A METHOD TO ESTIMATE WEIGHT AND DIMENSIONS OF SMALL AIRCRAFT PROPULSION GAS TURBINE ENGINES

FINAL REPORT AND USER'S GUIDE

by

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16. Abstract

A method has been developed to estimate the weight and major envelope dimensions of small aircraft propulsion gas turbine engines. The computerized method, called WATE-S (Weight Analysis of Turbine Engines -Small) is a derivative of the Boeing WATE-2 computer code. WATE-S determines the weight of each major component in the engine including compressors, burners, turbines, heat exchangers, nozzles, propellers, and accessories. A preliminary design approach is used where the stress levels, maximum pressures and temperatures, material properties, geometry, stage loading, hub/tip radius ratio, and mechanical overspeed are used to determine the component weights and dimensions. The accuracy of the method is generally better than ±10 percent as verified by analysis of four small aircraft propulsion gas turbine engines jointly selected by the NASA Program Manager and Garrett.

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SECTION I

1.0 SUMMARY

A method has been developed to estimate the weight and major envelope dimensions of small aircraft propulsion gas turbine engines. The computerized method, called WATE-S (Weight Analysis of Turbine Engines - Small) is a derivative of the Boeing WATE-2 computer code (ref. 1). As in WATE-2, WATE-S determines the weight of each major component in the engine including compressors, burners, turbines, heat exchangers, nozzles, propellers, and accessories. A preliminary design approach is used where the stress levels, maximum pressures and temperatures, material properties, geometry, stage loading, hub/tip radius ratio, and mechanical overspeed are used to determine the component weights and dimensions.

A relatively high level of detail was found necessary in order to obtain a total engine weight within the required ±10-percent accuracy. Component weight data from Garrett engines was used as a data base to develop the methods required for small gas turbine engine components. The small engine weight method is probably valid for other manufacturers, however, this has not been verified. The accuracy of the method is generally better than ±10 percent, on the order of ±5 percent. This accuracy was verified by applying the method to four Garrett propulsion engines, some of which were in the original data base. Engines used in the validation study were jointly selected by NASA and Garrett.

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SECTION II

2.0 INTRODUCTION

Aircraft propulsion system studies are frequently conducted
by industry and government. These studies may encompass a wide
variety of engine concepts ranging from relatively simple turbo-
prop and turbofan engines to complicated variable cycle engines.
The aerospace industry in general has acquired an adequate com-
puter capability to evaluate the thermodynamic performance of
these diverse engine concepts; however, until recently, accurate
methods of estimating engine weight and dimensions were not read-
ily available.

The Boeing WATE-2 (Weight Analysis of Turbine Engines) com-
puter program was written primarily to estimate the weight and
major envelope dimensions of large, axial-flow turbofan and turbo-
jet propulsion engines. A preliminary design approach is used
where the stress levels, maximum temperatures and pressures, mate-
rial properties, geometry, stage loading, hub/tip radius ratio,
and shaft mechanical overspeed are used to determine component
weights and dimensions.

Overall, the basic approach of the Boeing WATE-2 program is
valid for small gas turbine engines; however, major modifications
to some of the component modules were required to improve the
accuracy and flexibility of this program for small gas turbine
engines.

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A computer program specifically written to estimate the weight and dimensions of small gas turbine engines was derived from the Garrett version of the Boeing WATE-2 computer program. This program will be referred to as WATE-S (Weight Analysis of Turbine Engines - Small). It was configured on a stand-alone basis, the required input being obtainable from most general purpose thermodynamic engine cycle performance computer programs. A small gas turbine engine as defined for WATE-S suitability is outlined below:

o   Conventional and unconventional Brayton Cycles (regeneration, intercooling, reheat, afterburning, combinations)

o   Separate or mixed-flow turbofans

o   Core-corrected airflows from 0.23 to 4.54 Kg/s (0.5 to 10.0 lbm/s)

o   Compressor pressure ratios from 5 to 25

o   Turbine rotor inlet temperature from 1089°K (1960°R) to 1922°K (3460°R)

o   Propellers and propfans suitable for aircraft flight speeds up to Mach 0.8

o   Axial and radial flow turbomachinery components with input specified staging and shafting arrangements

o   Geared or ungeared propulsor drive.

WATE-S determines engine weight and dimensions by summing the weights and dimensions of each major component including propellers, fans, compressors, combustors, turbines, and nozzles.

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Each individual component specified in the input is individually modeled using fundamental physical relationships. The specific tasks accomplished are summarized in the following sections.

