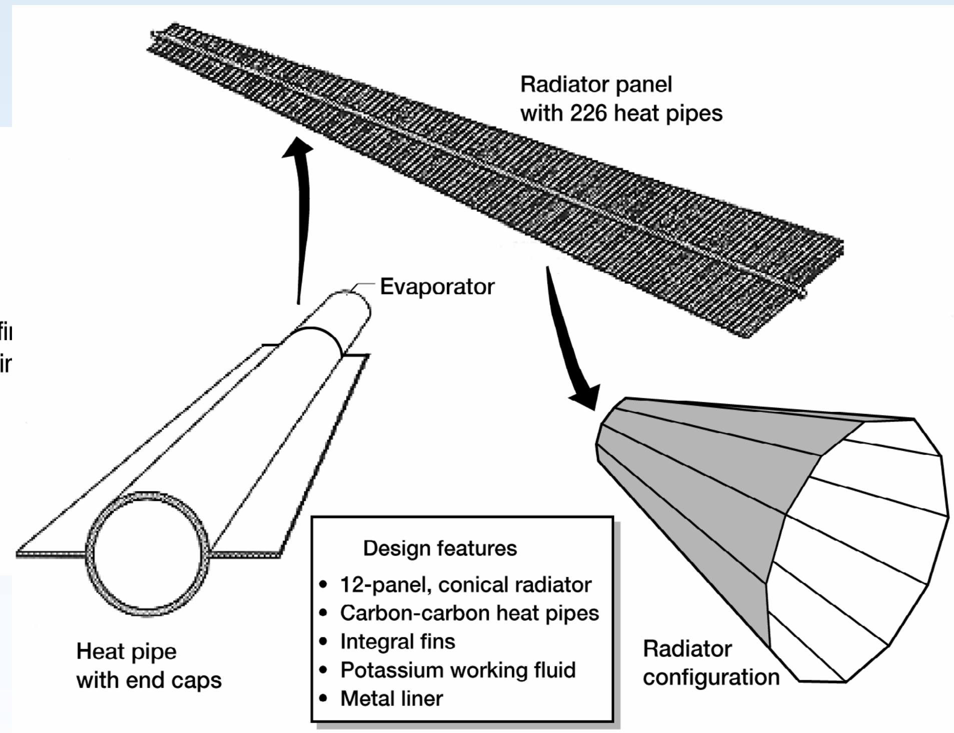


Space System Mass for 10 MWe CBC vs. Cycle Efficiency with Turbine Inlet Temperature TIT as a Parameter



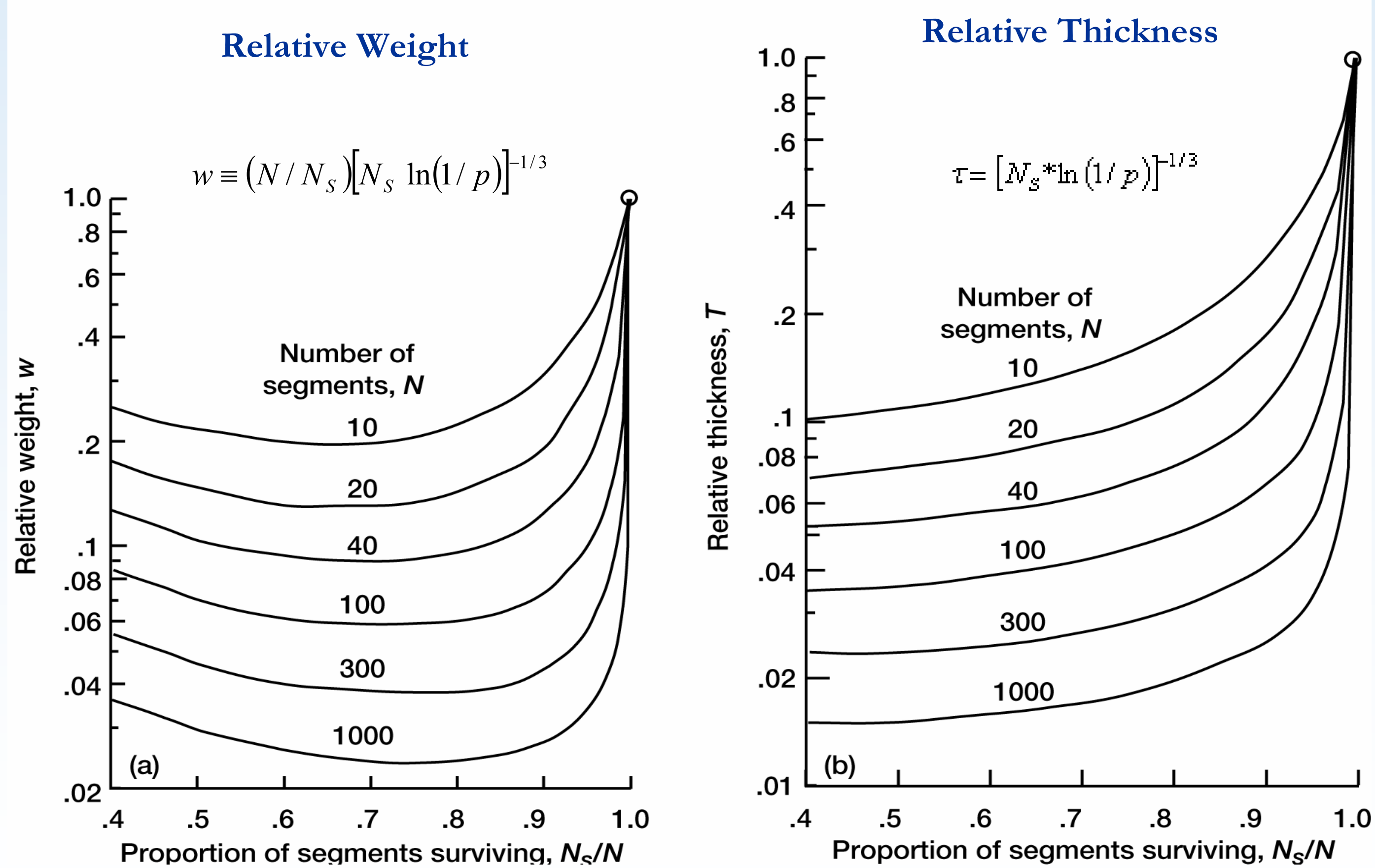
Carbon-Carbon Heat Pipe and SP-100 Radiator Assembly



