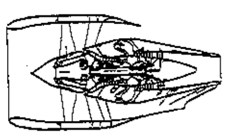
PRESENTATION TO

Dr. P. McElligiot's 2004-2005 Physics Class in
Fountain Hills, Arizona



The Physics and Applications of Heat Engine

API-00050-1

By SCOTT MEYERS, P.E.

April 25, 2005

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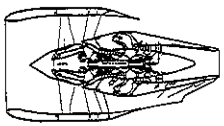
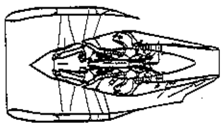
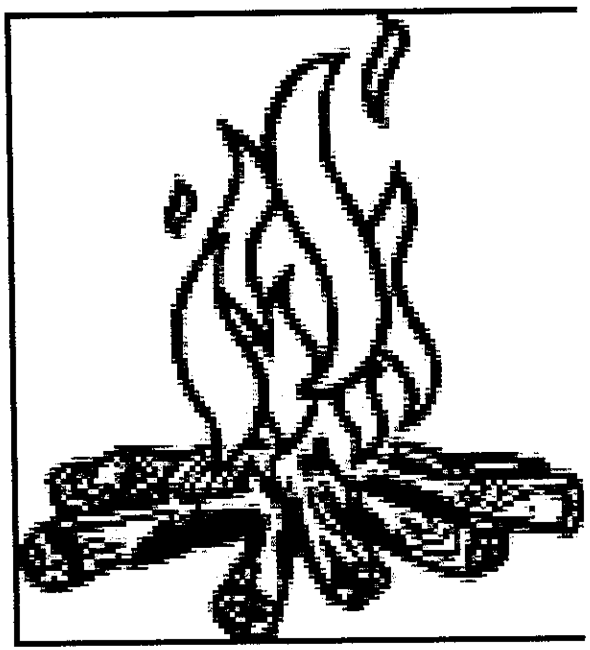


What is a Heat Engine?

- A heat engine is a device which uses the a working fluid or material to convert heat to useful work.
- This generally accomplished by "torturing the air" with pumps, turbine or cylinders and heat exchangers to convert heat to work.

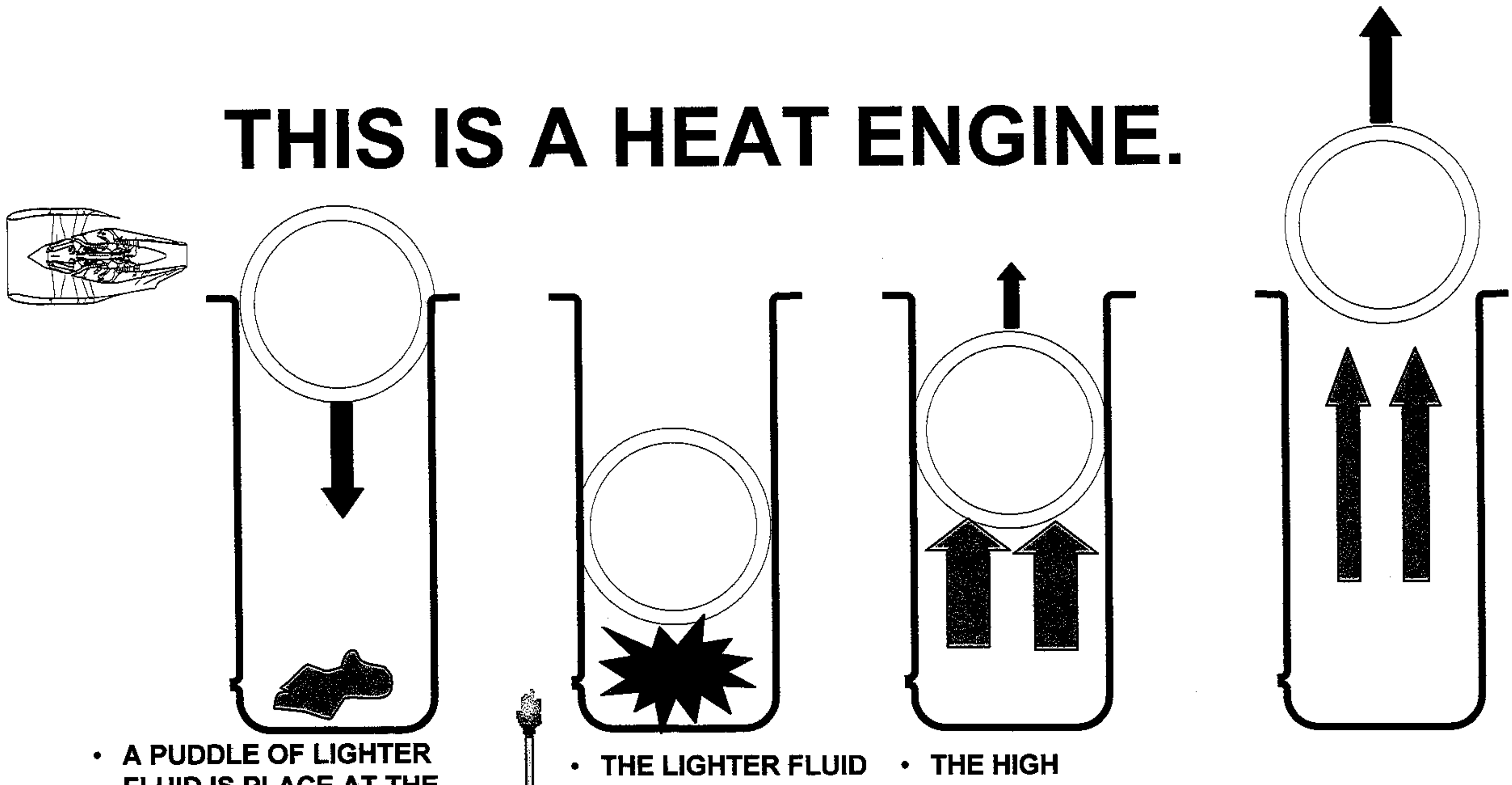
What is not a heat engine?





- What's happening here?
  - Chemical energy is the wood is being converted to hot gases.
- You can warm you hands or boil water.
- You can't move a log or rock.
- Spin a turbine or move a cylinder.
- ENTROPY HAS INCREASED BUT YOU CAN'T DO WORK WITH IT.

THIS IS A HEAT ENGINE.



- A PUDDLE OF LIGHTER FLUID IS PLACE AT THE BOTTOM OF CYLINDER AND TENNIS BALL IS DROPPED IN THE CAN.
- THE TENNIS BALL COMPRESSES THE GAS AS IT FALLS UNDER THE FORCE OF GRAVITY.

- THE LIGHTER FLUID IS IGNITED, RAISING THE TEMPERATURE OF AIR.
- THE PRESSURE RISES ABRUPTLY WITH THE TEMPERATURE.

