The total temperature and Mach number downstream of the propeller

$T_{T2} = T_{T1} + HP*550/778/(c_p*W)$ — T_{T1} - upstream (ambient) total temperature

$M_2 = V_2 / (\gamma*R*T_{T2} - (\gamma-1)/2*V_2^2)^{.5}$

T_{T2} - downstream total temperature
c_p - specific heat
M_2 -downstream Mach number
γ - specific heat ratio
R - gas constant

The total pressure downstream of the propeller is then:

$P_{T2} = P_{S1}*(1 + (\gamma-1)/2*M_2^2)^{\gamma/(\gamma-1)}$

P_{T2} - downstream total temperature
P_{S1} - upstream (ambient) static temperature

The heat transfer coefficient between the hot expansion side ducts and the surrounding air in the engine cowl has been determined based on a simple free convection correlation. The correlation applies to free convection around a heated circular duct.

3.2 Candidate Systems

Several types and arrangements of equipment have been considered for the turbomachinery system. These are shown and discussed below.

The turbocharger system consists of six characteristic functions, which are illustrated in Figure 7. The turbocharger extracts power from the exhaust stream and uses it to compress the intake charge. The intercooler (I.C.) and aftercooler (A.C.) reduce the temperature of the compressed air to increase the intake charge density. A power turbine can be used to extract additional exhaust energy for use as engine output shaft power. A gearbox is needed to connect the power turbine to the engine shaft. The exhaust wastegates bypass exhaust gas around the turbocharger to limit intake pressurization. Ducts provide the interface connections among the system components and between the system and the engine and airframe.

The system shown as an example in Figure 7 is a simple, thermodynamically complete turbomachinery system for a turbocompounded, turbocharged engine system. Many different candidate system arrangements can be devised from this system by varying the number of compression stages, the number of turbine stages, the order in which the exhaust gases pass through the turbines, and the presence or absence of the power turbine which provides the turbocompounding. A few of these possible configurations are shown in Figures 8 through 10.

Figure 8 shows three system configurations without turbocompounding. The first is composed of two conventional turbochargers (multiple spool system), each having a single compressor stage and a single turbine stage, with intercooling after each compressor stage. Intake manifold pressure is limited by sequential operation of the wastegates, starting with the low pressure spool. The second configuration combines the two compressors on a single shaft driven by a single turbine. This multistage turbocharger system promises to