2.1 Component Modules Requiring Modifications

Fans and Axial Compressors - The WATE-2 axial compressor model assumes the general design pressure-ratio corrected tip-speed relationship is applicable to fans as well as low- and high-pressure compressors. Garrett experience has demonstrated that this assumption is not valid for most small and intermediate turbofan engines. Separate fan accounting is provided in WATE-S as well as a design pressure-ratio corrected tip-speed relationship suitable for small axial compressors.

Centrifugal Compressors and Radial Turbines - The WATE-2 centrifugal compressor and radial turbine models are not consistent with the desired component preliminary design philosophy. These modules have been completely rewritten so that radial flow component weights and dimensions are determined on the basis of fundamental physical relationships similar to those used for axial flow components.

Reverse-Flow Combustors - The WATE-2 program's combustor logic is not applicable to reverse-flow combustors. The mean burner diameter is used as the geometric design parameter. For reverse-flow burners, where the burner is positioned around the HP turbine, the inner diameter has more geometric significance. The ability to use either of these diameters as the geometric design parameter is incorporated in WATE-S.

Engine Accessories - Engine accessory weights are currently lumped together as a percentage of bare engine weight. Small gas turbine engine accessory weight data including the starter/generator,

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battery, fuel pumps, oil pumps, propeller pitch control, fuel control, etc., was reviewed to determine if a more detailed weight model was warranted. A new accessory weight model has been developed and included in WATE-S.

2.2 New Component Modules

Gearboxes - The WATE-2 program gearbox weight accounting is spread through a number of subroutines. A different model is used for axial and centrifugal compressor gearboxes, and no method is available for linking a gearbox to a turbine for geared fan or propeller free-turbine engines. A new gearbox component module was necessary to provide the required flexibility for small gas turbine engines. In this way, gearboxes may be connected to any rotating component desired and consistent gearbox weights estimated.

Propeller and Propfans - Methods of estimating propeller and propfan weight and dimensions are not included in WATE-2. A new propeller component module based on Hamilton Standard propeller data has been developed and incorporated in WATE-S.

2.3 General Modifications

In addition to the above, the printer plot option of WATE-2 has been made operational for small gas turbine engines. Centrifugal compressors, reverse-flow combustors, and radial turbine elements were added to the axial flow component plot capabilities. A general review of the many geometric assumptions used in WATE-2 for large turbomachinery components was completed to determine their suitability to small gas turbine engine components.

A default engine configuration is incorporated in WATE-S. The default engine is a two spool turbofan engine consisting of a

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fan, axi-centrifugal high-pressure compressor, axial high-pressure turbine, and axial fan turbine. Four reference engines have been used for computer program checkout and validation. The accuracy of WATE-S in estimating engine weight and major envelope dimensions is ±10 percent or better. This has been demonstrated by analysis of the reference engines.

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3.0   METHOD OF ANALYSIS

The methods of analysis used in WATE-S are based on a preliminary design approach where the aerodynamic and mechanical design variables are taken into account. In the compressor, for example, rotor blade weight is calculated as a function of the specified geometric parameters. Blade centrifugal stress is then found, and the disk weight that will support the blade rotational force is determined. This type of preliminary design approach was also used for the other components.

The WATE-S method is intended to estimate the weight of a given engine design; it will not design an engine. This function must be performed external to the program. WATE-S utilizes component state conditions which are generated in an external engine thermodynamic cycle computer program.

In the normal use of WATE-S, the desired engine cycle is simulated at the engine design point. The user of WATE-S must be cognizant of other conditions in the flight envelope where maximum component temperature, work, speed, or flow occur. If these conditions are greater than the design values, they can size the component and have a significant impact on the component weight. WATE-S allows input of scalars to account for these off-design conditions.

A more accurate weight estimate can be achieved by developing an array of engine cycle data over the engine operating envelope. The WATE-S program will scan the input engine cycle data and select the maximum conditions for each component.

The engine cycle simulation may use components that are required mathematically, but are not desired in the engine weight. These can be selectively eliminated by the use of the component weight scalars.

3.1 Component Weight and Dimension Methodology

The methods of analysis described for each component in the following sections have been developed to achieve an overall engine accuracy of ±10 percent. Since the rotating components comprise the major part of the total engine weight, considerable detail was necessary in order to achieve the accuracy goal. Normal program users may not have sufficient knowledge to adequately define all of the necessary inputs; however, typical values are given in the User's Guide, Section 4.

