## APPENDIX C

## TURBOMACHINERY SYSTEM ANALYSIS FOR STRATIFIED CHARGE ROTARY ENGINE CRITICAL TECHNOLOGY/ENABLEMENT

## TABLE OF CONTENTS




| | Page Numbe |
|---|---|
| ABSTRACT | 1 |
| KEYWORDS | 2 |
| 1.0 INTRODUCTION | 3 |
| 2.0 ANALYTICAL MODELS | 4 |
| 2.1 System Model | 4 |
| 2.2 Turbines and Compressors | 4 |
| 2.3 Heat Exchangers | 8 |
| 2.4 Ducts | 8 |
| 2.5 Exhaust Pulses | 10 |
| 2.6 Gearboxes | 10 |
| 3.0 SYSTEM EVALUATION | 13 |
| 3.1 Design Conditions | 13 |
| 3.2 Candidate System | 16 |
| 3.3 Optimization Criteria | 21 |
| 3.4 Parametric Evaluations | 23 |
| 4.0 RESULTS AND RECOMMENDATIONS | 29 |
| 4.1 Results | 29 |
| 4.2 Recommendations | 42 |
| 5.0 REFERENCES | 42 |

## ABSTRACT

Analytical studies of turbomachinery systems to enhance the performance of stratified charge rotary engines were conducted under subcontract to John Deere Technologies International, Inc. (JDTI). JDTI was under contract with NASA Lewis Research Center (NAS3-25945) to demonstrate critical technologies for a general aviation aircraft engine in the Stratified Charge Rotary Engine Critical Technologies Enablement (SCRECTE) program. The design objective is an engine suitable for a high performance twin-engine light aircraft. To obtain adequate power density in high altitude cruise, as well as for stratified charge operation, turbocharging is mandatory. The turbomachinery analytical studies were conducted to determine the optimum system configuration. The Sundstrand effort included assembly of component sizing and performance prediction models into a system analysis model for evaluation of candidate systems. Evaluation criteria were developed, and an optimization routine used to find the preferred configurations. The best turbomachinery configuration included a compounding turbine, which converts some of the exhaust energy to shaft power, as well as a turbocharger having two compressor stages driven by a single-stage turbine. The intake charge was intercooled between compressor stages and between the second compressor and the engine intake port. Intake manifold pressure control was effected by exhaust wastegate operation.



KEYWORDS

Keywords or phrases for computerized technical information data base: SCRECTE, rotary engine turbocharger, turbochargers, general aviation, and turbocompound engine.

## 1.0 SUMMARY

The NASA Lewis Research Center contracted with John Deere Technologies International, Inc. (JDTI), under the Stratified Charge Rotary Engine Critical Technologies Enablement (SCRECTE) program, to demonstrate a competitive general aviation engine. The demonstrator was based on previous JDTI designs but required significant development in fuel economy and power density at cruise altitude. The engine specification required 40 percent thermal efficiency (brake specific fuel consumption, BSFC, of 0.34 lbs/hp/hr on Jet-A fuel) at cruise conditions and specified full power to be available from sea level to 25,000 feet altitude and 75 percent power for cruise up to 33,000 feet. In order to meet the power requirement at altitude, intake port air density needed to be as high as previously demonstrated at sea level. The compressor could not use shaft power, because this would increase BSFC, which needed to be lowered. The source of energy available to improve the BSFC and provide intake pressurization is the engine exhaust. The flow rates, pressures, and temperatures involved strongly suggest the use of turbomachines for these processes. JDTI employed Sundstrand to analyze the turbomachinery system for the engine.

Sundstrand originally planned, in a multiphase program, to provide system analysis, including component sizing and performance predictions; to design the turbomachinery and ancillary equipment; to procure, assemble, and test the turbomachinery system; and, finally, to support engine testing with the turbomachinery system. The program was subsequently descoped due to alterations in the contractual agreements between JDTI and NASA, and the Sundstrand effort was terminated before the design hardware effort was begun.

The system analysis process leading to system configuration selection, essentially complete at program termination, consisted of several tasks.

- Creation of candidate system configurations. Many suggestions were compiled from various sources, including Sundstrand, JDTI, and consultants.

- Assembly of component models. Each element of the system, including turbines, compressors, heat exchangers, ducts, and gearboxes, needed to be characterized in terms of weight, performance, and volume. Most of the component models were available or easily adapted from existing Sundstrand models.

- Define the parameters of interest in assessing the candidate systems, in order to be able to select the "best" configuration.