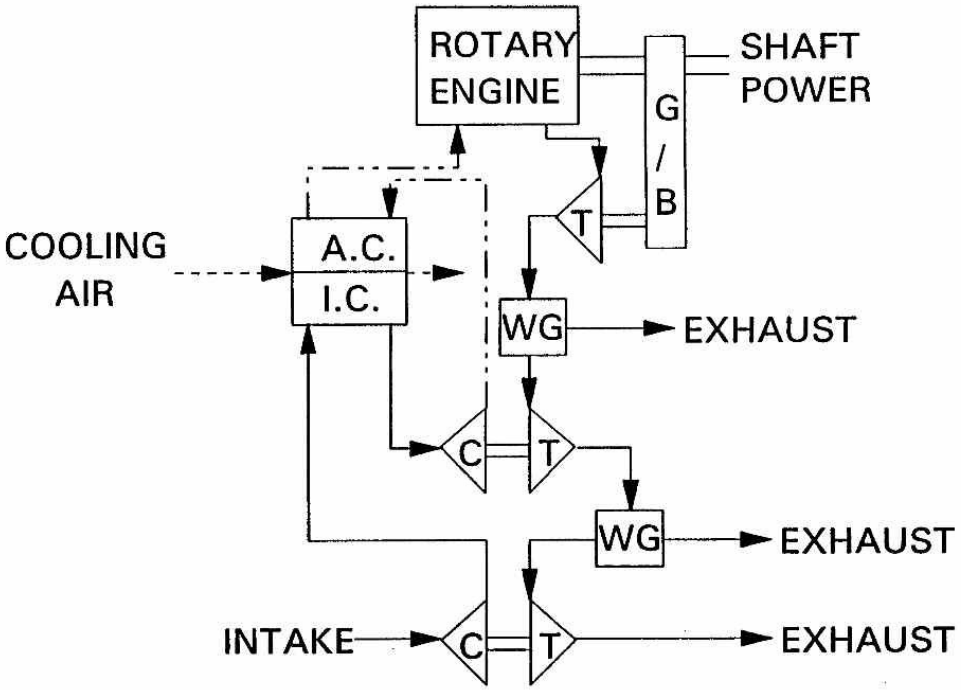
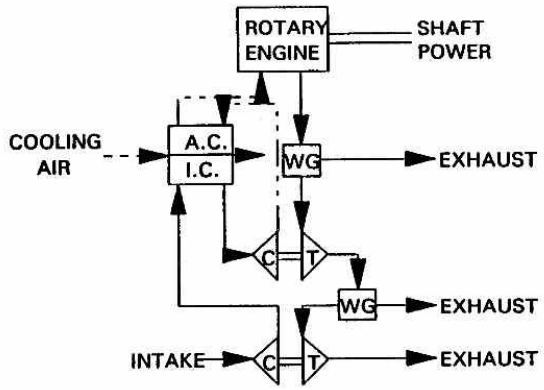
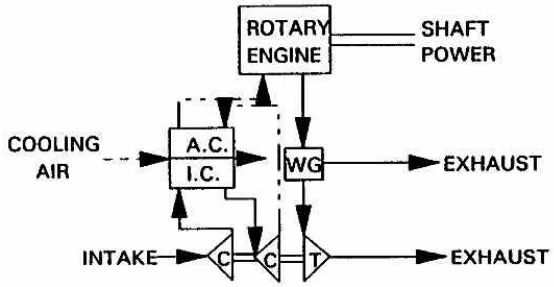


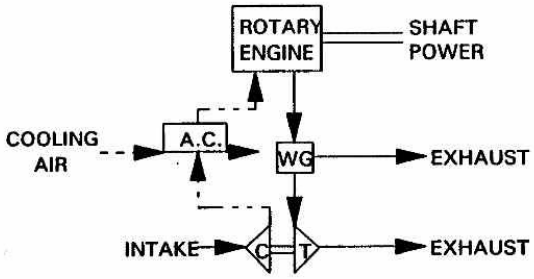
FIGURE 7. TURBOCOMPOUND ENGINE



MULTIPLE SPOOL TURBOCHARGER



MULTIPLE STAGE TURBOCHARGER



SINGLE STAGE TURBOCHARGER

FIGURE 8. CANDIDATE SYSTEMS (NO COMPOUNDING)