3.1.1 Axial Fans and Compressors

The procedure used for axial fan and compressor weight prediction is a stage-by-stage aeromechanical design as illustrated in Figure 1. Rotor blade volume and weight are determined; then, blade centrifugal stress, disk stress, and disk weight are calculated. Connecting hardware, stator blades, and cases are then estimated and summed to give the total component weight. The following input data is necessary:

o The number of compressor stages. Stage work is held constant for multistage axial compressors. Alternatively, a maximum first-stage pressure ratio, which reflects the design approach and technology level, may be input

o Inlet and exit Mach numbers of the compressor
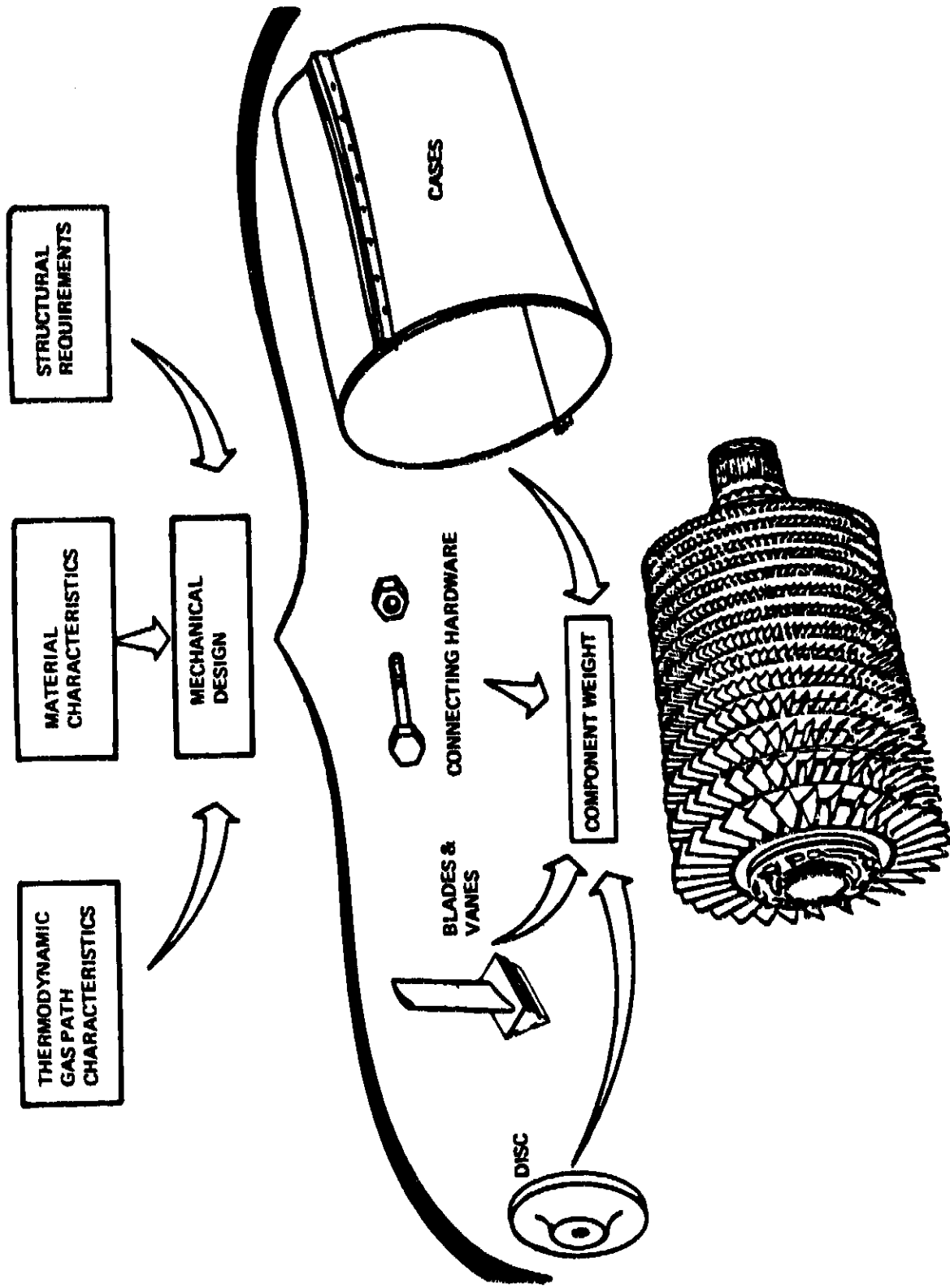
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STRUCTURAL REQUIREMENTS

MATERIAL CHARACTERISTICS

MECHANICAL DESIGN

THERMODYNAMIC GAS PATH CHARACTERISTICS

CASES

CONNECTING HARDWARE

COMPONENT WEIGHT

BLADES & VANES

DISC

Figure 1. Compressor Weight Method.