- Encode a computer program, including an optimization algorithm, to find the best implementation of each of the candidate system configurations, to estimate the characteristics of the components, and to calculate the system selection parameters.

The design/sizing analysis was essentially complete at program termination, and a recommended system configuration was selected. Some additional detailed analysis was needed to confirm estimated exhaust pulse recovery benefits, which were expected to provide significant improvements in exhaust energy recovery and, therefore, engine BSFC.

The selected turbomachinery system configuration incorporates a turbocharger consisting of two compressor stages and one turbine stage on a single shaft, intercooling after each compressor stage, and a compounding turbine upstream of the turbocharger (at the engine exhaust). The system is estimated to weigh 206.50 lbm, to impose a net ram drag of 5.05 lbf on the aircraft, and to produce 49.4 hp of shaft power through turbocompounding (increasing engine output). The following sections of the report describe the above activities in more detail.

## 2.0 ANALYTICAL MODELS

In order to rapidly evaluate a number of candidate system configurations, computer models were constructed to estimate and optimize characteristics of components. These were combined into a system thermodynamic analysis computer program which balances component functions and computes system parameters. An optimization function, called equivalent power, was defined to enable the "best" system to be selected (the optimization function derivations are given in Section 3.3).

### 2.1 System Model

A typical turbomachinery system for a rotary engine is shown in Figure 1. This system, like all the systems evaluated, employs various turbine and compressor stages, heat exchangers for rejection of charge air heat of compression to ambient air, charge air lines and ram air ducts. A gearbox is employed for the power turbine options. Each of these component types is modelled by unique component sizing subroutines which predict component size and weight. Most of the routines perform heat transfer and thermodynamic analysis and some use empirically derived sizing relationships. The line sizing subroutine was adapted for this contract; the remaining subroutines existed before the contract began and are Sundstrand proprietary.

The system analysis computer program can be adapted to model various system configurations by altering input flags. A system schematic with various configuration options is shown in Figure 2. The program calculates system state points (temperature, pressure and flow rate) at the numbered locations, based on the input design conditions, constraints and the current values of the optimization parameters (defined in Section 3.4) and calls the various component sizing models to size the components based on the calculated state points. The equivalent power function is evaluated for the resultant values of engine exit pressure, power turbine power, incurred drag and fixed weight. An optimization routine is included in the system analysis computer program (flow chart provided in Figure 3). The optimization routine varies the system optimization parameters until the equivalent power is maximized.

### 2.2 Turbines and Compressors

The turbomachinery models incorporated in the system model use specific speed curves and empirical relations to determine wheel diameters which are then used with scaling functions to estimate component weight. For the turbomachines which include more than one wheel on a shaft (i.e. one turbocharging spool), the shaft speed is selected such that