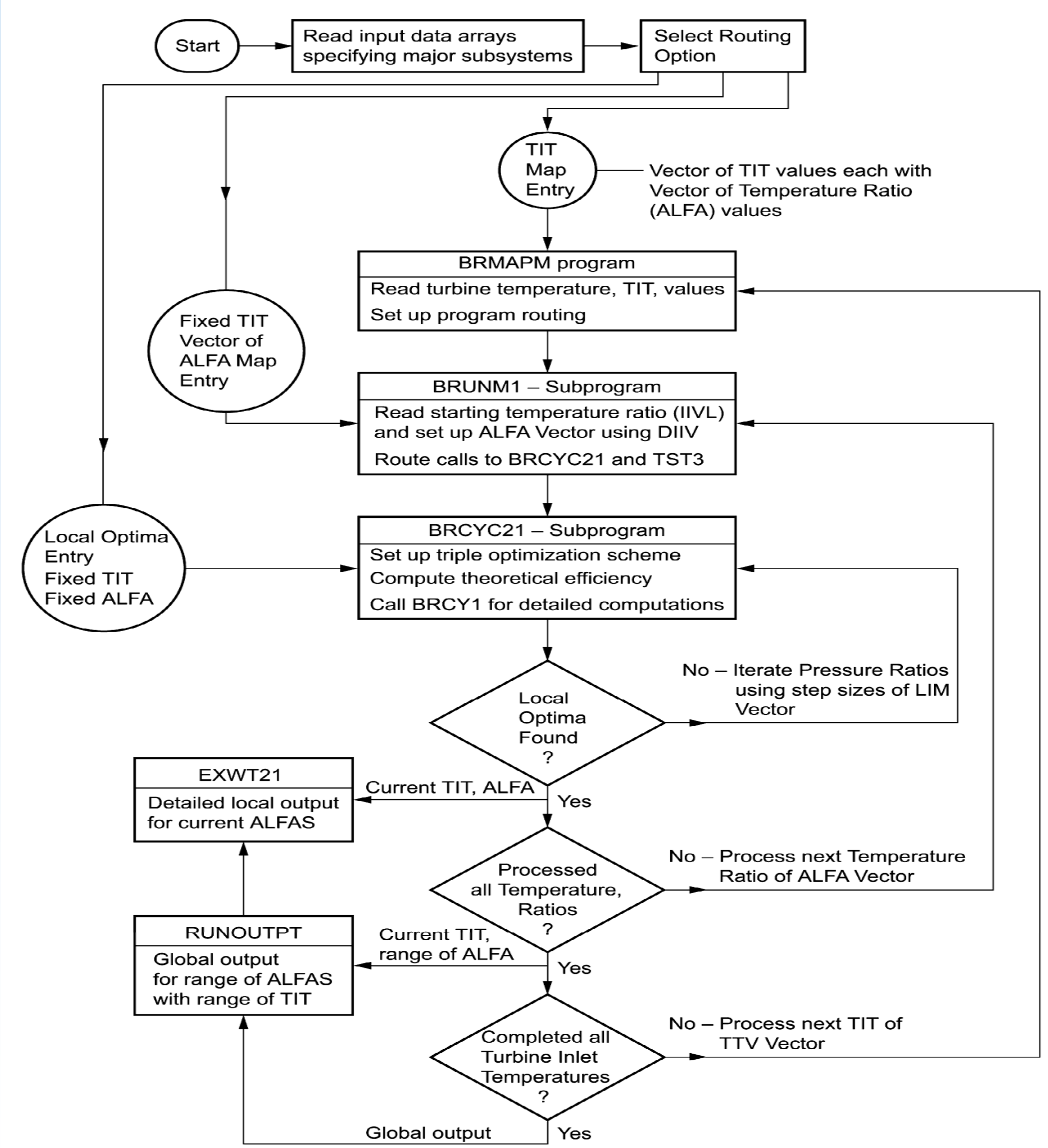


Segmented Radiator Characteristics for Survival Probability S=0.999

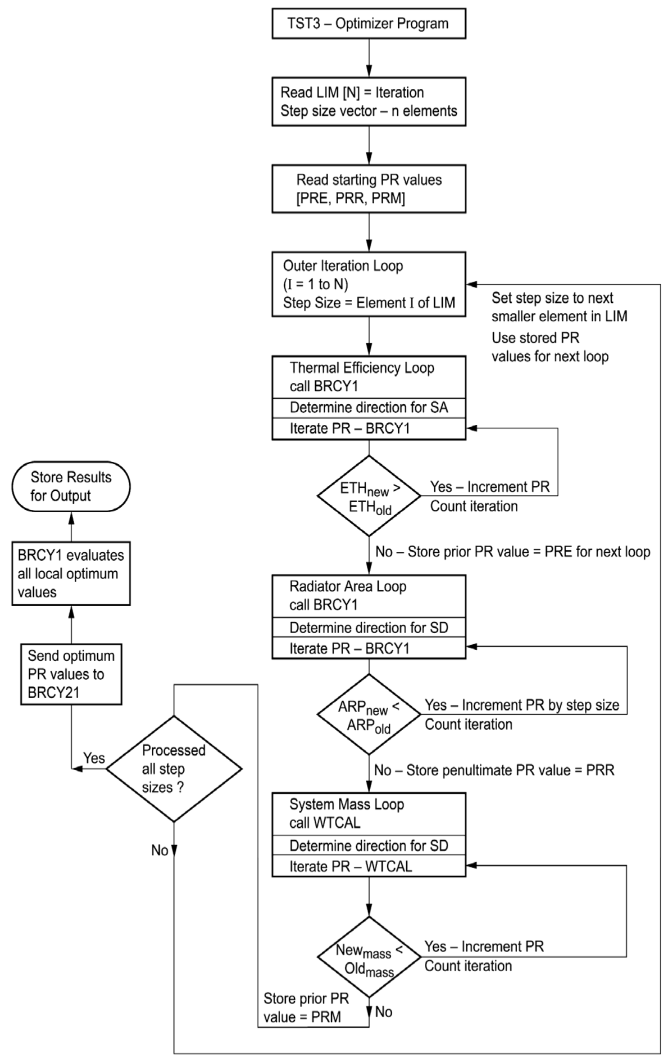
$$S = \sum_{n=N_s}^{n=N} \frac{N!}{n!(N-n)!} (1-p)^{N-n} p^n$$

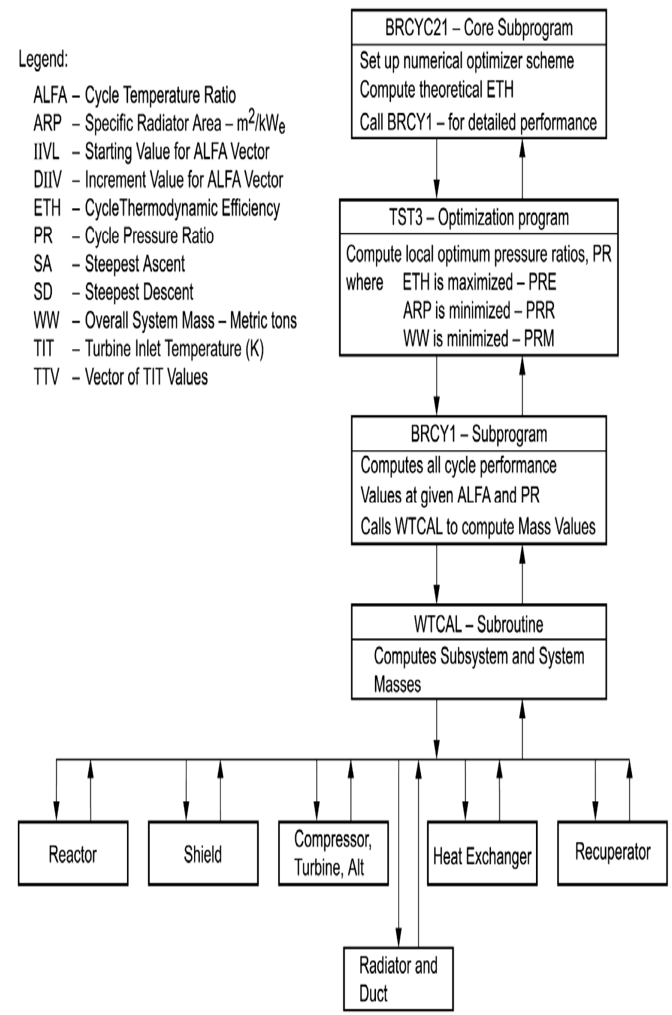


Brayton Cycle Mapping Code - BRMAPS

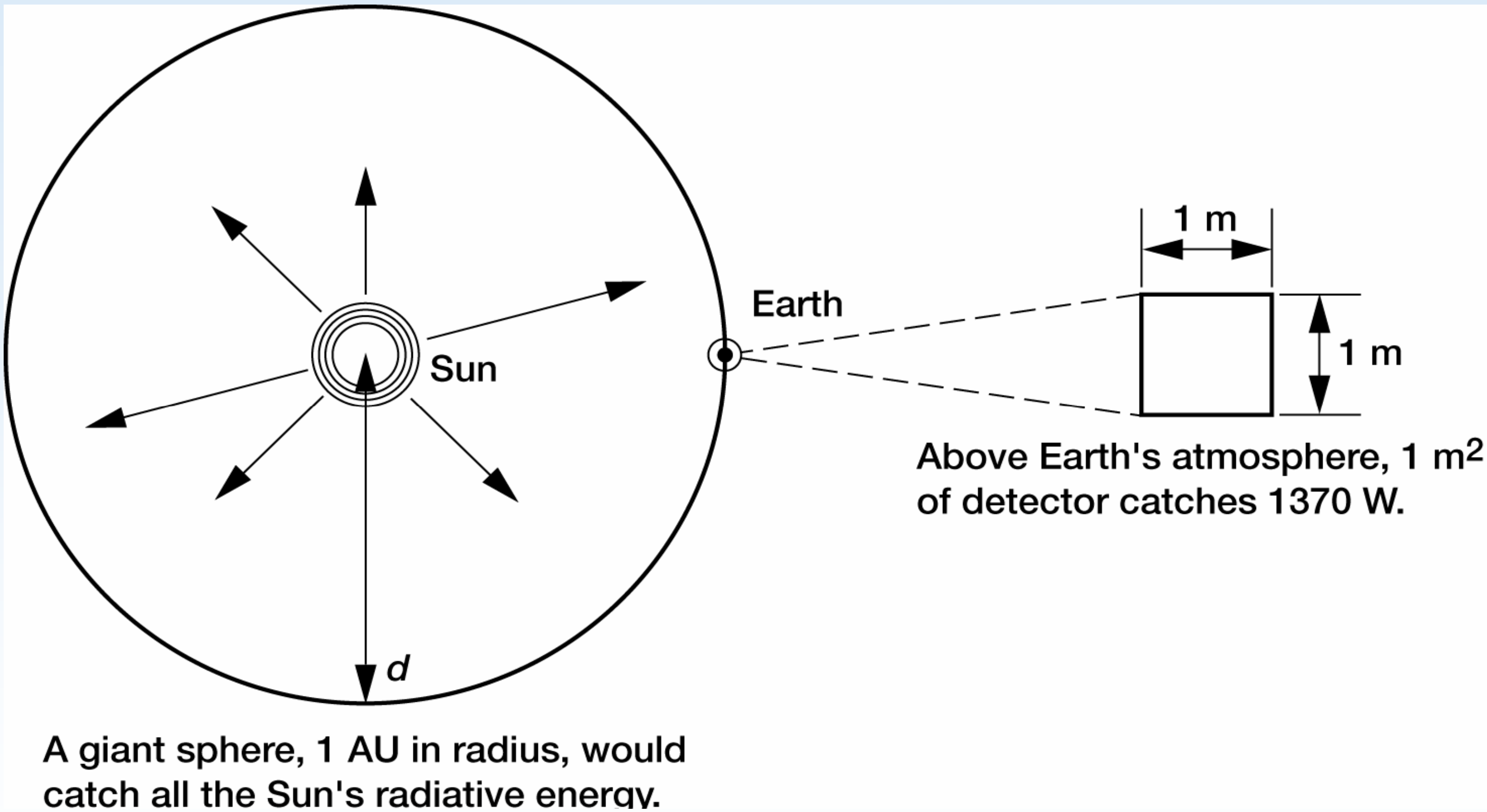


Optimization Code – TST3 Brayton Cycle Code BRCY1





Theoretical Basis for Space Sink Temperature Analysis Code *TSCALC* (developed by author)



Solar Fusion Energy Generation via Proton-Proton Chain Reaction

1. ${}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + v$(neutrino) (0.42 MeV)
2. $e^+ + e^- \rightarrow \gamma$ (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: $4\ {}^1_1H \rightarrow {}^4_2He + 2\ e^+ + 2\ v$