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o   Inlet hub/tip radius ratio of the first-stage blade

o   Compressor design mode; i.e., constant meanline, con-
     stant hub, or constant tip diameter

o   Effective density of blade material; defined as the
     ratio of total blade weight and volume

o   Maximum inlet and exit temperatures, if not at design

o   Aspect ratios for the first and the last stage blades

o RPM_{max}/RPM_{des} overspeed factor

o   Blade tip solidity, ratio of blade tip chord and spacing

o   Density of disk material

o   Blade taper ratio

o   Blade volume factor; ratio of blade volume and total
     annulus volume.

The total enthalpy change for the component is available from
the engine cycle data. Equal work for each stage is assumed, and
the number of stages required is found by iteration until the
first-stage pressure ratio is equal to or less than the specified
maximum.   When the number of stages is specified, first-stage
pressure ratio is calculated based on the equal work per stage
assumption and the maximum allowable pressure ratio input is
ignored. Shaft speed is determined from the axial fan and com-
pressor tip speed correlations given in Figure 2.   These com-
pressor tip speed correlations are based on current (1982) tech-
nology levels. The rpm of additional compressors driven on the
same shaft will be set by the first upstream compressor.

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AXIAL FANS: $\dfrac{U_t}{\sqrt{\theta}}$ = 362. + (24.6 - 219.7 ℓn h/t) (PR-1.295)

WHERE $\dfrac{U_t}{\sqrt{\theta}}$ = CORRECTED TIP SPEED, m/s

h/t = HUB/TIP RADIUS RATIO

PR = FIRST-STAGE PRESSURE RATIO
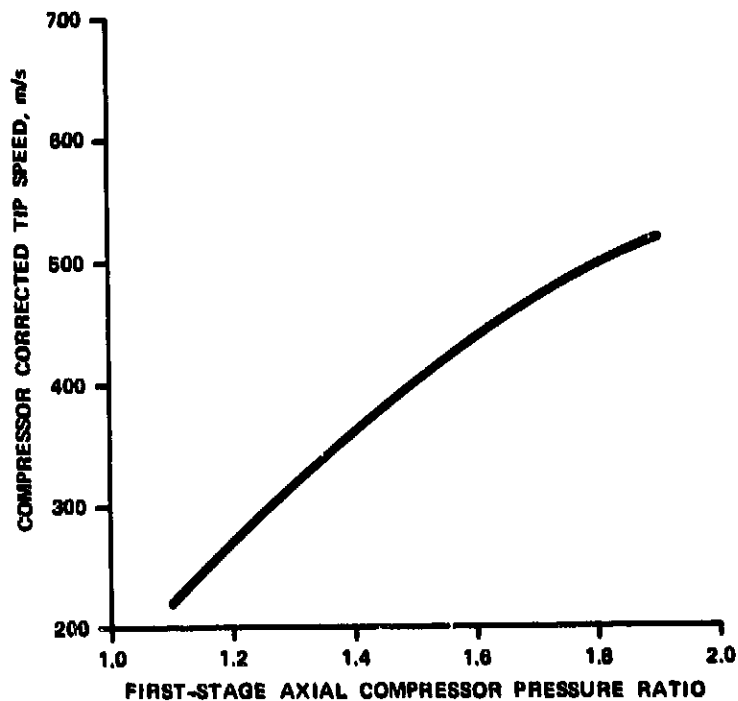
Figure 2.   Axial Fan and Compressor
            Tip-Speed Correlation.

In the event that an existing compressor is being weighed, or the shaft speed is already known, a speed scalar can be applied to the shaft speed found from Figure 2 to achieve the desired value. The speed scalar can also be used to modify the estimate of shaft speed for high-pressure compressors, where the inlet temperature significantly affects the pressure ratio capability, or for external iterations of an engine design.