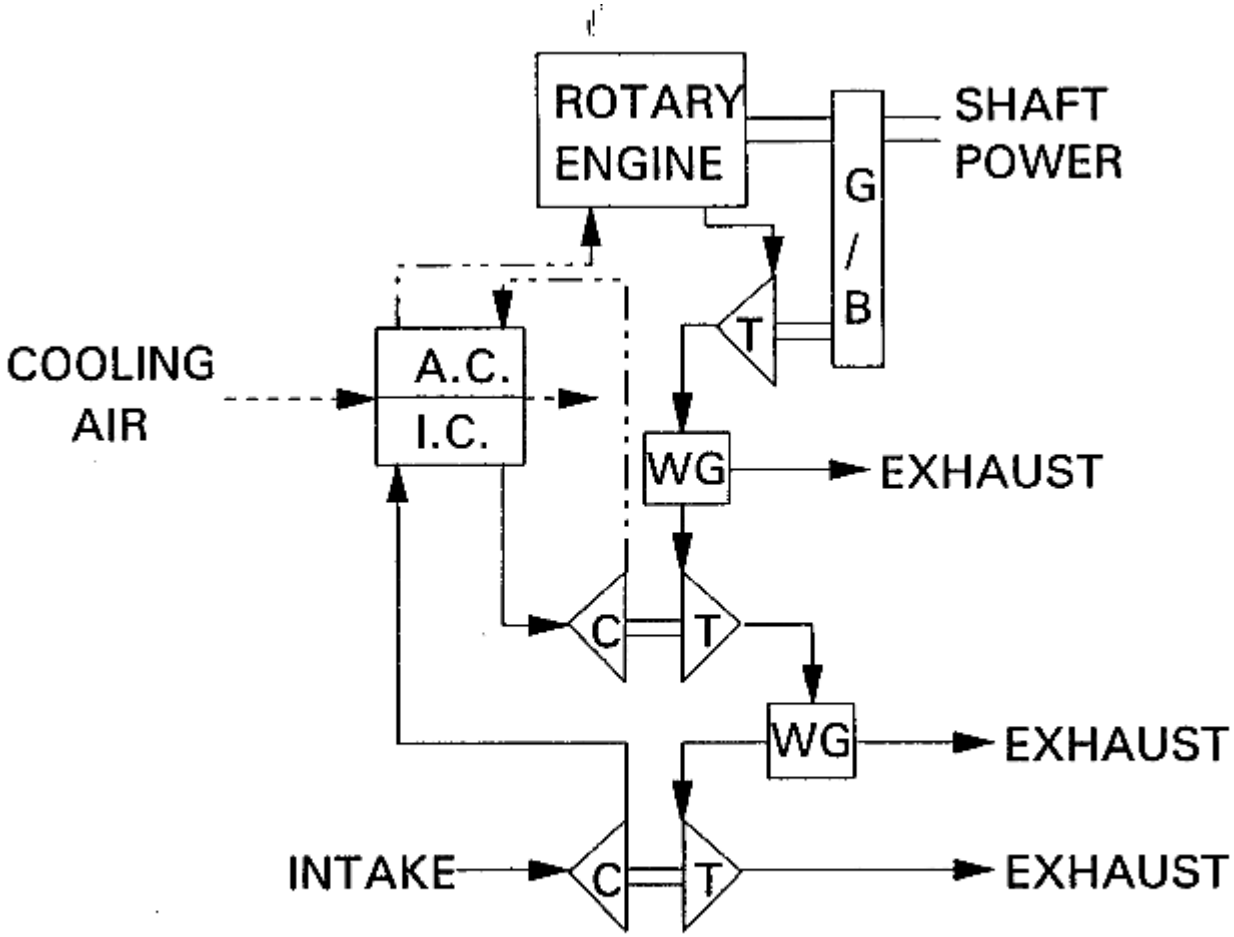



FIGURE 1. TURBOCOMPOUND ENGINE

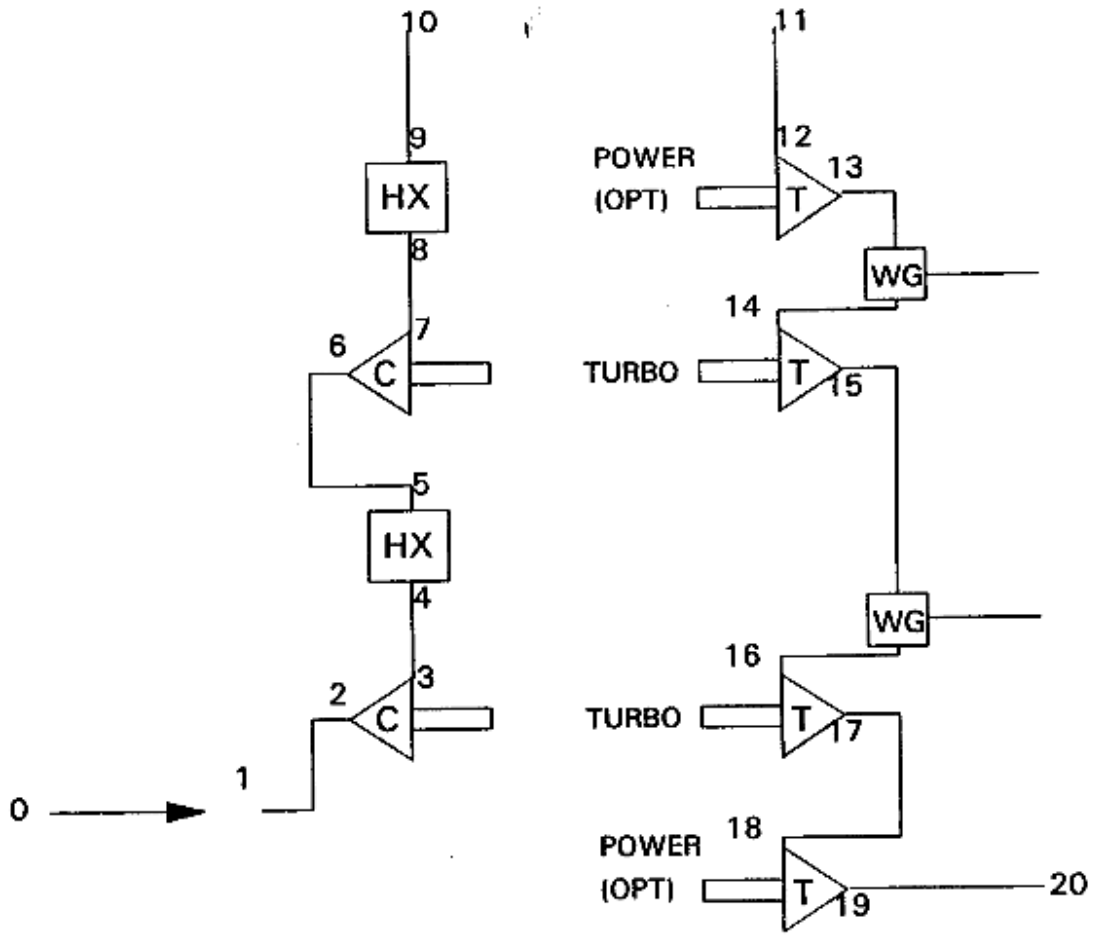



FIGURE 2 TURBOMACHINERY SYSTEM STATE POINTS

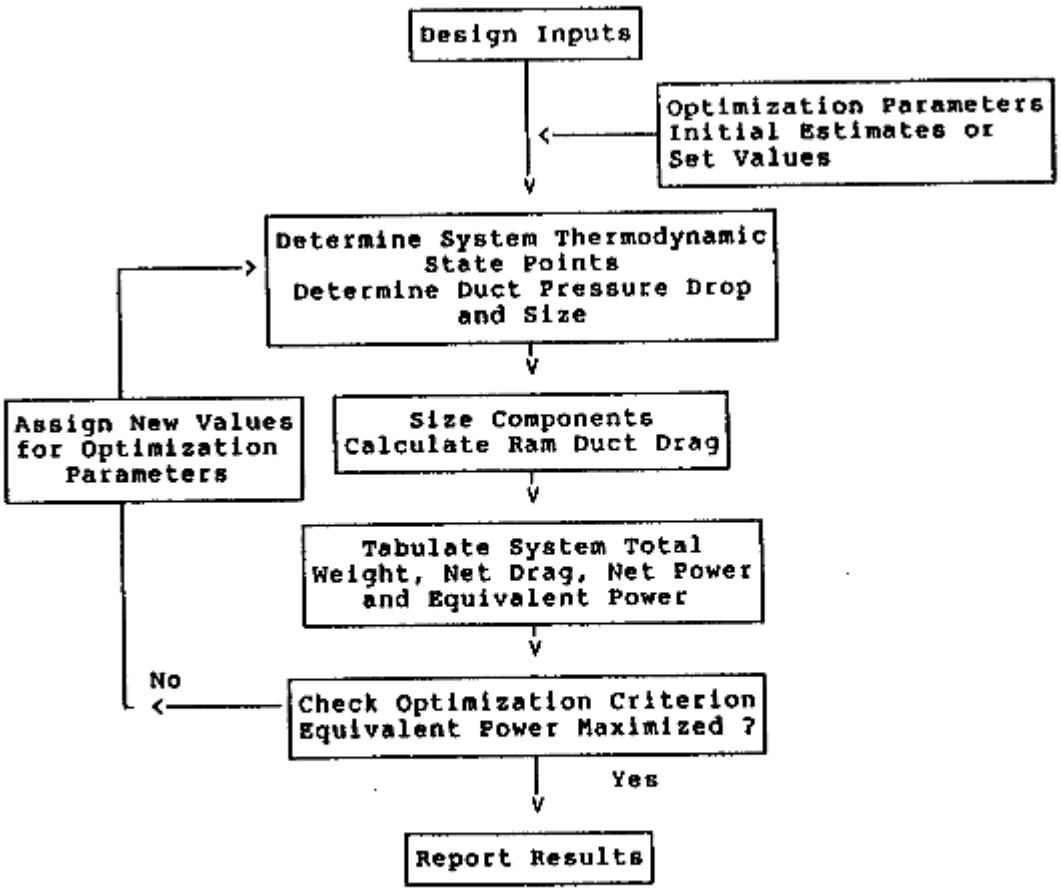



**FIGURE 3. SYSTEM ANALYSIS PROGRAM FLOW CHART**

all of the wheels on that shaft operate at near-optimum specific speeds. The acceptable specific speed ranges are set such that efficiencies range between 0.7 and 0.85. For turbomachines with only one wheel on a shaft (i.e. a power turbine on a gearbox), the shaft speed is determined such that the specific speed is optimal for maximum efficiency.

