THE UNIVERSITY OF MICHIGAN

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NUCLEAR POWERED GAS TURBINES FOR LIGHTWEIGHT POWER PLANTS

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ABSTRACT

The suitability of closed-cycle gas turbine power plants in combination with various types of nuclear reactors is examined. Typical examples of both a heterogeneous and a homogeneous reactor power plant are presented. Weight, cost, and performance are compared for various possible fluids over a range of temperature and pressure. Comparisons are made with alternative heat engine systems.

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1.0 INTRODUCTION

Nuclear power plants, which employ high temperature nuclear heat sources coupled to closed-cycle gas turbine power generating devices, offer promise for application to light-weight power plants of relatively low power output. In conventional fossil fueled gas turbine plant design in that power range in which gas turbines are of interest, the closed-cycle is at a disadvantage with respect to open cycle units in that the closed-cycle combustor is a bulky and costly item which is required to replace the simple internal combustion heater of the open cycle. In fact, compromise semi-closed units, in which the fuel is burned internally, and continuous make-up air provided to insure adequate oxygen for combustion, have been constructed to avoid the requirement of a closed heater.[1] With a nuclear power plant, the heat source for the heat engine cycle must be a closed heat exchanger, and the simplified combustor of an open cycle is not possible in any case. Thus, one of the most important advantages of an open-cycle in a fossil-fueled plant does not apply presently to a nuclear plant.

Some of the advantages of the closed-cycle design which apply to both fossil-fueled and nuclear plants are:

1. Increased capacity for given size and/or weight
2. Wider range of loads without substantial loss of efficiency since power may be reduced by reducing pressure level without affecting temperatures, pressure ratios or speeds.
3. Reduction of size tends to control difficulties resulting from differential temperature expansions.

An advantage of closed-cycle over open-cycle units, applying only to nuclear plants, is that containment of the working fluid allows direct cooling of the reactor without the release of radioactive gas to the atmosphere. An example of the advantage of nuclear gas turbines in general over nuclear steam plants is that direct cooling of the reactor with the heat engine working fluid becomes feasible at high temperature without prohibitive pressure. A disadvantage is that fairly high temperatures (say 1200 - 1500 F) appear necessary to achieve efficiencies and capital costs comparable with steam plants.

Some of the disadvantages for the closed-cycle gas turbine as compared to the open-cycle are:

1. Water or air or some other coolant is required in the heat sink which is necessary for any closed cycle.
2. Higher internal pressures involve complicated design of heat exchangers.
3. Complex shaft sealing arrangements may be required.
4. Ability to react to rapid speed change requirements is impaired by the closed nature of the cycle.

Escher Wyss, Ltd. has developed a closed-cycle gas turbine with external combustion, whereby the working fluid for the cycle exchanges heat with the combustion gases so that no combustion products come in contact with the internal surfaces of turbines, compressors, and heat exchangers. The heat rejection for the cycle is through a precooler upstream of the compressors. With fossil-fueled units, the advantages claimed for this modification are:

1. Contaminated gases do not pass through the mechanism. Hence, corrosion is materially reduced.
2. Gases other than air can be employed without difficulty.
3. Several types of fuels may be employed in the combustion chamber.

The disadvantages of an externally-fired closed-cycle gas turbine are:

1. The gas heater, when using fossil fuels, must be very large and made of high-grade materials since hot gas at low pressure is a poor heat transfer medium.
2. The maintenance of the combustion chamber containing heat transfer tubes will be high.
3. For a given maximum temperature, the cycle efficiency is reduced by stack losses and degradation of energy in the heat exchanger.

With a nuclear heat source, such a power plant offers advantages which cannot be achieved with fossil-fueled firing. The ultimate achievement of a nuclear heat source coupled with a closed-cycle gas turbine is dependent largely upon the success by which materials can be developed so that high temperatures, which may be generated by fission, can be transferred directly to a suitable working fluid. Nuclear properties of the fluid, as well as thermodynamic properties, are important in order to produce the highest percentage of useful work in terms of the heat power generated by nuclear fissions. Possibilities exist for a closed-cycle gas turbine working fluid extracting heat directly from reactor fuels, providing such working fluid does not become irradiated to the extent that major biological shielding is required for the power plant as well as for the nuclear reactor.

A number of plants, ranging from a 500 hp research unit to a 12,500 kw plant for central station duty, have been built using fossil fuels as the energy source.[2] Recently a number of organizations in conjunction with the Atomic Energy Commission and the U. S. Maritime Administration have undertaken preliminary studies to delineate the engineering parameters and evaluate technical and economic feasibilities of nuclear powered gas turbines. Recent publications have presented data and information on open and closed-cycle systems with potential nuclear heat sources for application to packaged reactors, and large and small gas turbine reactor plants.[2]

Nuclear powered closed-cycle gas turbines can be coupled with a heterogeneous fuel element nuclear heat source from which the working fluid extracts heat and flows directly through the closed cycle gas turbine system and then returns to the reactor. Alternatively, a second promising type of nuclear reactor for this purpose would be the high temperature liquid metal homogeneous fueled reactor of the general type being developed by Brookhaven National Laboratories in which the gaseous working fluid heat exchanges with circulating fissioning fuels. This paper endeavors to discuss specific examples of both a heterogeneous and a homogeneous reactor in conjunction with a closed-cycle gas turbine. Although there are numbers of variations for both heterogeneous and homogeneous high temperature reactors, specific examples of each are discussed in terms of the thermodynamic parameters and the requirements for the efficient conversion of heat to energy in such a plant. An attempt is made to delineate the trends of the variations in efficiency, size, weight, and cost of closed cycle gas turbine systems as affected by working fluid, temperature, pressure, and plant size, and to afford rough comparisons between closed-cycle gas turbines and alternative heat engine types which might be utilized.

An application as a packaged power plant generating electrical power and process steam in locations where the electrical power requirements are in the range from 5,000 to 30,000 kw, and where steam requirements are in the range of 10,000 to 70,000 lbs. per hour at 250 psig, has been selected for discussion. While many other applications are possible, a nuclear powered closed-cycle gas turbine power plant of this type has tremendous technical and economic potential in many remote locations of the world where fossil fuel costs are high, or where multiple utilizations of thermal heat can be made simultaneously. An example of such a multiple purpose reactor would be a chemical plant or a petroleum refinery where requirements are for chemical heat, space heat, process steam, and electrical power. Such an installation would also provide a convenient source of nuclear radiation, if such were of use in the process.

1.1 Simplified Closed-Cycle Gas Turbine Power Plant With a Nuclear Heat Source

A schematic flow diagram representing a typical system for a nuclear heat source coupled to a closed-cycle gas turbine is given in Figure 1. The operation of this cycle is as follows: The working fluid serves as the reactor coolant, and enters the reactor at a given pressure and temperature. As it flows through the reactor, it extracts the heat generated by the fission process so that the outlet gas leaving the heat source is at a temperature suitable for efficient gas turbine operation. The gas serving as the working fluid is expanded in a high pressure turbine which provides the mechanical energy to drive low and high pressure compressor units. Starting equipment and auxiliary electrical generating equipment might well be attached to this shaft. The gas leaves the high pressure turbine and is expanded a second time in a low pressure turbine to provide the maximum of mechanical work for driving an electrical generating unit. Upon leaving the low pressure turbine, the gas exchanges heat in a recuperator with the gas stream re-cycling to the reactor. The gas leaving the recuperator is then at the lowest pressure level of the system. In order to close the cycle, it is necessary to extract heat from the working fluid prior to compression in a precooler. The gas is cooled to as low a temperature as is practicably possible by an external coolant such as water or air. The cooled gas then enters into a low pressure compressor unit. To achieve maximum cycle efficiency, an intercooler between the compressors seems desirable. The cooled gas

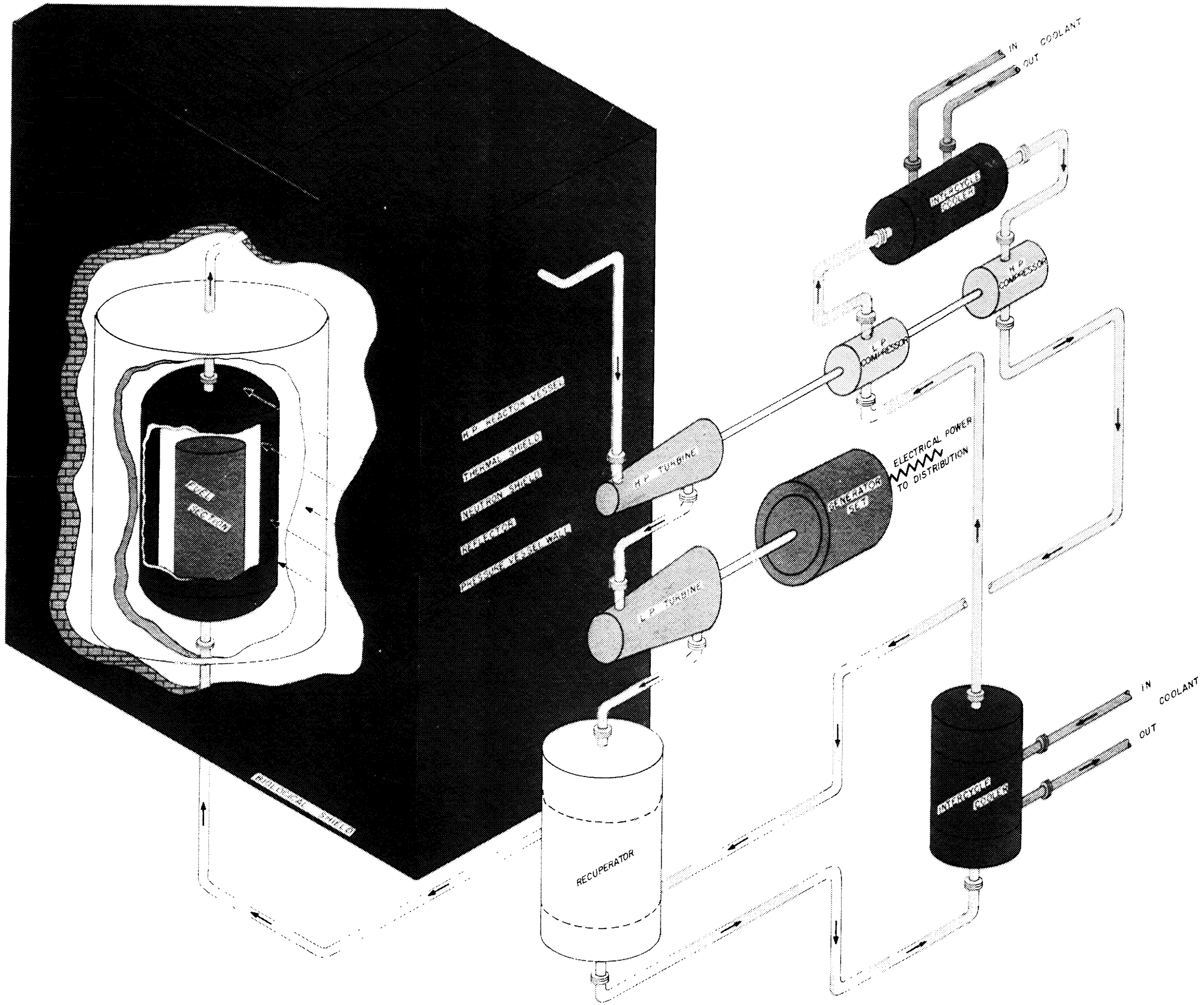

Fig. 1 SIMPLIFIED NUCLEAR POWERED GAS TURBINE SYSTEM
CLOSED CYCLE TYPE

then enters the high pressure compressor and is compressed to a pressure adequate to overcome the pressure drops through heat exchangers, ducts, valves and fittings, and reactor, as well as the expansion in the turbines. The high pressure gas again flows through the recuperator, exchanging heat with the gas exhausted from the low pressure turbine so that the temperature of the high pressure stream is raised to a level satisfactory for the operation of the nuclear reactor, and suitable for minimum required heat addition.

With such a nuclear heat source, heat sink, coolers, recuperators, turbines and compressors, a number of process variables involving nuclear and thermodynamic parameters must be considered to optimize the system. The general equation for the thermal efficiency of a closed-cycle gas turbine plant of this type is:

$$\eta_{th} = \frac{T_R \, \eta_T \left[1 - (\eta_p P_R)^{-\gamma}\right] - \frac{2}{\eta_c} (P_R^{\gamma/2} - 1)}{T_R \left\{1 - \eta_R + \eta_R \, \eta_T \left[1 - (\eta_p P_R)^{-\gamma}\right]\right\} + \frac{\eta_R - 1}{\eta_c} (P_R^{\gamma/2} + \eta_c - 1)} \qquad (1.1)$$

The meaning of the symbols is listed under Nomenclature. It is noted from this equation that for equal component efficiencies, the overall thermal efficiency is not a function of pressure level, power output, or gas molecular weight. It is a function, however, of pressure ratio, temperature ratio, and the ratio of specific heats* of the working fluid. The influence of these various factors as well as the effect of pressure and power levels upon component efficiencies, and hence, upon overall thermal efficiency, is discussed further in a later section.

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* If a compressor temperature ratio, say T_{R_c}, were used instead of pressure ratio, the above equation becomes:

$$\eta_{th} = \frac{T_R \, \eta_T \left[1 - (\eta_p)^{-\gamma} T_{R_c}\right] - \frac{2}{\eta_c} (T_{R_c}^{1/2})}{T_R \left\{1 - \eta_R + \eta_R \, \eta_T \left[1 - (\eta_p)^{-\gamma} T_{R_c}\right]\right\} + \frac{\eta_R - 1}{\eta_c} (T_{R_c}^{1/2} + \eta_c - 1)}$$

It is then noted that the dependence of η_{th} on γ is only through η_p. η_p is the ratio between required pressure ratios for compressor and turbine to overcome the duct and heat exchanger pressure losses.

2.0 CLOSED-CYCLE GAS TURBINE PERFORMANCE CHARACTERISTICS

In the design of a closed-cycle gas turbine system there are to be considered not only the choice of fluid and pressure and temperature levels, but also the question of cycle arrangement. Generally, there is the possibility of using high pressure-ratio cycles with a minimum of regeneration, or alternatively low pressure-ratio with maximum regeneration to achieve high efficiency. This choice constitutes an unresolved issue, since conventional plants of either type are being and have been designed and constructed. However, the closed-cycle, in which a maximum mean working fluid density is to be obtained at low pressure ratio, and in which the size of heat exchanger components is drastically reduced by the high fluid density, appears to favor the low pressure ratio, highly regenerative cycle. Also regenerative cycles, at their own optimum efficiency pressure ratios, which may be as low as say 3.0, attain the highest thermal efficiencies. For these reasons, the regenerative cycle has been emphasized in these studies. As previously explained, Figure 1 is a flowsheet of the cycle under consideration. Included are heat source, heat sink, single intercooler, regenerator, compressor, and turbine. A possible variation would be the inclusion of reheat. For the cycle of Figure 1, the thermal efficiency is given by equation 1.1 previously shown. Using this relation as a basis, it can be shown that for equal component efficiencies and available temperature limits, a larger ratio of specific heats, under these assumptions, results in:

1. Reduction of peak efficiency
2. Movement of peak efficiency point to lower pressure ratio
3. Increase of the sensitivity of efficiency to pressure ratio.

Thus, helium or any monatomic gas under these conditions appears less favorable than air or nitrogen or any diatomic gas, which in turn, are less favorable than a polyatomic gas such as carbon-dioxide. These trends are illustrated in Figure 2. It is noted that the effect increases at low temperature. For example, at 900°F maximum cycle temperature, for the component conditions specified on the figure, there is a decrease of about 2% points out of 22 between carbon-dioxide and helium. At 1500°F, the decrease is only about 1 point out of 41. Of course, for a given capital investment in machinery, a higher overall efficiency may be obtainable with helium, for example, than with air because of its more favorable heat transfer and/or duct pressure drop characteristics.

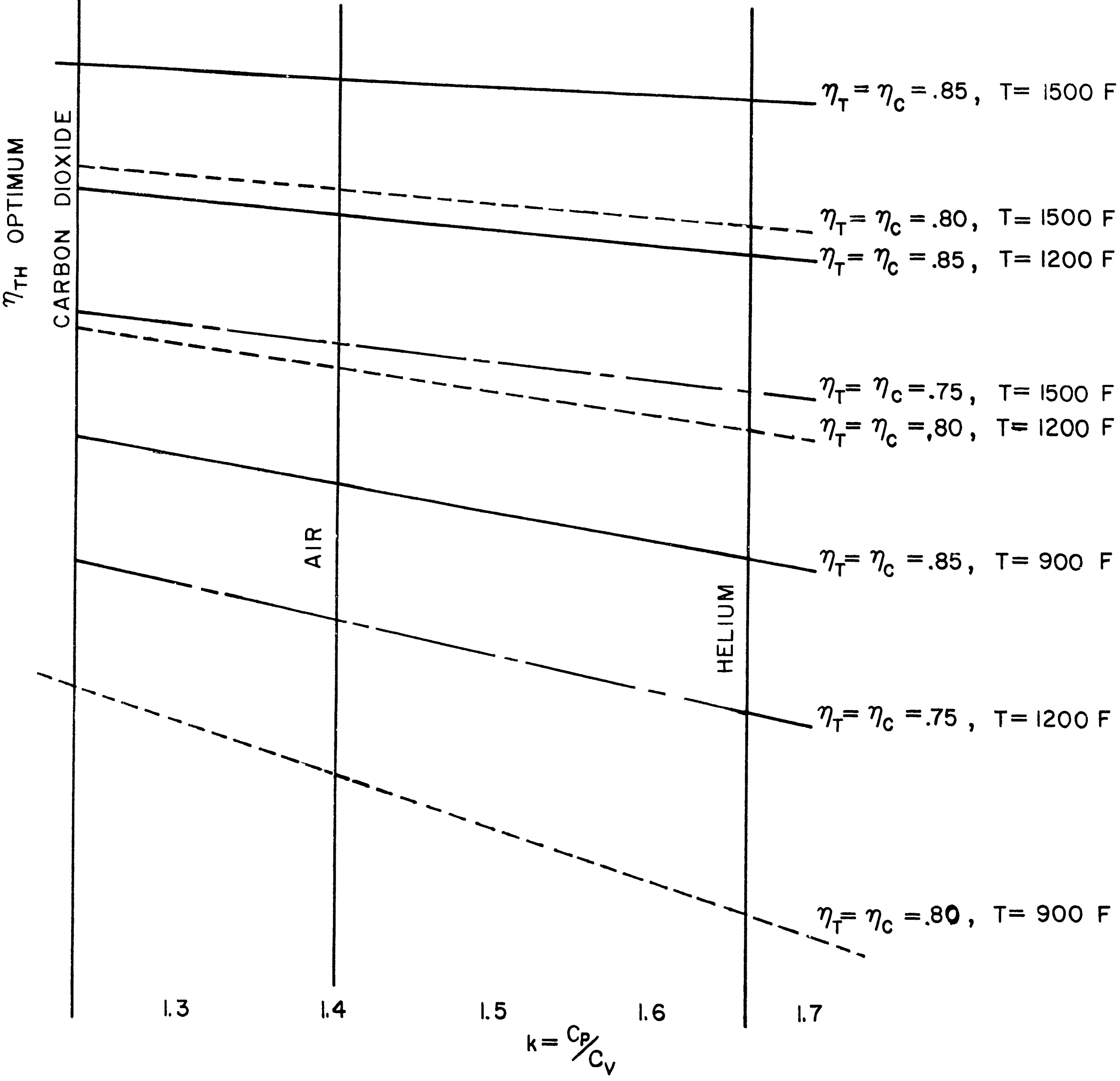
Thermal efficiency increases strongly with temperature while volumetric flow decreases. It is for these reasons that temperatures at least in excess of 1200°F seem necessary. Regenerator effectiveness, and heat exchanger and duct pressure losses, are also important parameters to which cycle efficiency is very sensitive. The effect of these is shown in Figures 3 to 8 for both a diatomic and a monatomic gas. The calculations are based on a "Basic Cycle." The component efficiencies and revelant data for this cycle are listed in Table I.