The first-stage flow area is determined by the specified Mach number and the corrected inlet airflow from the cycle data. Inner and outer diameters of the flow path are calculated from the specified radius ratio:

$$D_t = \sqrt{\frac{4A_{inlet}}{\pi[1-(h/t)^2]}} \tag{1}$$

$$D_h = D_t \cdot \frac{h}{t} \tag{2}$$

Compressor RPM is determined by dividing the tip speed (found from Figure 2) by the product of π and the tip diameter (D_t).

Stage length is found in the following manner. Axial blade chord (C), as shown in Figure 3, is the quotient of the blade height and aspect ratio:

$$C = \frac{h_B}{AR} \tag{3}$$

ASPECT RATIO $= \dfrac{h}{C}$

h = MEAN HEIGHT

C = MEAN CHORD

FIR TREE

SOLIDITY $= \dfrac{C}{S}$

THICKNESS RATIO $= \dfrac{t}{C}$
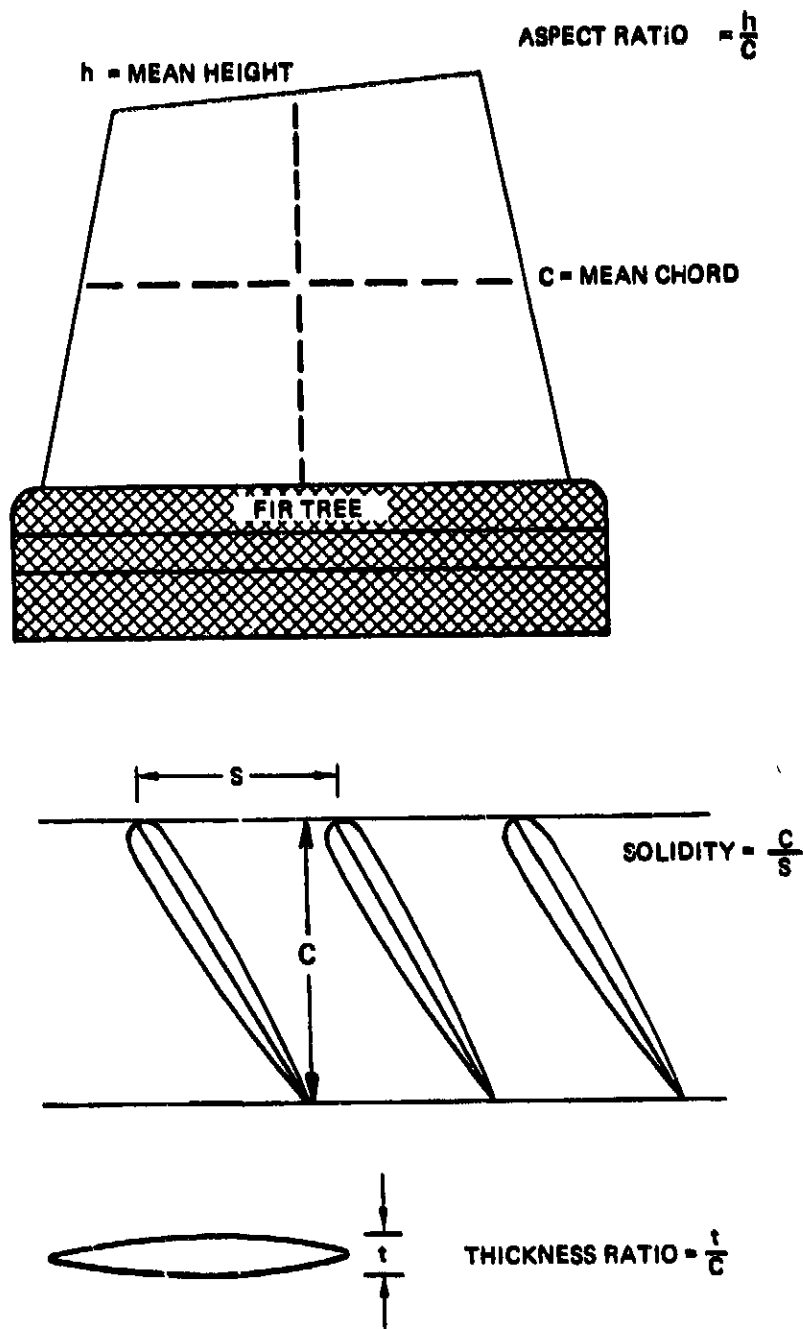
Figure 3.   Blade Schematic.

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The stator length was assumed to be equal to the rotor length (or blade chord), and 17 percent of the rotor length required for clearance between rotor and stator and the same clearance between the stator and the next rotor.