Compressor and turbines sizes are determined by somewhat different techniques. For compressors, the tip speed, determined by the head coefficient, and shaft speed are used to determine wheel diameter. For turbines, a specific speed/specific diameter correlation for peak efficiencies is used to determine the optimum specific diameter; the wheel diameter is calculated from the specific diameter. In either case, the wheel diameter is used in an empirical correlation to determine wheel and housing weight. The weight correlation has been calibrated using turbocharger data supplied by Beech Aircraft.

Turbine and compressor designs generated by the system models have been checked using more detailed Sundstrand proprietary computer programs to assure reasonable accuracy. The results of these check runs provided the efficiency predictions input to the system program. Turbomachinery inlet conditions and isentropic head rise are input to the design routine, which then calculates shaft speed, turbomachine weight, and volume.

## 2.3 Heat Exchangers

The heat exchangers are modelled as crossflow plate fin devices. Alternating layers of fin stock and parting plates make up the heat exchanger core as illustrated in Figure 4. Aluminum fins with aluminum parting plates are used for heat exchangers with service temperature below 350°F while nickel fins with stainless steel parting plates are used for service temperatures above 350°F. Typical values of fin height, spacing and thickness, parting plate thickness, etc. are assigned to each side of the heat exchanger based on the whether the fluid is liquid or gas. The required heat exchanger UA is determined by the effectiveness-NTU method. An iterative approach (outlined in Kays and London [1]) where the hot and cold side mass fluxes are iterated until the desired pressure drop on each side is met, is used to determine heat exchanger geometry. Plate fin correlations for friction factor and Colburn J factor are used to determine friction factor and heat transfer coefficient. The design routine takes hot and cold side inlet and exit temperature, pressure drop and flow rate as input and calculates heat exchanger weight, volume and face area.

## 2.4 Ducts

The duct model determines duct pressure drop, heat loss, and weight for a specified inlet Mach number. The duct area is determined which yields the specified inlet Mach number for the required duct flow rate. The duct pressure drop is calculated based on a friction factor correlation and the determined duct diameter. Insulation properties, local ambient conditions, and duct diameter are used to determine the duct heat loss. Finally, weight and volume are determined based on the duct diameter and wall thickness and the insulation properties. Duct inlet conditions, duct and insulation length, thickness, density and conductivity, and local ambient conditions are input to the routine and duct pressure drop, temperature drop, weight and volume are calculated.