It is noted from Figures 3, 4, and 5 that at 1200°F, for example, for the "Basic Cycle" for air, there is a decrease of about 7% points in maximum thermal efficiency (i.e: from 0.345 to 0.275) as the regenerator effectiveness drops from 0.93 to 0.75, and a further loss of about 4 points for an effectiveness drop to 0.50. At the same time the pressure ratio for

FIG. 2 THERMAL EFFICIENCY AT OPTIMUM PRESSURE RATIO AS A FUNCTION OF THE RATIO OF SPECIFIC HEATS.
BASIC GAS TURBINE POWERPLANT WITH REGENERATOR AND INTERCOOLER.

RATIO OF SPECIFIC HEATS FOR WORKING FLUIDS VARIED.
INLET TEMPERATURE= 1500 F, 1200 F, and 900 F
REGENERATOR EFFECTIVENESS= .93
DISCHARGE TEMPERATURE= 90 F
DUCT AND HEAT EXCHANGER PRESSURE LOSSES= .07

CODE: ———————— TURBINE AND COMPRESSOR EFFICIENCY= .85
– – – – – – – – TURBINE AND COMPRESSOR EFFICIENCY= .80
———— – – ———— TURBINE AND COMPRESSOR EFFICIENCY= .75



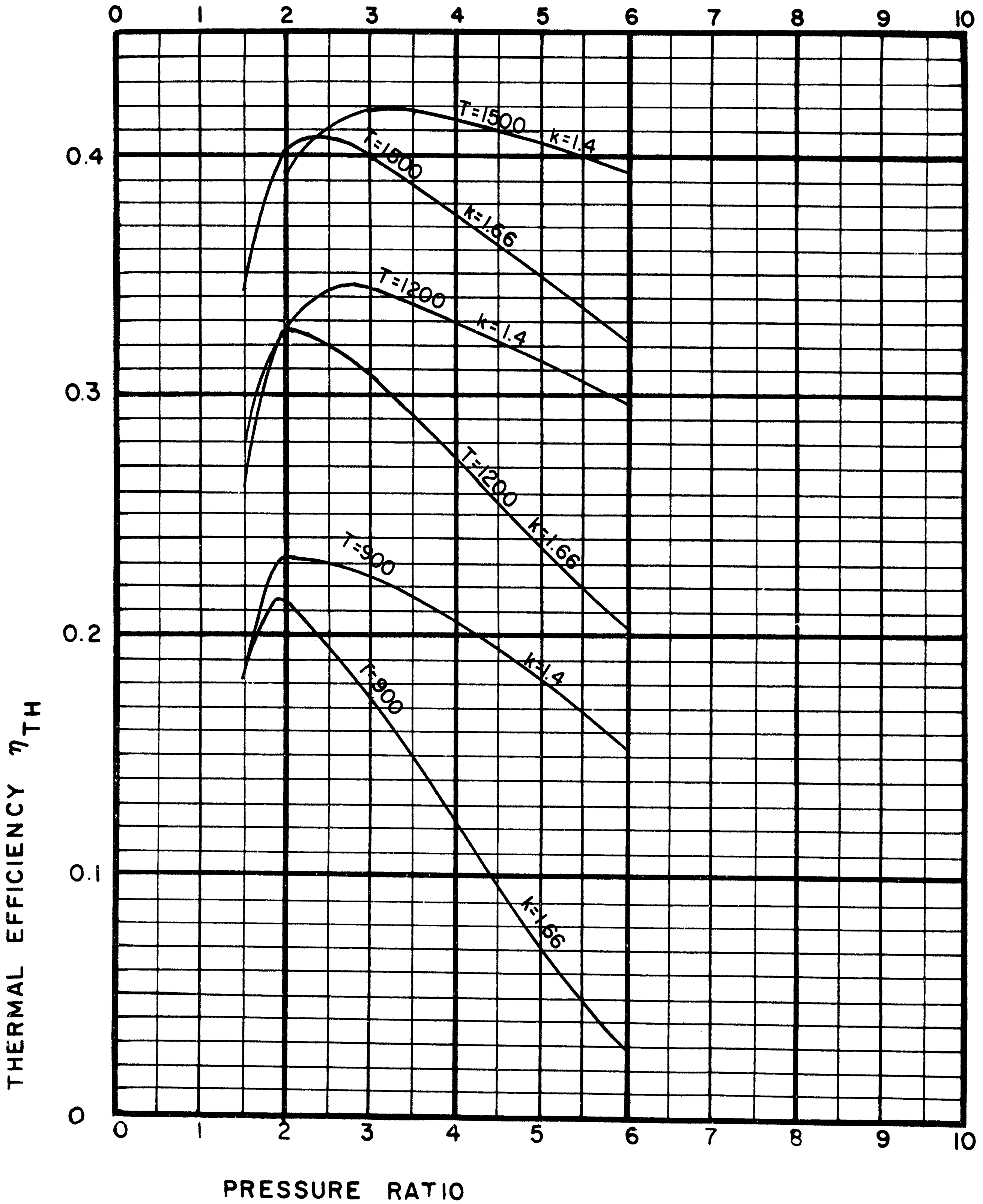


FIG. 3 THERMAL EFFICIENCY OF A "BASIC" GAS TURBINE CYCLE WITH RECUPERATOR EFFECTIVENESS = 0.93 , AND FRICTIONAL PRESSURE LOSS = 0.07