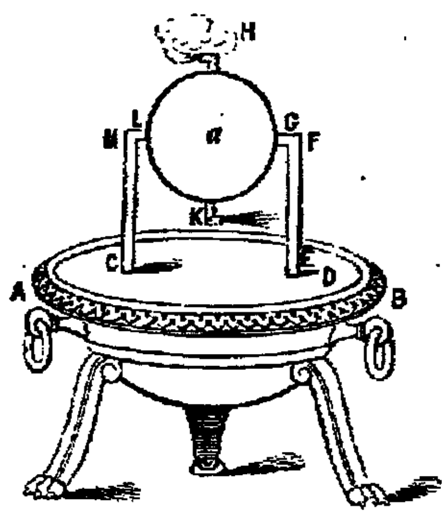
$$P = RT/V$$

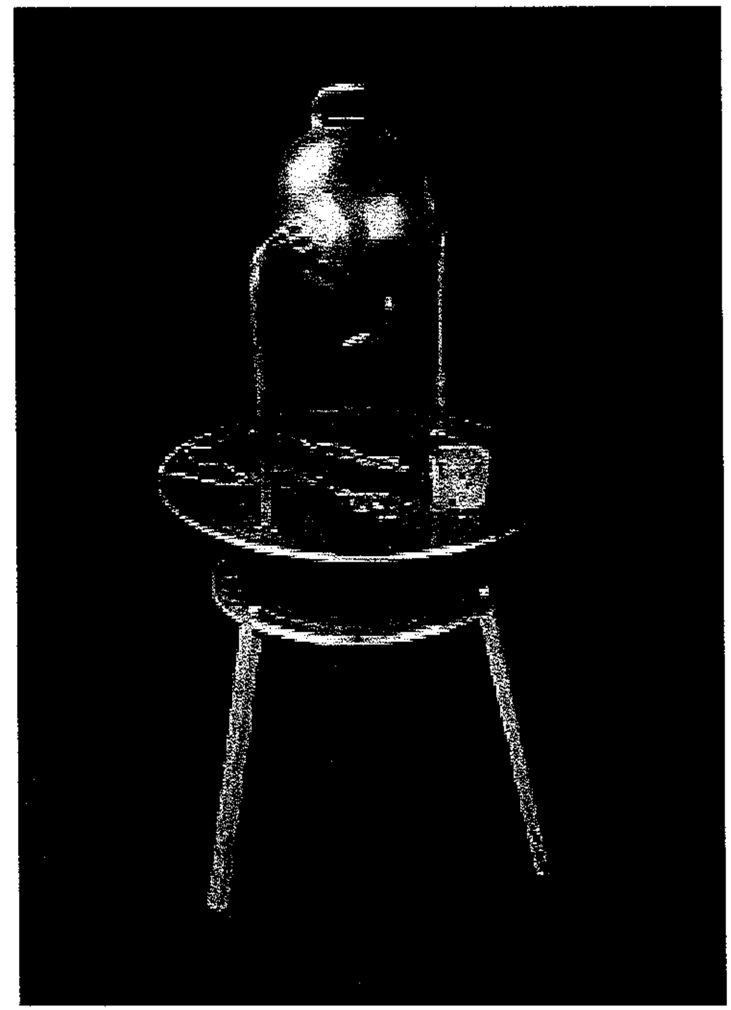
- THE HIGH PRESSURE ACTS OF THE BALL AND DOES WORK ON THE BALL.
- THE WORK IS CONVERTED INTO KINETIC ENERGY OF THE BALL.

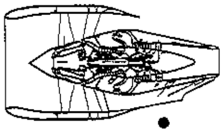
$$\frac{1}{2} M V^2 = P^* A^* \Delta X$$

The World's First Heat Engine

- Invented by the Greek Hero about 200 BC
- Water is heat in the cauldron below to make steam.
- The steam vents from high pressure to creat two jets.
- These spin the ball.
- It is not know if useful work was accomplished with the machine.





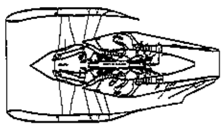


Modern History of Heat Engine

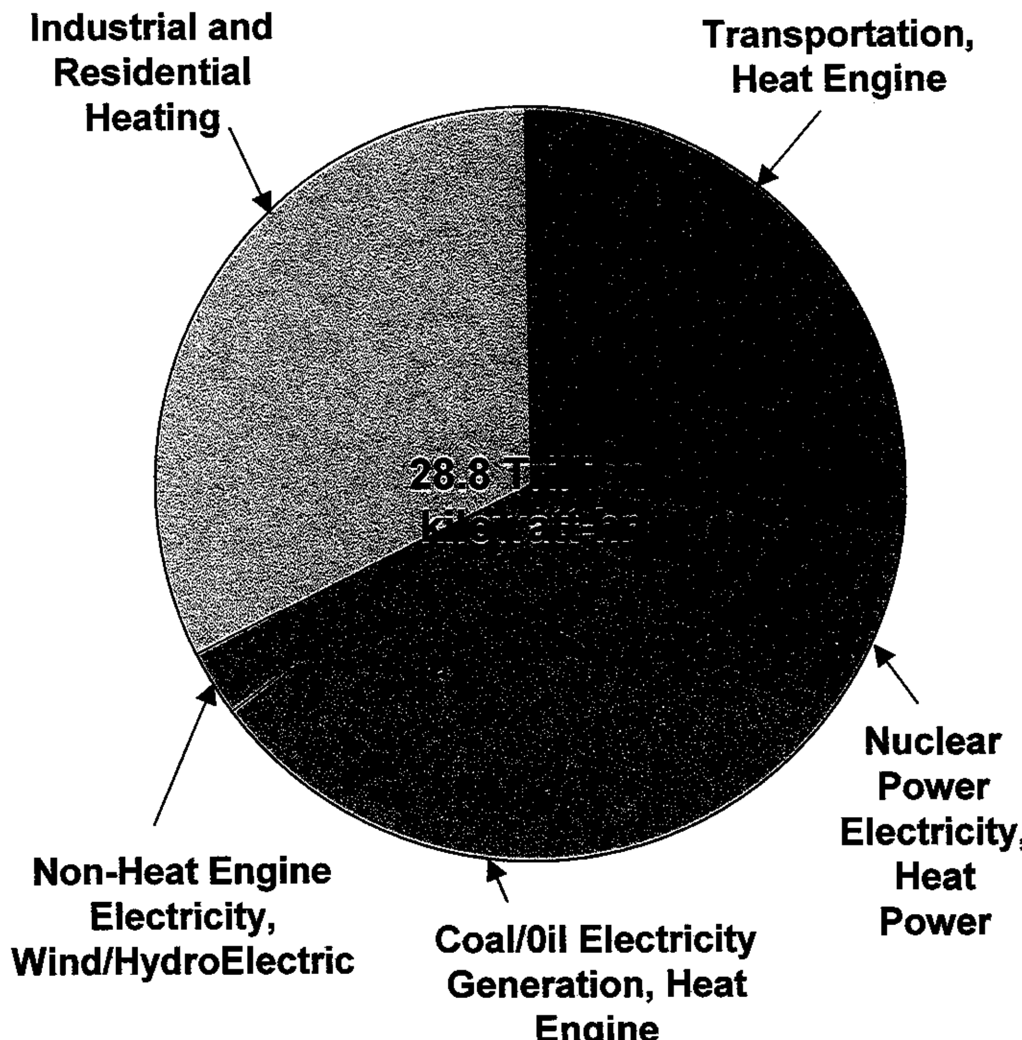
- Until Steam Engines where invented in 1600-1700s, all human endeavors where powered by:
  - Animal power (horses, oxen, even dogs)
  - Man power including extent slavery
  - Water power through water wheels
  - Wind power (wind mills, ships, etc.)