$4*1.0078265\ u = 4.002603\ u + (2\ e^+ + 2v + 2\ \gamma + 12.86\ MeV)$

Total Energy Generated – $E = m*c^2$

$E_t = (4.0313008 - 4.002603)\ u * 1.66*10^{-27}\ kg/u * (3*10^8\ m/sec)^2$

= 26.76 MeV/*p-p* cycle which checks Σ reaction step energies, E_{RS}

E_{RS} = 2*(0.42 MeV +1.02 MeV + 5.49 MeV) + 12.86 MeV = 26.76 MeV/*p-p*

Solar Luminosity, L, is due to $9*10^{37}$ p-p cyc/sec

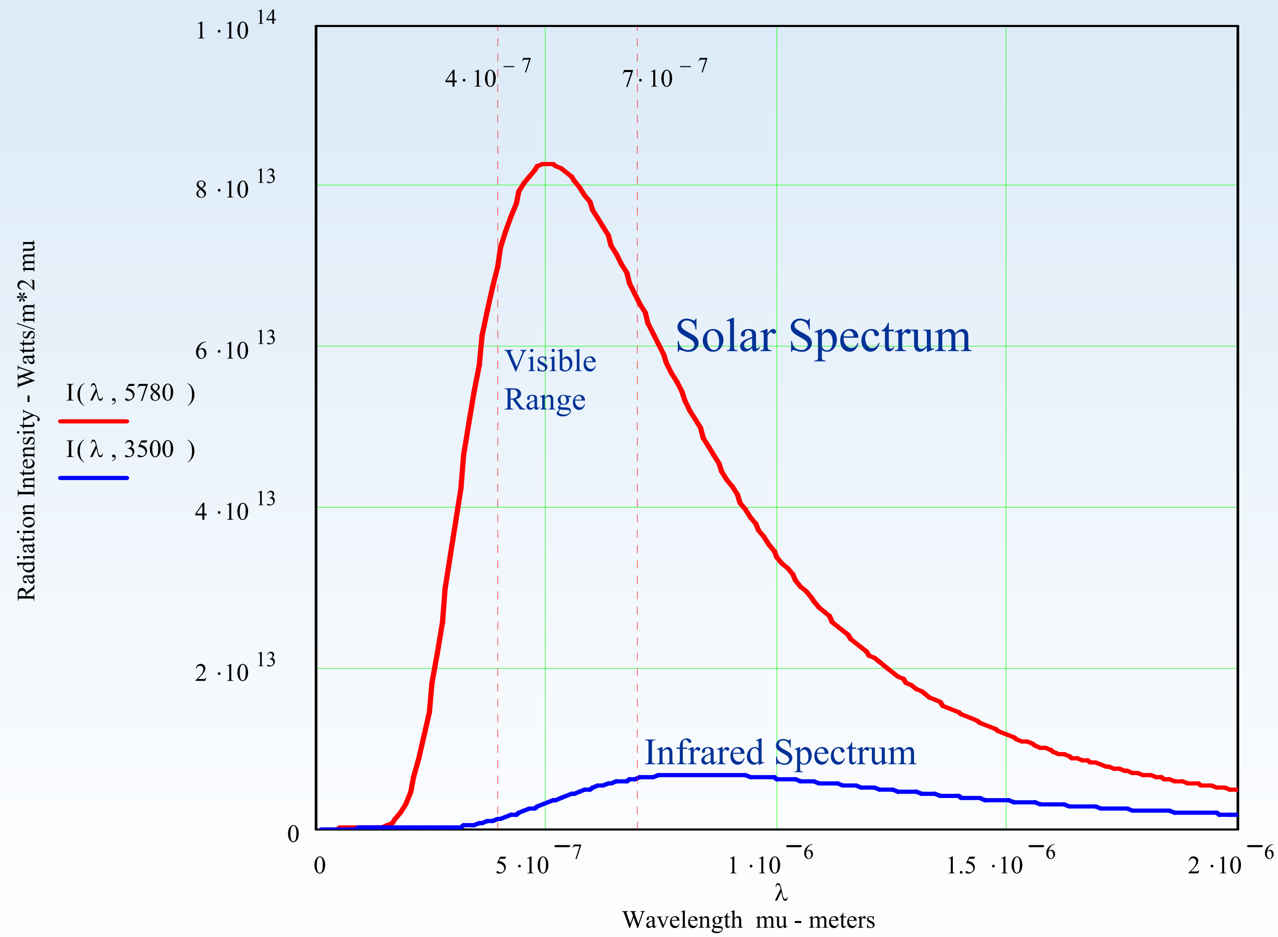
L = 26.76 MeV*1.602*10^{-13}J/MeV * 9*10^{37}/sec = 3.86*10^{26} Watts