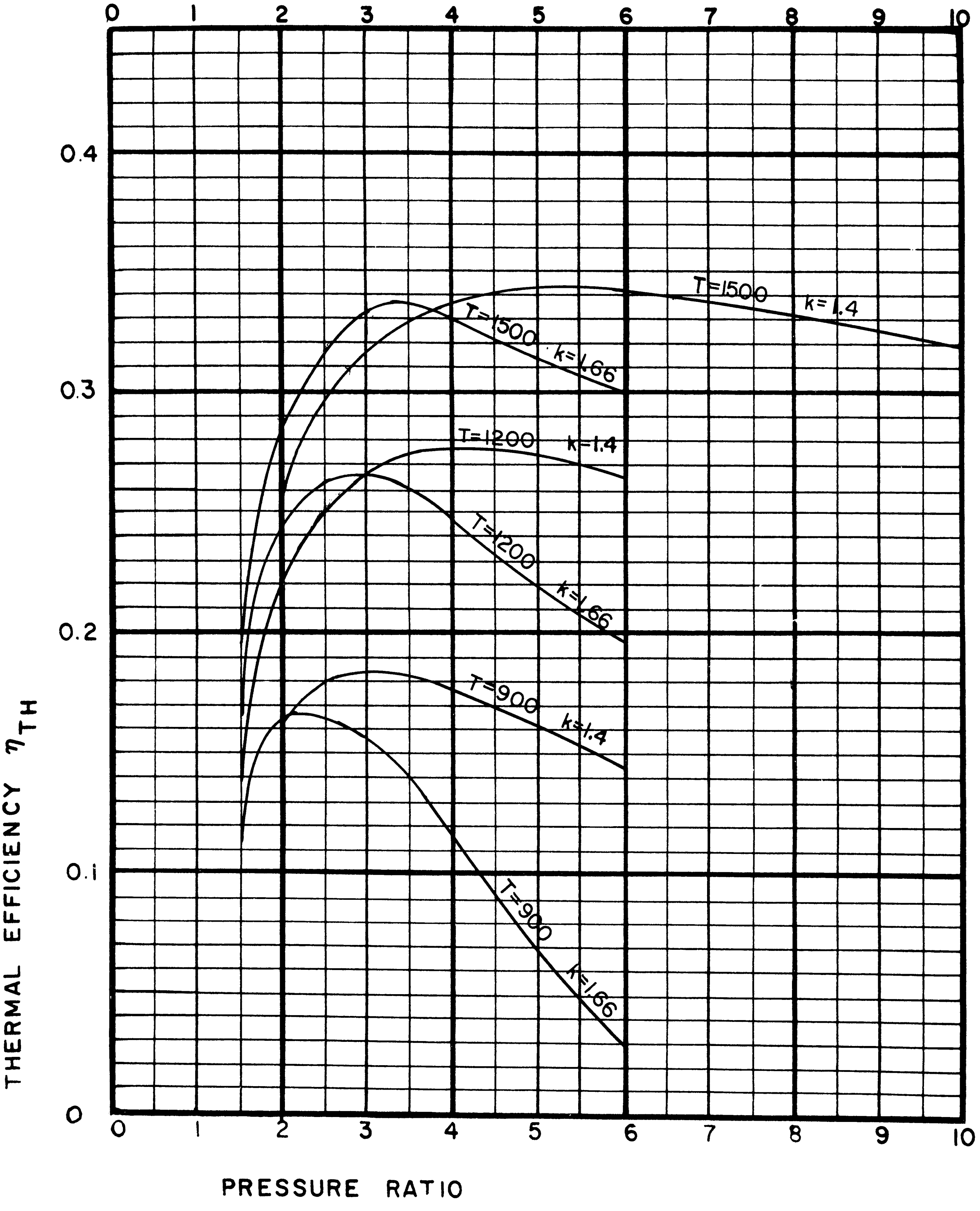


FIG. 4 THERMAL EFFICIENCY OF A "BASIC" GAS TURBINE CYCLE WITH RECUPERATOR EFFECTIVENESS = 0.75

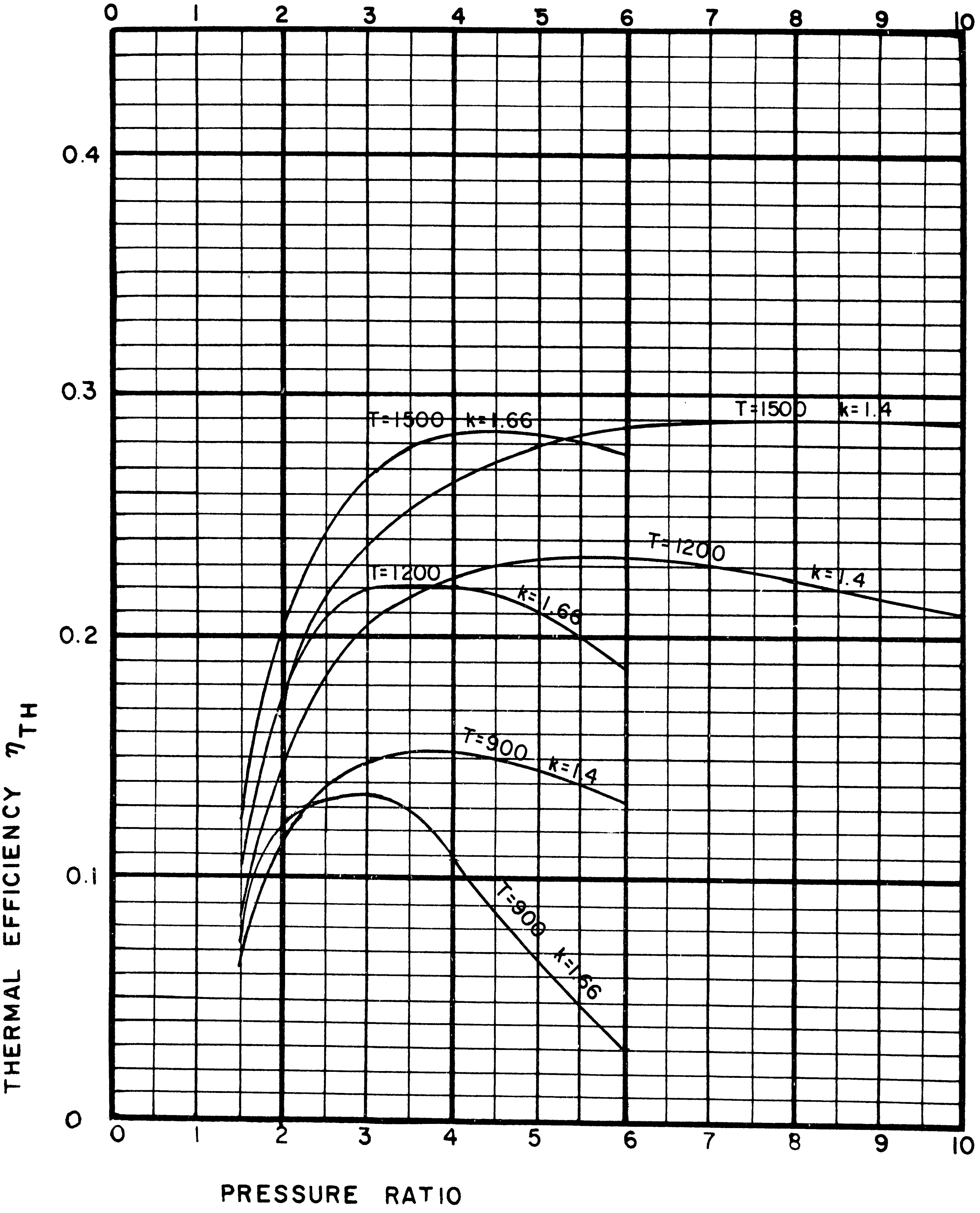


FIG. 5 THERMAL EFFICIENCY OF A "BASIC" GAS TURBINE CYCLE WITH RECUPERATOR EFFECTIVENESS=0.50

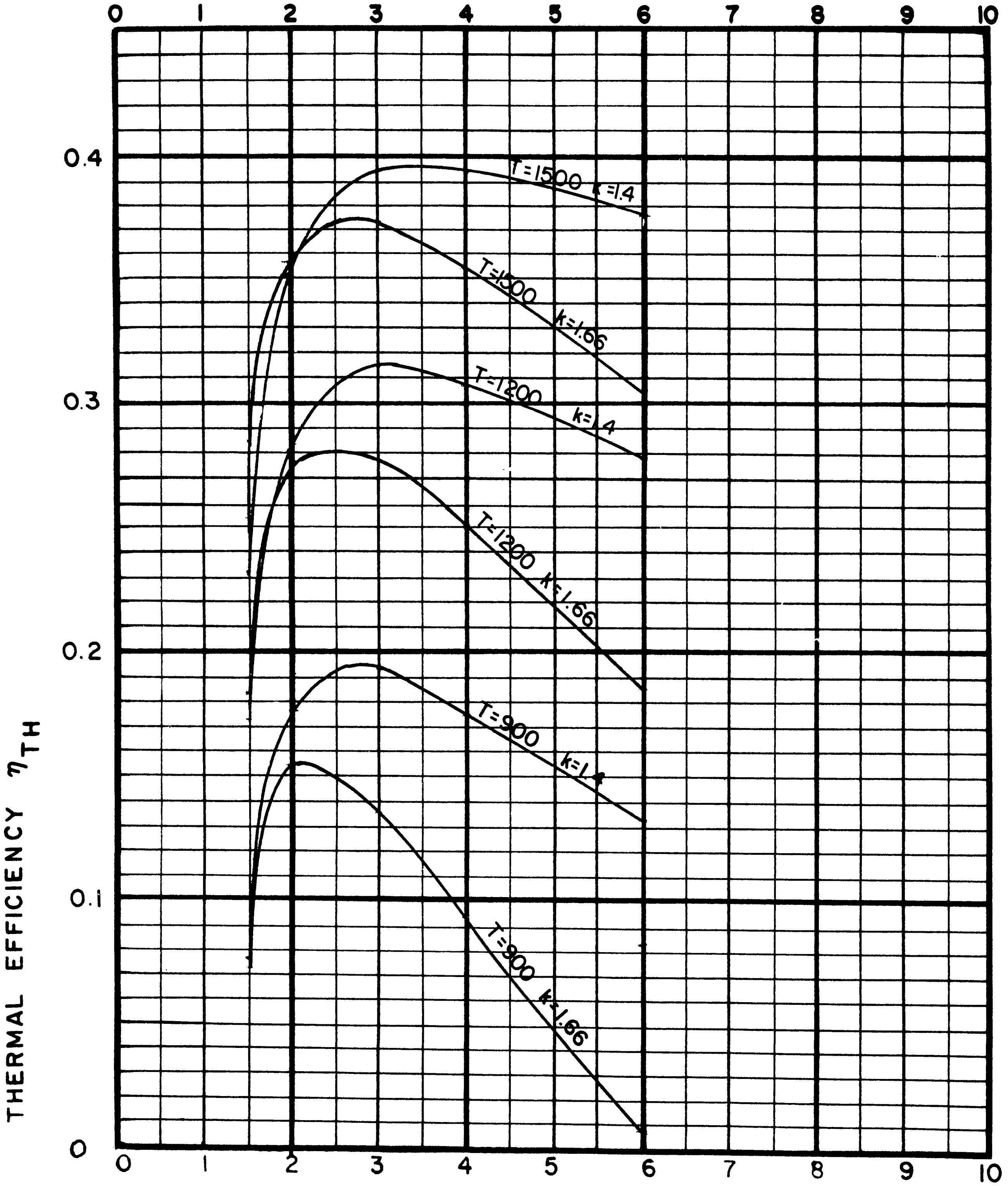


FIG. 6 THERMAL EFFICIENCY OF A "BASIC" GAS TURBINE CYCLE WITH FRICTIONAL PRESSURE LOSSES = 0.12

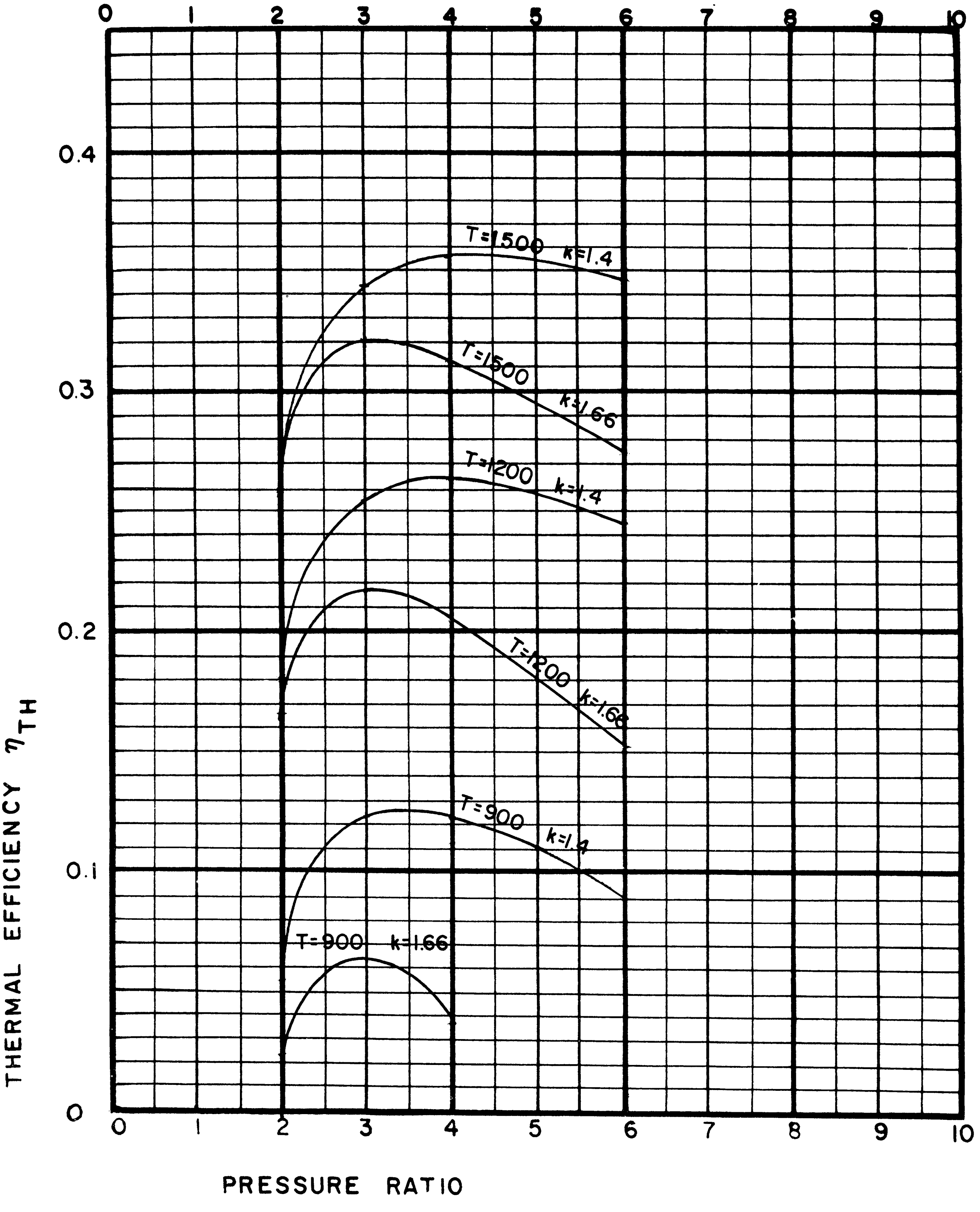


FIG. 7 THERMAL EFFICIENCY OF A "BASIC" GAS TURBINE CYCLE WITH FRICTIONAL PRESSURE LOSSES=0.20

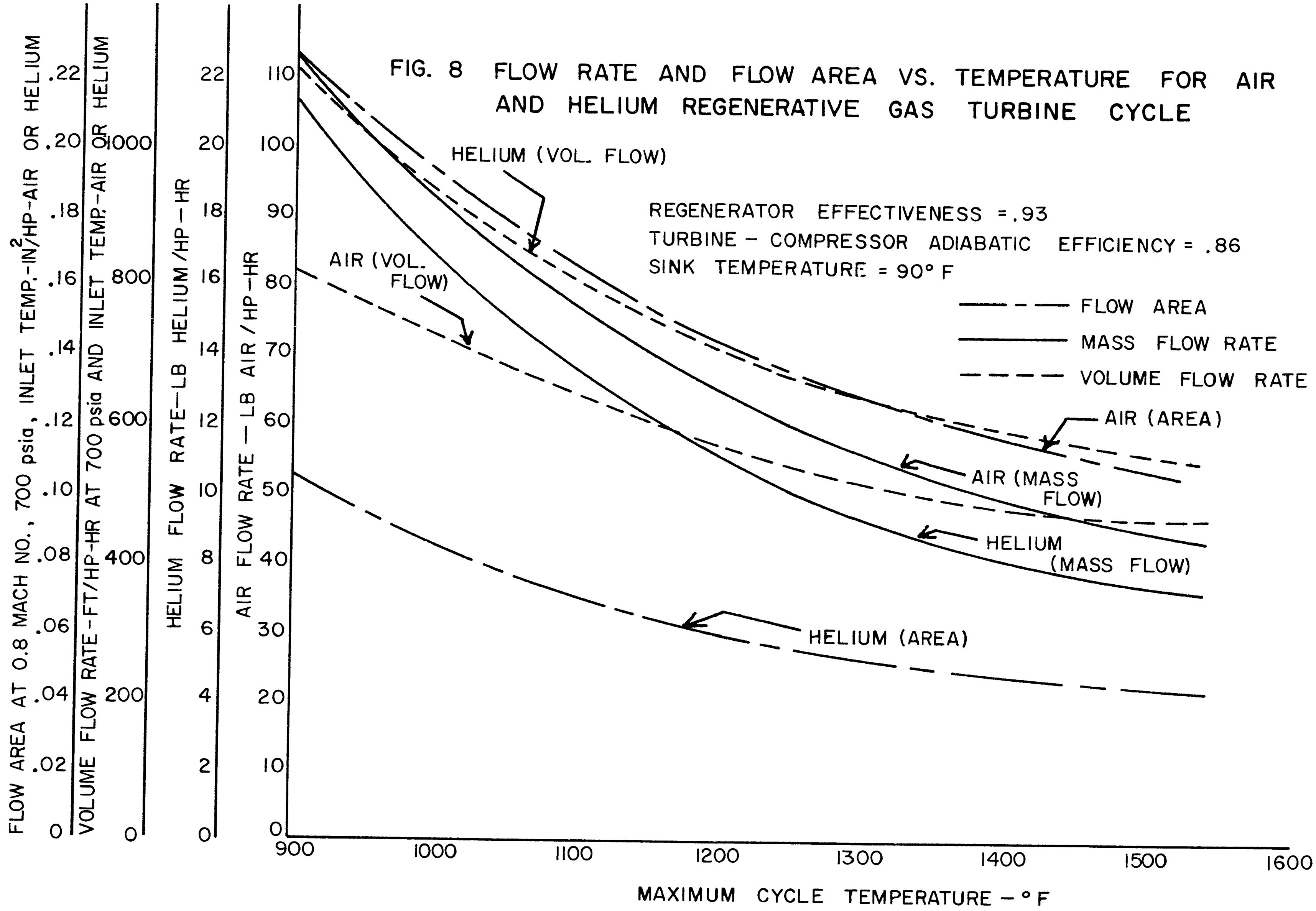


FIG. 8 FLOW RATE AND FLOW AREA VS. TEMPERATURE FOR AIR AND HELIUM REGENERATIVE GAS TURBINE CYCLE

REGENERATOR EFFECTIVENESS = .93
TURBINE - COMPRESSOR ADIABATIC EFFICIENCY = .86
SINK TEMPERATURE = 90° F

maximum efficiency shifts from about 2.7 to about 5.5. At 1500°F the efficiency losses are similar. The loss of efficiency for a drop in regenerator effectiveness from 0.93 to 0.75 is about 7.5 points out of an initial value of 0.42, and the further loss to 0.50 effectiveness is 6 points. The maximum efficiency pressure ratio shifts from 3.3 for 0.93 regenerator effectiveness to about 8 for 0.50 effectiveness.

Figures 3, 6, and 7 show the effect of an increase in frictional pressure losses around the cycle. This is measured as an increase in the required ratio between turbine expansion and compressor compression ratios. For the "Basic Cycle" of Figure 3, this ratio is 0.93. If it is decreased to 0.88, there is an efficiency loss of about 2-1/2% points for air at 1500°F, and 3 points at 1200°F. A further decrease of the ratio to 0.80 reduces the 1500°F efficiency by an additional 4% points, and the 1200°F efficiency by 5 points. Thus, the effect becomes proportionately more serious for lower temperature cycles. In the process, the maximum efficiency pressure ratio is increased although not so substantially as for reduction of regenerator effectiveness.

In both instances, the effects with helium are similar. It will be noted, however, that the loss in efficiency for helium with increased frictional pressure drops is much more serious than for air.

Figure 8 shows the variation of relative mass flow, volumetric flow, and cross-sectional flowpath area with temperature assuming a given allowable Mach number for both air and helium. It is noted that there is approximately a 2.7 to 1 increase of mass flow requirement between 1500°F and 900°F, a 1.9 to 1 increase in volume flow (as measured at the maximum cycle temperature) and a 2.2 to 1 increase in flow path area, measured at maximum cycle temperature, for a fixed Mach number for either air or helium. It is believed that the last index is probably most closely related to the size of the various components.

While helium holds approximately a 6 to 1 advantage in mass flow over air for a 1200°F cycle, there is a disadvantage in volume flow of 1.2 to 1. However, due to a much higher sonic velocity, the advantage in flow path area is 2.4 to 1. This probably is the most accurate indication of relative machine sizes.

The foregoing does not include the effect of power output and pressure level. In an actual plant, the efficiency which may be attained by the turbomachines is a function at least of Reynold's number, flow path dimensions (leakage effects, etc.), and Mach number. These, in turn, depend upon the power output and pressure level as well as, to some extent, a compromise between mechanical design factors (thermal stress problems, etc.) and optimum flowpath considerations. A generalized study cannot attempt to predict the precise efficiencies which will be attainable for any given set of design conditions. However, an attempt can be made to indicate the trend of efficiency with operating pressure and power level, and thus, to guide to some extent the choice of the pressure level in the design of a plant for given output.

A study of this type has been carried out at the University of Michigan for plants utilizing air and helium respectively for power outputs ranging between 600 hp and 60,000 hp, and pressure levels from 45 psia for a 3:1 pressure ratio open-cycle to 1000 psia for a closed cycle over a range of inlet temperatures. The resulting curves of efficiency versus output are included in Figures 9 through 14. It is noted that there is a fairly sub-

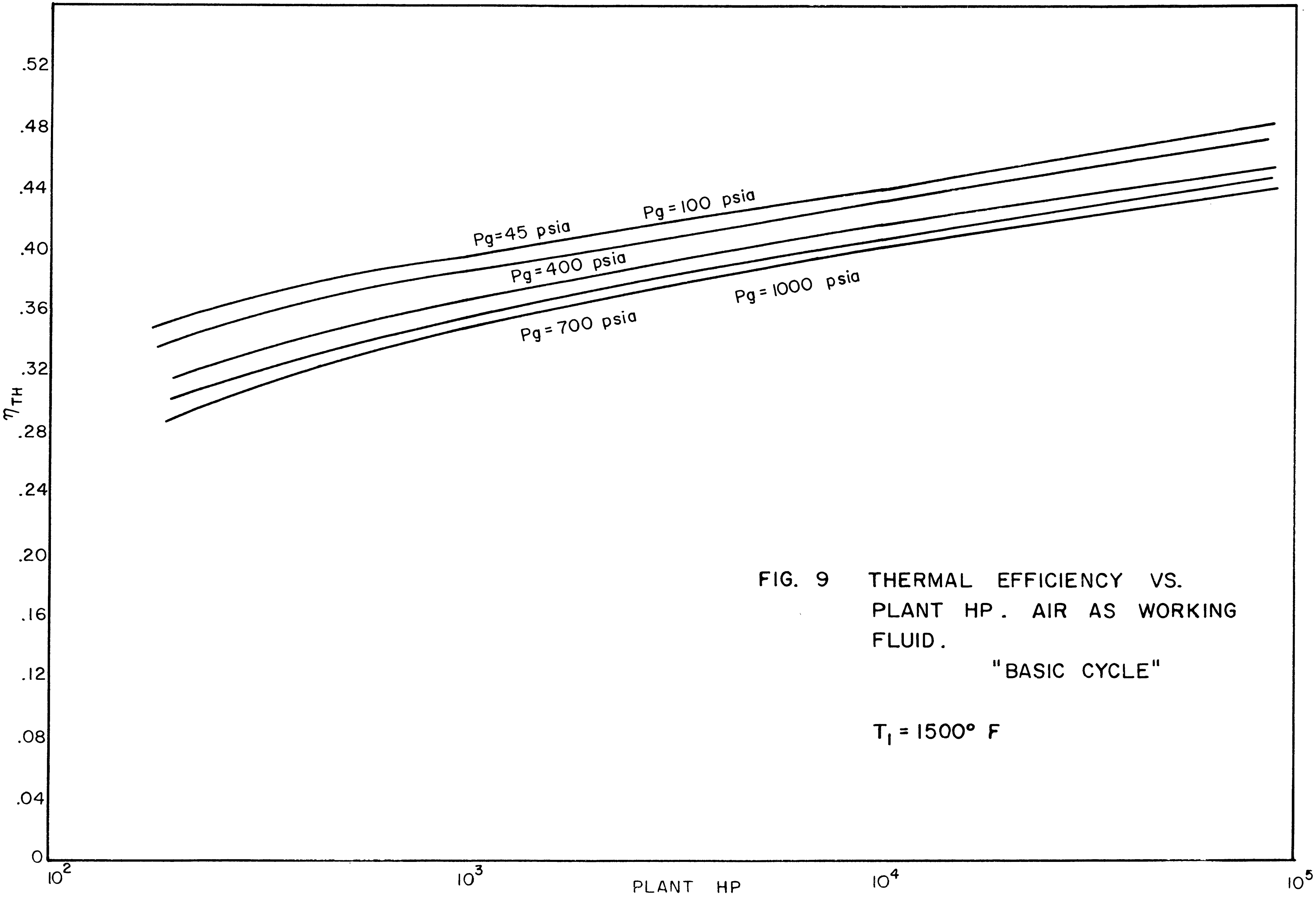


FIG. 9 THERMAL EFFICIENCY VS. PLANT HP. AIR AS WORKING FLUID.

"BASIC CYCLE"

$T_1 = 1500°\ F$

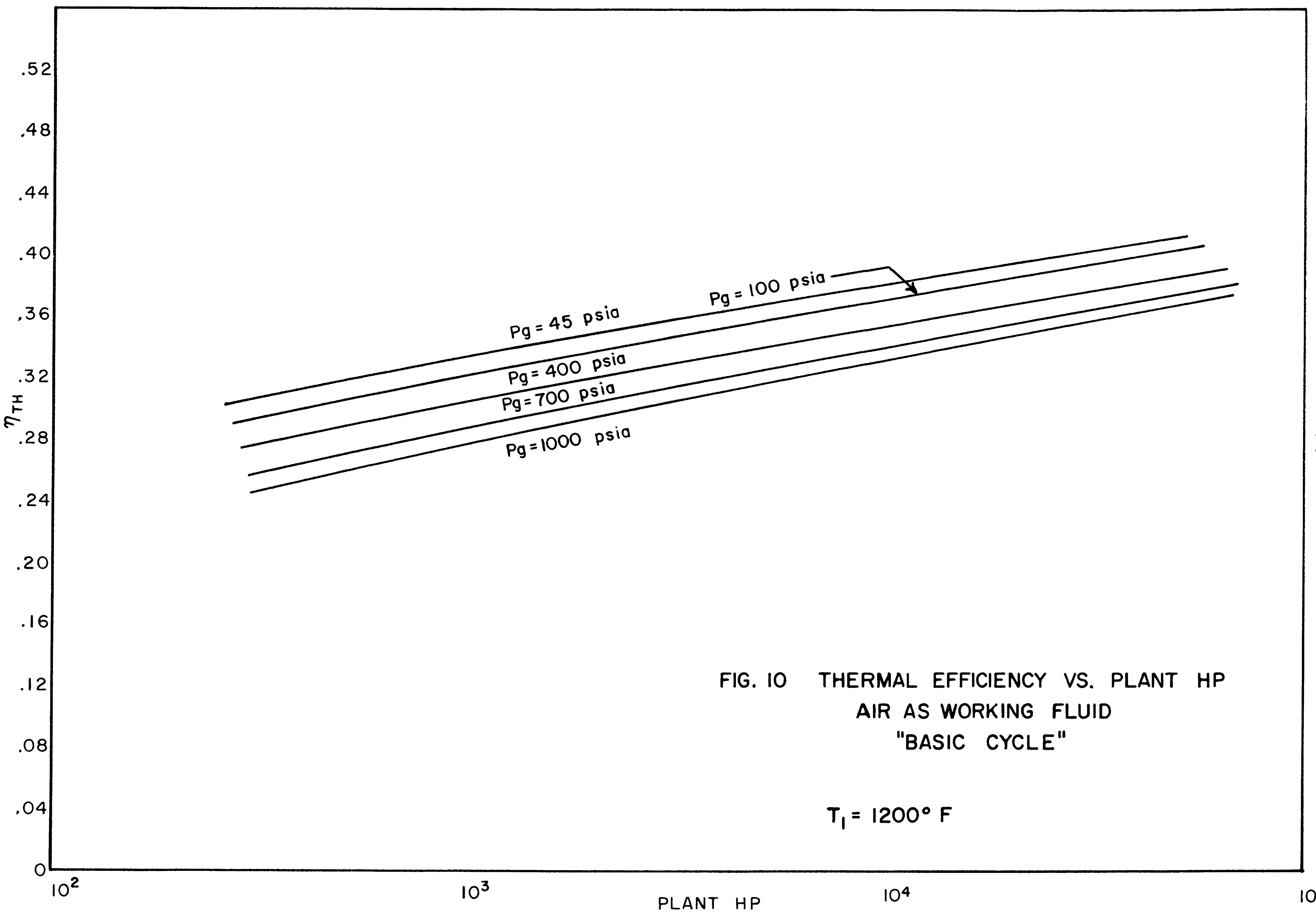


FIG. 10 THERMAL EFFICIENCY VS. PLANT HP
AIR AS WORKING FLUID
"BASIC CYCLE"