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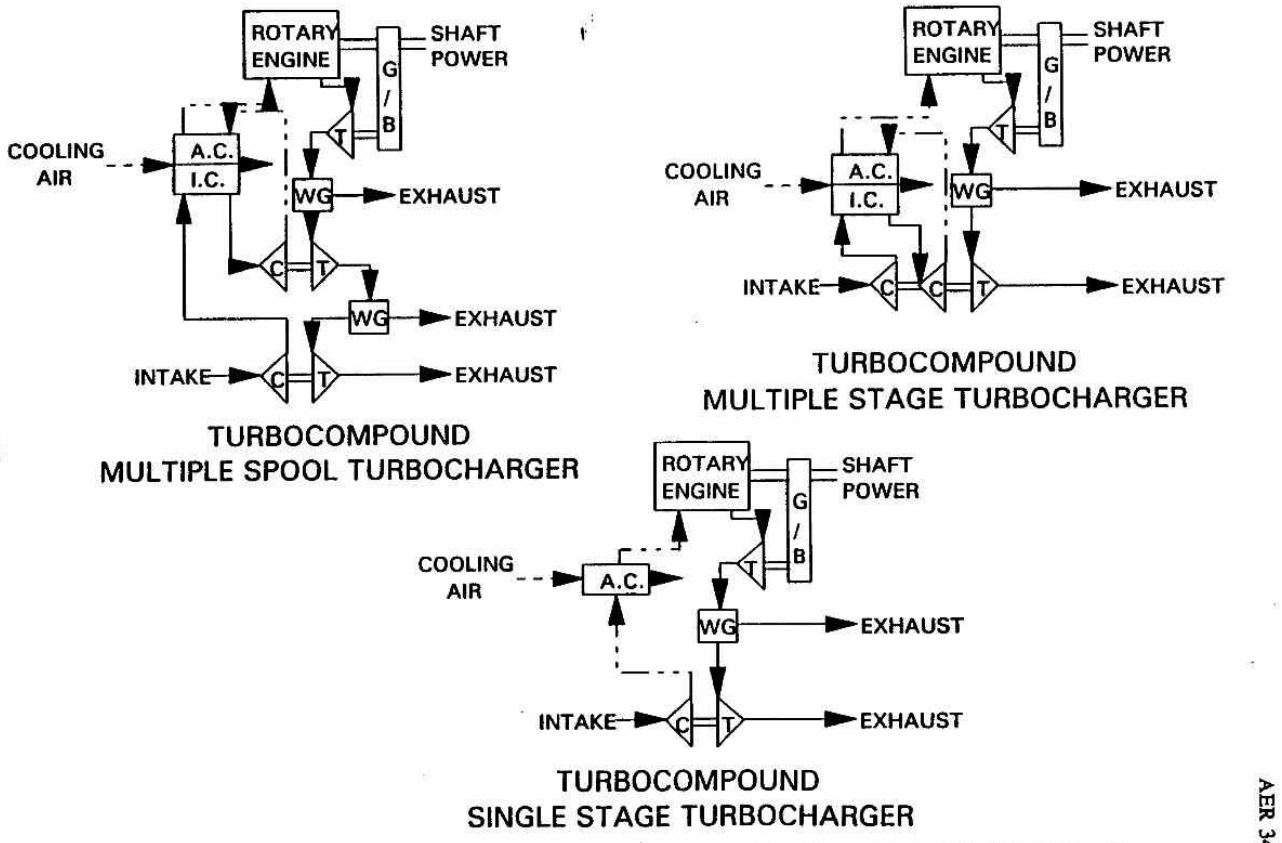
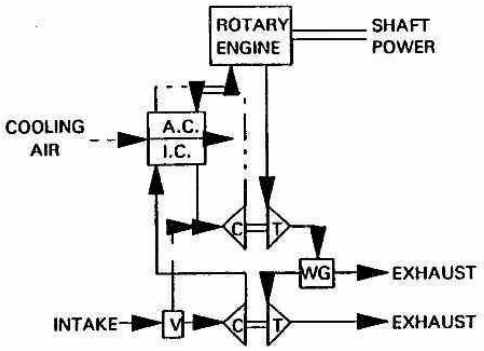
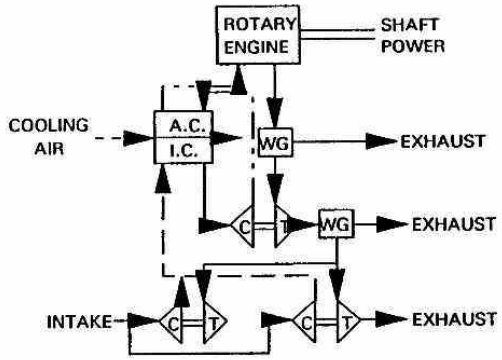