- First Steam Pump in 1698.
- First Practical Steam Engine in 1701 by Thomas Newcomen.
  - Wood powered then coal.
- Stirling Engines in 1840s. (You could buy a low efficiency Stirling Engine out of the Sears Catalog until early 1900s.)
- Internal combustion engines and automobiles, mid 1800s, becoming automobiles in late 1800s.
- Rankine cycle/freon airconditioners in the early 1900s.
- Gas turbine in 1914. First jet airplane in Germany late 1930s.
- Nuclear Powered Ships and Power Plants late 1940s.

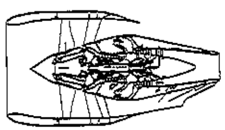
Significance of Heat Engines in the United States



- The United States Uses 28.8 Trillion kilowatt-hr (98.15 x 10^{15} Btu) of energy per year.
- Heat Engines are used to produce:
  - 10.9 Trillion kilowatt-hrs of electrity (38% of total US energy)
  - 7.9 Trillion kilowatt-hrs of energy to power cars, trains and airplanes (27% of total US energy.)
- Non-Heat Engine systems make 0.86 Trillion kilowater-hrs of electrity (8% of electricity in the US and 3% of total US energy)



Carnot Efficiency



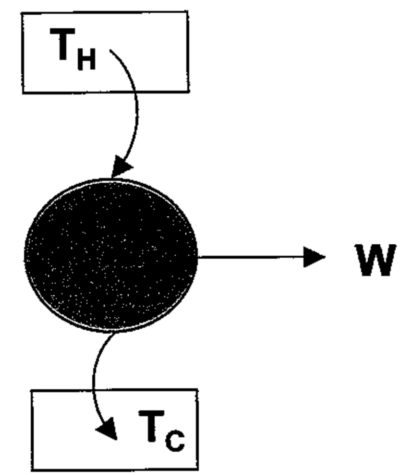
First law of thermodynamics, Energy Balance:

$dU = dQ + dW$

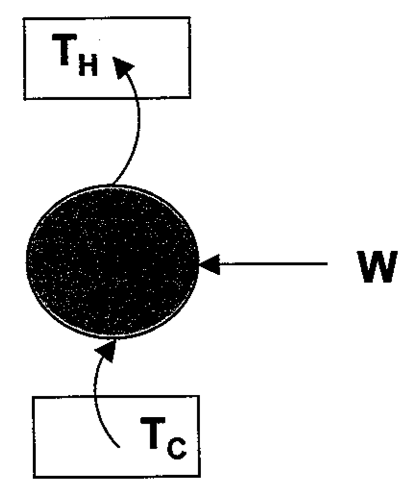
Second law of thermodynamic, Entropy Production:

$dP_S =$ $dS -$ dQ/T

increase in entropy storage — entropy inflow



REVERSIBLE ENGINE



For a reversible cycle/system:

$dP = 0 = S_1 - S_2 + Q_H/T_H - Q_C/_{TC}$

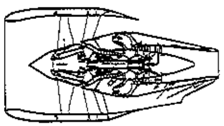
And $S_1 = S_2$ and $dU = 0$ for a steady state system.

$Q_H/T_H = Q_C/T_C \qquad Q_H/Q_C = T_H/T_C$

$W = Q_H - Q_C$

Efficiency is defined and substituting:

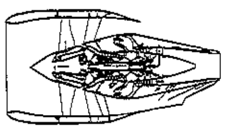
$\eta_{carnot} = (Q_H-Q_C)/Q_H = 1 - Q_C/Q_H = 1 - T_C/T_H$



Carnot Efficiency

What is the best efficiency an engine can have if it burns fuel at 2500°K and rejects the heat to water at 273°K?

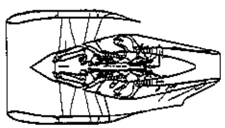
$$\eta_{carnot} = 1 - T_C/T_H = 1 - 273/2500 = 0.89$$



Carnot Efficiency

A thermocouple direct energy conversion system works using dis-similar metal junctions held at different temperatures to generate a voltage and current. What is the best efficiency a thermoelectric generator is one side is held in boiling water (373°K) and the other side in ambient water (298°K)?

Rankine - Steam Cycle Heat Engine



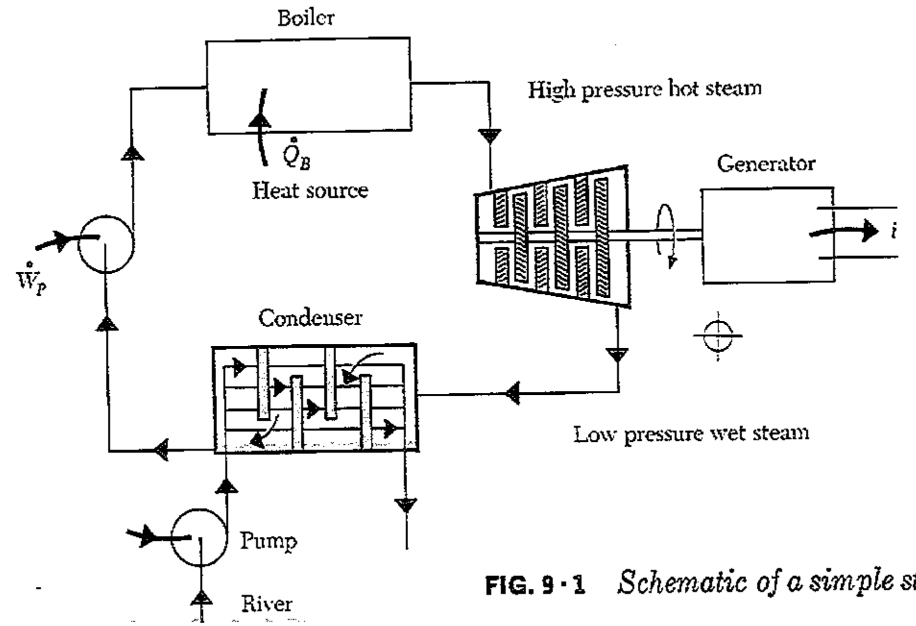
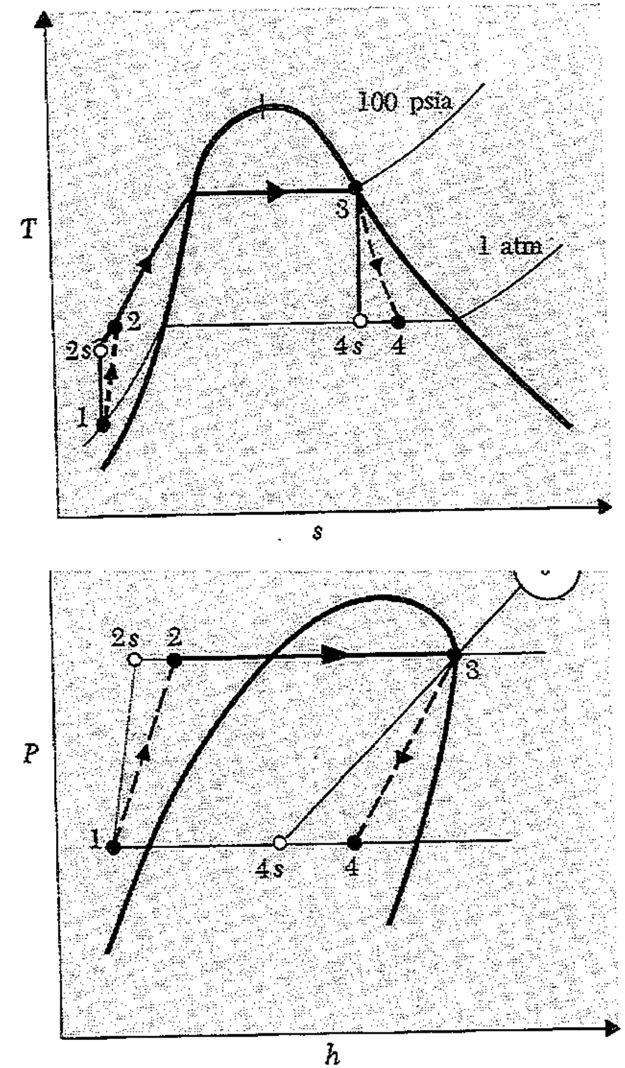
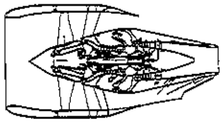