Solar Mass Loss

(4.0313008 – 4.002603) u*1.66*10^{-27} kg/u * 9*10^{37}/sec = 4.3*10^9 kg/sec

= 4.3 Million tonnes/sec

Solar and Arbitrary Infrared Spectra

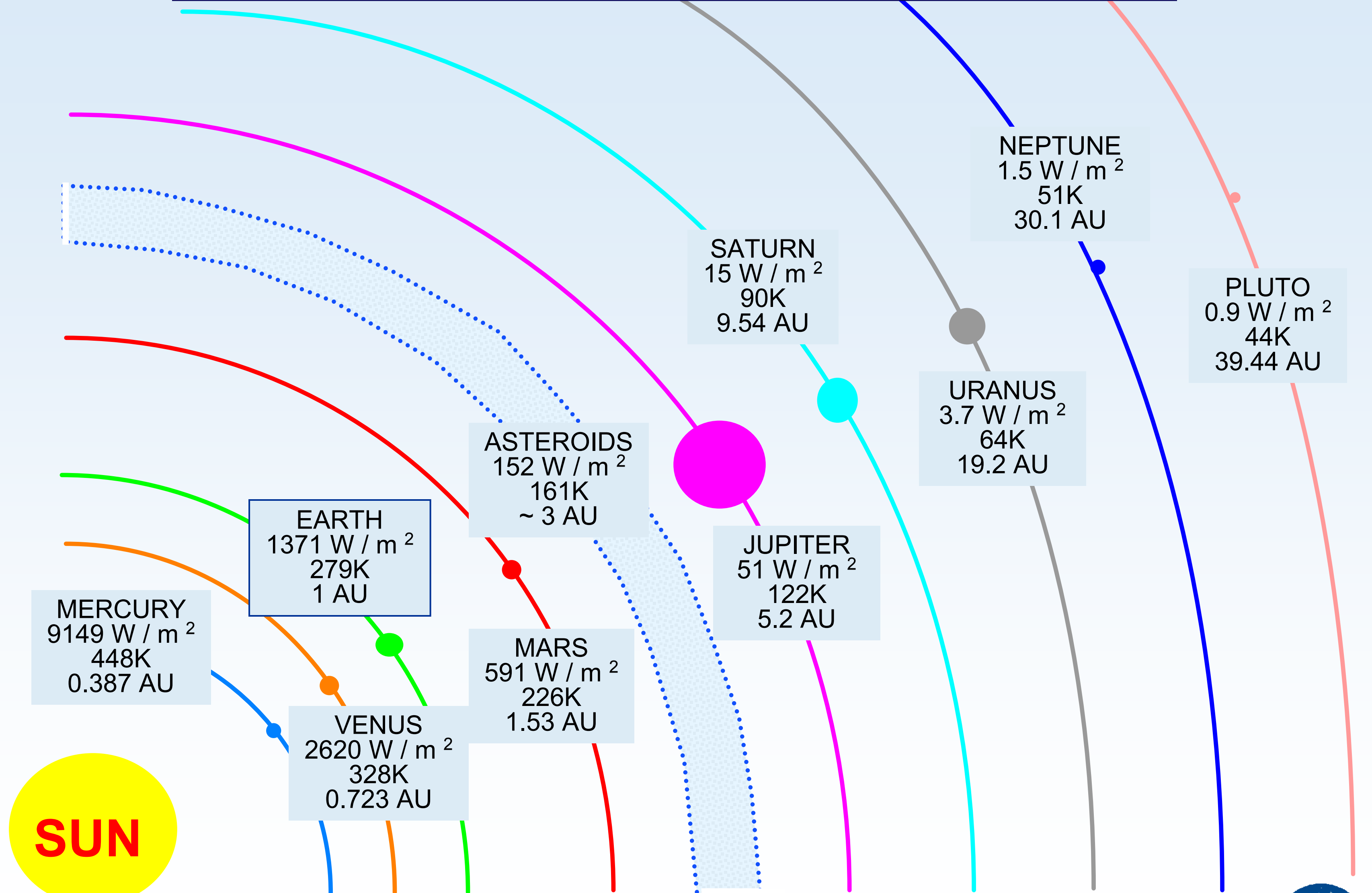


Equilibrium Temperatures, TS(K), at Various AU Distances

CONDITIONS FOR SPACECRAFT APPROACHING SUN

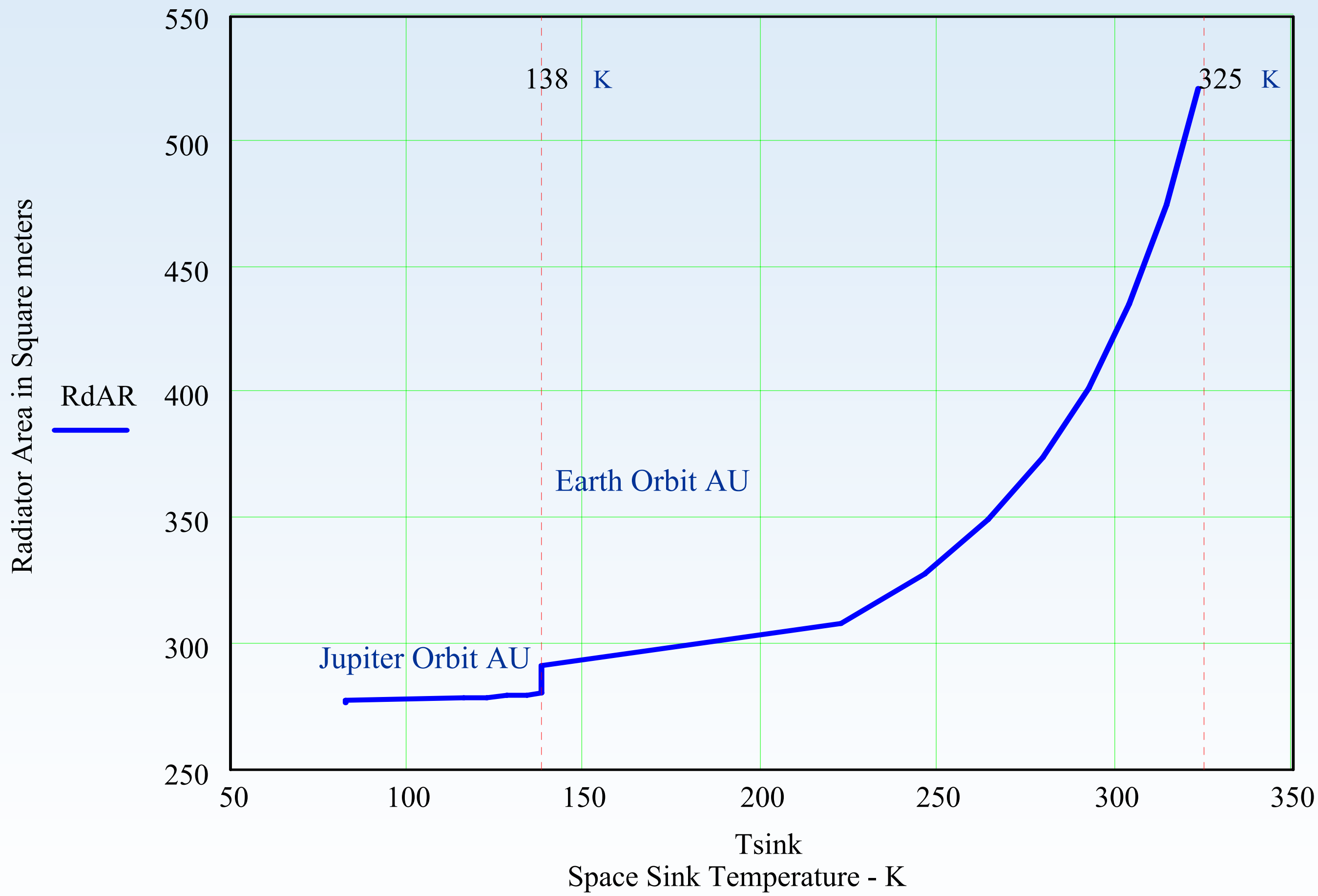
ILUMANG (DEG)	FV	EPS	AE	AU	Q/A(W/M2) (at 90 deg)	TS(K)	ORBIT
25.00	1.0	.90	.60	220.000	.03	18.9	HELIOPAUSE
25.00	1.0	.90	.60	39.438	.88	44.6	PLUTO
25.00	1.0	.90	.60	30.058	1.52	51.1	NEPTUNE
25.00	1.0	.90	.60	19.182	3.73	63.9	URANUS
25.00	1.0	.90	.60	9.539	15.08	90.6	SATURN
25.00	1.0	.90	.60	5.203	50.70	122.7	JUPITER
25.00	1.0	.90	.60	3.000	152.50	161.6	ASTEROIDS
25.00	1.0	.90	.60	1.524	591.18	226.8	MARS
25.00	1.0	.90	.60	1.000	1372.51	279.9	EARTH
25.00	1.0	.90	.60	.723	2623.26	329.1	VENUS
90.0	1.0	.9	.92	1.00	1372.5	386	*Moon @ Noon*
25.00	1.0	.90	.60	.387	9164.15	450.0	MERCURY
25.00	1.0	.90	.60	.020	3431265.02	1979.3	CORONA
90.00	1.0	.90	1.00	.005	64163903.86	5800.2	PHOTO SPHERE

Solar Heat Flux & Space Probe Temperatures At Various Orbital Distances (AU)

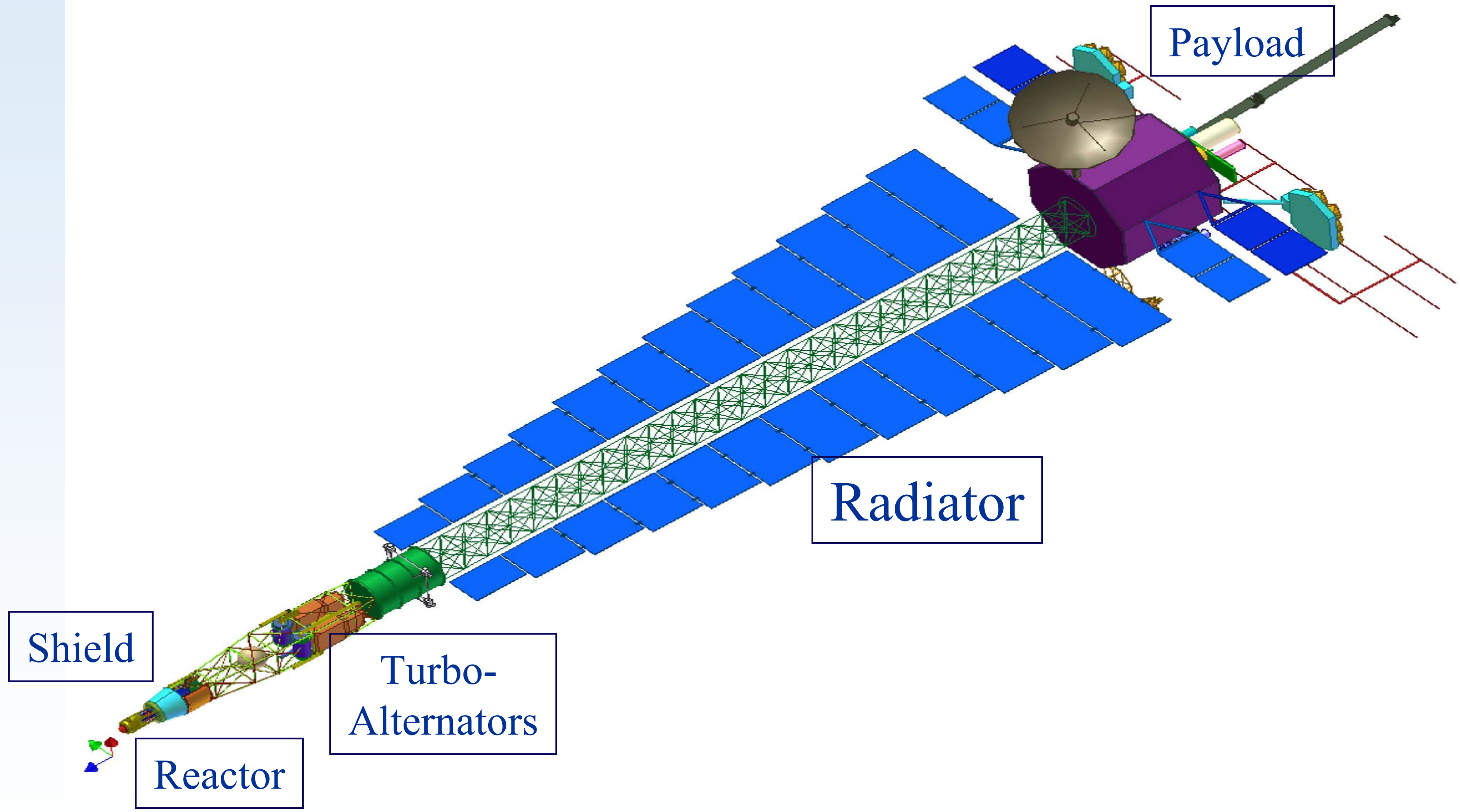


A. Juhasz
NASA GRC.
10/31/03

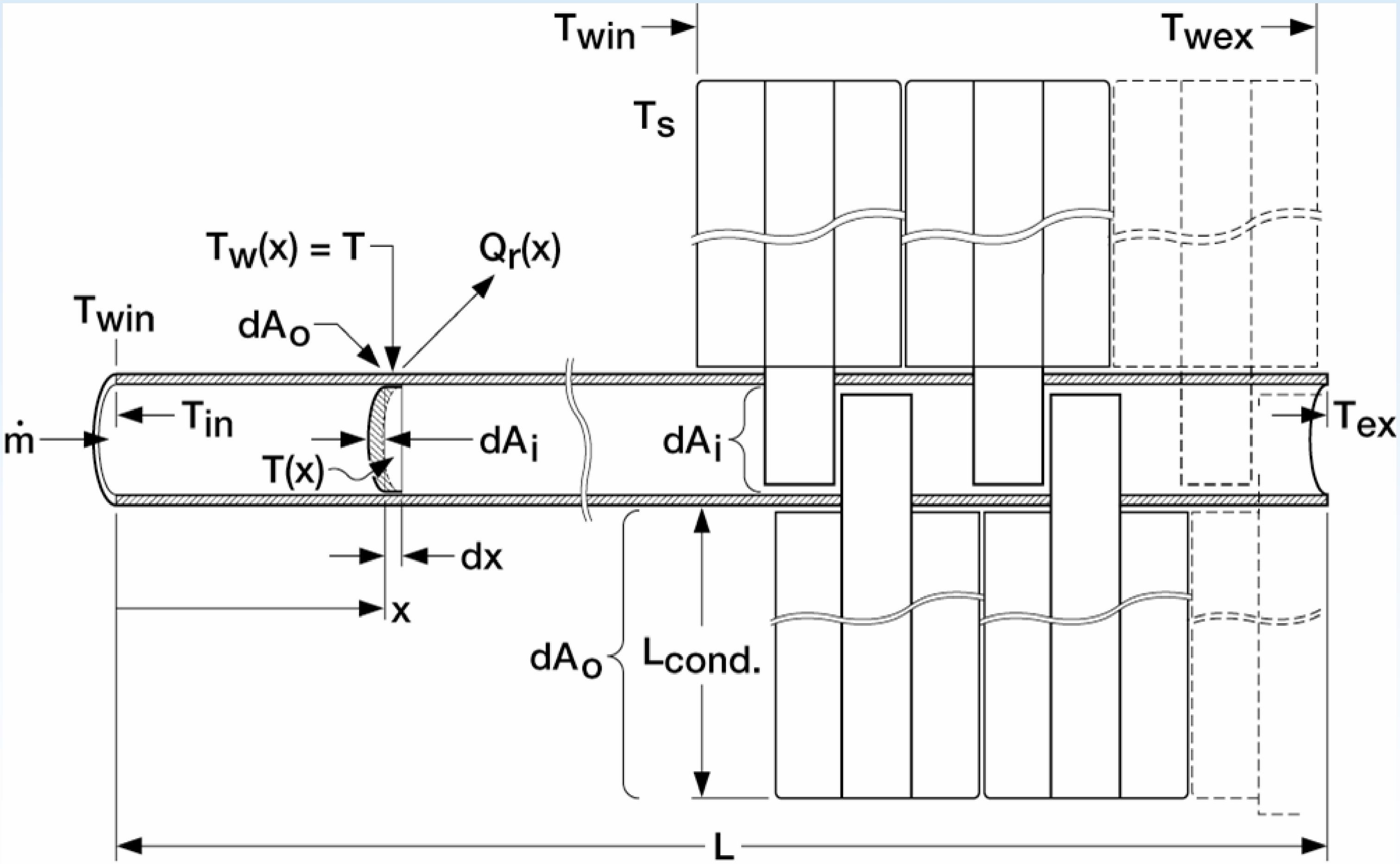
Radiator Area Requirement for 300 kW_t Heat Load at Avg. Radiator Surface Temperature = 390 K (θ = 25°; FV = 1; α/ε ranging 0.1 to 1.0)