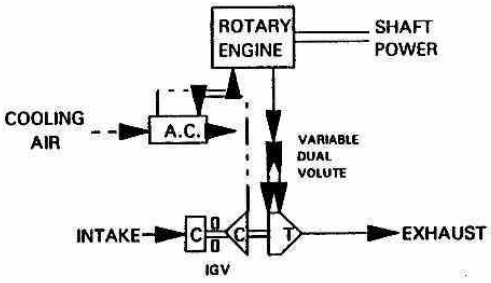
FIGURE 9. TURBOCOMPOUND CANDIDATE SYSTEMS



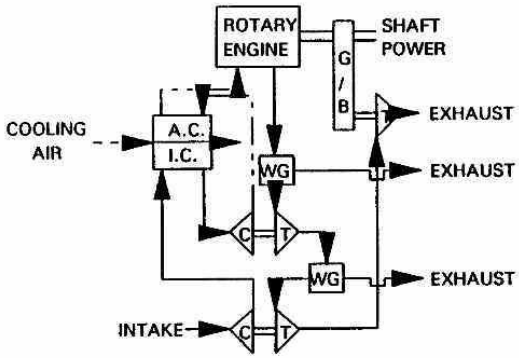
REDIV ALTERNATE 1



3 EQUAL TURBOCHARGERS



REDIV ALTERNATE 2



ALTERNATE TURBOCOMPOUND ENGINE

FIGURE 10. ALTERNATE CANDIDATE SYSTEMS

be more compact than the multispool system, while delivering similar thermodynamic performance. The third system achieves the required compression in a single stage. The single stage turbocharger appears to provide the simplest system, but was determined to have thermodynamic disadvantages and to be a more risky approach.

The three systems in Figure 9 are similar to those in the previous figure, except that each has a power turbine in the exhaust stream preceding the turbocharger(s). This turbine provides the "turbocompounding" effect, extracting excess power from the exhaust to add to the engine output shaft power. The analysis shows that there is significant gas power available for turbocompounding, and that this function may be necessary to achieve the engine BSFC goal.

In Figure 10 are shown four other schematics which were proposed but discarded for various reasons. The first configuration is like the basic multiple spool configuration, but uses an additional valve to control the compressor flow split. This causes additional compressor matching problems without adding any performance to the system. The second schematic, REDIV Alternate 2, suggests using a variable geometry turbine instead of wastegate control and an axial/centrifugal compressor. This is thermodynamically equivalent to the multistage turbocharger at design operation, which is the only operating condition analyzed to date. Some operational (off-design) advantages may accrue from using variable geometry instead of wastegate control. Controls would be more complex, and development would be necessary. The three equal turbochargers were proposed as a potential approach for constructing a ground test article to demonstrate thermodynamic performance. The additional pieces of hardware and plumbing would make it impractical for aircraft installation. The alternate turbocompound schematic illustrates the potential for positioning the power turbine last in the exhaust, instead of first. This is suggested in the literature as a technique for improving engine throttle response, because it tends to maintain turbocharger turbine pressure ratios at a more constant level. However, it also eliminates the increase in turbocharger output with increasing altitude, which is an absolute must for the aircraft engine.

3.3 Optimization Criteria

A mathematical optimization process, such as included in the system analysis, requires an objective function which smoothly varies with the independent parameters of the problem. The NASA contract for this engine development set goals for power, weight, and fuel consumption of the entire system; however, the allotments for the turbomachinery were not known, nor was there any guidance given for tradeoffs. In order to proceed with the system optimization, it was necessary to develop optimization functions.

The turbocharger system imposes three penalties on the airframe and engine. These are the system fixed weight, the drag incurred by the ram air cooled heat exchangers, and the back pressure imposed at the engine exhaust. The formulated penalty function relates the relative impact on the airframe and engine of these three factors. The optimization parameters are varied (or optimized) by an optimization algorithm to minimize this penalty function and thus maximize the benefits of the turbomachinery system to the aircraft.

The approach taken to formulate the penalty function recognizes that the purpose of the rotary engine and its turbomachinery system is to provide propulsive power to the airframe. Benefits and penalties to the aircraft performance which are generated by the turbomachinery system can be accounted as a combination of thrusts and drags (or the equivalent powers). Thus, the ram drag of the system, drag due to lift incurred by system weight, engine power changes due to exhaust pressure changes, and power turbine contributions can all be combined into a single expression for net output power due to the turbomachinery system. (The "best" turbomachinery, by this definition, is the one which maximizes installed thrust-minus-drag.)