FIG. 9·1 *Schematic of a simple steam power plant*



Reverse Rankine – Freon Airconditioning Cycle



of refrigeration systems (Fig. 9·21).

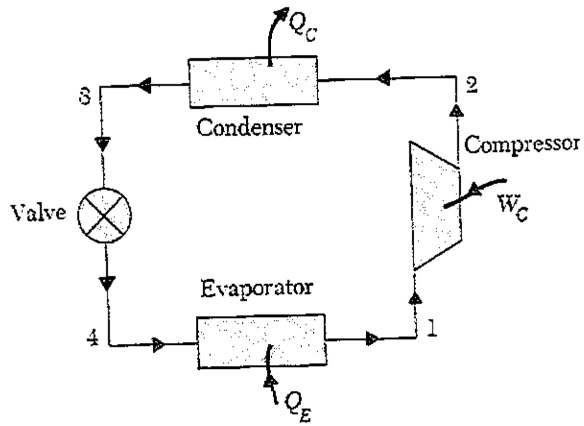
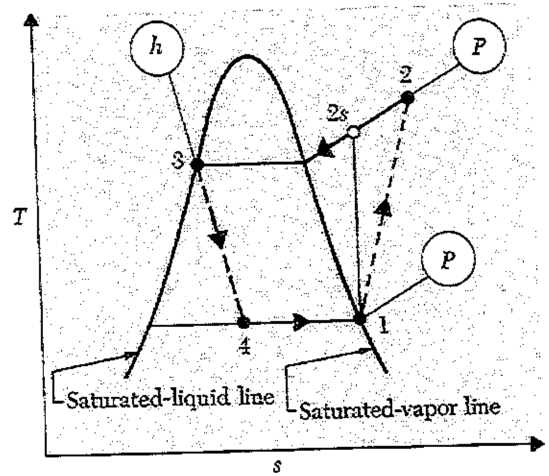
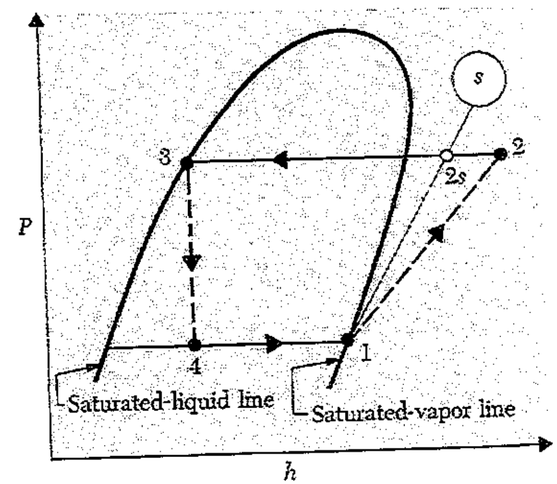
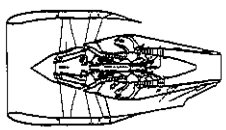


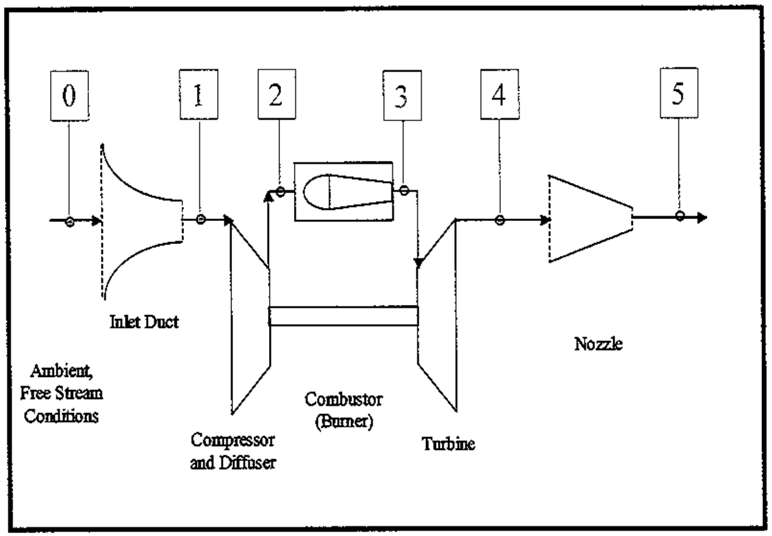
FIG. 9·21 *Vapor-compression refrigeration system*