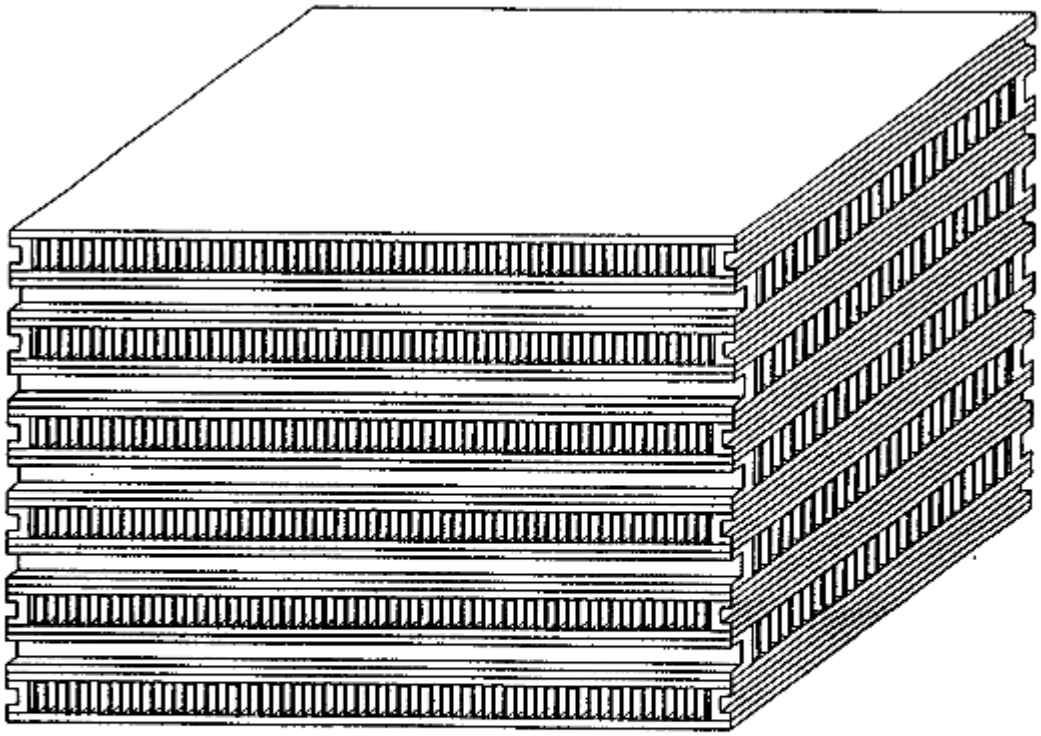


**FIGURE 4. CROSSFLOW HEAT EXCHANGER CORE**

A ram air circuit model calculates the duct losses and drag incurred by the ram air ducts. This routine tracks total pressure and accounts for frictional losses through an assumed duct geometry. The duct configuration, shown in Figure 5, includes a flush inlet, an inlet diffuser, a heat exchanger, a 90° bend section leading to a fan, the fan, a section of duct leading to an exit nozzle, and an exit nozzle. The SCRECTE system does not require a ram air fan, so the fan and the upstream 90° bend duct are deleted from the ram air duct analysis by a flag in the subroutine. Friction factor correlations and diffuser and nozzle loss correlations are used to model the pressure drops in the circuit. Ambient conditions, heat exchanger flow area and pressure drop, ram air flow rate, and fan pressure rise are input to the model and duct drag and fan power are calculated. If the inlet area is not specified (and usually it should not be) it is determined such that the inlet Mach number is 76 percent of the free stream Mach number. Inlet Mach numbers lower than this could cause boundary layer separation, causing flow instability and large losses at the inlet. Due to the many possible ram air duct installations the weight of the ram air duct is not estimated.

## 2.5 Exhaust Pulses

All of the component models, as well as the system model, predict performance and size of components on the basis of steady state flow conditions. It is well known, however, that the intermittent flow in the exhaust of an internal combustion causes pressure and flow pulses which greatly alter the distribution of energy with time and affect turbomachine size and performance. In order to assess these effects, a model of the exhaust system was created to calculate correction factors to be used in the system model. The transient model integrates the engine exhaust port and turbine inlet flows to determine the rate of change of mass in the exhaust duct and the resulting exhaust duct pressure. Wave dynamics have been ignored. Figure 6 shows some sample calculations of one exhaust cycle of one rotor; the variations shown are due to changes in the exhaust duct exit pressure and in exhaust duct length (volume). The taller pulses contain more energy, indicating the need for low volume exhaust systems. The pressures shown are not high enough to affect engine internal flow processes. The pulse modelling was not completed, but clearly indicates that care should be taken in the sizing of the exhaust system to preserve the power potential of the pulses. Preliminary results also indicate that the pulsed flow can contain 50 to 100 percent more power than a steady flow, and that up to 50 percent larger turbine and duct flow areas are required than for steady flow. Turbine average efficiency is lower than for steady flow by a few percentage points, but this is a small effect compared to the extra available energy, which greatly increases turbine power.

## 2.6 Gearboxes

Gearbox weight is determined from a correlation of weight versus power. Weights were estimated for several gearbox designs over a range of power turbine powers and speeds to derive this correlation. An allowance for unsteady shaft dynamics was included by sizing all gearbox elements for three times the rated power. Engine rotor accelerations and decelerations, due to intermittent combustion, are amplified through the power turbine gear train and can result in large loads and/or shaft deflections. It is recognized that a much more rigorous shaft dynamics analysis is needed for actual gearbox design.