$T_1 = 1200°$ F

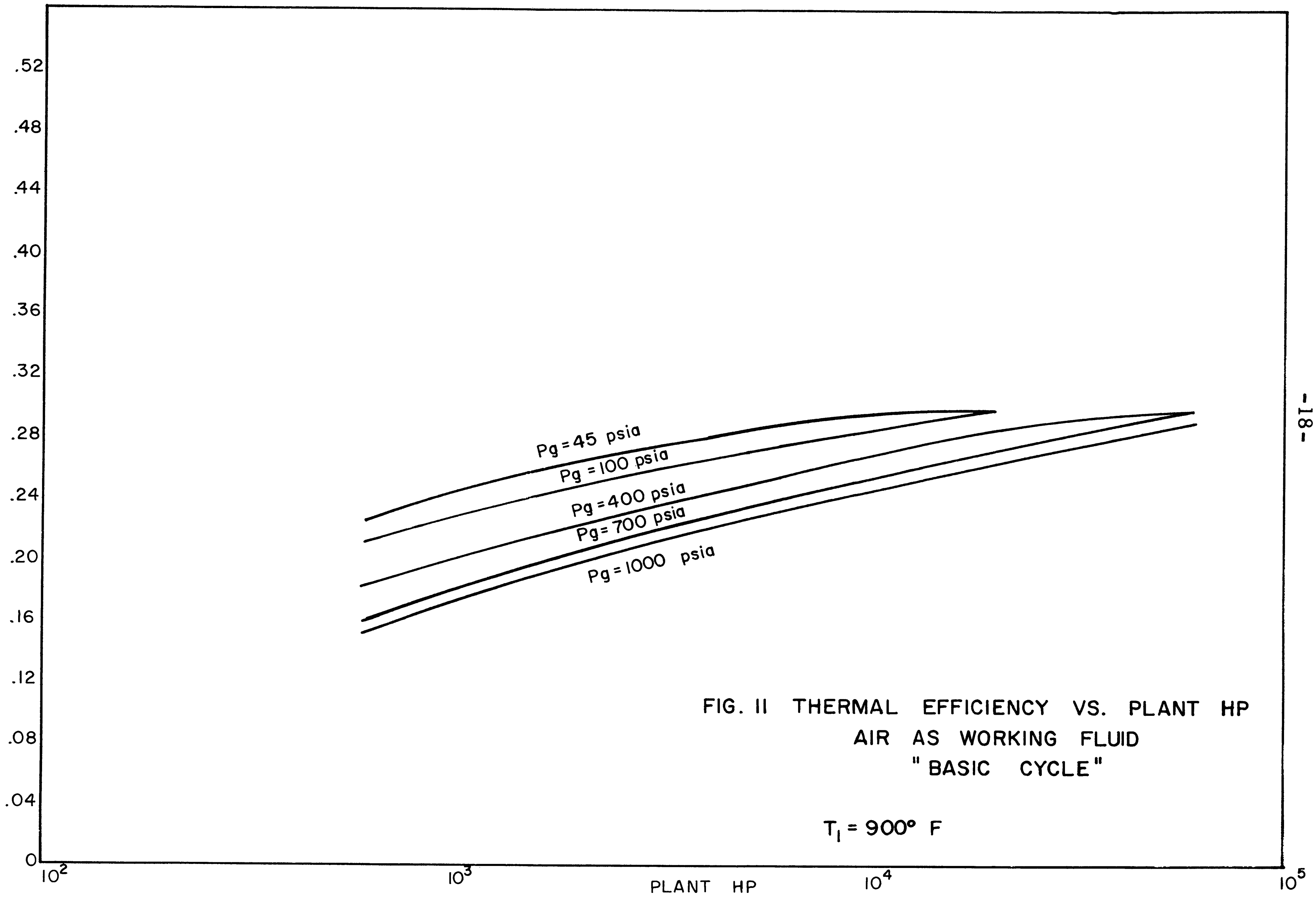


FIG. II THERMAL EFFICIENCY VS. PLANT HP
AIR AS WORKING FLUID
"BASIC CYCLE"

$T_1 = 900°$ F

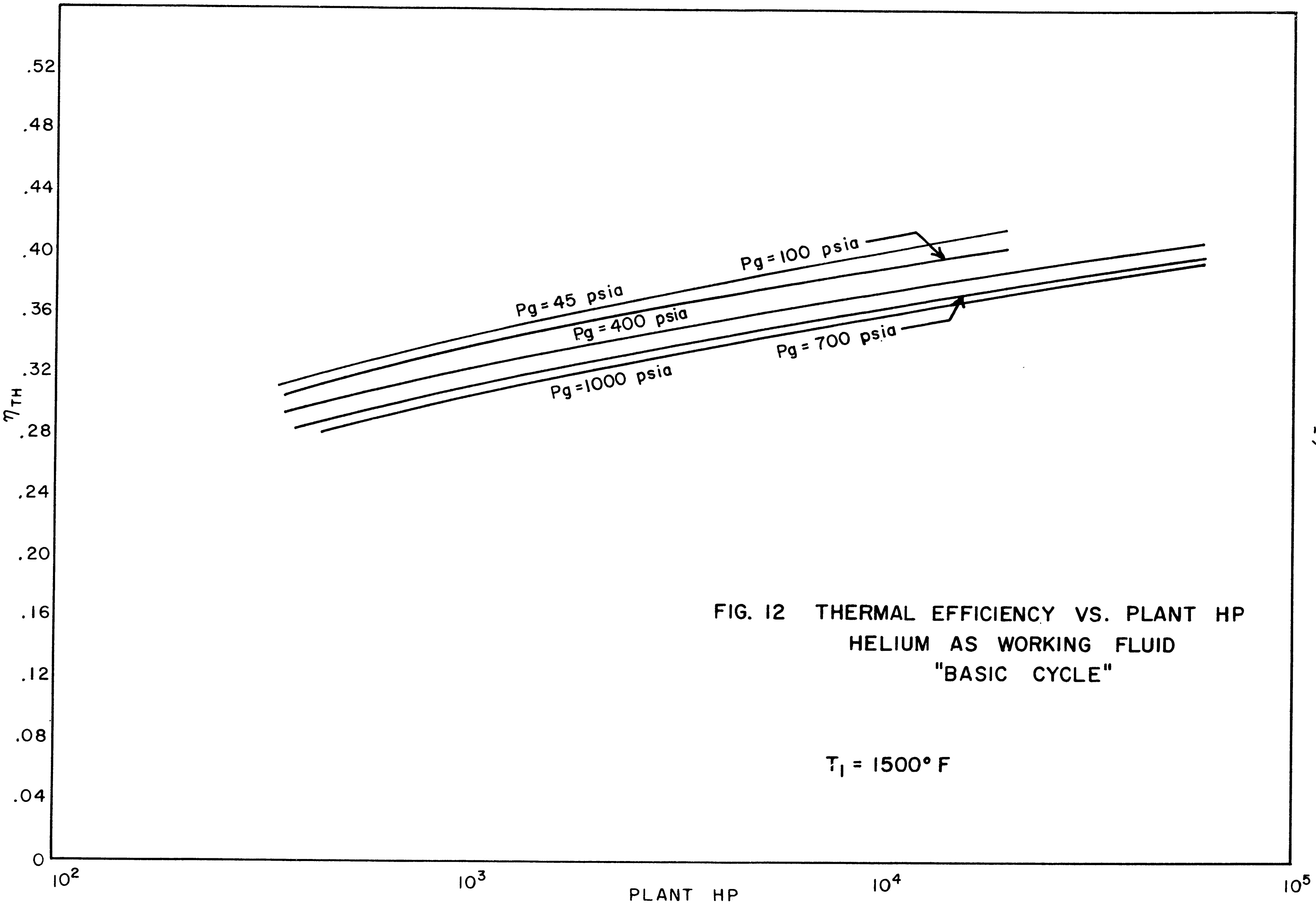


FIG. 12 THERMAL EFFICIENCY VS. PLANT HP
HELIUM AS WORKING FLUID
"BASIC CYCLE"

T_1 = 1500° F

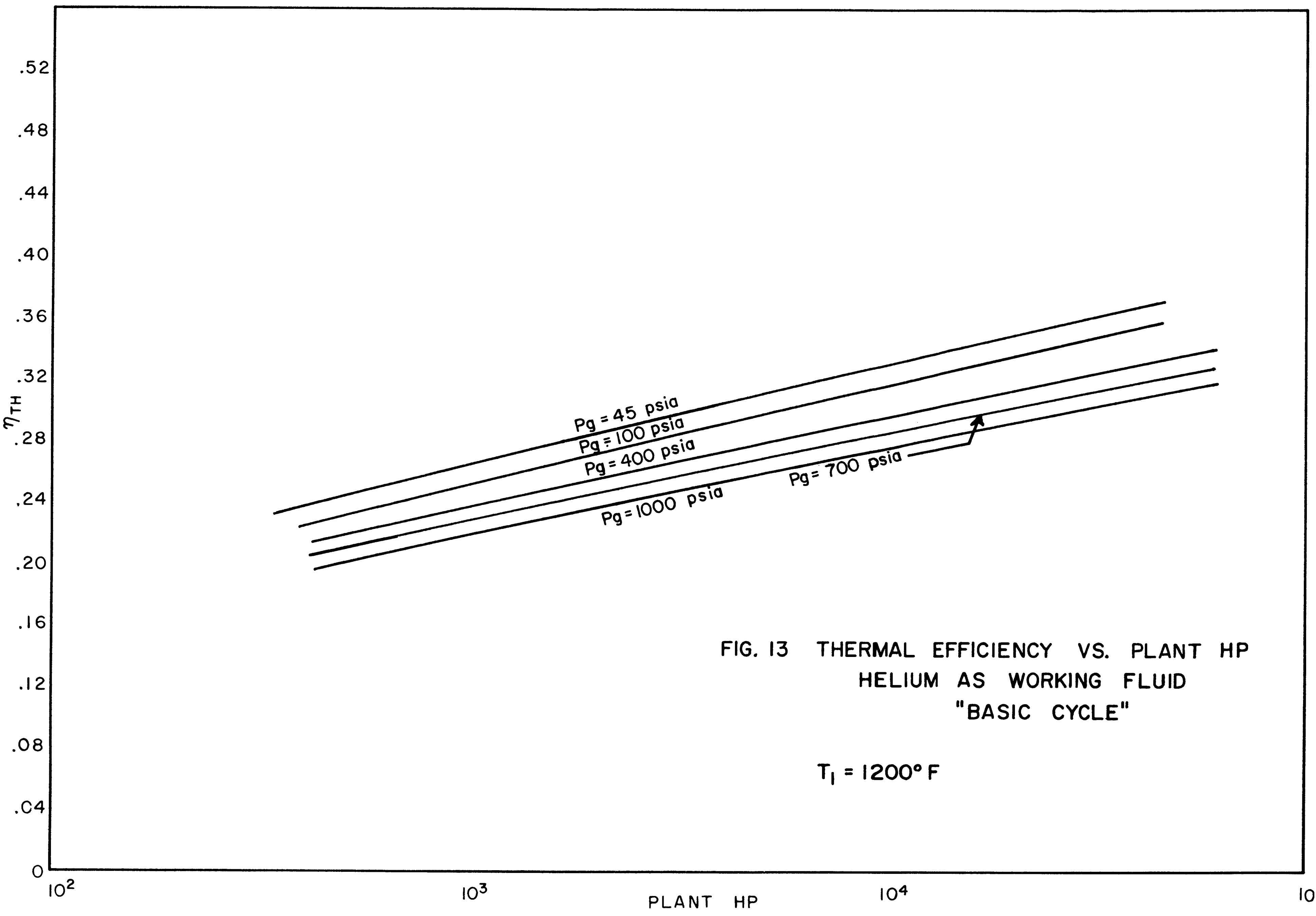


FIG. 13 THERMAL EFFICIENCY VS. PLANT HP
HELIUM AS WORKING FLUID
"BASIC CYCLE"

$T_1 = 1200°F$

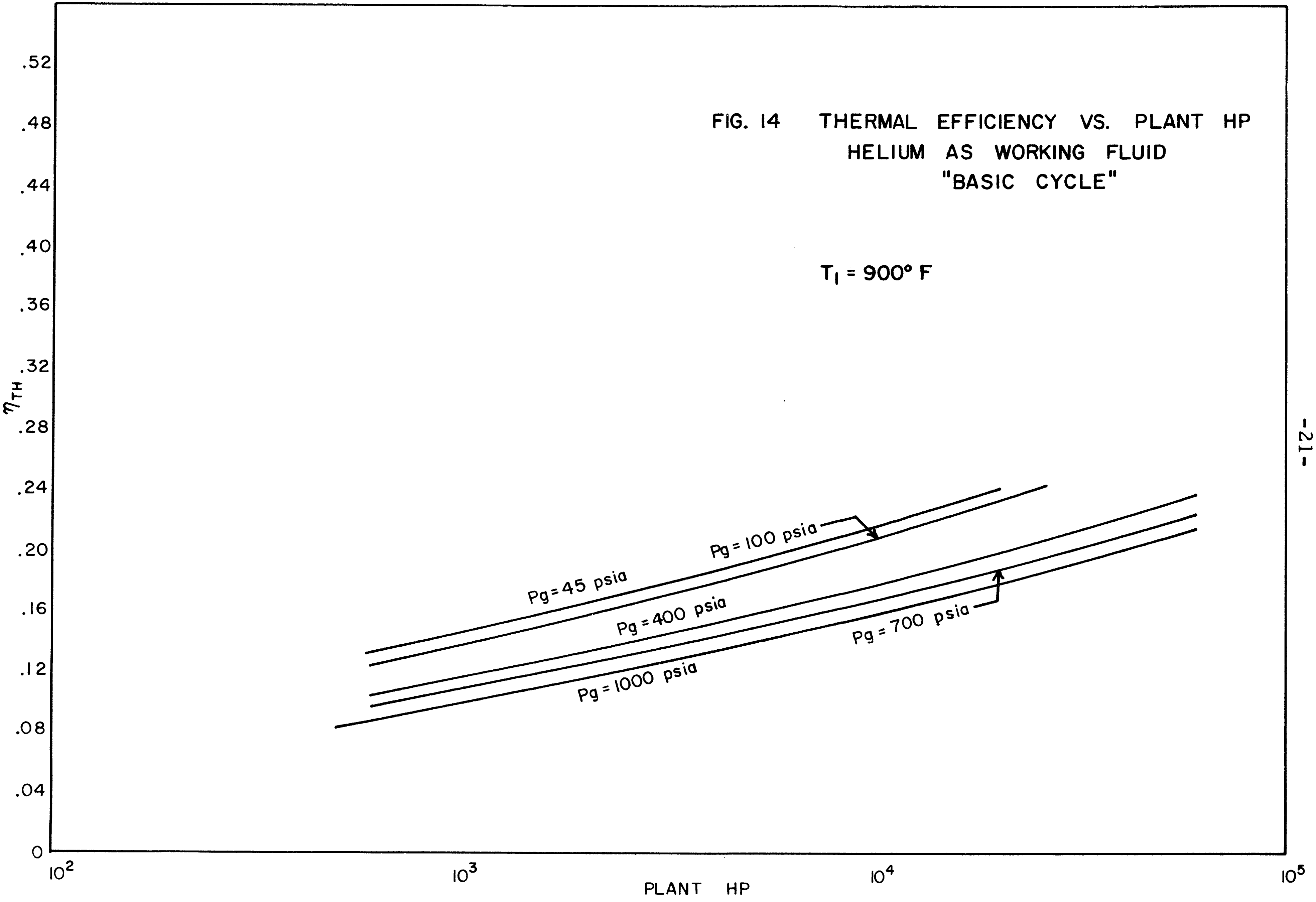


FIG. 14 THERMAL EFFICIENCY VS. PLANT HP
HELIUM AS WORKING FLUID
"BASIC CYCLE"

$T_1 = 900°$ F

stantial reduction of efficiency for any power level with increasing pressure. This is attributed to the fact that although Reynold's numbers are increased with the higher densities achieved by increasing pressure (for a constant velocity and flow rate, Reynold's number is roughly proportional to the square root of pressure, since density is directly proportional and hydraulic diameter inversely to the square root of pressure), the influence on the efficiency of the decrease in machine size, through all factors, as abstracted from reference 4, is greater. There is also a substantial reduction of efficiency with plant output.

It is noted, for example, that a decrease of thermal efficiency from about 0.395 to about 0.35 is shown for a 1200°F air plant at 20,000 hp as maximum cycle pressure is increased from 45 psia to 1000 psia. Also a decrease from 0.395 to about 0.335 is shown for a 1200°F air plant with 45 psia maximum pressure as the design output is decreased from 20,000 to 1000 hp. The corresponding decrease at 1000 psia is from 0.35 to 0.275. Similar results are obtained at the other temperatures, and also for helium. While it is certainly possible to design plants for a range of efficiencies for any of the conditions investigated, it is believed that these results are fairly representative of the trends which will be encountered.

The cycle calculations are based on the conditions of the "Basic Cycle" (Table I) except that the turbine and compressor efficiencies are varied according to the operating conditions, and a 3% radiation heat loss is included.

For the larger sized units these results are based on the compressor and turbine velocity diagrams shown in Figures 15 and 16. Thus, the Mach number effects are the same for all units. The variation of blading loss coefficients is taken from reference 3. The overall compressor efficiency is taken from reference 4 for conventional atmospheric air machines for units of various size. Corrections according to the blade loss coefficients for the various Reynold's numbers are then applied to the basic efficiency of the applicable air unit. Since turbine efficiencies should vary according to the same relations, it was assumed that for the large units, turbine and compressor efficiencies could be considered equal,* at least from the viewpoint of indicating the trend. An arbitrary cut-off of component efficiency at .90 was assumed regardless of Reynold's number since it was felt that practicality considerations rule out machines of extremely large dimensions.