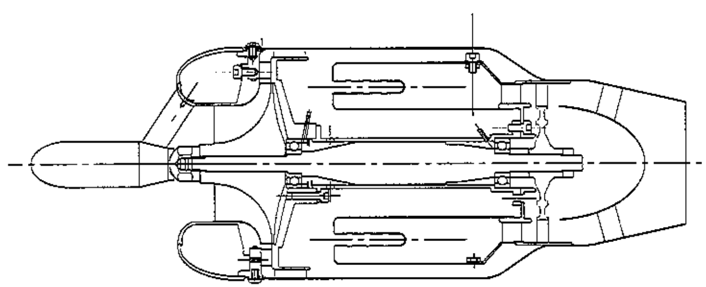


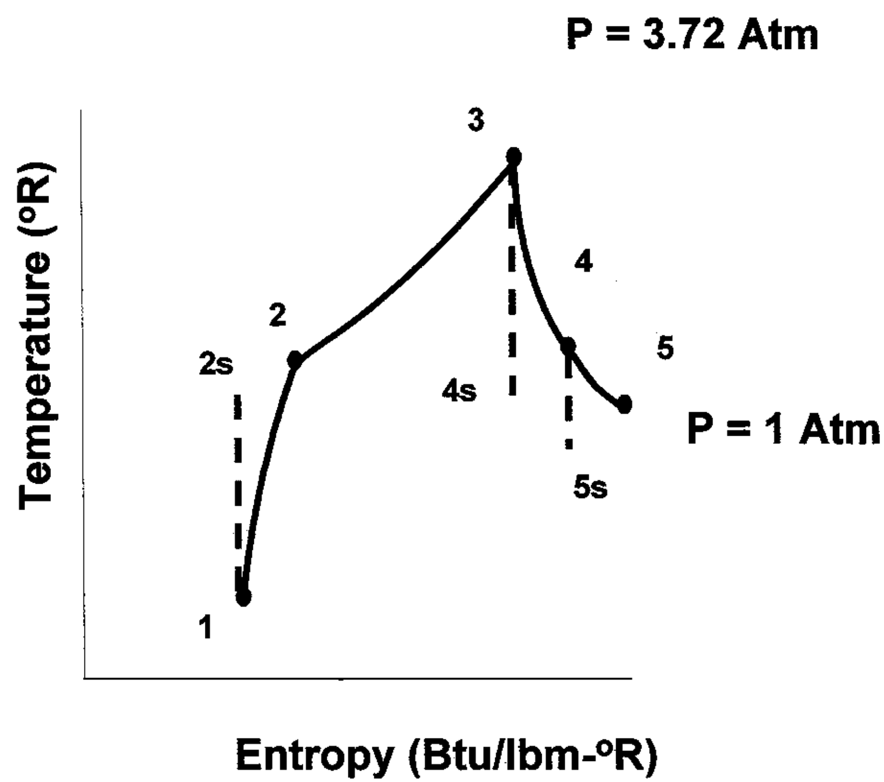


Simple Gas Turbine Heat Engine

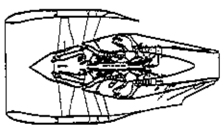








Thermodynamic Analysis
Simple Gas Turbine Engine



GIVEN: P_1 = 14.696 psia, T_1 = 59°F (581.6°F)

m_1 = 0.91 lbm/sec, $\eta_{compressor}$ = 0.665

$PR_{compressor}$ = 3.72 $\eta_{core\ turbine}$ = 0.83

For a reversible compression or expansion process:

$s_1 = s_{2s}$

$S_1 - s_{2s} = 0 = c_p \ln (T_{2s}/T_1) - R \ln (P2/P1)$

where
- s – entropy (Btu/lbm/°R)
- cp – heat capacity (Btu/lbm/°R)
- T - temperature (°R)
- R – gas constant (Btu/lbm/°R)
- P - pressure (psia)
- 1 - station at beginning of process
- 2s – station at end of process

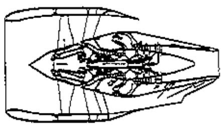
$T_{2s}/T_1 = (P_{2s}/P_2)$ ^ (R/c_p)

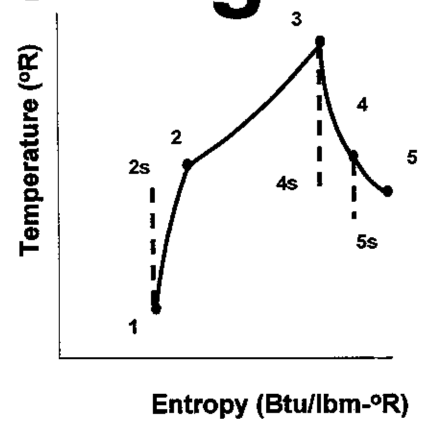
Substituting $c_p - c_v = R$ and $g = c_p/c_v$

where c_v - heat capacity at constant volume (Btu/lbm/°R)
γ – ratio of specific heats

$T_{2s}/T_1 = (P_{2s}/P_2)$ ^ $((\gamma-1)/\gamma)$

Thermodynamic Analysis (cont)
Simple Gas Turbine Engine





(1) **Compressor:**

$T_{2s}/T_1 = (P_{2s}/P_2)$ ^ $((\gamma-1)/\gamma)$

$T_{2s} = T_1 * PR_{compressor}$ ^$((\gamma-1)/\gamma)$ where $\gamma = 1.4$

T_{2s} = 518.6 * 3.72 ^((1.4-1)/1.4) = 518.6 *3.72^.286 = 518.6 * 1.455
= 754.8°R (295.2°F)

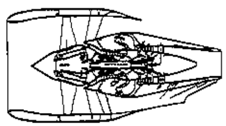
$\eta_{compressor} = W_{cs}/W_c$ where W_C - actual compressor work (Btu/lbm)
W_{cs} - reversible, 100% efficiency compressor work (Btu/lbm)

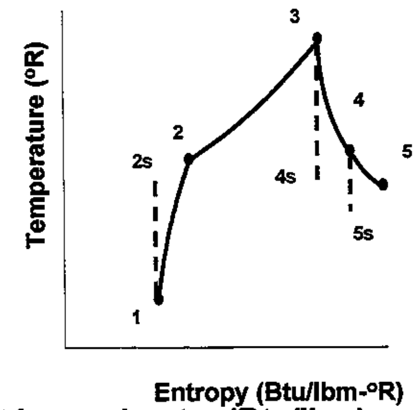
$W_{cs} = c_p *(T_{2s}-T_1)$ & $W_c = c_p *(T_2-T_1)$ where c_p = .242 Btu/lbm/R over the temperature range

Wc = $c_p *(T_{2s}-T_1) / \eta_{compressor}$ = .242 *(754.8-518.6)/.665 = 85.9 Btu/lbm

$T_2 = W_c/c_p + T_1$ = 85.9/.242 +518.6 = 873.8°R (414.2°F)

Thermodynamic Analysis (cont)
Simple Gas Turbine Engine





(1) Combustor (Station 2- 3)

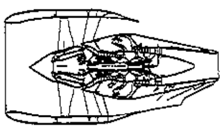
$\Delta Q_{2\text{-}3} = c_p * (T_3 - T_2)$ where Q – heat input in combuster (Btu/lbm)
cp = ..262 Btu/lbm/R

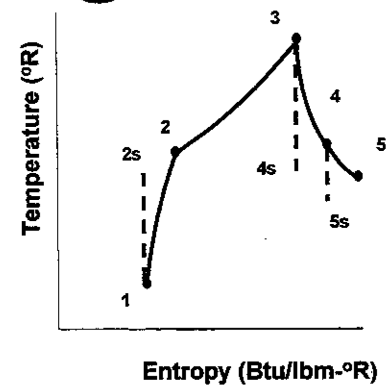
$\Delta Q_{2\text{-}3} = .262 * (1959.6 - 873.8) = 284.47$ Btu/lbm