Spacecraft with Trapezoidal Heat Pipe Radiator



Thermal Energy Transfer in a Heat Pipe Radiator



Relationships Resulting from Closed Brayton Cycle Analysis

Radiator Area

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

Brayton Cycle Thermal Efficiency

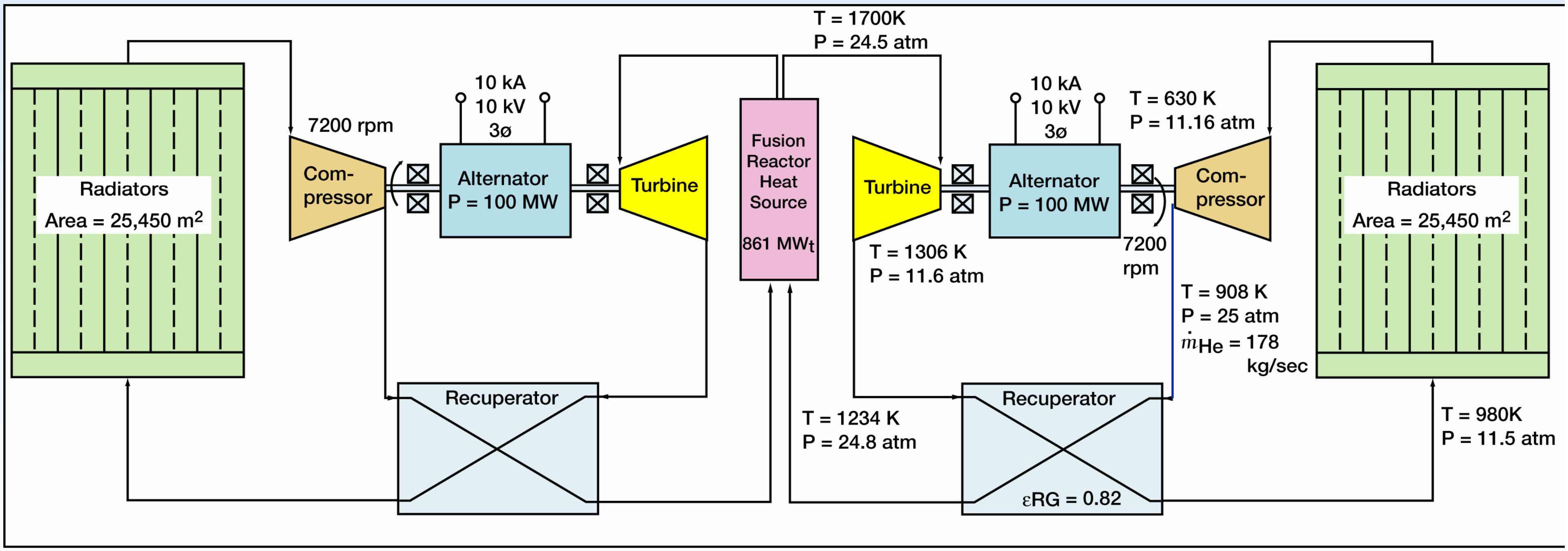
$$\eta_{th} = \frac{\eta_b \left(\frac{\Theta_T - 1}{\Theta_C} \right) \left(\alpha \, \eta_t - \frac{\Theta_C}{\eta_C} \right)}{\alpha \left(1 - \varepsilon_R\right) + \varepsilon_R \, \eta_t \, \alpha \left(1 - \frac{1}{\Theta_T} \right) + \varepsilon_R - 1 + \frac{1}{\eta_C} \left(1 - \Theta_C + \Theta_C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

where

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

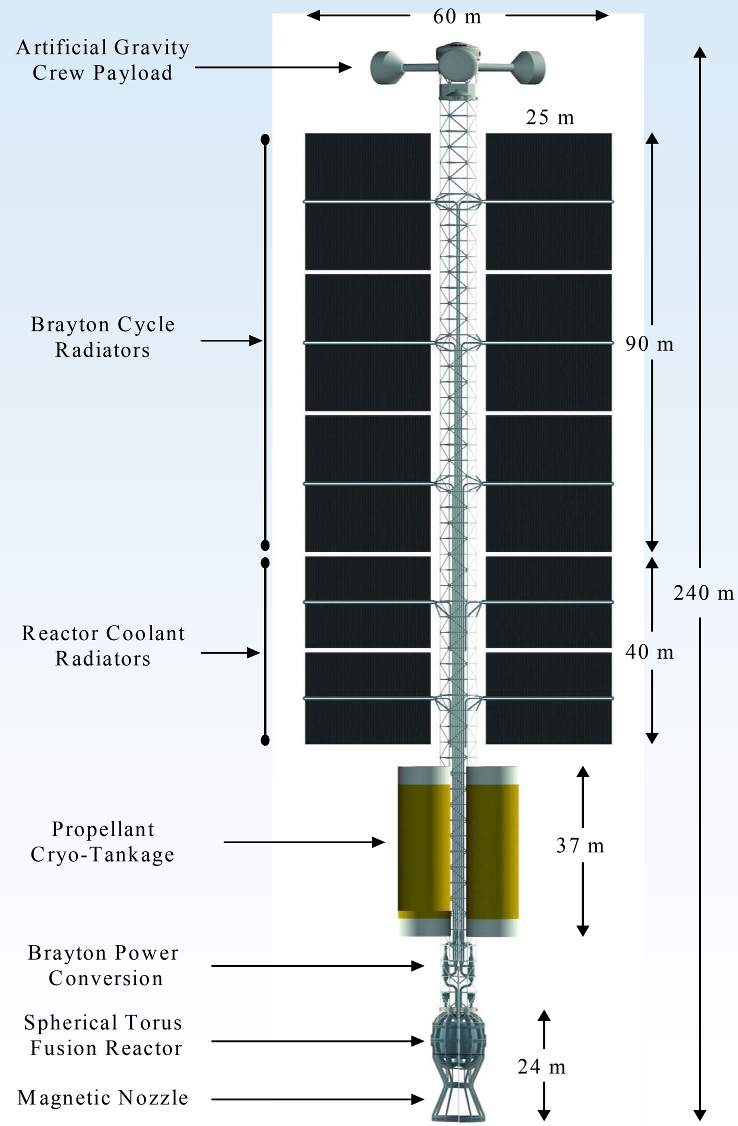
$\Theta_T = (P_{IT} / P_{OT})^{(\gamma-1)/\gamma}$ is the turbine pressure ratio parameter

Sample Power Plant Analyzed for Large Inter-planetary Spacecraft

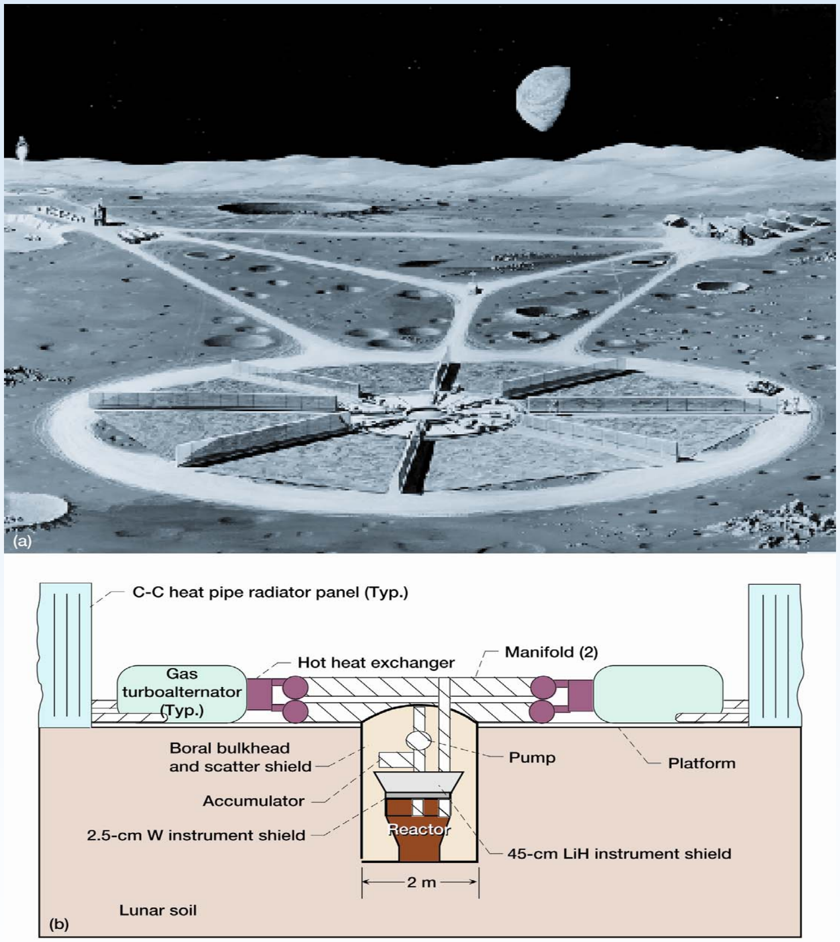


Dual Loop 200 MWe Closed Cycle (He) Gas Turbine (CCGT) Power System with Nuclear Fusion Reactor Heat Source