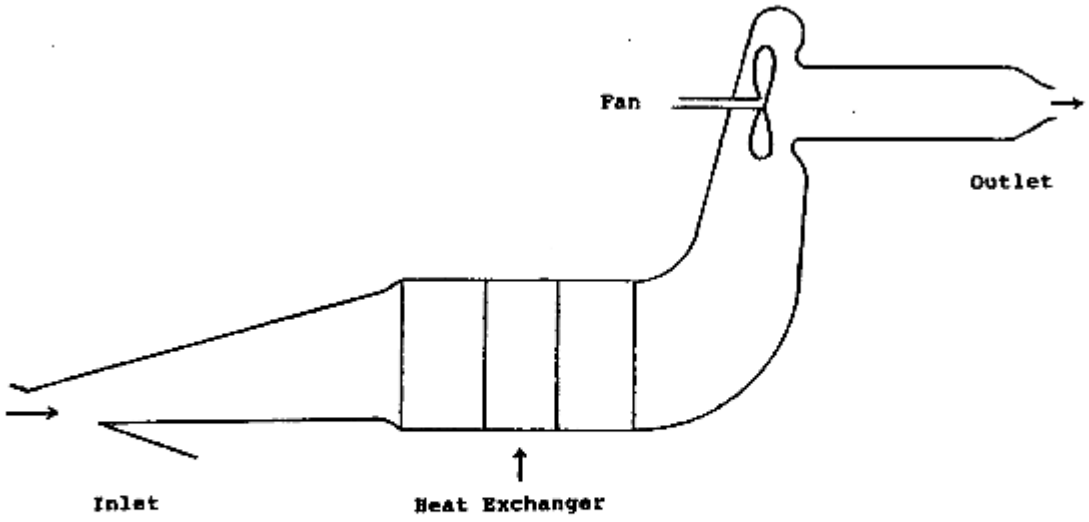



**FIGURE 5. RAM AIR DUCT SYSTEM**

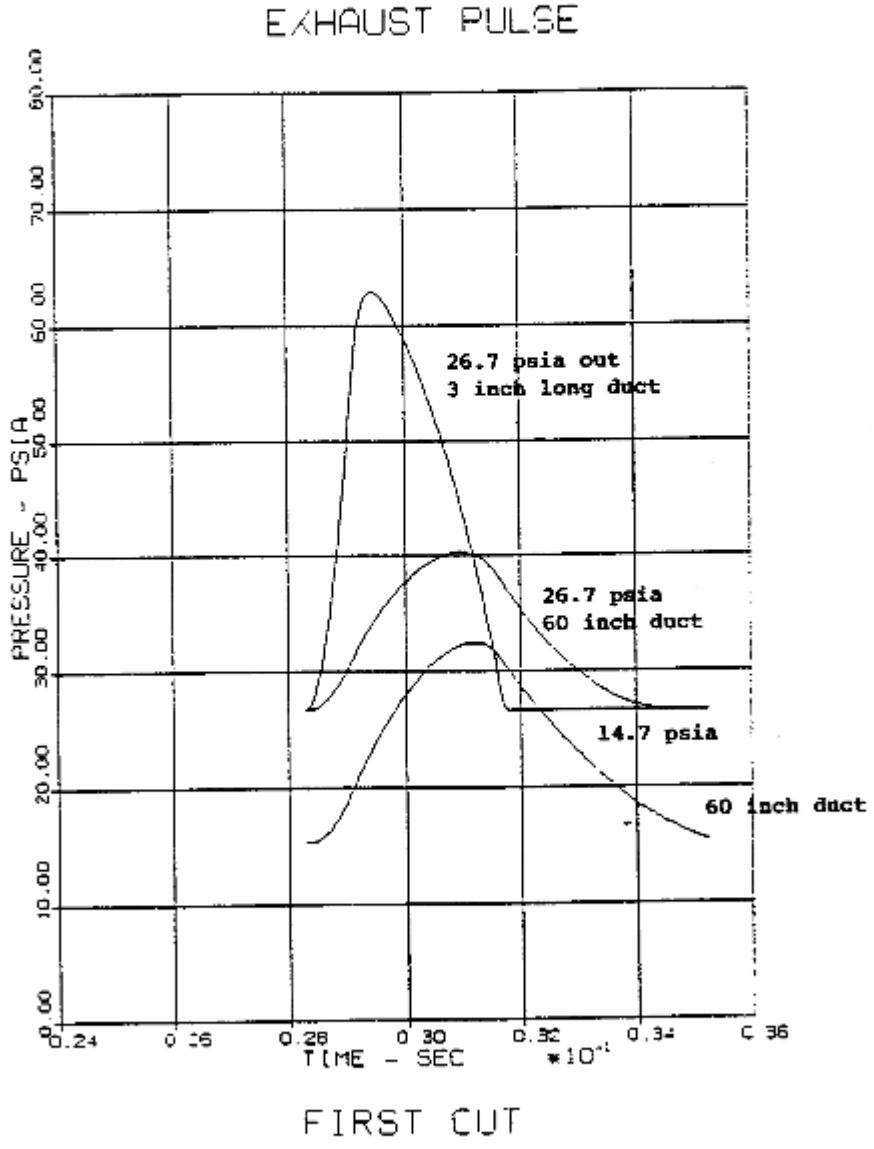



**FIGURE 6. EXHAUST PULSES**

## 3.0 SYSTEM EVALUATION

The functional requirements for the turbomachinery system are described in Section 3.1. These form the boundary conditions for analysis of any proposed system. The comparative evaluation of candidate turbomachinery systems required several steps subsequent to development of the system analysis computer program. Initially, an array of candidate system configurations was identified by brainstorming and extraction from publications or other experienced sources on turbocharging. Some sorting of these schematics was done based on operational considerations, the rest using the system analysis program. The candidate systems are discussed in Section 3.2. Secondly, it became clear that there was no clear definition of what constituted the "best" turbomachinery system; significant effort was expended in defining and encoding the optimization parameters. These are discussed in Section 3.3. Finally, the system analysis/optimization computer program was used to calculate comparative values of the system criteria for the most promising system configurations. Results are given in Section 3.4.

### 3.1 Design Conditions

A list of design conditions for 25 kft climb, which constrain each turbocharger system design, is given in Table 1. These values are either taken or calculated from information given to Sundstrand by John Deere and Beech Aircraft. Table 2 lists the assumed design constraints which depend on installation.

The total pressure and temperature of the flow entering the heat exchanger cooling circuit ram air scoop are affected by the engine propeller. An analysis at the propeller, based on propeller information supplied by Beech Aircraft, has been performed to determine these conditions . The thrust developed by the propeller and the power required to supply this thrust can be expressed as:

$$T = W * (V_2 - V_1) / g_c$$
$$W = \rho_1 * V_1 * A_1$$
$$A_1 = A_p$$