$f = \Delta Q_{2\text{-}3} / Hv$ where Hv - heating value of fuel = 17560 Btu/lbm
f - fuel-air ratio - lbm fuel/lbm inlet air

$= 284.7/17560 = .0162$

Thermodynamic Analysis (cont)
Simple Gas Turbine Engine





(3) Core Turbine:

$W_T = -W_c$ where W_T - is the actual work done by the core turbine

$W_T = c_p * (T_4 - T_3) * (1+f)$

$T_4 = -W_c/c_p/ (1+f) + T_3$ where cp = =.280 Btu/lbm/R over the temperature range

= -85.9/ .280/(1+.0162) + 1959.6 = 1657.2°R (1198.1°F)

from turbine efficiency, reversible expansion temperature is determined:

$\eta_{core\ turbine} = W_T/W_{Ts} = c_p* (T_3-T_4)/ c_p *(T_3-T_{4s})$

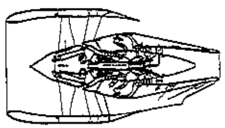
$T_{4s} = T_3 - (T_3-T_4)/ \eta_{core\ turbine}$ = 1959.6- (1959.6-1657.2)/.84 = 1600.2°R(1140.6°F)

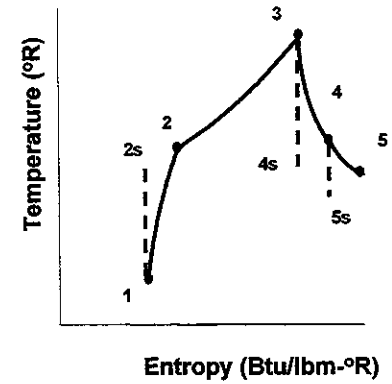
the turbine exhaust temperature is calculated using a reversible expansion:

$T_{4s}/T_3 = (P_4/P_3)$ ^ $((\gamma-1)/\gamma)$ where γ = 1.33 over the temperature range

P4 = P3 * (T4s/T3)^ $(\gamma/(\gamma-1))$ = 3.72 * (1638.8/1959.6)^(1.33/(1.33-1) = 1.644

Thermodynamic Analysis (cont)
Simple Gas Turbine Engine





(5-6) Jet Nozzle:

Using Bernoulli's Equation, calculate the jet velocity:

$P_5/\rho + V_5^2/2 = P_6/\rho + V_6^2/2$

Assume V_5 is small. Calculate ρ from perfect gas law.

$\rho_5 = P_5*144/(R_5*T_5) = (24.16 \text{ psia})* 144/((1545/28.97)*(1600.2)) = .041 \text{ lbm/ft}^3$

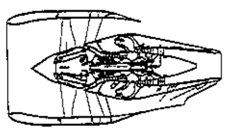
$V_6 = (2* g_c*(P_5-P_6)*144/\rho_5)$^.5 where $g_c = 32.167 \text{ lbm*ft}^2\text{/sec}^2\text{/lbf}$

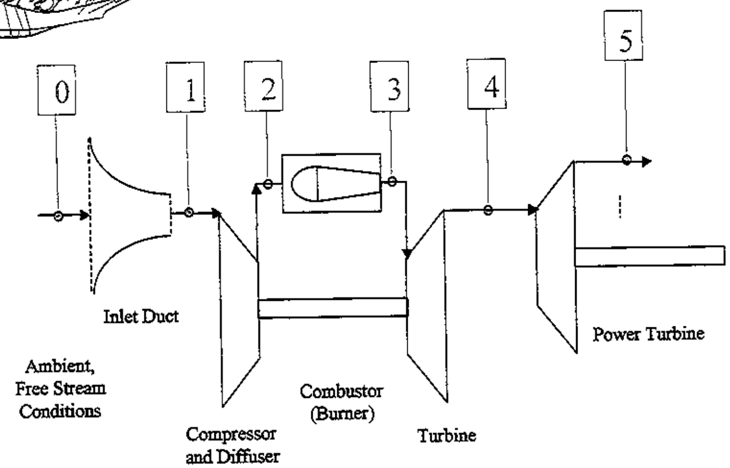
= (2* 32.167*(24.16-14.696)*144/.041)^.5 = 1034 ft/sec

Thrust is defined as $T = (m_o * V_o - m_i * V_i)$

$T = (0.91 * 1.0162)$ lbm/sec * 1034 ft/sec/32.167 $\text{lbm*ft}^2\text{/sec}^2\text{/lbf}$
= 29.72 lbf

Thermodynamic Analysis (cont)
Simple Gas Turbine Engine





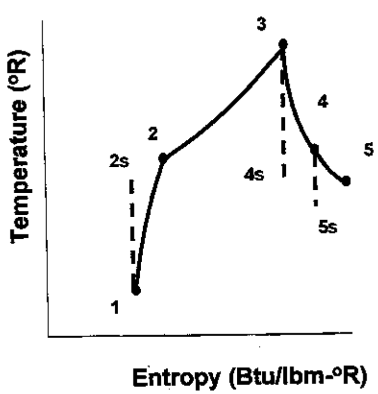
GIVEN: $P_4 = 24.16$ psia, $T_4 = 1600$ R