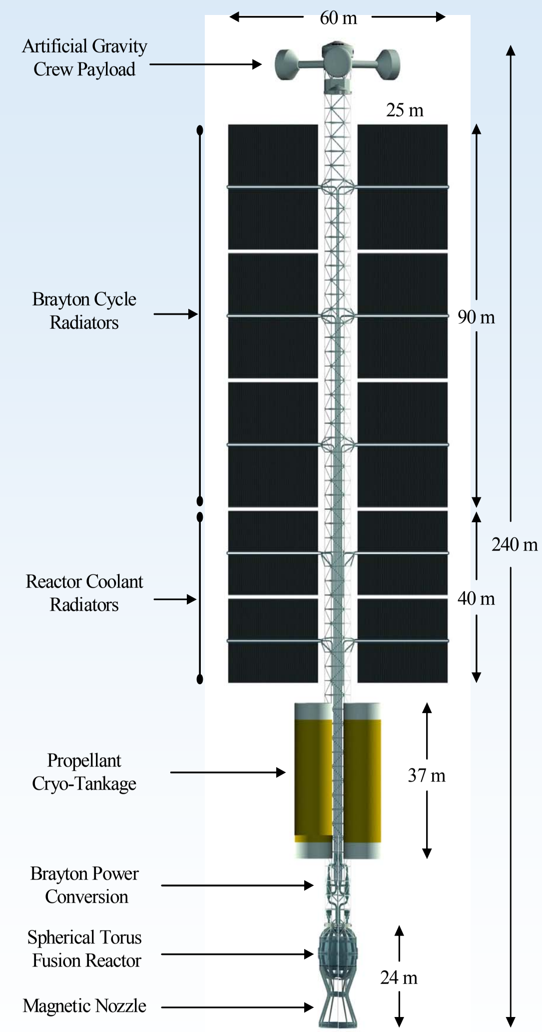
Interplanetary Crew Transport Vehicle



Advanced Power System Applications



Lunar Base Power System

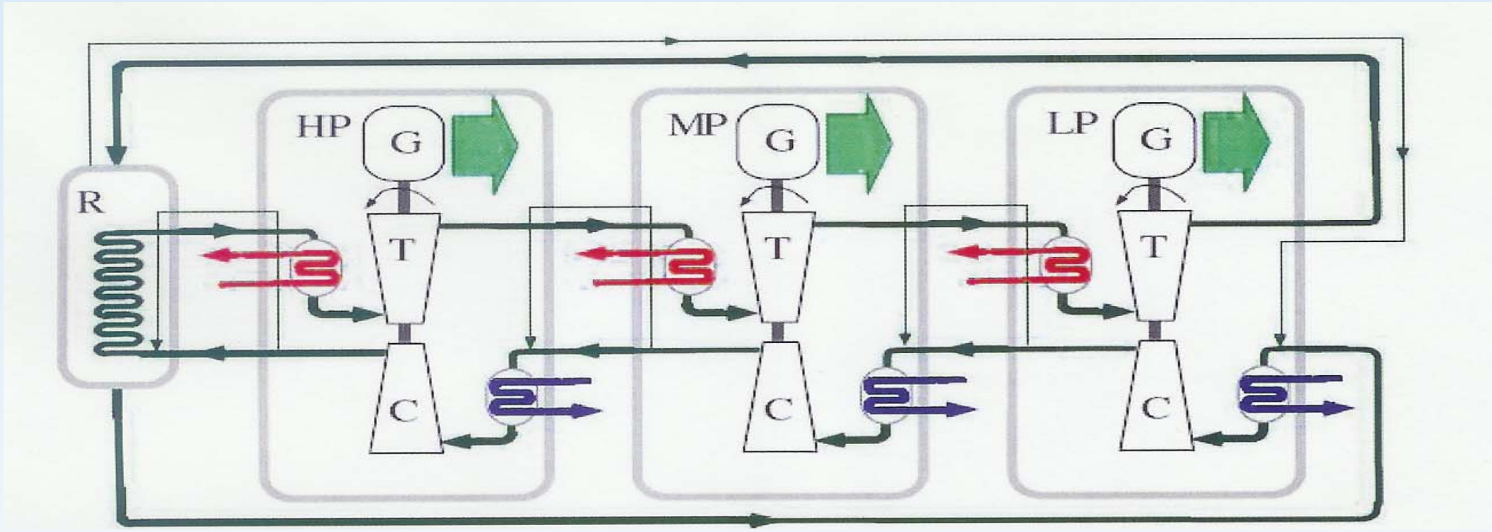


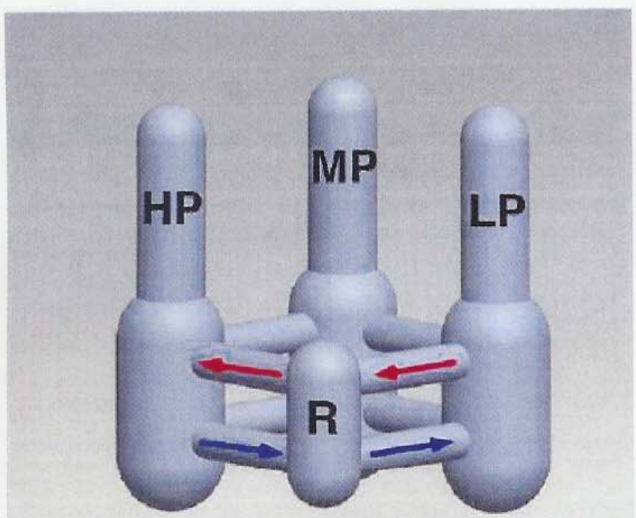
Interplanetary Fusion Propulsion Space Vehicle

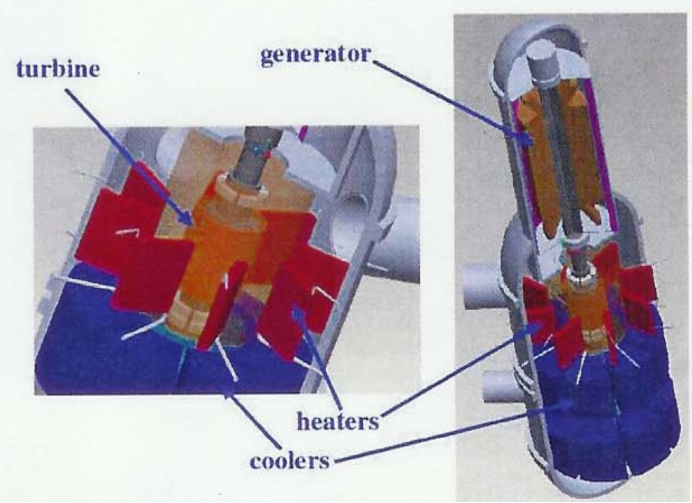
For Space Nuclear Powered Multi-Megawatt Closed Cycle Gas Turbine (CCGT) Systems with Nuclear can achieve Specific Mass (SPM) < 5 kg/kw

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

Terrestrial Nuclear Power Plant w. LFR and HP, MP, LP Heat Exchangers for Reheat/Intercool Brayton Cycle



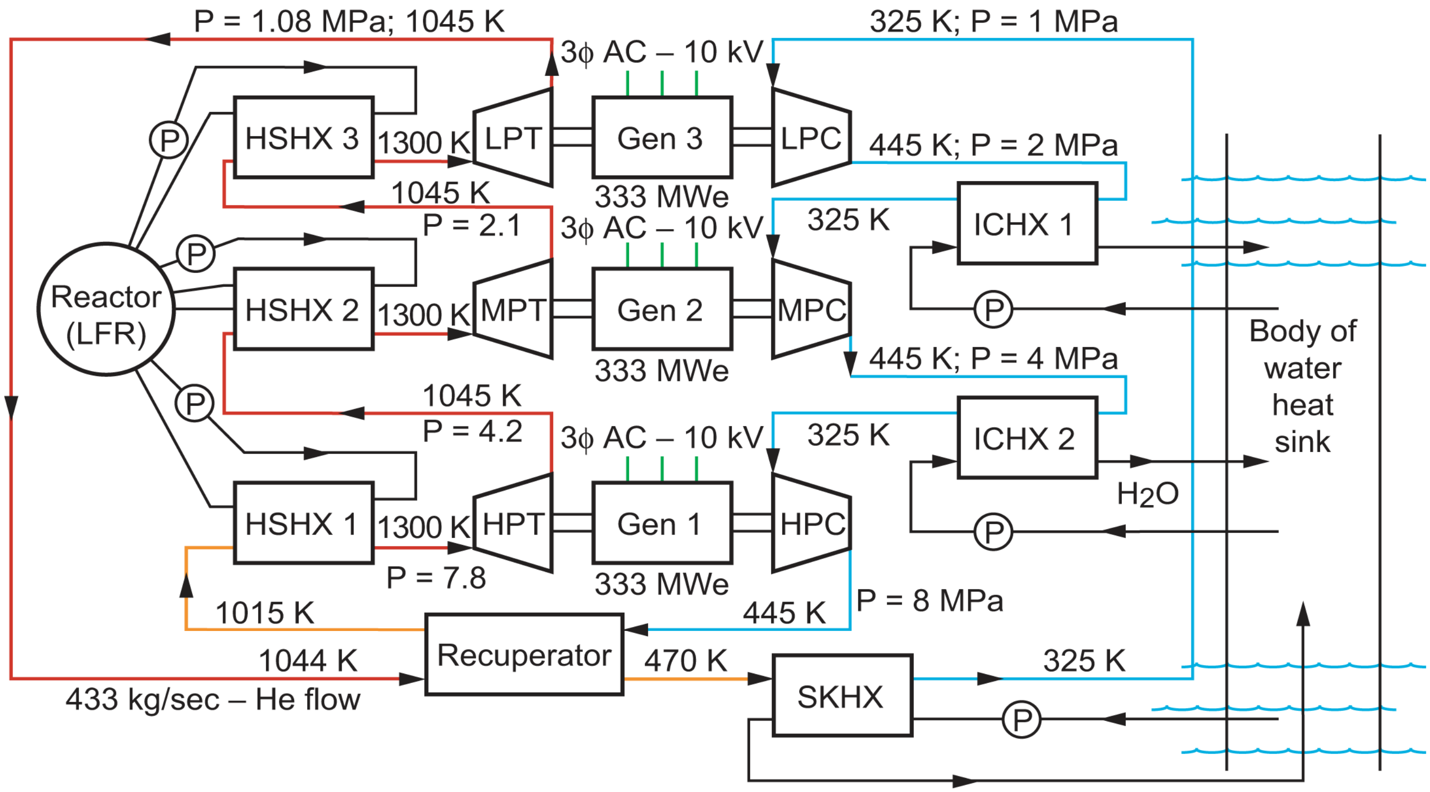




Ground Based Nuclear Power System (1000-MWe Helium Plant)
With Turbine Reheat and Compressor Intercooling