For the smaller machines, centrifugal compressors or positive displacement units such as the Lysholm-type were assumed below 2000 CFM. Efficiencies were extrapolated from reference 4. It is realized that there is a wide variation in efficiency for machines of these types, but again, the results should be illustrative of the trends. Turbine efficiency for the smaller units was estimated by direct computation of typical machines using the blade coefficient data of reference 3, and computing reasonable leakage, windage, and bearing losses. It was assumed that a 5-inch diameter, 5/8-inch blade height represented an approximate practical minimum. If flow rates were insufficient to provide full flow for such a wheel at the velocities corresponding to the diagram (Figures 15 and 16), it was assumed that all velocities were reduced proportionately as required.

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* This is an attempt to balance the higher efficiency inherently attainable with a turbine for a given blading design against the likelihood of a reduction in number of stages for mechanical simplicity of this high temperature component.

TABLE I

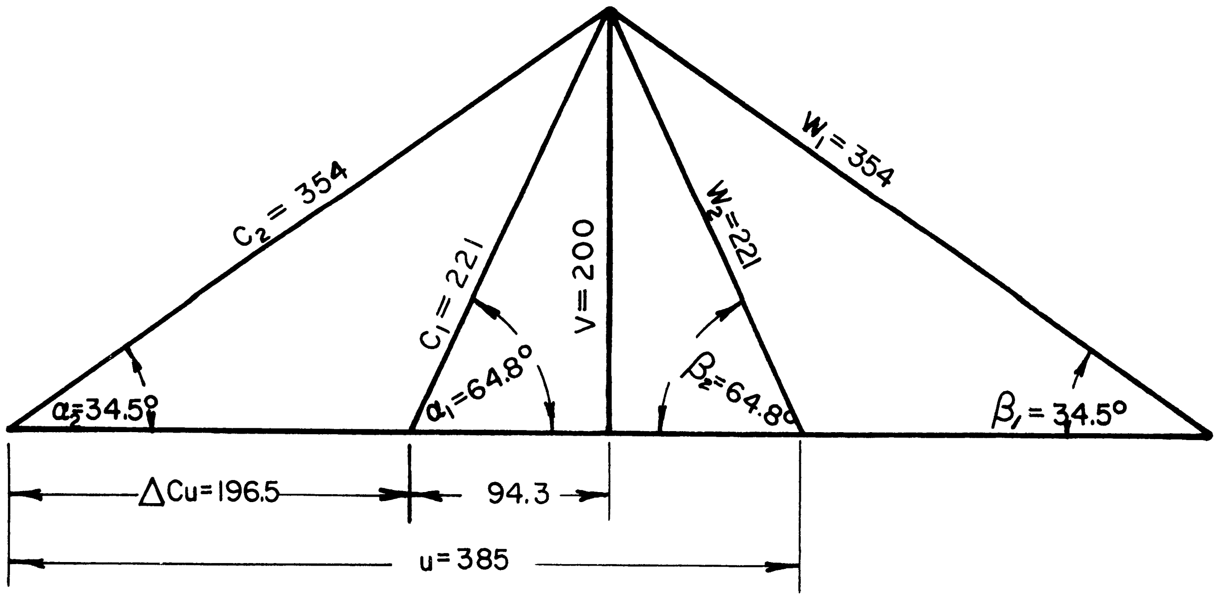
"BASIC CYCLE" PARAMETERS

Description	Data
Effective Average Adiabatic Turbine and Compressor Efficiency	0.85
Recuperator Effectiveness	0.93
Ratio: Turbine Expansion Ratio to Compressor Compression Ratio	0.93
Compressor Ratio	3.0
Minimum Gas Temperature	90°F

Cycle includes recuperator precooler and single intercooler.

AIR - 14 STAGES

PRESSURE RATIO PER STAGE = 1.082



HELIUM - 16 STAGES

PRESSURE RATIO PER STAGE = 1.071

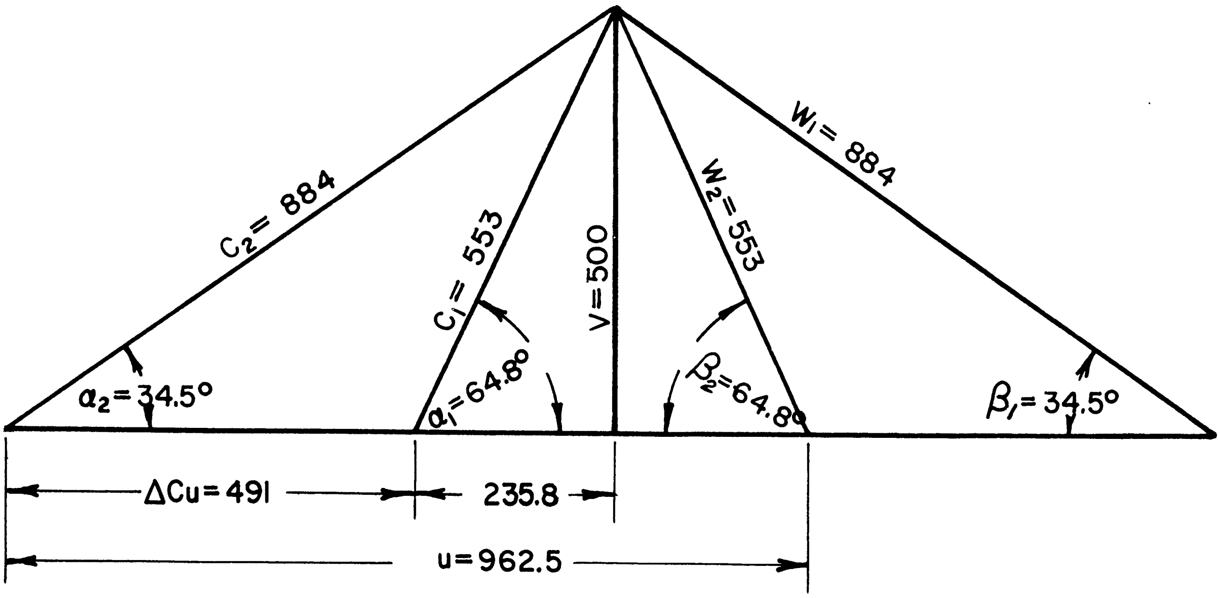
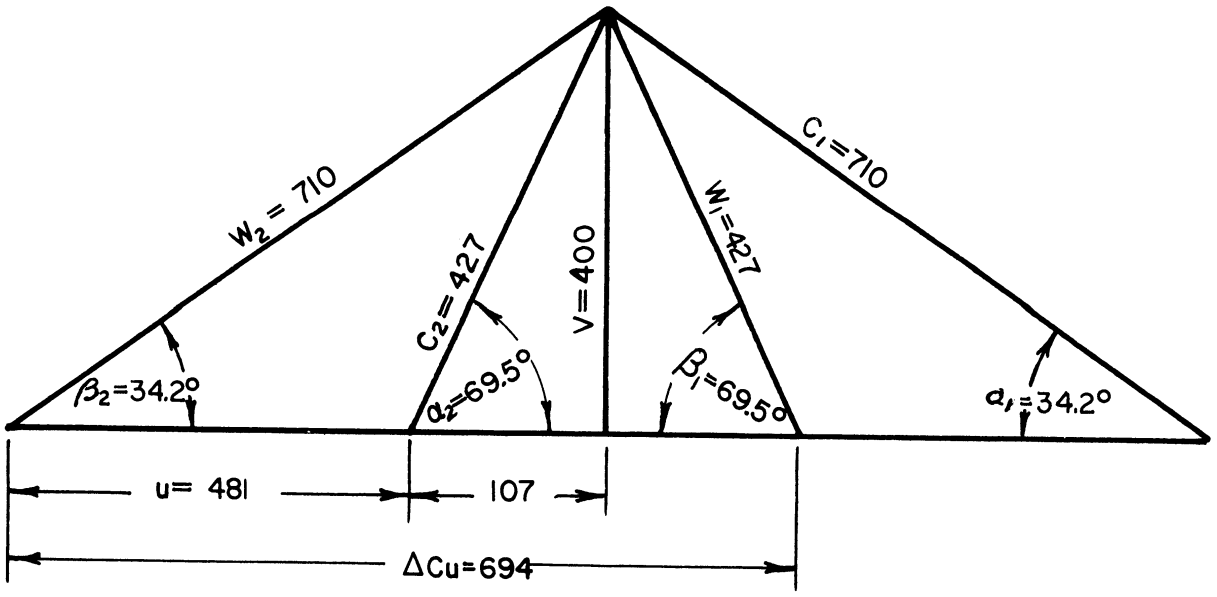


FIG. 15 VELOCITY VECTOR DIAGRAMS FOR AIR AND HELIUM.
a. COMPRESSOR DIAGRAM

AIR - 9 STAGES
PRESSURE RATIO PER STAGE = 1.121



HELIUM - 21 STAGES
PRESSURE RATIO PER STAGE = 1.050

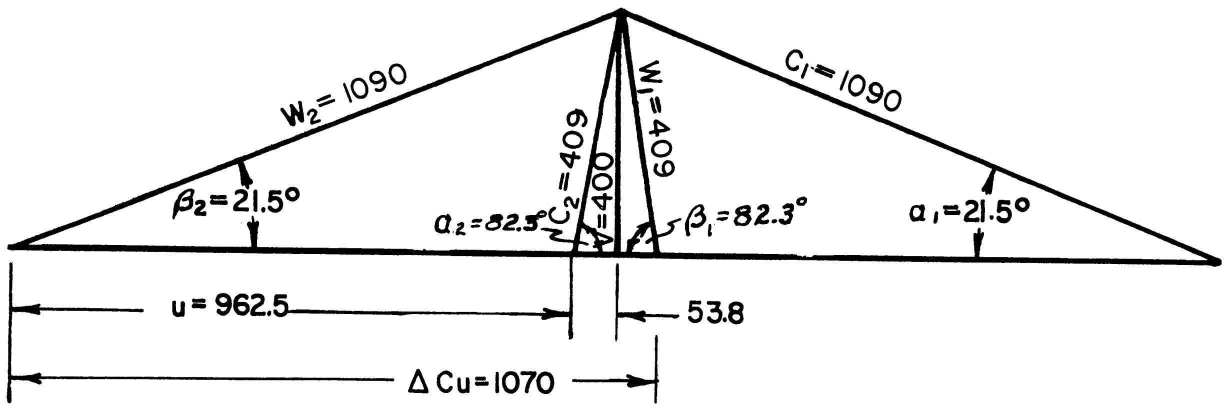


FIG. 16 VELOCITY VECTOR DIAGRAMS FOR AIR AND HELIUM.
b. TURBINE DIAGRAMS

3.0 SELECTION OF WORKING FLUID

As is apparent from the foregoing discussion and the curves of Figures 2 through 14, thermodynamically there are no really conclusive reasons for omitting any of the common gases from consideration as closed-cycle gas turbine working fluids. There are, however, certain factors which may be worth mentioning.

From the viewpoints of availability, cost, and "state of the art," air shows great advantages. On the other hand, it exhibits a certain disadvantage because of its oxidizing characteristics at high temperature. Thermodynamically, it appears that light gases with low values of the ratio of specific heats are very favorable from the viewpoint of minimizing heat exchanger costs. Preliminary calculations have indicated that from this viewpoint hydrogen is most favorable, with helium next, and carbon-dioxide superior to air or nitrogen. A comparison of pumping work per unit heat transferred for various fluids is given in reference 5, which agrees substantially with this conclusion. However, hydrogen might create material problems at high temperature due to hydrogen embrittlement as well as explosive hazards. Nitrogen or air may create difficulties due to nitriding.

The properties of low molecular weight and ratio of specific heats, which make a gas particularly advantageous from the viewpoint of heat transfer, result in a very low attainable pressure ratio per stage for turbomachinery, if it is considered that the work input per stage is limited by mechanical considerations according to the relation:

$$P_R = \left[1 + \frac{W_{ST}}{T_1} \; \frac{k-1}{k} \; \frac{M.W.}{1545} \right]^{k/K-1} \qquad (3.1)$$

where the work per stage, W_{ST}, is constant. However, for conventional axial flow compressors, it is not usual to design to the stress limits. Rather the Mach number may be limiting if acceptable efficiencies for gas turbine plant components are to be obtained. Thus, if it is assumed that Mach numbers are to be held constant between machines for different fluids, the allowable velocities for a low molecular weight, high ratio of specific heats fluid such as helium will be very high, and centrifugal stresses may be the limiting factor. In this case, the number of compressor stages to achieve a given pressure ratio appears in a typical case to be only slightly greater than for air. As was shown in Figures 3, 4, 5, 6, and 7, the desired pressure ratio for a high ratio of specific heats gas is relatively low. For these reasons, it appears that the number of stages of turbomachinery necessary for air and helium plants, respectively, may be approximately equal, although at a given pressure the diameters of the helium machine will be considerably less (see Figure 8). Such an equality in number of stages may well apply fairly closely for any gas.

The selection of a fluid on thermodynamic grounds alone would involve a detailed economic analysis of all factors including both machinery costs and efficiencies. However, there are other factors to be considered including corrosion, availability, toxicity, handling hazards, etc., as well as induced radioactivity in the case of nuclear plants. If hydrogen, helium, nitrogen, carbon dioxide and air are considered, only hydrogen and helium have nuclear properties so that nuclear inter-reactions will not create radiation problems in the power plant. If nitrogen, carbon dioxide or air is to be used in a system in which the working fluid extracts heat directly from the reactor fuel, these materials will inter-react with neutrons and present problems of a radioactive working fluid in the power plant cycle. If the system is to be designed so that air, nitrogen or carbon dioxide does not see neutrons or inter-react therewith, it becomes necessary to provide secondary heat transfer loops where a fluid extracts the fission heat from the reactor and flows through suitable external heat exchange equipment to transfer the heat to the power plant working fluid. In this case, it becomes necessary to sacrifice a portion of the available temperature in the heat exchange equipment. Therefore, in order to attain the same temperature of working fluid, it would be necessary to operate the reactor at higher temperatures than when direct cooling is used.

Since the maximum temperature attainable in nuclear fuels is limited by the types of materials of constructions available which have satisfactory nuclear properties, it appears advisable to consider the development of nuclear powered closed-cycle gas turbines in which the working fluid can be used as the medium to extract the heat directly from the fissioning fuels. Therefore, one of the working fluids worthy of consideration and development is high-pressure, high-temperature helium. However, even with helium there are certain aspects which must be considered. Helium 4 does not have a measurable neutron captured cross-section, and thus, no coolant activity is produced. Natural helium, however, contains 1.3 x 10^{-6} weight fraction of helium 3 which has a captured cross-section of 5000 barns. This reaction is an np reaction in which tritium is produced, which decays with a soft beta emission. This presents no shielding problem, but creates a hazard from viewpoints of biological injection. Also, commercial helium is reported to contain up to 700 ppm of carbon-dioxide, 80 ppm of argon, and 2800 ppm of nitrogen. Consequently, it might well be necessary to purify commercial helium before its use in a direct-cooling system.

Aside from induced radioactivity, there is also the possibility of the coolant gases affecting the nuclear design of the reactor. However, although in some cases the thermal neutron absorption cross-section per atom is fairly substantial (1.8 barns for nitrogen), even at the highest practicable pressures, for those gases which have been discussed, the number of molecules is so low that the main effect is only as a void.

4.0 TYPICAL NUCLEAR POWERED GAS TURBINE POWER PLANTS

It appears in general that gas turbine power plants in a moderate output range (perhaps 1000 to 60,000 kw) must be provided maximum cycle temperatures of the order of 1200°F minimum, if they are to be economically competitive with steam plants. Two general types of reactors possess possibilities for nuclear heat sources which are capable of achieving temperatures in excess of 1200°F. Each of these reactor types have a number of alternative choices in regard to neutron energy range, type of fuel, type of reflectors, type of working fluid, type of controls, type of reflectors, and types of moderators. Two specific examples of these general types of reactors are discussed herein. Basically, they have been elected in order to bring out the variables and optimizations of an integrated system in terms of those problems which must be resolved through aggressive research and development. The types of reactors in general which are discussed are:

1. A high temperature heterogeneous gas-cooled reactor in which the gas is used as the working fluid for the power plant cycle; and

2. A liquid metal homogeneous fueled reactor in which the liquid metal fuel exchanges heat with the working fluid of the power plant.

The limitations of each of these reactor types is contingent upon the maximum temperature which can be obtainable in the working fluid as related to the structural materials employed in the reactor, and the total volume and weight of the reactor system.

With due consideration to such structural materials, it appears that with presently known materials, a working fluid temperature of 1300°F might be achieved in economically feasible heterogeneous reactor cores. In the case of a circulating liquid metal homogeneous reactor system, a possibility exists that a temperature approaching 1500°F in the working fluid might be attained because of the elimination of high working fluid pressure in the reactor.

The maximum pressure which can be achieved for a heterogeneous fueled reactor in which the working fluid extracts fission heat by flowing through the reactor fuel element, is limited primarily to the design of the pressure vessel required to contain the heterogeneous reactor core, and the method by which the vessel wall temperatures can be maintained at a temperature within the creep and tensile limits of the materials selected. In general, for the requirement of a packaged power plant with electrical requirement in excess of about 8000 kw, pressures on the order of 1000 psi appear desirable to limit the reactor heat transfer area requirement. When the electrical power requirements are less, corresponding reductions in the pressure of the working fluid can be allowed with sacrifices to weight and size of the heat engine component.

4.1 A Typical Heterogeneous Gas-Cooled Reactor With a Closed Cycle Gas Turbine for Generation of Electrical Power and Process Steam

A comprehensive review of a great number of different types of heterogeneous reactors employing gas as a coolant has been made. The results have indicated that a specific type of heterogeneous reactor and power plant combination have possibilities of measured improvements in the next several years for applications to packaged electrical generating power plants. In the present analyses, an emphasis has been placed upon attainment of high thermal efficiencies in terms of major reductions in nuclear fuel consumption. Emphasis has been directed toward achievement of a composite reactor design which will initially give working fluid temperatures no less than 1300°F, with possibilities of gradually increasing the temperature through developments in new and improved types of structural materials for heterogeneous reactor fuels. Although the system which is described herein is by way of example only, it is believed that the specific reactor discussed might be developed in the foreseeable future to a promising small-size, small-weight, and inexpensive electrical power generating facility which has capabilities also of generating steam at 250 psig.