$P5 = 14.696$ psia

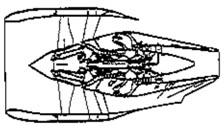
$m_4 = 0.925$ lbm/sec,

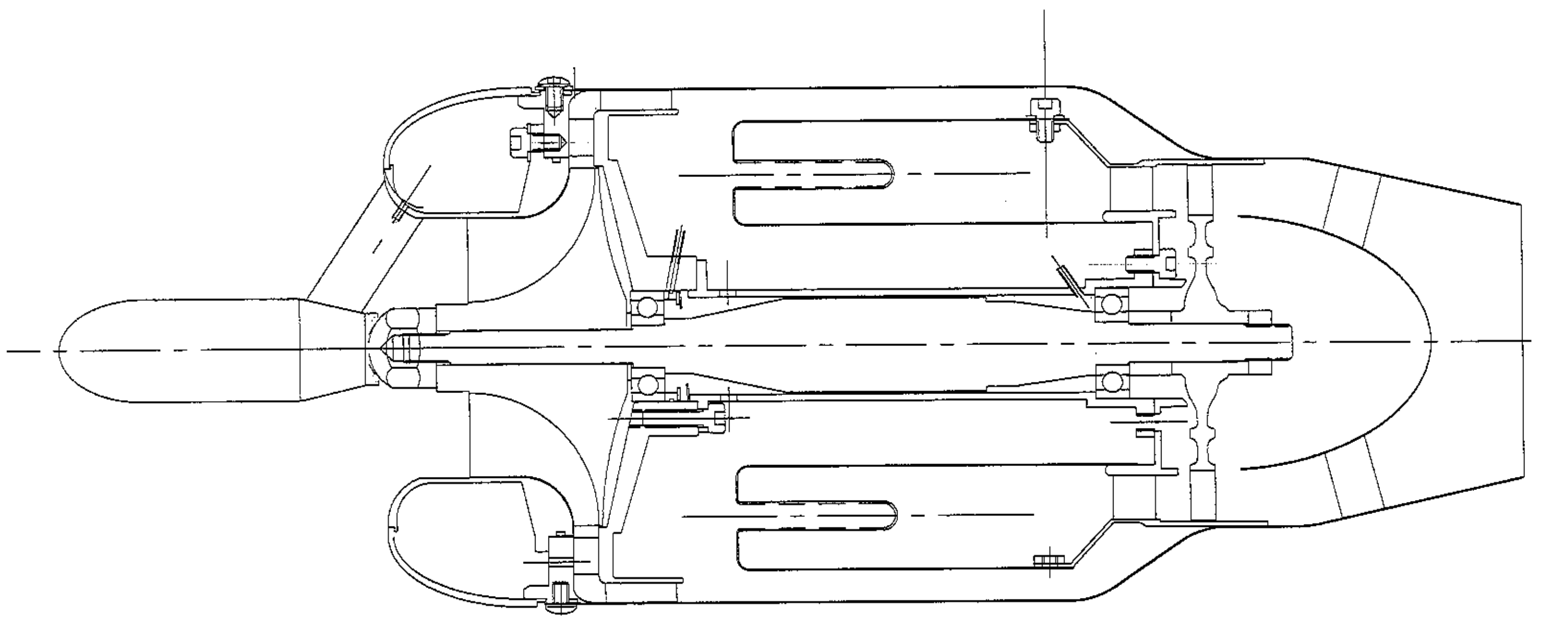
$\eta_{\text{core turbine}} = 0.87$

DETERMINE: The shaft power output of a power turbine used on the simple gas turbine engine in lieu of a jet nozzle.

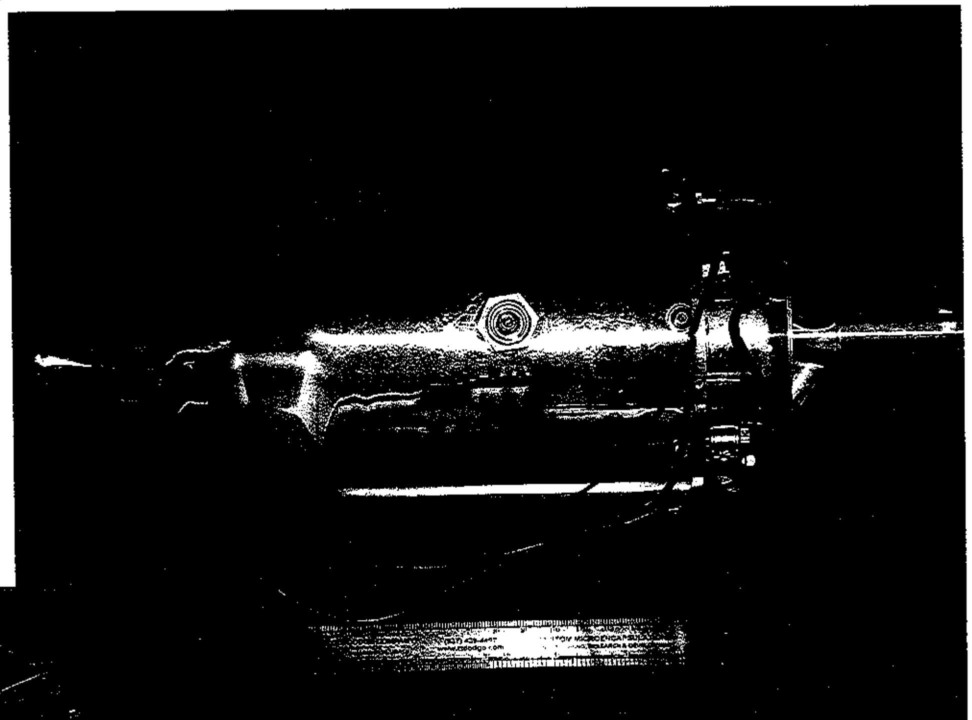


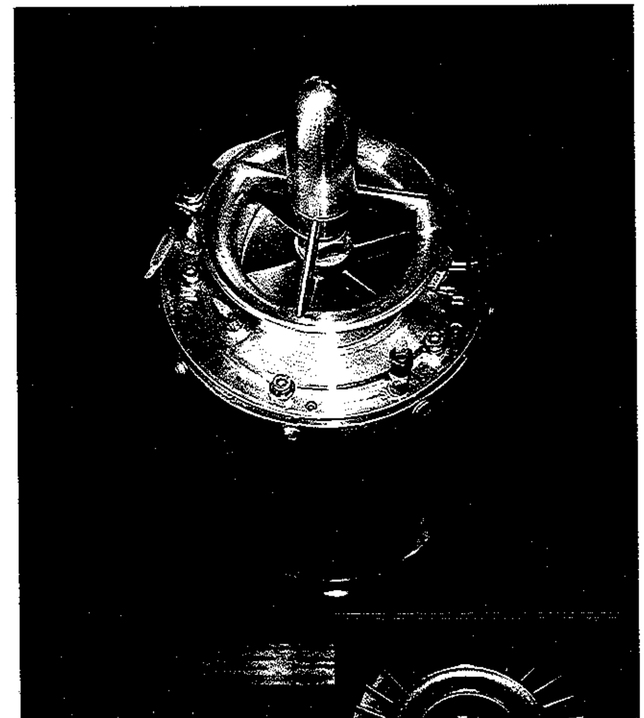
The Simple Gas Turbine Jet Engine - Cross-section