Legend:

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



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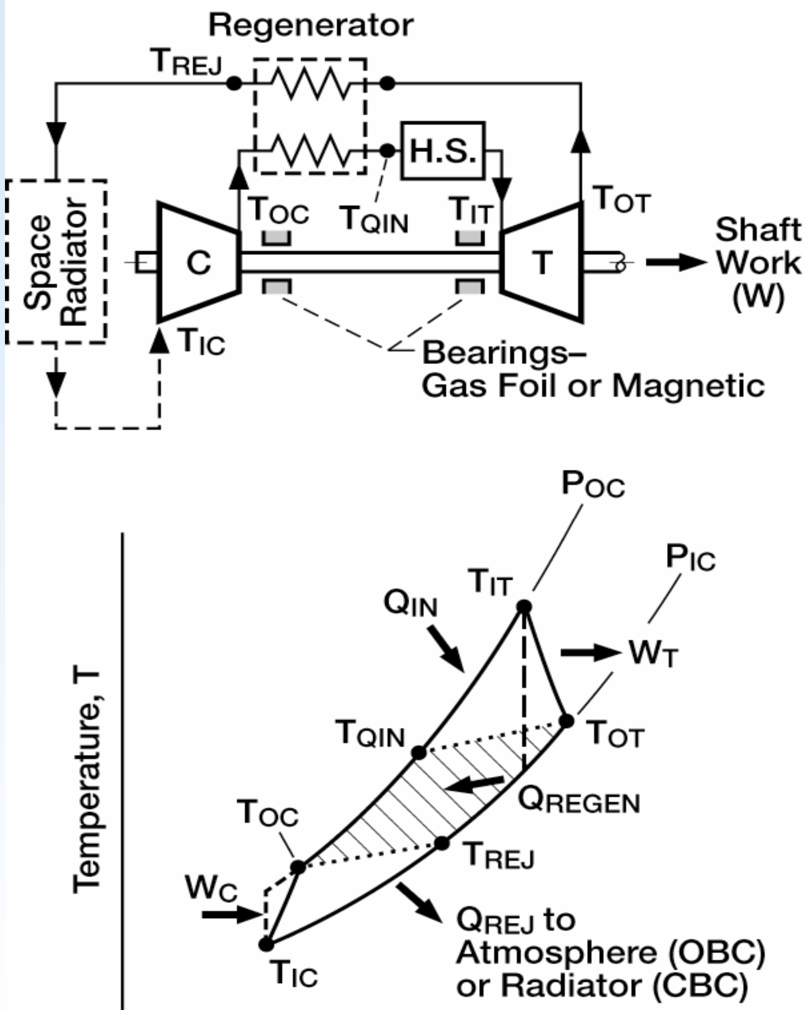
GAS TURBINE (BRAYTON CYCLES)



Regenerated Cycle

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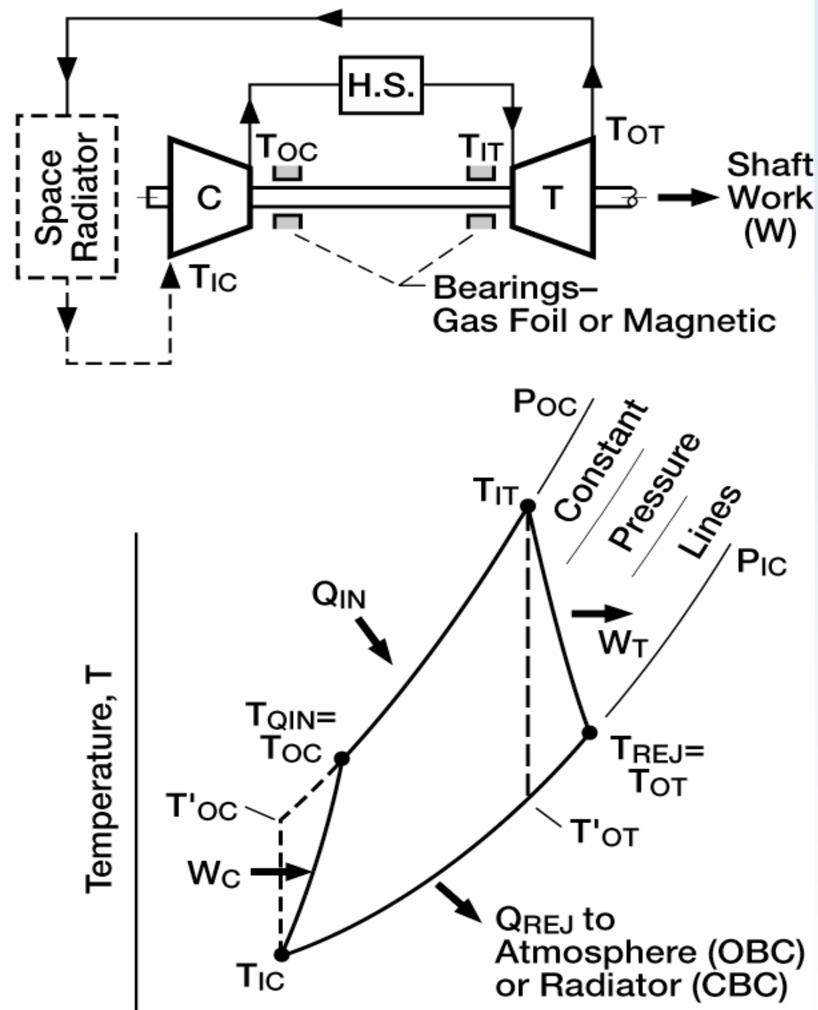
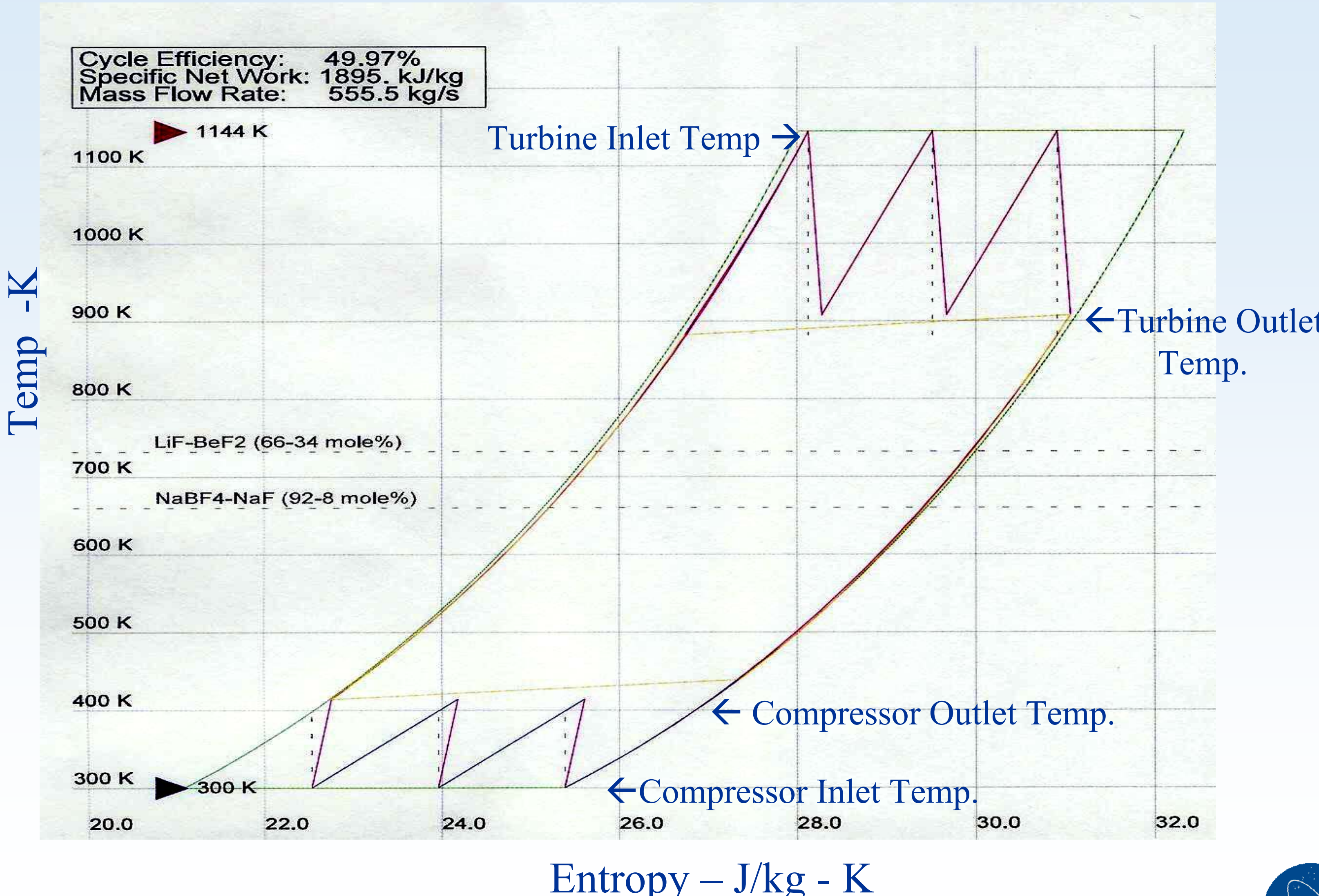