The reactor type herein discussed, includes a heterogeneous fuel element assemblage located in a high pressure vessel and employing helium as a coolant which is also the working fluid for the closed-cycle gas turbine. It is a thermal, moderated reactor. Reactor design is patterned somewhat after a helium-cooled program originated at the Oak Ridge National Laboratories in 1947, in which it was proposed to extract fission energy by means of helium gas and use such gas as the working fluid in a power plant.

It is proposed for this example that electrical power output be 20 megawatts, and that at the design point it be also possible to furnish 10,000 pounds per hour of process steam at 250 psig saturated. The cycle is illustrated in Figure 17. The steam is to be procured through bypassing of the high temperature portion of the recuperator. It is possible to obtain varying amounts of steam in this manner. If electrical output is considered constant, then it is necessary that reactor heat load be varied to accommodate these varying amounts of steam. The approximate capabilities of the system are listed in Table II.

In order to minimize the required size of the reactor core, it is necessary that the coolant pressure be a maximum. Premised upon helium as a working fluid whose outlet temperature is 1300°F, a working pressure of 1460 psig has been selected. If the entering gas stream is used to cool the pressure shell containing the core (see Figure 17), then the returning gas stream temperature is limited by the pressure vessel design. To allow a reasonable design of carbon steel for this vessel, a maximum returning temperature of about 750°F has been chosen. For a maximum cycle temperature of 1300°F, such a return temperature is consistent with a gas turbine cycle, operating at a pressure ratio of 3 (slightly in excess of the maximum efficiency pressure ratio to reduce flow rates) and employing a feasible maximum of regeneration. If a maximum cycle temperature greater than 1300°F were employed, it would be necessary to reopen the question of suitable return temperature, and reach a compromise between pressure ratio, regenerator effectiveness, and the requirements of the reactor pressure shell.

Under the pressure and temperature conditions stated above, it appears possible to achieve a design of heterogeneous fuel elements employing highly enriched uranium in the thermal energy range so that the resultant core is relatively small. Calculations which have been made for uranium dioxide (90% U^{235}) with a stainless steel matrix and clad in a

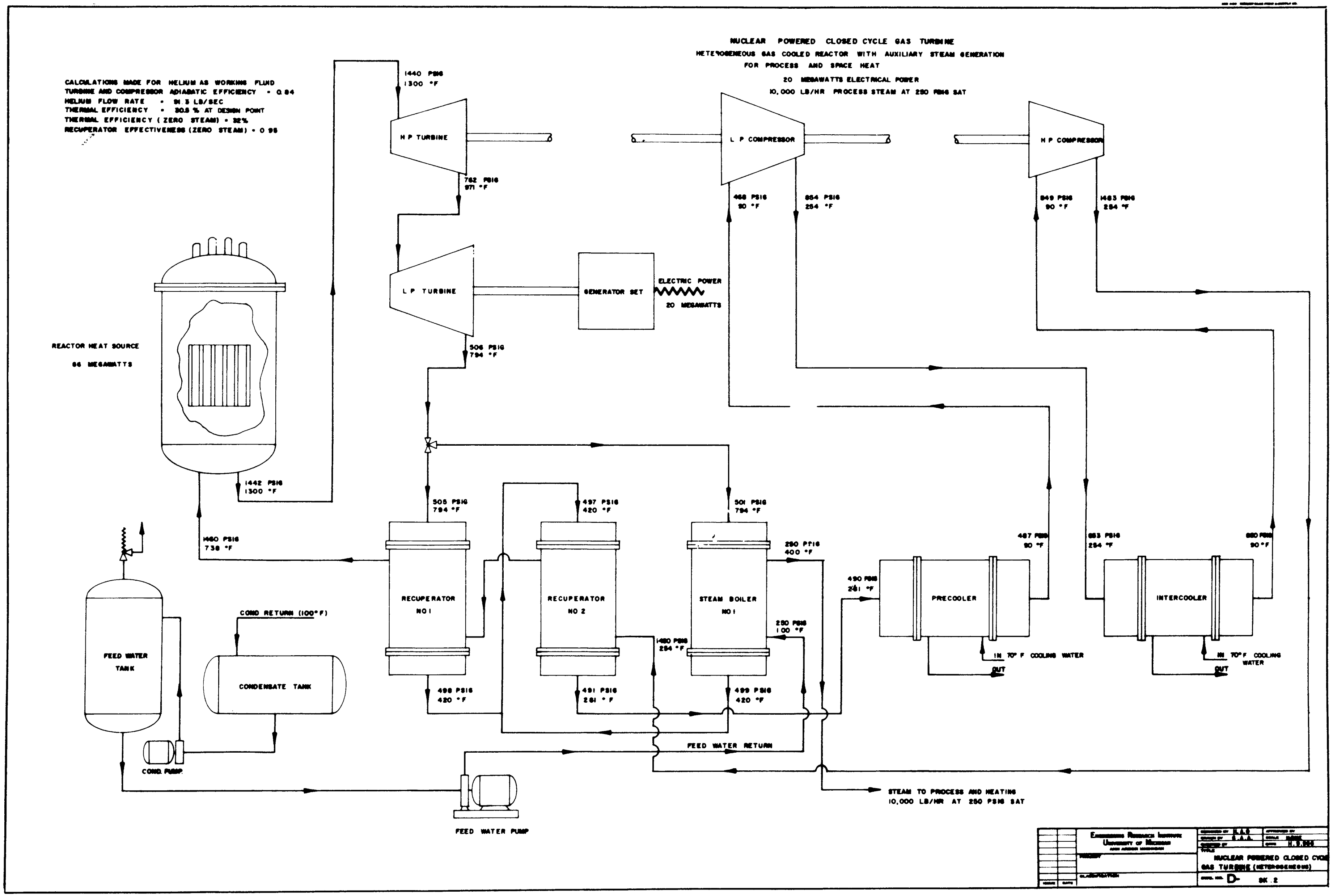

NUCLEAR POWERED CLOSED CYCLE GAS TURBINE
HETEROGENEOUS GAS COOLED REACTOR WITH AUXILIARY STEAM GENERATION
FOR PROCESS AND SPACE HEAT
20 MEGAWATTS ELECTRICAL POWER
10,000 LB/HR PROCESS STEAM AT 250 PSIG SAT
CALCULATIONS MADE FOR HELIUM AS WORKING FLUID
TURBINE AND COMPRESSOR ADIABATIC EFFICIENCY = 0.84
HELIUM FLOW RATE = 91.5 LB/SEC
THERMAL EFFICIENCY = 30.5 % AT DESIGN POINT
THERMAL EFFICIENCY (ZERO STEAM) = 32%
RECUPERATOR EFFECTIVENESS (ZERO STEAM) = 0.95
REACTOR HEAT SOURCE
66 MEGAWATTS
1442 PSIG
1300 °F
1460 PSIG
738 °F
1440 PSIG
1300 °F
H P TURBINE
762 PSIG
971 °F
L P TURBINE
506 PSIG
794 °F
GENERATOR SET
ELECTRIC POWER
20 MEGAWATTS
L P COMPRESSOR
468 PSIG
90 °F
854 PSIG
254 °F
H P COMPRESSOR
849 PSIG
90 °F
1463 PSIG
254 °F
505 PSIG
794 °F
RECUPERATOR
NO 1
498 PSIG
420 °F
497 PSIG
420 °F
RECUPERATOR
NO 2
491 PSIG
261 °F
1460 PSIG
254 °F
501 PSIG
794 °F
STEAM BOILER
NO 1
499 PSIG
420 °F
250 PSIG
400 °F
250 PSIG
100 °F
490 PSIG
261 °F
PRECOOLER
487 PSIG
90 °F
IN 70° F COOLING WATER
OUT
853 PSIG
254 °F
INTERCOOLER
850 PSIG
90 °F
IN 70° F COOLING WATER
OUT
FEED WATER TANK
COND RETURN (100° F)
CONDENSATE TANK
COND. PUMP
FEED WATER PUMP
FEED WATER RETURN
STEAM TO PROCESS AND HEATING
10,000 LB/HR AT 250 PSIG SAT
ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR MICHIGAN
TITLE
NUCLEAR POWERED CLOSED CYCLE
GAS TURBINE (HETEROGENEOUS)
D-
SK. 2

Fig. 17

TABLE II

HETEROGENEOUS HELIUM-COOLED REACTOR CLOSED-CYCLE GAS TURBINE POWER PLANT PERFORMANCE

20 Megawatts of Electrical Power

Process Steam at 250 psig Saturated

Helium Flow Rate - 91.3 pounds/second

Maximum Cycle Pressure and Temperature - 1460 psig, 1300°F

Steam Production Pounds/hour	Reactor Heat Power Megawatts	Reactor Helium Inlet Temperature °F	Plant Thermal Efficiency (based on electrical output only)
0	62.5	767	0.320
6,100	64.5	750	0.310
10,000	65.6	738	0.305
50,000	80.0	629	0.250
134,500	107.0	394	0.188

suitable stainless steel, with a suitable moderator such as carbon, beryllium, or zirconium hydride indicate that an acceptable design can be achieved. Recent developments by the Sylvania Corporation have indicated that zirconium hydride offers excellent promise as a moderator in thermal reactors. Assuming that the maximum temperature at the maximum point of neutron flux can be no greater than 1800°F, calculations indicate that a flat plate-type of fuel element is required in which the fuel bearing section is 30 mils in thickness when the concentration of uranium dioxide in a stainless steel matrix is 25%. In considering the heat conduction-convective heat transfer problem from the heat generated in the uranium to the working fluid at the maximum point of flux, the stainless steel cladding for the fuel bearing section is determined to be about 10 mils. Arranging the flat fuel plates into a rectilinear assemblage for a fuel element so that proper mass velocities of the coolant flowing between the fuel plates results in effective convective heat transfer, the core size resulting therefrom when employing zirconium hydride as a moderator, is about 3' x 3' x 3-1/2' long.

The power level of the reactor is maintained by control rods composed of hafnium and stainless steel which replace fuel lattice positions. It appears possible to arrange the control rods in such a fashion that changes in re-activity result in only small fluctuations of the spacial flux. Employing zirconium hydride as a moderator, and carbon as a reflector, with an adequate thermal shield, it appears that a pressure vessel to contain these reactor components can be designed to a maximum pressure of 1460 psig when the wall temperature of the reactor shell is no more than 750°F.

4.1.1 Heterogeneous Reactor Control

In a packaged type of power plant generating electrical power, a fluctuating electrical power demand can be expected. Also, there can be expected a fluctuation in steam requirements for processing or space heating. The reactor design, therefore, must take into consideration the changes in power output. As a first consideration, it may be worthwhile to consider controls whereby the reactor power level is maintained essentially at some constant power level, while electrical power and steam production are changed by by-passing of turbines and oversizing of heat sinks. However, this approach would require burning of nuclear fuels without useful work, and as a result, higher fuel costs and losses in thermal efficiency.

The increase in the power level of a nuclear reactor is limited only by the rate at which the neutron flux can be increased, which in turn is determined by reactor kinetics and safeguard. Decreases in power output are similarly limited although the so-called "delayed neutrons" prevent a very rapid shut-down. It is desirable, therefore, to develop controls which automatically reset the power level in the reactor by means of turbine throttle for rapid load change, or change in the working fluid pressure level by pumping fluid into or out of the system for long-term changes. Since a reactor of the type here considered has only a small negative temperature coefficient of reactivity, considerable development must be conducted upon dynamic control rods, shim rods, and reactor scram controls which have capacities to absorb the entire neutron production of the fuel elements. It will be necessary to locate such controls in the fuel lattices so that a fuel element might be displaced when a control rod moves into position. Xenon build-up tends to provide this type of reactor with positive temperature coefficients so that rises in temperature suddenly might result in an excursion. Therefore, a major parameter which requires resolution for this type of a gas-cooled reactor, lies in the kinetics of the system. Assuming that throttling or pressure level control and reactor heat power can be correlated with the power output of the power plant, Table III presents the results of calculations for nuclear data for the reactor.

Table IV presents the results of the thermal data which has been calculated for a heterogeneous gas-cooled reactor with the nuclear characteristics mentioned.

4.1.2 Power Plant Design

Premised upon these general conditions, Figure 17 indicates a schematic flow diagram with the temperature and pressure conditions listed at various points , for a nuclear power closed-cycle gas turbine power plant generating 20,000 kw of electrical power and producing 10,000 pounds per hour of 250 psig steam at the design point. As shown in Table II, increased steam production can be achieved at commensurate sacrifice of thermal efficiency and increase in reactor power.

The closed-cycle helium gas turbine plant employed with this reactor is similar to the "Basic Cycle" of Figure 1. However, a process steam generating system has been added by dividing the recuperator into two units, and incorporating a controlled by-pass around the high temperature portion through a steam generator. The quantity of steam to be generated is controlled by that portion of the entire helium stream which flows through the by-pass line. It is assumed that the helium flow rate and the temperature and pressure conditions leaving the reactor, will remain constant so that the turbo-compressor set will be undisturbed by changing steam requirements, and electrical output will remain constant. Under these conditions, a change in steam generation will affect the helium temperature entering the reactor. This has been fixed to a maximum of about 750°F because of pressure shell requirements and this temperature applies approximately at the design point (temperatures and pressures at various cycle points shown on Figure 17) where 10,000 pounds per hour of steam are generated. If the steam generation is increased to a maximum (high temperature recuperator by-passed completely) the steam generation is 134,500 pounds per hour, and the helium temperature returning to the reactor 394°F (see Table II). Under these conditions, reactor power must be increased to 107 megawatts. The log mean temperature difference in the reactor is, of course, increased by the drop in reactor inlet temperature. However, assuming fuel element temperature cannot be increased for reasons of thermal stress, etc., it is probable that the leaving temperature would decrease to some

TABLE III

HETEROGENEOUS GAS-COOLED REACTOR NUCLEAR DATA

Description	Data
Fuel elements - type	Flat plate
Fuel material	Highly enriched Uranium 90% U^{235}
Fuel matrix	25% UO_2 - Stainless Steel
Thickness of fuel bearing section	30 mils
Thickness of cladding	10 mils
Total thickness of plate	50 mils
Number of plates per element	17
Dimensions of fuel bearing core	3' x 3' x 3'6" long
Number of elements	400
Core diameter	3'
Core height	3'6" (same as fuel elements)
Nuclear characteristics - Calculated fuel loading as 90% U^{235}	135 kgs.*
Neutron Energy	Epithermal
Average neutron flux Φ of average	1.35×10^{15} neutrons per square cm. per second
Maximum neutron flux - Φ of maximum	2.12×10^{15}
Ratio of max. flux to average flux (radial)	1.57
Ratio of max. flux to average flux (transverse)	1.40
Cold start-up $\Delta K/K$	0.40
$\Delta K/K$ at shutdown	0.05
Calculated neg. temp. coefficient $\Delta K/K/{}^\circ F$	4×10^{-5}
Calculated fuel burnup	25%
Ratio of UO_2 to stainless steel	0.60
Ratio of zirconium hydride moderator:	
to fuel at reactor startup	1400
at reactor shutdown	2300
Maximum temperature in fuel bearing section	1800°F
Maximum temp. of stainless steel cladding	1650°F
Shim rods	stainless steel-hafnium
Control rods	stainless steel-hafnium
Drive mechanisms	electrical servo mechanisms

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* Includes loading for critical mass and one year's inventory.

TABLE IV

THERMAL DATA FOR HEAT EXTRACTION FROM HETEROGENEOUS GAS-COOLED REACTOR

Description	Data
Design point reactor heat power	66 megawatts
Coolant flow rate	91.3 pounds/sec.
Design point inlet temperature of helium to reactor	738°F
Outlet temperature of helium from reactor	1300°F
Inlet pressure of helium	1460 psig
Outlet pressure of helium	1442 psig
Estimated coolant velocity	400 ft. per sec.
Design point specific power	9,250,000 BTU/hr/ft^3 of core
Estimated convective heat transfer coefficient for helium in reactor	1,000 BTU/hr/sq.ft/°F
Temperature of reactor shell	775°F
Thermal shield material	Carbon steel
Moderator	Zirconium hydride clad in stainless steel
Reflector material	Carbon blocks, 1' thick, surrounding core and adjacent to walls of vessel

extent. Then to maintain electrical output, some increase in flow rate would become necessary. It has been assumed that these secondary effects are relatively small. This is certainly the case for more moderate steam production up to, perhaps, 50,000 pounds per hour. At this steam rate, the reactor power is only increased about 20% over the design point.

The turbine and compressor efficiencies to be applied have been selected from the results of the previously discussed study for the applicable fluid, temperature, and pressure. In this case, the effective average of adiabatic turbine and compressor efficiencies is 0.84. Friction pressure losses, heat sink temperature, and pressure ratio are as assumed for the "Basic Cycle," Table I. A recuperator effectiveness of 0.95, based on zero steam production, was assumed because of the extremely high pressure. Determination of the economic feasibility of this value would require an involved optimization study. A net heat loss of 3% of reactor power through insulation was assumed.

At the design point, the helium at 1460 psig and 750°F enters the reactor and flows along the vessel walls and the thermal shield, so that the reactor vessel wall temperature will not exceed 775°F. The helium gas enters a plenum chamber, and flows downward through and between the flat plate fuel elements, which are provided with channels 50 mils x 3 inches wide so that helium gas velocities of about 400 ft. per second are achieved. The calculated ratio of maximum-to-average flux transversely along the flow of the coolant in the fuel channel is about 1.57. The temperature of the helium leaving the system will be 1300°F. It is estimated that the pressure drop for the helium through the reactor itself is about 20 psig.

4.1.3 Power Plant Shielding Requirements

There are four main sources of radioactivity which may present problems in shielding the closed-cycle gas turbine power plant. These are: (1) Induced radioactivity in helium and its impurities; (2) Induced radioactivity in particulate matter carried in the gas stream; (3) Recoil of radioactive atoms due to knock-off; (4) Fission product escape from the fuel elements into the working fluid. A brief discussion of each of these may be worthwhile.

4.1.3.1 Induced Radioactivity in Helium and Its Impurities

This problem was discussed in some detail in an earlier section of this paper.

4.1.3.2 Particulate Matter

Particulate matter in the form of dust, dirt, and scaling of equipment on start-up and shutdown might introduce particles into the gas stream which have high capture cross-sections, and offer gradually increasing problems in the power plant equipment. It might be necessary to provide in the design, a system for continuously purifying a portion of the helium gas for the removal of particulates with suitable dust collectors, electrostatic precipitators, etc.