Drag:

The system fixed weight and incurred drag can be combined into the net drag imposed on the airframe by the turbomachinery system. The weight results in a drag penalty on the airframe due to additional lift required; this can be expressed by dividing the weight by the lift over drag (LOD) ratio. The net drag function takes the form:

$$\text{net drag} = \text{incurred drag} + \text{fixed weight/LOD}$$

Power:

The engine exhaust pressure can be converted into a net power change from the baseline power, produced by the engine and power turbine pair. The pumping loop contribution to engine power can be expressed as:

$$Pw_{pl} = \Delta V \times N \times (Pe_{in} - Pe_{out})$$

Pw_{pl} - pumping loop power
N - engine speed
ΔV - swept volume
Pe_{in} - engine inlet pressure
Pe_{out} - engine exhaust pressure

The power at some reference engine exhaust pressure has been given by the engine manufacturer. The pumping loop power portion of total engine power at this reference exhaust pressure ($Pe_{out,ref}$) is given by:

$$Pw_{pl,ref} = \Delta V \times N \times (Pe_{in} - Pe_{out,ref})$$

Assuming that a change in the exit pressure effects only the pumping loop power, the change in the engine power (which is just the change in pumping loop power) for this exit pressure is given by:

$$\Delta Pw = Pw_{pl} - Pw_{pl,ref}$$
$$\Delta Pw = \Delta V \times N \times (Pe_{out,ref} - Pe_{out})$$

The net power change from the engine power baseline also includes the power turbine contribution. The net power change is given by:

$$\Delta Pw_{net} = \Delta Pw + Pw_{pt}$$

Pw_{pt} - power to propeller shaft from power turbine

Equivalent Power:

The net effect of the turbomachinery system on engine shaft power available for propulsion is obtained by converting the net drag to a (negative) thrust power and adding to the net power. The "equivalent power" optimization function for the turbocharging system has the form:

$$Pw_{eq} = \Delta Pw_{net} + V_{free} \times \text{net drag} / \eta_{prop}$$

V_{free} - free stream velocity
η_{prop} - propeller efficiency

or,

$$Pw_{eq} = \Delta V \times N \times (Pe_{out,ref} - Pe_{out}) + Pw_{pt} - V_{free} \times (\text{incurred drag} + \text{fixed weight/LOD})$$

3.4 Parametric Evaluations

Optimization Parameters:

Nine parameters have been identified which affect the optimization function, as well as weight, drag, and engine exhaust pressure. Some affect only one or two of these. The optimization parameters are listed below along with a description of the penalty factors they affect.

1.	First stage compression ratio	affects system weight and engine exit pressure (net power), affects heat exchanger size which has only slight effect on incurred drag
2.	Intercooler charge air exit temperature	same effects as above
3.	Inter/aftercooler charge air side pressure drop	trades heat exchanger weight against engine exit pressure (net power), affects heat exchanger size which has only slight effect on incurred drag
4.	Duct mach number	trades duct weight against engine exit pressure (net power), no effect on incurred drag
5.	Power supplied to prop shaft from power turbine	affects power turbine weight (and system weight slightly) and engine exit pressure (net power), no effect on incurred drag
6.	Expansion side duct insulation thickness	trades weight of insulation against engine exit pressure (net power), no effect on incurred drag
7.	Inter/aftercooler air side pressure drop	trades weight of heat exchangers against ram air drag, no effect on engine exit pressure (net power)
8.	Intercooler air flow rate	trades weight of heat exchangers against ram air drag, no effect on engine exit pressure (net power)

9.	Aftercooler air flow rate	trades weight of heat exchangers against ram air drag, no effect on engine exit pressure (net power)

Results:

The effects of each of the optimization parameters was examined individually. Several were found to have optima which fell into narrow ranges and could be fixed for system optimization studies.

The dual stage turbocharger system (two compressor stages driven by one turbine stage) was used for evaluating the effects of insulation thickness, pressure ratio split, intercooler charge air exit temperature, and air side pressure drop and flow rate through the intercooler and aftercooler on net drag, net power and equivalent power. Turbocompounding was not included, inter/aftercooler charge air side pressure drop was set to 0.125 psid, and duct Mach number was set to 0.175 for this set of optimization studies.