Non-Regenerated Cycle

Three Stage Reheat & Intercool Brayton Cycle Temperature – Entropy Diagram



Power Cycle Schematic and T-S Diagram for Single Expansion Inter-Cooled Triple Compression System

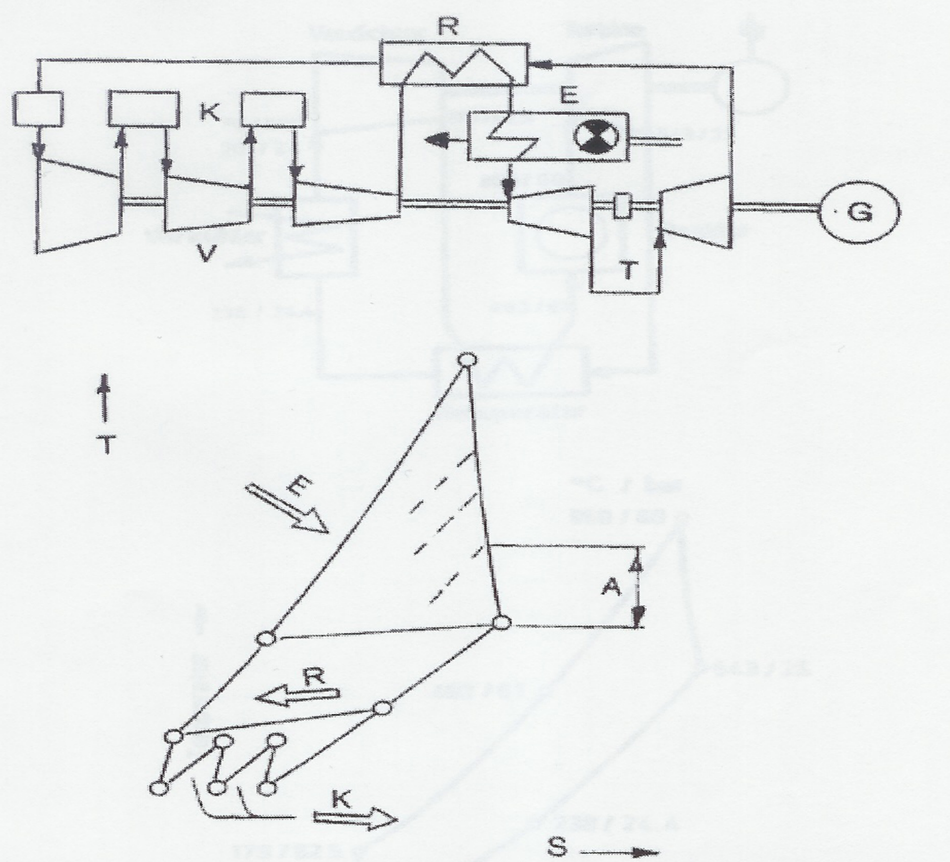


Fig. 2 Cycle and entropy diagram of the first closed-cycle gas turbine plant AK 36, Escher Wyss 1939.
V Compressors, T Turbines, E Air Heater (Heat Input), R Recuperator, K Coolers (Heat Rejection), A Usable Work, G Generator.

(Frutschi)

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 = 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 MP a and Pr=2; (**TIT=1200K; TR=4**)
  - Mass Flowrate ~ 434 kg/sec (One 300 MWe Turbo-Gen.)
  - Dia. = 3.8 m; L = ~8.8 m; Speed = 3600 rpm
  - Recuperator Volume ~ 96 m^3
  - Thermal Eff. = 48%
- Three Reheat/Intercooled Turbo-Alt's (**TIT=1200K; TR=4**)
  - Mass Flowrate ~ 142 kg/sec (Three 100 MWe Turbo-Gens.)
  - P=20 Mpa (Pr=2); Dia = 1.4 m, L = 3.3 m, Speed = 8700 rpm
  - P=10 Mpa (Pr=2); Dia = 1.9 m, L = 4.4 m, Speed = 6200 rpm
  - P= 5 Mpa (Pr=2); Dia = 2.7 m, L = 6.3 m, Speed = 4360 rpm
  - Recuperator Volume ~ 34 m^3
  - Thermal Eff. = 51.6%

Typical Machine Sizes for 150 MWe He Plant

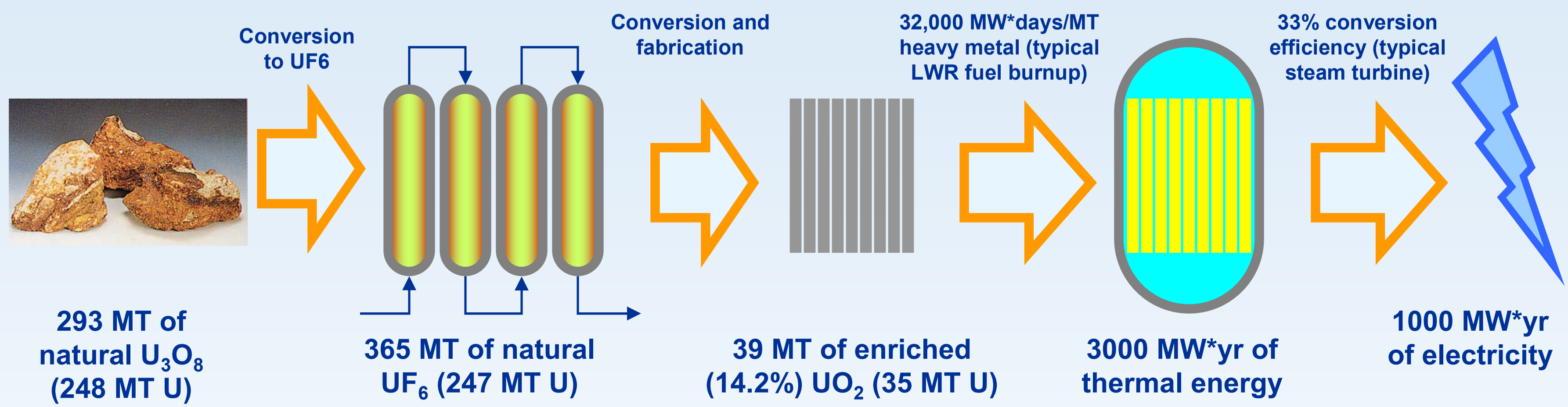
- Single Turbo-Alt at 10 MPa and Pr=2; (**TIT=1200K; TR=4**)
  - Mass Flowrate ~ 217 kg/sec (One 150 MWe Turbo-Gen.)
  - Dia. = 2.3 m; L = ~5.3 m; Speed = 5040 rpm
  - Recuperator Volume ~ 48 m^3
  - Thermal Eff. = 48.4%
- Three Reheat/Intercooled Turbo-Alt's (**TIT=1200K; TR=4**)
  - Mass Flowrate ~ 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 m^3
  - Thermal Eff. = 51.6%

Typical Machine Sizes for 150 MWe He Plant

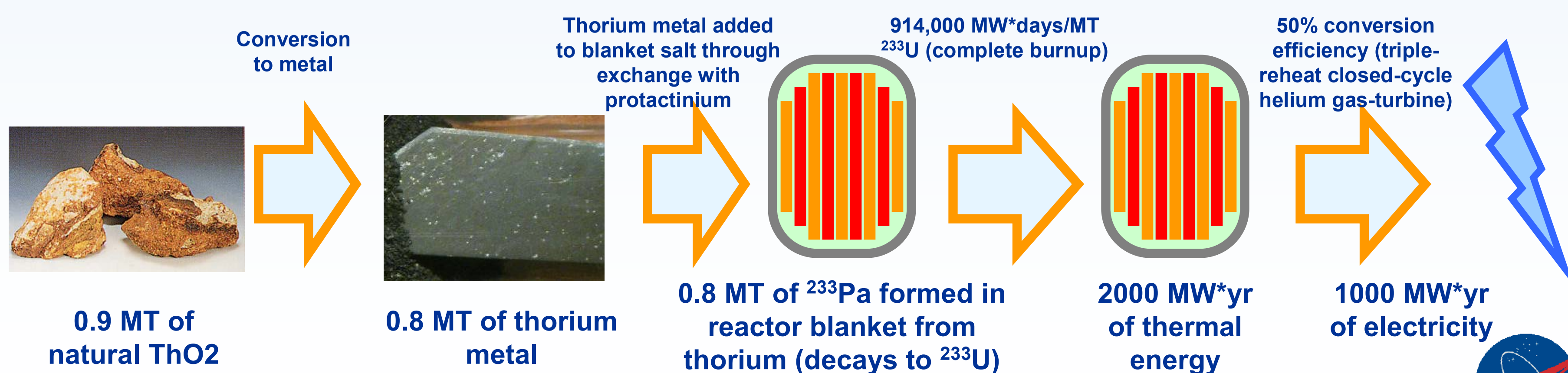
- Single Turbo-Alt at 10 MPa and Pr=2; (**TIT=1300K; TR=4.333**)
  - Mass Flowrate ~ 178 kg/sec (One 150 MWe Turbo-Gen.)
  - Dia. = 2.2 m; L = ~5.1 m; Speed = 5240 rpm
  - Recuperator Volume ~ 38 m^3
  - Thermal Eff. = 51.4%
- Three Reheat/Intercooled Turbo-Alt's (**TIT=1300K; TR=4.333**)
  - Mass Flowrate ~ 59.5 kg/sec (Three 50 MWe Turbo-Gens.)
  - P=20 Mpa (Pr=2); Dia = 0.87 m, L = 2.0 m, Speed = 13,150 rpm
  - P=10 Mpa (Pr=2); Dia = 1.23 m, L = 2.9 m, Speed = 9300 rpm
  - P= 5 Mpa (Pr=2); Dia = 1.74 m, L = 4.0 m, Speed = 6600 rpm
  - Recuperator Volume ~ 13.5 m^3
  - Thermal Eff. = 53.7%

Energy Extraction Comparison for 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

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.