4.1.3.3 Recoils

One of the ways in which radioactivity can build up in the working fluid stream is through recoil atoms. There are two types of recoil: recoil of an atom due to the emission of a particle; and recoil due to a collision with a high energy particle. If the surfaces within the reactor are steel or stainless steel, the most important reactions are of the first type in which either an n-γ reaction converts manganese 55 to manganese 56, which is a gamma emitter, or iron 56 to manganese 56 through an n-p reaction. The first reaction is possible because although most steels contain only 1-2% manganese, the cross-section for this reaction is relatively high (12 barns). The recoil momentum is so low that only those atoms within about 10^{-8} cm of the surface can escape. While the cross-section for the second reaction is much smaller, the number of iron atoms is larger, and the recoil of the proton is sufficient to remove atoms within about 10^{-7} cm of the surface. It appears that the proton recoil of the iron atoms is several times more important, and hence, the type of steel used is relatively unimportant. It is difficult to say where these radioactive atoms will go. From a maintenance viewpoint, the manganese 56 is not serious, since it decays to reasonable values within about 30 hours. The second general type of reaction (recoil due to collision with high energy particles) occurs due to collision with high energy neutrons, and will cause radioactive iron, chromium, nickel, and cobalt atoms to enter the gas stream. Some of these atoms contain long life isotopes, so that the background levels will gradually build up in the primary loop equipment. However, direct maintenance should still be possible although a reduction of working time may be necessary.

4.1.3.4 Fission Products

Radioactivity may enter the working fluid stream due to diffusion of fission product gases through the fuel element, or fractures occurring in the fuel elements themselves. Methods by which fission products can escape into the working fluid are: (1) rupture due to shock and thermal cycling; (2) pin holes in cladding; (3) diffusion; (4) melting of a fuel element. The cladding on a fuel element can rupture from thermal cycling and thermal shock. The probabilities of ruptures occurring must be reduced to acceptable levels by proper fuel element manufacture and operating techniques. Monitors must be provided in the gas stream to detect such ruptures, and permit corrective action to be taken before activity becomes excessive or dangerous. Defects in cladding can allow gaseous fission products to migrate into the gas stream. Therefore, carefully controlled inspection and testing of fuel elements prior to installation in the reactor is requisite. Gaseous fission products can enter the working fluid stream by diffusion at high temperatures. As temperatures exceed 1800°F, the rates of diffusion of gaseous fission products are unknown, and research and development are necessary. For the type of heterogeneous reactor described herein, it is conceivable that a fuel element or a group of fuel elements could have temperature rises so rapid that melting would occur before the controls could operate. In the event of such a catastrophe, two problems could result: (1) a sudden increase in radiation levels outside of the biological shields with resultant depositions throughout the piping and components of the closed cycle gas turbine; and (2) the necessity for undertaking major decontamination of the facilities to permit direct maintenance. The decontamination of the helium loop through the reactor system and through the entire power plant would offer serious problems. Major developments must be undertaken to assure that the most credible accident would not result in the melting of fuel elements.

Evaluation of the conditions and programs of investigations and demonstration,which are requisite for early achievement of a heterogeneous heat power reactor associated with a closed cycle gas turbine in which the reactor coolant serves directly as working fluid,can be achieved with a nominal program of research, development, and demonstration. In this case, the major development problems appear to lie in the nuclear reactor, and in use of helium at a satisfactory temperature and pressure in a closed cycle gas turbine plant. Some of the problems which require resolution are: (1) development of suitable high temperature fuel elements capable of operating for long periods of time when the fuel temperature is at 1800°F maximum; (2) Development of a fuel-to-moderator combination which reduces the inventory of nuclear fuel to a minimum, and reduces the critical configuration so that a high pressure reactor vessel can be achieved; (3) development of positive controls so that xenon buildup and changes of working fluids do not decrease temperature coefficients.

The control problem for a heterogeneous gas-cooled reactor is relatively simple, if the reactor power level can be maintained independent of the fluctuating requirements of power output in terms of electrical and steam energy. In the event it is desired to achieve output control which resets the reactor power level, a major program of development for heterogeneous gas-cooled reactors may be required.

5.0 A TYPICAL LIQUID METAL HOMOGENEOUS FUELED REACTOR IN CONJUNCTION WITH A CLOSED-CYCLE GAS TURBINE POWER PLANT FOR GENERATION OF ELECTRICAL POWER AND PROCESS STEAM

A homogeneous liquid metal fueled reactor employing bismuth with highly enriched uranium for high temperature operation, offers a great potential for early achievement of a highly compact, high temperature nuclear heat source in conjunction with a closed-cycle gas turbine. Uranium metal is appreciably soluble in bismuth above approximately 400°C in varying concentrations. Solubility of uranium, and also plutonium and thorium, in bismuth as a function of temperature is given in Figure 18. The data for these curves is abstracted from reference 6.

As noted from Figure 18, at a temperature approaching 1,000°C, a uranium bismuth solution is obtainable where the ratio of uranium to bismuth at the limit of solubility is about 10-15%. A uranium bismuth reactor system has been developed basically by the Brookhaven National Laboratories. Numerous published reports have been made available for this system. A number of private industries are presently undertaking the study of applications and modifications to a uranium-bismuth liquid metal fueled reactor for power generation. Recently, the Atomic Energy Commission arranged a contract with the Babcock and Wilcox Company for a demonstration reactor called "The Liquid Metal Fueled Reactor Experiment - LMFRE." Studies which are presented in this paper suggest that through proper developments of materials, it might be possible within the foreseeable future to achieve a reactor operating at a temperature approaching 1,000°C. By employing internal and external reflectors, it is possible to achieve a power reactor which is small and compact. It is reported that such a reactor, in terms of a sphere, may have a critical radius on the order of 7-8 inches.[6] Recent developments in new types of carbons of high density and uniform structure might serve as container material for such a reactor.

For the purposes of this paper, preliminary calculations have been made for a system which circulates a uranium bismuth system to a critical configuration, thence to a heat exchanger where the fission energy is extracted to a gaseous working fluid, and the cooled uranium-bismuth is pumped back to the reactor (Figure 19). The specific system studied consists of uranium dissolved in bismuth at 1550°F (reentering reactor), so that the maximum permissible concentration of U^{235} is limited by this temperature. The uranium bismuth solution is circulated through a critical configuration in a cylindrical shell which is 18" in diameter by 2' high. Interspersed within the critical configuration are rods of carbon for internal moderation. Surrounding the core is an external reflector of carbon. On the outside of the external reflector is a thermal shield which is gas cooled. Surrounding the thermal shield is a reactor vessel. Because of the inherent safety of a uranium bismuth core, it is visualized that the only controls necessary are controls for shutdown or scram. The nuclear data for the reactor under these conditions are given in Table V.

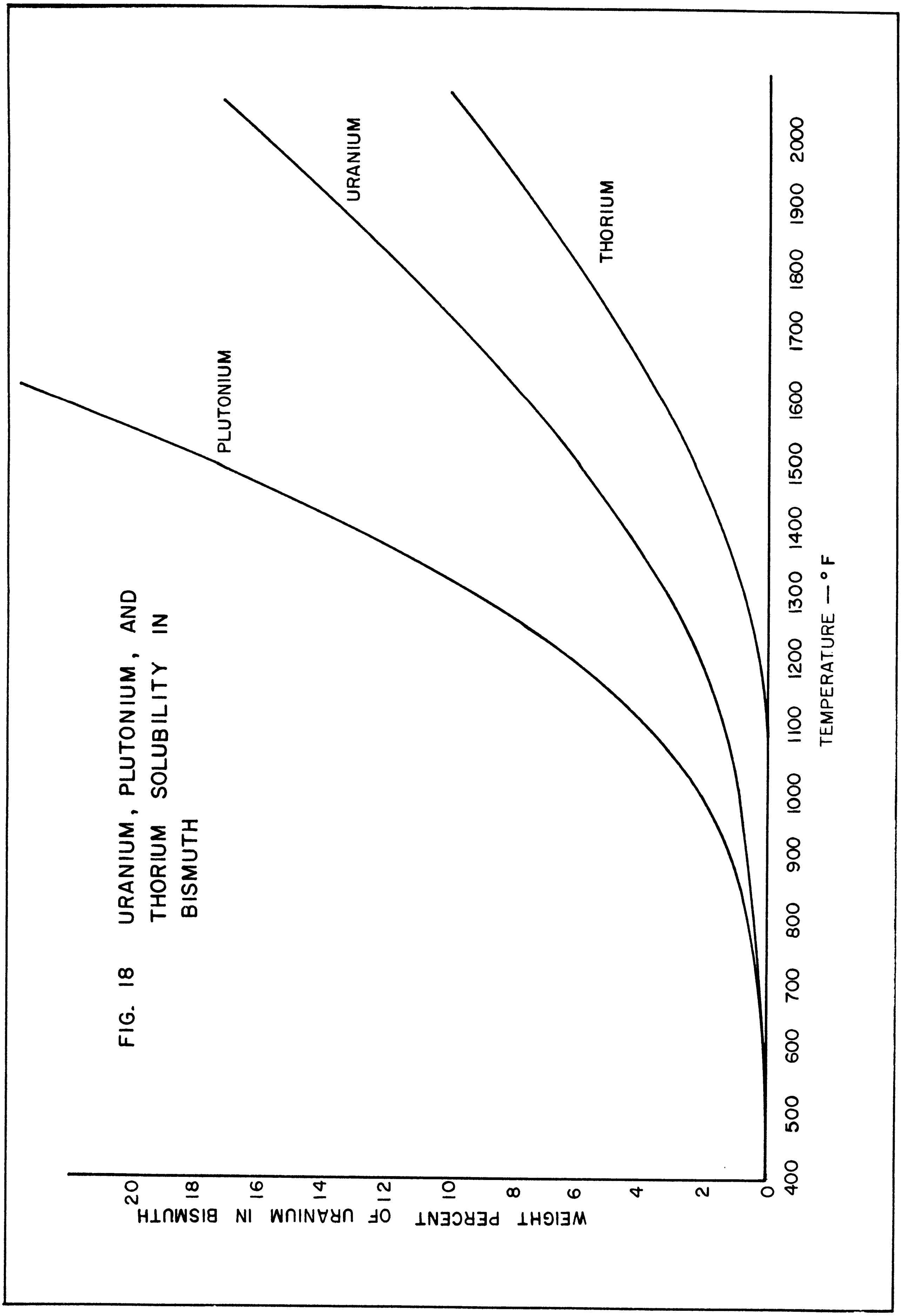


FIG. 18 URANIUM, PLUTONIUM, AND THORIUM SOLUBILITY IN BISMUTH

TABLE V

NUCLEAR DATA FOR A LIQUID METAL FUELED REACTOR BISMUTH-URANIUM TYPE

Description	Data
Dimensions	3.5' dia. x 4'0 high
Total fuel loading	33.5 kilograms*
Design point power level of reactor	78.4 megawatts
Average neutron flux	Φ aver. 1×10^{15} neutrons per sq. cm. per second
Φ max. - Φ aver. in spherical core	1.50
Type of internal reflector - moderator	Special carbon
Thermal shield	Laminates of iron and carbon
Fission product removal	Continuous de-gaser - 90% removal per pass
Neutron energy	Epithermal

* Includes loading for volume of system, and one year's inventory.

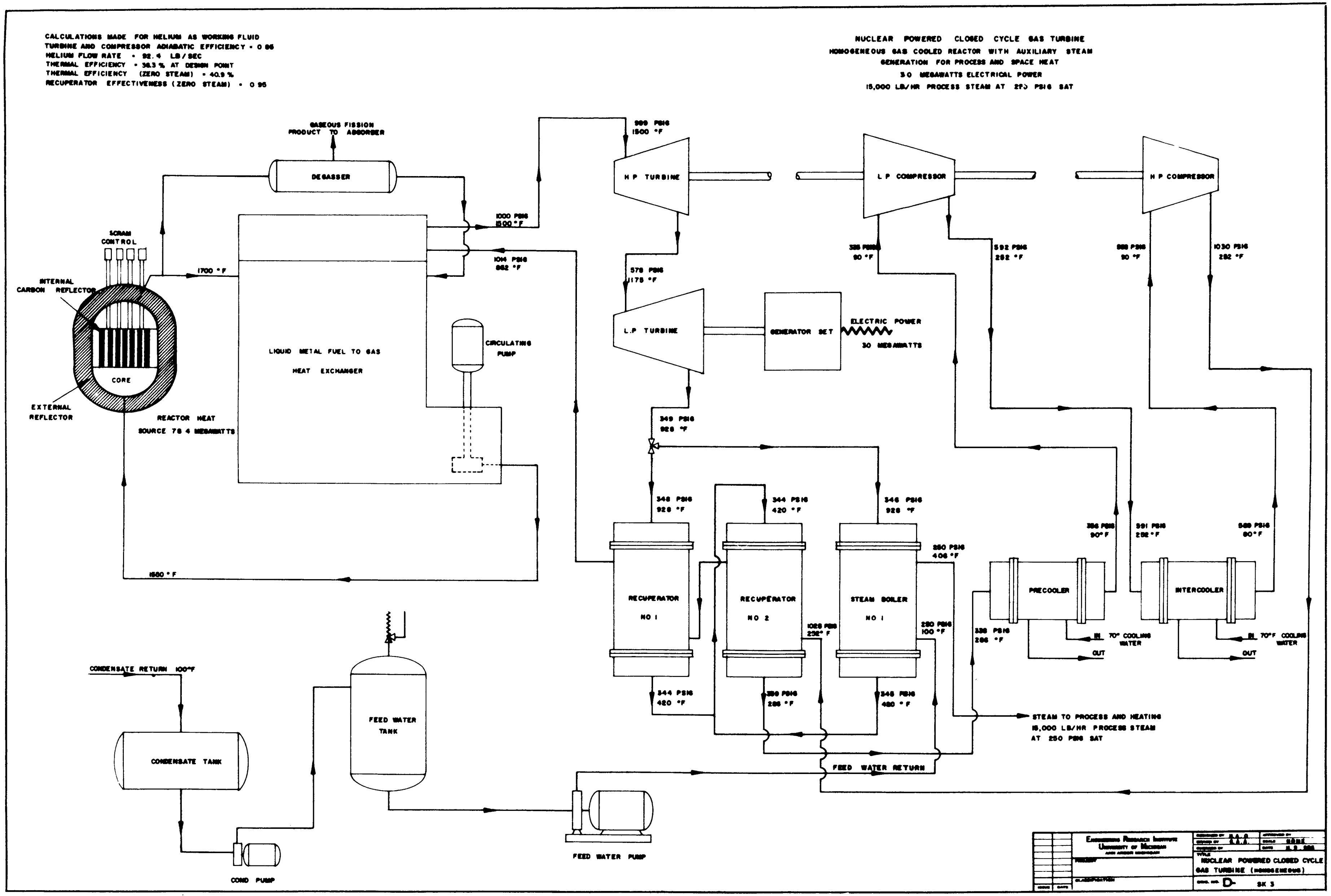

CALCULATIONS MADE FOR HELIUM AS WORKING FLUID
TURBINE AND COMPRESSOR ADIABATIC EFFICIENCY = 0 86
HELIUM FLOW RATE = 92.4 LB/SEC
THERMAL EFFICIENCY = 36.3 % AT DESIGN POINT
THERMAL EFFICIENCY (ZERO STEAM) = 40.9 %
RECUPERATOR EFFECTIVENESS (ZERO STEAM) = 0 95
NUCLEAR POWERED CLOSED CYCLE GAS TURBINE
HOMOGENEOUS GAS COOLED REACTOR WITH AUXILIARY STEAM
GENERATION FOR PROCESS AND SPACE HEAT
30 MEGAWATTS ELECTRICAL POWER
15,000 LB/HR PROCESS STEAM AT 250 PSIG SAT
GASEOUS FISSION PRODUCT TO ABSORBER
DEGASSER
SCRAM CONTROL
INTERNAL CARBON REFLECTOR
CORE
EXTERNAL REFLECTOR
REACTOR HEAT SOURCE 78 4 MEGAWATTS
1700 °F
1550 °F
1000 PSIG 1500 °F
1014 PSIG 862 °F
LIQUID METAL FUEL TO GAS HEAT EXCHANGER
CIRCULATING PUMP
999 PSIG 1500 °F
H P TURBINE
578 PSIG 1175 °F
L.P TURBINE
GENERATOR SET
ELECTRIC POWER 30 MEGAWATTS
L P COMPRESSOR
335 PSIG 90 °F
592 PSIG 252 °F
H P COMPRESSOR
588 PSIG 90 °F
1030 PSIG 252 °F
349 PSIG 928 °F
348 PSIG 928 °F
344 PSIG 420 °F
346 PSIG 928 °F
RECUPERATOR NO 1
RECUPERATOR NO 2
STEAM BOILER NO 1
344 PSIG 420 °F
339 PSIG 286 °F
345 PSIG 480 °F
1028 PSIG 252° F
250 PSIG 406 °F
250 PSIG 100 °F
338 PSIG 286 °F
336 PSIG 90° F
591 PSIG 252 °F
589 PSIG 90° F
PRECOOLER
INTERCOOLER
IN 70° COOLING WATER
OUT
IN 70°F COOLING WATER
OUT
STEAM TO PROCESS AND HEATING
15,000 LB/HR PROCESS STEAM
AT 250 PSIG SAT
FEED WATER RETURN
CONDENSATE RETURN 100°F
CONDENSATE TANK
COND PUMP
FEED WATER TANK
FEED WATER PUMP
ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR MICHIGAN
PROJECT
CLASSIFICATION
ISSUE
DATE
DESIGNED BY
DRAWN BY
CHECKED BY
APPROVED BY
SCALE
DATE
TITLE
NUCLEAR POWERED CLOSED CYCLE GAS TURBINE (HOMOGENEOUS)
DWG. NO. D- SK 3

Fig. 19

The liquid metal fuel leaves the reactor core at about 1700°F, and flows into a specially designed liquid metal fuel to gas heat exchanger. The design which is presented herein consists of a U-tube bundle. The liquid metal flows through the shell side, and the high pressure gas through the tubes. A circulating pump of the vertical overhung shaft type is mounted directly into a channel of the heat exchanger. This pump circulates the fluid leaving the heat exchanger to overcome the pressure drop in the system. The calculated thermal data for the reactor is given in Table No. VI.