Insulation Thickness:

As insulation is added to the exhaust ducts, less thermal energy is lost and lower engine back pressure is required to drive the turbines, resulting in a net power increase. However, duct weight and net drag increase. The net effect is for equivalent power to drop as insulation thickness is increased. Therefore, insulation thickness is set to zero since this leads to maximum equivalent power.

Compressor Pressure Ratio Split:

Over a wide range of the other optimization parameters, the first stage compression ratio (Pr) is optimal between 3.6 and 3.8 for maximum equivalent power. Pressure ratio was, therefore, fixed at 3.7.

Ram Air Heat Exchanger Pressure Drop:

As intercooler and aftercooler air side pressure drop (ΔPc) increases, heat exchanger weight decreases but ram air drag increases. Only net drag is effected. A value of ΔPc of 0.1 psid was found to be optimal for minimum net drag.

Intercooling:

Figure 11 shows the effect of intercooler charge air exit temperature (Tic_o) on net power, net drag and equivalent power. For each value of Tic_o, inter/aftercooler ram air flow rate (Wc_{ic} and Wc_{ac}) are optimized for minimum net drag (they have no effect on net power). Over a range of Tic_o from 140.0 °F to 210.0 °F the equivalent power is constant within 0.7%. Net drag decreases from 21.71 to 20.11 and net power decreases from 28.19 to 27.74 over this range. Tic_o is set to 150.0 °F since it yields high net power. The values of Wc_{ic} and Wc_{ac} for which net drag is minimum for this temperature are 53.3 and 54.7 lbm/min.

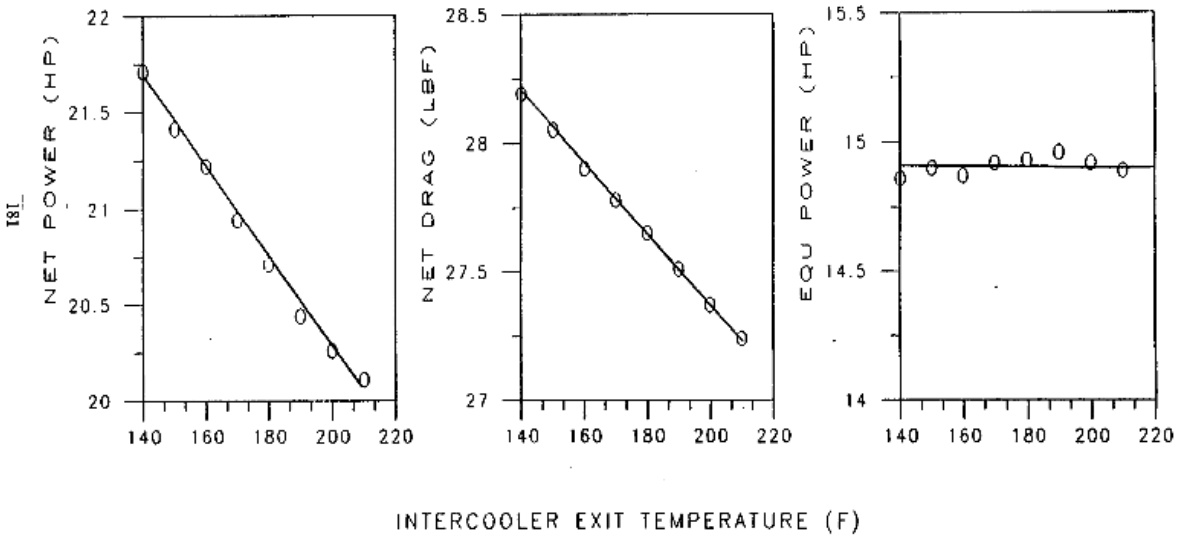


FIGURE 11. EFFECT OF INTERCOOLING

Charge Air Heat Exchanger/Duct Pressure Drop:

With the previously discussed optimization parameters fixed, the optimal values of intercooler/aftercooler charge air pressure drop (ΔP_{hx}), duct Mach number (M_d), and turbocompounding power remain to be determined. The power turbine is placed upstream of the turbocharger as this results in the lowest weight power turbine, with little effect on the turbocharger. Figure 12 shows the effect of heat exchanger pressure drop and duct Mach number, at various levels of power turbine output power, on net power, net drag, and equivalent power. (The analysis is for steady state flow, analysis with pressure pulse effects is discussed below.) The heat exchanger pressure drop, ΔP_{hx}, and duct Mach number, M_d, together characterize the charge air pressure drop. In order to vary them together systematically, normalized parameters are used:

normalized pressure drop, $(\Delta P_{hx} - \Delta P_{hx,min})/(\Delta P_{hx,max} - \Delta P_{hx,min})$

and

normalized duct Mach number, $(M_d - M_{d,min})/(M_{d,max} - M_{d,min})$

The normalized pressure drop and Mach number are increased together along the x-axis of the three plots, from $\Delta P_{hx,min}$ of 0.05 psid to $\Delta P_{hx,max}$ of 0.25 psid, and $M_{d,min}$ of 0.10 to $M_{d,max}$ of 0.30. As the pressure drop and Mach number increase, the heat exchangers and duct weights decrease, which results in a net drag decrease, but power must be expended to overcome the increased charge air pressure drops, and thus net power is decreased. The resultant equivalent power curves are nearly flat with a slight maximum between 25 percent and 50 percent of the pressure drop range, and decrease at higher pressure drops. Values of 0.125 psid and 0.175 Mach number are selected for ΔP_{hx} and M_d.

Power Turbine Power:

Power turbine power is indicated by the coding numbers on the curves, in tens of horsepower (e.g., the curve having the numeral "4" embedded in it indicates a fixed power turbine power of 40 horsepower). With increasing power turbine power, net power increases. Net drag at first increases; there is a jump in weight, and thus in net drag from zero power (no turbine or gearbox) to finite power output. Then net drag decreases as increasing power turbine pressure ratios (at fixed flow) result in faster, smaller turbines. Equivalent power decreases with the initial addition of hardware between zero and non-zero turbine power, then increases. Net and equivalent power increase monotonically with increasing power turbine power, seemingly indicating very large power availability. However, there is probably a practical limit at back pressures sufficiently high (exhaust pressures near engine inlet pressure) to cause engine scavenging difficulties. The inlet and exhaust pressures specified by REDIV (34.9 and 30.6 psia, respectively) are shown on the net power plot. They show a practical power turbine maximum design power to be in the 50-60 horsepower range (with NO pulse effects), with resulting equivalent power of 35-40 horsepower.

Figure 13 shows the effect of ΔP_{hx} and M_d, again using the parameter k, at various levels of turbocompounding power, on net drag, net power, and equivalent power with initial