$$T = \rho_1 * V_1 * A_p * (V_2 - V_1) / g_c$$

$$HP = T * V_1 / \eta_p / 550$$
$$T = HP * \eta_p * 550 / V_1$$

Definitions:
- $T$ - thrust
- $W$ - air flow rate
- $V_2$ - air velocity downstream of propeller
- $V_1$ - air velocity upstream of propeller (true air speed)
- $\rho_1$ - upstream density
- $A_p$ - propeller diameter
- $HP$ - engine power
- $\eta_p$ - propeller efficiency

So $V_2$ can be expressed as:

$$V_2 = V_1 + HP*\eta_p*550*g_c / (\rho_1*V_1^{2}* A_p)$$

Table 2
Assumed Design Constraints

| | | |
|---|---|---|
| Charge Air Ducts | | |
| Compression side | | |
| Length (ft) | | 5.0 |
| Material | | Al |
| Wall thickness (in) | | 0.03125 |
| Density (lbm/ft$^3$) | | 172.8 |
| Conductivity (Btu/hr ft °F) | | 110.0 |
| Expansion side | | |
| Length (ft) | | 3.0 |
| Material | | Steel |
| Wall thickness (in) | | 0.03125 |
| Density (lbm/ft$^3$) | | 499.5 |
| Conductivity (Btu/hr ft °F) | | 8.67 |
| Insulation | | |
| Density (lbm/ft$^3$) | | 11.9 |
| Conductivity (BTU/hr ft °F) | | 0.10 |
| Inlet and Exit | | |
| Inlet diffuser half angle (deg) | | 10.0 |
| Exit nozzle half angle (deg) | | 10.0 |
| Ratio of nozzle exit to freestream momentum | 1.0 | |
| Heat loss to surroundings | | |
| Heat transfer coefficient (Btu/hr ft$^2$ °F) | 2.0 | |
| Ram air heat exchanger cooling duct | | |
| Inlet diffuser half angle (deg) | | 10.0 |
| Angle of exit flow relative to free stream | | 0.0 |

Table 1
Design Conditions
25000 ft climb

| | |
|---|---|
| Ambient | |
| Pressure (psia) | 5.46 |
| Temperature (°F) | 6.71 |
| Mach number | 0.267 |
| Downstream of Propeller | |
| Pressure (psia) | 5.84 |
| Total Temperature (°F) | 16.14 |
| Mach number | 0.311 |
| Engine air requirements | |
| Inlet temperature (°F) | 140.0 |
| Inlet flow rate (lbm/min) | 70.55 |
| Inlet Pressure (psia) | 34.9 |
| Exit temperature (°F) | 1154.0 |
| Exit flow rate (lbm/min) | 72.84 |
| Engine parameters | |
| Propeller efficiency | 0.83 |
| Displaced volume ($in^3$) | 80.0 |
| Engine Speed (rpm) | 8500.0 |
| Exit pressure for 400 HP (psia) | 30.6 |
| Aircraft lift over drag | 11.2 |