TABLE VI

THERMAL DATA FOR HEAT EXTRACTION FROM HOMOGENEOUS GAS-COOLED REACTOR

DESCRIPTION	DATA
Design Point Reactor Heat Power	78.4 megawatts
Bismuth-Uranium Design Point Coolant Flow Rate	10,600 GPM
Design Point Inlet Temperature of Coolant to Reactor	1550°F
Outlet Temperature of Coolant from Reactor	1700°F
Specific Power/liter of Bismuth	1,000,000 BTU/hr/ft^3
Design Point Specific Power/Reactor Volume	7,000,000 BTU/hr/ft^3

In the event it is possible to attain a maximum reactor temperature of 1700°F entering a liquid metal-to-gas heat exchanger, and to exhaust the liquid metal fuel at 1550°F, it appears possible to design a suitable heat exchanger so that helium as a working fluid will enter the heat exchanger at 1015 psig and 850°F, and will exchange heat with the liquid metal fuel so that the working fluid entering the power plant is at 1500°F and at 1000 psig. The flowsheet for the gas turbine portion of the cycle is the same as that described for the heterogeneous reactor plant, and is shown in Figure 19 with appropriate temperatures and pressures at the various cycle points. Because of the higher efficiency made possible by the increased turbine inlet temperature, somewhat higher levels of electric power and process steam generation have been considered. The design point has been set at 30 megawatts electrical and 15,000 pounds per hour of process steam at 250 psig saturated. Again, it is possible to obtain varying amounts of process steam, if the electrical output is held constant, by adjusting the portion of the helium by-passed to the steam generator from the high temperature portion of the recuperator. The steam output is increased, then, at cost to reactor power. The upper limit for steam generation for this arrangement is 185,000 pounds per hour if the high temperature recuperator is completely by-passed. The capabilities of the system in this respect are listed in Table VII.

TABLE VII

HOMOGENEOUS REACTOR CLOSED-CYCLE GAS TURBINE POWER PLANT PERFORMANCE

30 Megawatts of Electrical Power

Process Steam at 250 psig Saturated

Helium Flow Rate - pounds/second

Maximum Cycle Pressure and Temperature - 1015 psig, 1500°F

Steam Production Pounds/hour	Reactor Heat Power Megawatts	Reactor Helium Inlet Temperature °F	Plant Thermal Efficiency (based on electrical output only)
0	73.3	894	0.410
15,000	78.4	852	0.383
70,000	96.6	701	0.310
185,000	134.8	387	0.223

In line with the studies on probable compressor and turbine efficiencies previously discussed, the effective average of adiabatic turbine and compressor efficiencies was assumed as 0.85. The increase in one point over the assumed value for the heterogeneous reactor cycle is due to the increased volumetric flow rate due both to reduced pressure and increased temperature. The mass flow for the two plants is nearly the same. The greater power output of the homogeneous reactor plant is due to the higher thermal efficiency with the higher temperature. As in the previous cycle, a recuperator effectiveness of 0.95, based on zero steam production, was assumed. Again, a 3% heat loss due to imperfect insulation was assessed.

Although the limit on helium temperature for the stream leaving the recuperator was set at approximately 750°F for the heterogeneous reactor cycle, a maximum temperature of 894°F has been allowed in this case. The reason for the greater leniency in this respect, is that the high pressure gas is heated in heat exchanger tubes and does not enter a large pressure vessel as it did for the heterogeneous reactor system. This lack of a high pressure vessel is felt to be one of the most cogent reasons for the possibility of obtaining very high temperatures with this type of reactor.

A liquid metal fueled reactor can generate heat power up to temperature levels which are limited only by the development of suitable container materials for the liquid metal fuels which are at approximately ambient pressure. For power output above approximately 20 megawatts, it appears necessary to provide external heat exchanger surface for the efficient extraction of the heat. The liquid metal fueled reactor offers promise for continuous addition of fuel without shutting the reactor down, and the removal of the major portion of the fission products during the course of operation. The reactor appears to be one which is self-controlling, and sets a maximum power limit without the use of special controls. The maximum power is established by the concentration of the uranium in the bismuth. Provisions can be made so that special scrams and shutdown controls are provided in the event emergency so requires. Such a scram control can remove the contents of the liquid fuels to a critically safe geometry in the form of dump tanks or inventory tanks. It appears possible that by suitable heat exchange, helium at 1000 psig and at 1500°F could be achieved. At these levels of temperature and pressures, and an electrical generating capacity of 30,000 kw, a closed-cycle gas turbine power plant appears to be an ideal system. As shown in Table VII, it is indicated that a thermal efficiency (zero steam generation) of 41% can be achieved by optimum selection of components and arrangements of systems.

5.1 Efficiency and Cost Comparisons With Alternative Heat Engine Systems

The applicability of the gas turbine cycle to nuclear power plants depends upon the thermal efficiency, capital cost, and weight which may be achieved by this type of heat engine installation, versus the various alternatives which are available. The most obvious alternative is the steam plant. A comparison of steam plant efficiencies which may conceivably be obtained versus temperature for central station sized plants is shown in Figure 20 (all efficiencies consider zero stack loss for a nuclear plant). The steam plant data is based on actual plant performance up to 1100°F. The high temperature portion of the curve is based on the predictions of reference 7.

The gas turbine efficiencies are based on component efficiency estimations as previously described in this paper. They may well be above the economical optimums. It is noted that even so, the steam plant efficiency exceeds the gas turbine at any temperature up to 1500°F. However, whereas the advantage is about 8 points out of 39 at 900°F, it is only about 4 points out of 49 at 1500°F. For smaller outputs in the range discussed in this paper, i.e., up to 30,000 kw, it is believed that the economically justified optimum for steam plants will be reduced considerably, so that if high temperature (say 1200 - 1500°F) can be made available, the gas turbine plant may be the more efficient. If the available temperature is no more than 1000°F, it appears that the steam plant will be considerably superior both in efficiency and capital cost.

As a further alternative to steam, if very high temperatures are available, there is the possibility of a binary Rankine cycle thermodynamically similar to the mercury-steam cycles which have operated for years in certain central station applications. There is the possibility that a liquid metal might be boiled directly in a reactor or a portion of a circulating liquid stream flashed to vapor (Sodium is a possibility, mercury seems poor because of its high neutron cross-section; others such as potassium, rubidium, zinc, etc., may be suitable). The vapor would then operate a liquid metal turbine, condense against an ordinary steam system (or gas turbine) and be recirculated. The upper curve in Figure 20 has been plotted for such systems, assuming reasonable component efficiencies. It is noted that at high temperature, the efficiencies are considerably in excess of either the steam or the gas turbine (only slightly below the Carnot line).

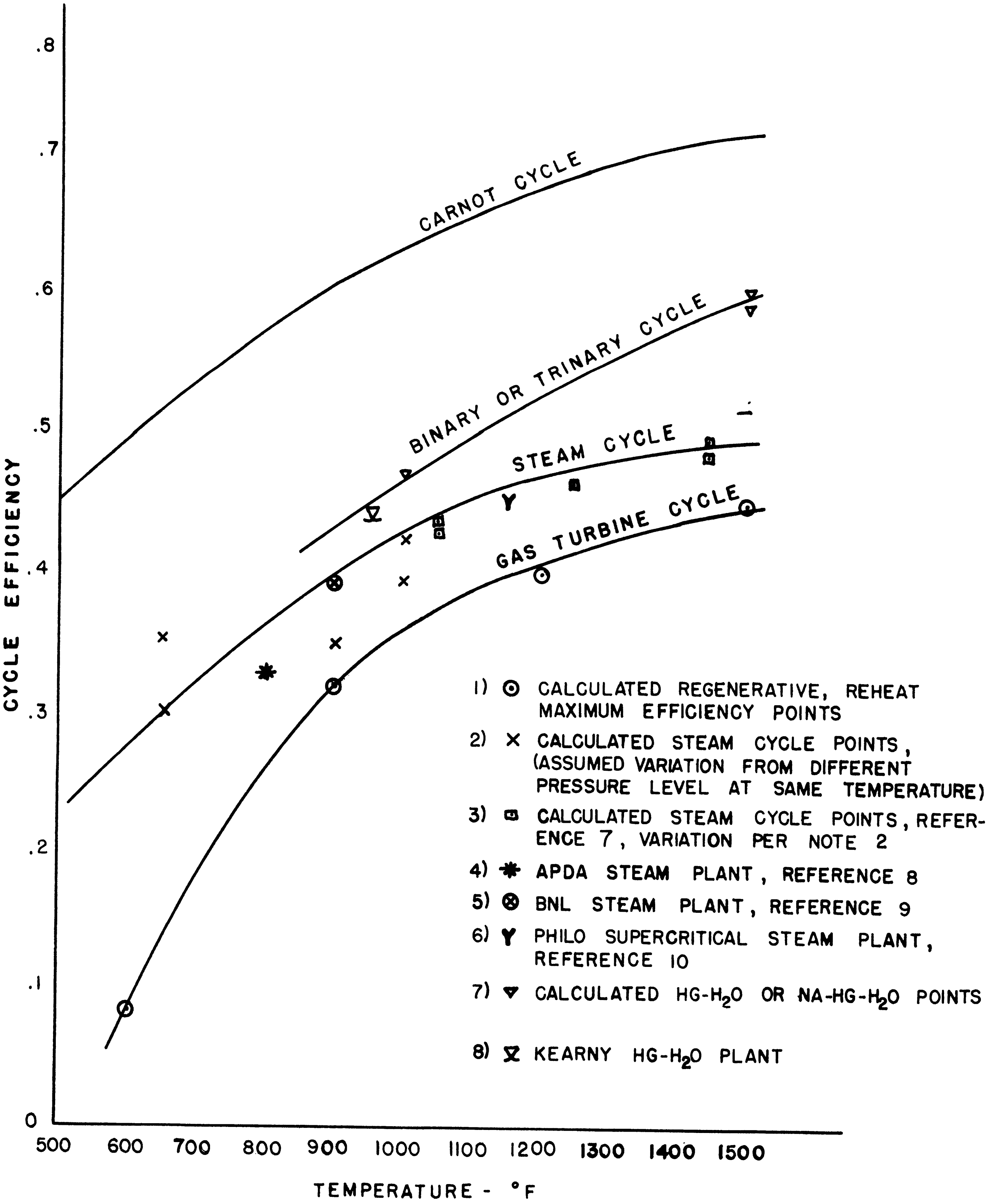


FIG. 20 MAXIMUM FEASIBLE EFFICIENCY VS TEMPERATURE VARIOUS HEAT ENGINE CYCLES COOLING WATER AT 70° F

5.2 Cost Comparisons

For the small-output (5 to 30 megawatts) nuclear powerplant of the liquid metal fuel reactor type, it appears that thermal efficiency is not of over-riding importance since fuel costs may be only a fairly small portion of the total. In a typical case which we studied, for example, the cost breakdown appeared very generally somewhat as below for a steam or gas turbine unit coupled with a homogeneous liquid metal fueled reactor.

Fuel Burn-up - 30%

Capital Costs

Reactor and Uranium Inventory - 40%

Heat Engine - 30%

Thus, it appears that the capital cost of the heat engine is as important as the efficiency. It is very difficult to obtain comparative cost data for the various systems. However, according to preliminary estimates which we have obtained from various manufacturers, it appears that in the range of 5000-30,000 kw, steam plants, exclusive of the boiler, cost on the order of $100/kw for a 900°F plant. Open cycle gas turbine plants appear to be considerably more expensive at about $250/kw for a plant of comparable efficiency.

It would appear that the cost of high pressure closed-cycle plants should be considerably less since it is obvious that the weight of material must decrease rapidly with increasing pressure. For example, the weight of an axial flow turbo-machine for a given pressure level, fluid, and power output might be considered to be proportional to $(1/p)^{1/2}$. This is based on an examination of the casing and its consideration as a pressure vessel. It is assumed that there will be a decrease in length proportionate to the decrease in diameter. The weight of the rotor and of the heat exchange equipment should at least vary in the same direction. For machines of similar type in a somewhat similar size range, it seems quite reasonable that cost should reduce more or less with weight, after developmental costs have been assimilated. If this be the case, the high pressure closed-cycle plant seems to hold promise of eventual considerably reduced capital cost, even as compared with steam plants.

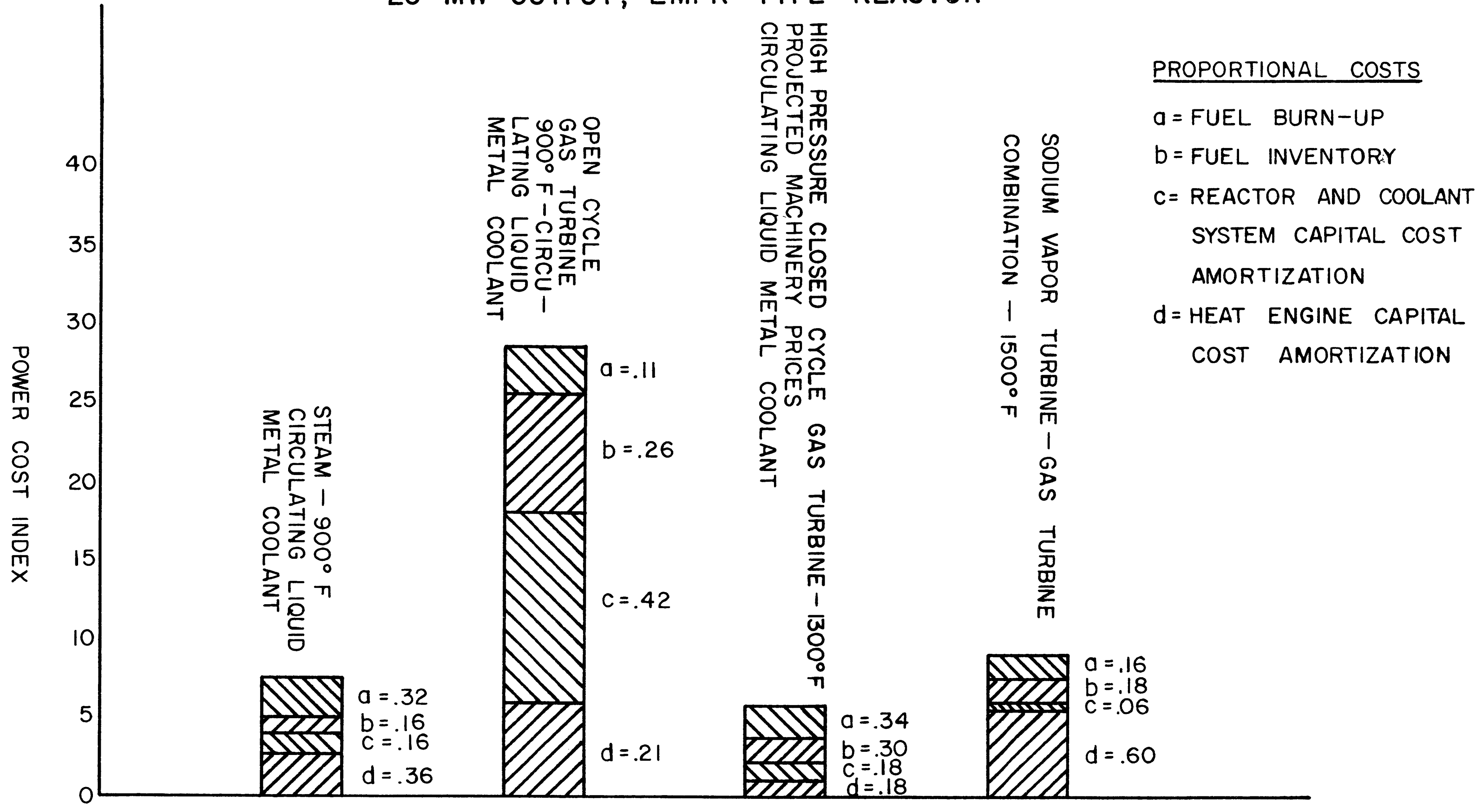
The results of a preliminary study which we have conducted shows cost comparisons for liquid metal fuel reactor plants coupled both to steam plants and gas turbine plants for 20,000 kw output. If a very conservative temperature level for this type of reactor is considered, of about 900°F in the heat engine working fluid, and an intermediate liquid metal loop utilized, then with present-day prices the steam plant appeared favorable (Figure 21). The comparison is shown between steam and open cycle gas turbine under these conditions, with more than a 2:1 advantage for steam. However, if the temperature level can be raised to exceed 1300°F, and if high pressure closed-cycle plants are assumed with the gas turbine cost reduced from present prices proportionate to machinery weight, then according to our preliminary study the gas turbine showed an overall advantage in power cost over the steam plant of about 1.5:1. For comparison, an estimated power cost for a sodium-gas turbine combination plant is shown. The estimated power cost at this particular output is greater than that of the present-day steam plant by about 25%. At higher outputs, the very high thermal efficiency of the sodium cycle becomes more effective in overcoming the high capital cost of the machinery.

5.3 Weight Comparisons

It appeared from our investigations to date, that the total plant weights for a homogeneous reactor steam plant, and a homogeneous reactor open-cycle gas turbine plant in the 5-30 megawatt range for the same types of duty, are roughly comparable. However, the weight of the closed-cycle plants is considerably less (a factor of about 3.5 at 30 atmospheres for 20 mw). It appears that weight-wise, a helium plant should show an advantage of about 1.3 to 1.0 over air, although there appeared to be little significant overall cost gain. The sodium boiler - gas turbine cycle appears to weigh about the same as the steam plant.

These results, and the previously discussed cost results, are extremely tenuous in nature, and are based on numerous assumption and over-simplifications which require detailed examination.

FIG. 21 APPROXIMATE POWER COSTS;
20 MW OUTPUT, LMFR-TYPE REACTOR



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7.0 NOMENCLATURE

Symbol	Meaning
η_{th}	Thermal Efficiency
η_c	Adiabatic Compressor Efficiency
η_T	Adiabatic Turbine Efficiency
η_p	Ratio Between Turbine Expansion and Compressor
T_R	Ratio Between Minimum and Maximum Absolute Cycle Temperatures
T_{R_c}	Ratio Between Compressor Outlet and Inlet Absolute Temperatures
P_R	Cycle Compression Ratio
γ	$k - 1/_k$
k	Ratio of Specific Heats
W_{ST}	Work per Stage of a Compressor
T_1	Absolute Inlet Temperature to Compressor
K	Effective Multiplication Factor for Reactor
ΔK	Change in Effective Multiplication Factor for Reactor