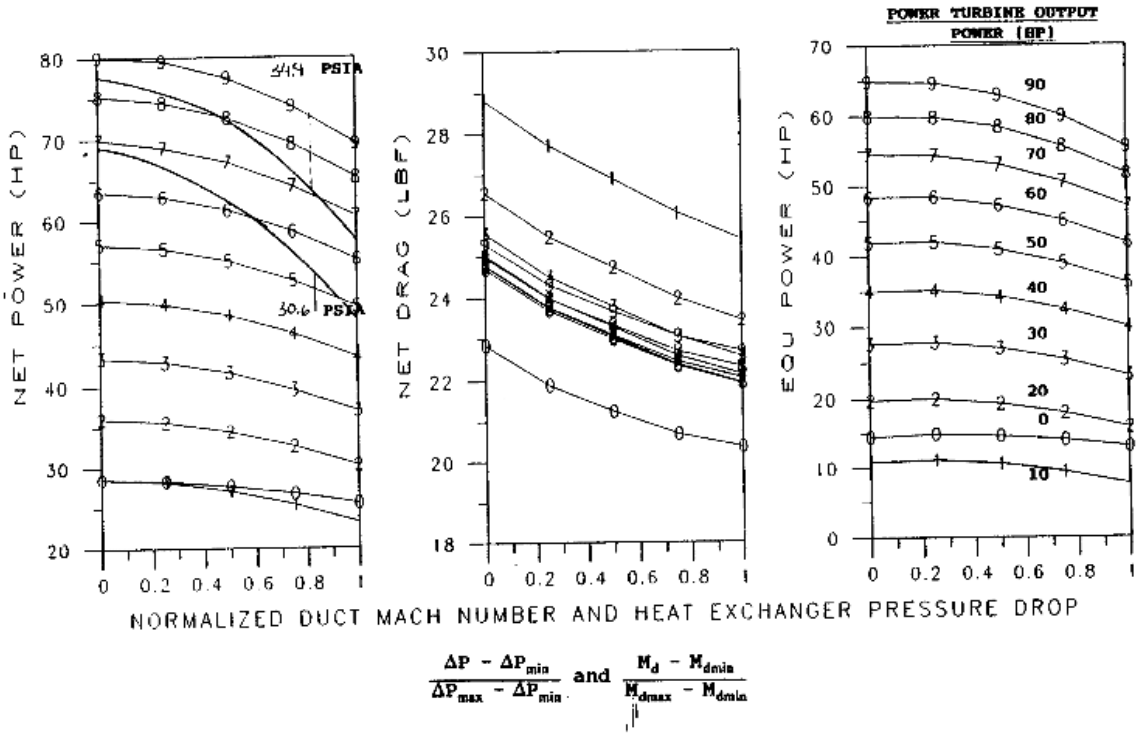


FIGURE 13. EFFECT OF CHARGE AIR PRESSURE DROP (WITH PULSE EFFECT)

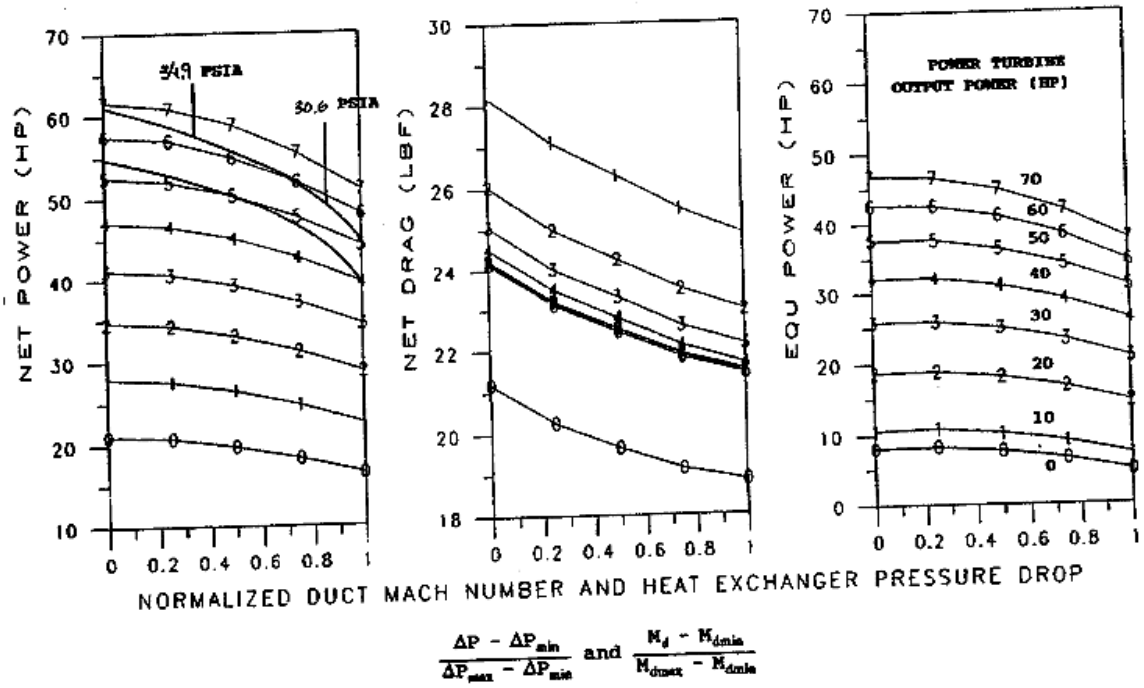


FIGURE 12. EFFECT OF CHARGE AIR PRESSURE DROP (NO PULSE EFFECTS)