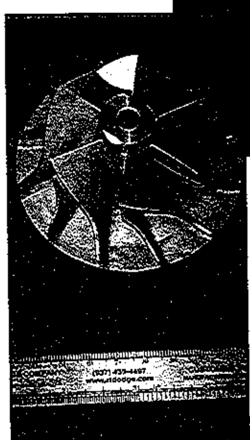


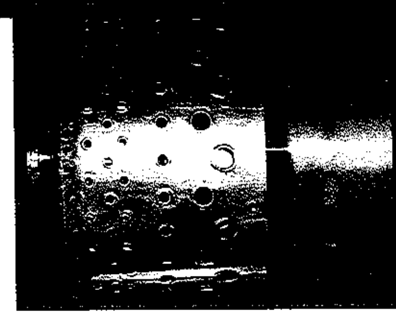


The Simple Gas Turbine Jet Engine - AMT ATT450 Turbojet

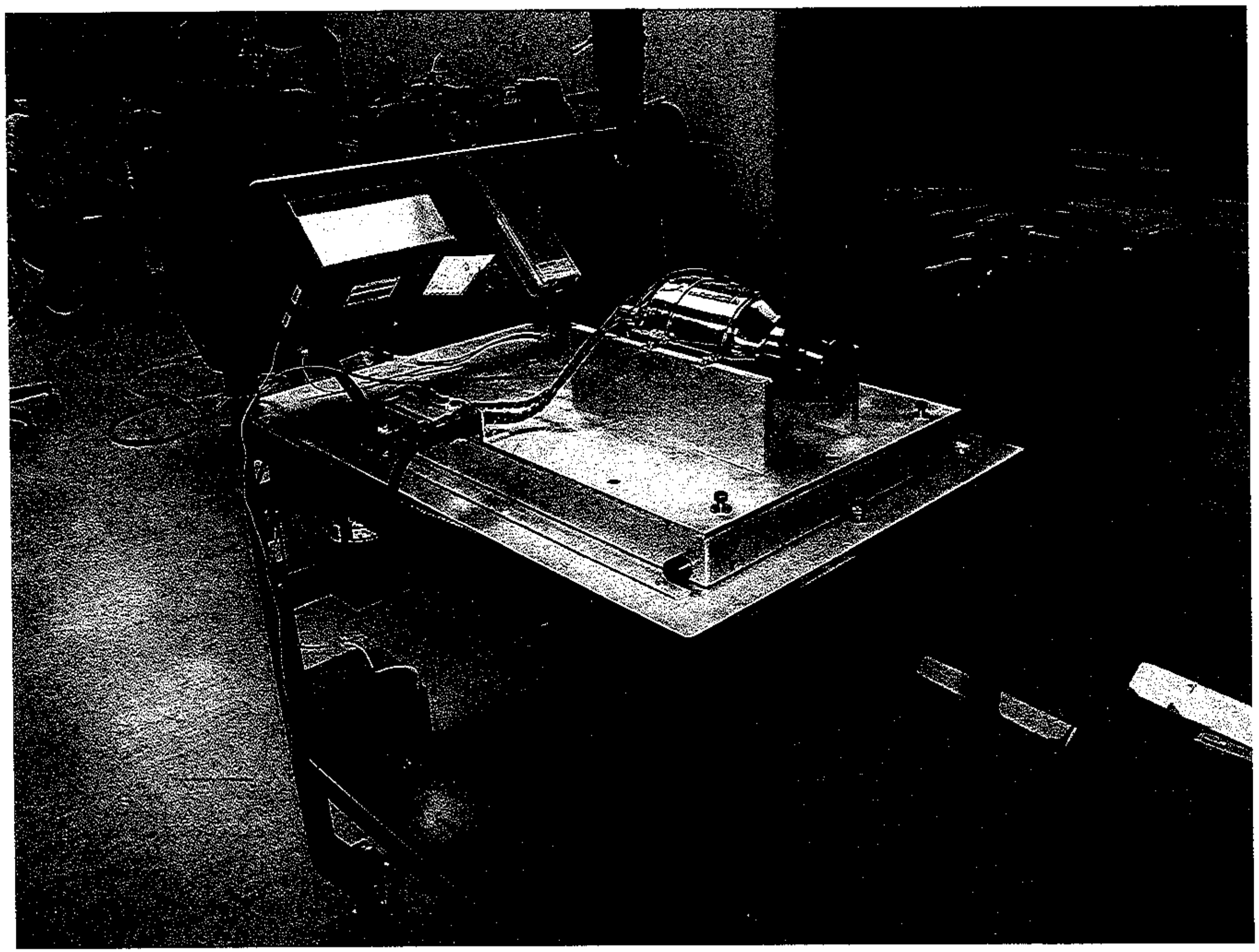




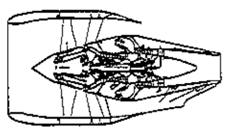




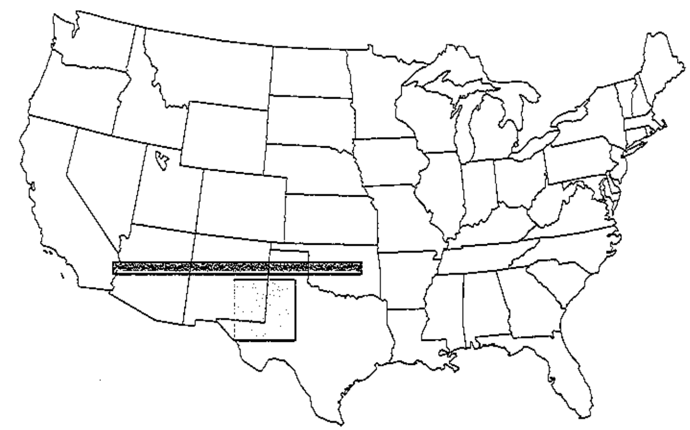
The Simple Gas Turbine Engine Model and Test Stand



SOLAR POWER IS THE USA ENERGY SOLUTION



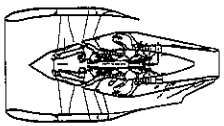
- USA USES 98 QUADRILLION BTUs OF ENERGY (IN ALL FORMS) PER YEAR
- 10^9 API THERMAL SOLAR POWER SYSTEM (TSPS) 10 kWe UNITS WOULD SUPPLY THIS NEED.
- ADDITIONAL, EXHAUST HEAT CAN DESALINATE ¼ WATER RQMTS FOR USA.
- THE CAPITAL COST IS $10-20 TRILLION.
- POWER IS PRODUCED AT 2.5 cents/kWe
- LAND AREA COMMITTED TO POWER UNITS WOULD COVER 66,000 sq/mi (2% AREA OF CONTINENTAL USA). (AVAILABLE FOR DUAL FARMING USE.)
- NO IMPORTATION ENERGY.
- ELIMINATES IMPORTS, CO_2, RADIOACTIVE WASTE, MINING/DRILLING.
- API SYSTEM USES NO STRATEGIC OR HAZARDOUS MATERIALS.



LAND COMMITTED TO API TSPS – EITHER RED-STRIP OR GREEN-SQUARE

WORLDWIDE IMPLICATIONS

- POWER INDEPENDENT OF OIL AND NUCLEAR POWER.
- POWER COST ½ TO 1/10 CURRENT SYSTEMS.
- DISTRIBUTED POWER NOT DEPENDENT ON INFRASTRUCTURE (GRID).
- DISTRIBUTED POWER INDEPENDENT OF URBAN/CENTRALIZED POLITICAL POWER. (DEMOCRACY?)
- DESALINATION OF WATER.
- REFRIGERATION FROM WASTE HEAT.
- COOKING AND HEATING IN VILLAGE ENVIRONMENT (ELIMINATION OF THE PRIME SOURCE OF DEFORESTATION IN THIRD WORLD.)
- INSTALLATION CONCEPT ALLOWS FOR USE OF 95% OF LAND UNDER UNITS FOR LIVING AND AGRICULTURAL SPACE.
- INCREMENTAL NATURE OF INVESTMENT ALLOWS FOR PHASED DEPLOYMENT OF SYSTEM, I.E., LOCAL CAPITAL SOURCES AND VILLAGES CAN AFFORD IT.
- DESIGN OF SYSTEM ALLOWS FOR MAJORITY OF STRUCTURE TO BE PRODUCED LOCALLY. HIGH VALUE SUBSYSTEMS LOW IN WEIGHT AND VOLUME AND READILY IMPORTED.



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