The total number of blades is calculated from the specified tip solidity (C/S) and aspect ratio (AR), and previously calculated tip diameter (D_t) and blade height (h_B):

$$N_B = \pi \cdot D_t \cdot C/_S \cdot \frac{AR}{h_B} \tag{4}$$

This value is truncated to an integer number of blades, and the same value is used for the stator.

The total volume of metal in the compressor blades is then calculated from;

$$V_B = \frac{K \cdot h_B^3}{AR^2} \tag{5}$$

where K is a volume factor which accounts for firtree mount volume, taper ratio, and thickness-to-chord variations in typical blades. For the data base engines, K was found to be 0.06 for fan blades and 0.12 for compressor blades with hub/tip radius ratios less than 0.8. For compressor blades with hub/tip radius ratios greater than 0.8;

$$K = 0.12 + 0.04 \, (h/t - 0.8) \tag{6}$$

The rotating blade weight of each stage is determined from the blade volume and material density. Material density automatically changes from titanium to steel when the stage inlet temperature exceeds a specified maximum, normally 644°K (1160°R). Stage temperature is determined from the engine cycle data, the equal work assumption, and the specified over-temperature ratio. Stator blade weight and dimensions are assumed equal to the rotor blades and include the inner shroud.

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The maximum blade centrifugal stress occurs at the blade root and is a function of tip speed, blade height, taper ratio, and material density. Expressed in terms of the nondimensional blade geometry, the equation for blade root centrifugal stress is:

$$\sigma = \frac{100 \rho U_t^2}{g \cdot TR} \left[\frac{1 - (h/t)^2}{2} + \frac{TR-1}{12} (1 - h/t) (1 + 3 h/t) \right] \quad (7)$$

where U_t is the product of the design tip speed and the overspeed factor, RPM_{max}/RPM_{des}. An inserted blade is assumed, and the disk material is assumed to be titanium or steel forgings with ultimate strengths of 82.7 KN/cm^2 and 110.3 KN/cm^2 respectively. The rim of the disk is assumed to be 10 percent of the blade hub radius or 1.91 cm, whichever is greater. The remaining disk volume is assumed to be a trapezoidal section rotated about the axis. The thickness of the trapezoid at its outer radius is sized for 75 percent of the ultimate strength. Thickness of the trapezoid at the inner radius is based on 50 percent of ultimate strength for the tangential stress. This value was selected based on an experimentally determined burst speed margin.

If the average tangential stress can be satisfied with a constant thickness disk, the bore radius is increased until the lowest weight disk is achieved that just meets the design criteria.

Disk stresses are calculated based on the total blade force acting on the outer circumference of the disk, and are therefore sensitive to changes in blade aspect ratio and solidity, as well as blade centrifugal stress and hub radius.

Dimensions of succeeding stages are based on the design mode selected (constant mean, tip, or hub radius). In the constant mean line method, for example, the mean radius is based on the mean flow area of the first stage. This mean radius is held

constant for subsequent stages. Corrected airflow at the entry of each stage is determined from the calculated state conditions derived from the equal work per stage assumption. Stage inlet Mach number is assumed to vary proportionally to the number of stages when different inlet and exit Mach numbers are specified. Tip speeds for the downstream stages are then calculated from the stage dimensions and shaft speed. Blade aspect ratio is determined by assuming a proportional change for each stage if inlet and exit aspect ratios are different.

Figure 4 illustrates the stage coupling method that was developed by Boeing and used in WATE-S. The spacer, nuts, and bolts are assumed to be steel, with the spacer being a 0.191-cm thick cylinder located at 75 percent of blade hub radius. The connecting hardware weight (W_{hw}) is estimated by the following equation:

$$W_{hw} = 2\pi \ (0.75 \ . \ R_h) \ . \ 0.191 \ . \ L_{STG} \cdot \rho \qquad (8)$$

where R_h is the blade hub radius, L_{Stg} is the stage length, and ρ is the material density.

The outer case is the last item of weight included in the compressor weight buildup. Average case thickness in the data base engines was 0.254-cm equivalent thickness, including fasteners and flanges. Case weight is calculated stage by stage, and the same material used in the disk is also assumed for the case:

$$W_c = \pi D_t \ . \ L_{STG} \ . \ 0.254 \ . \rho \qquad (9)$$

where D_t is the stage tip diameter.

Total stage weight is the sum of the rotor blades, stators, disk, connecting hardware, and case. Stage weights are summed to

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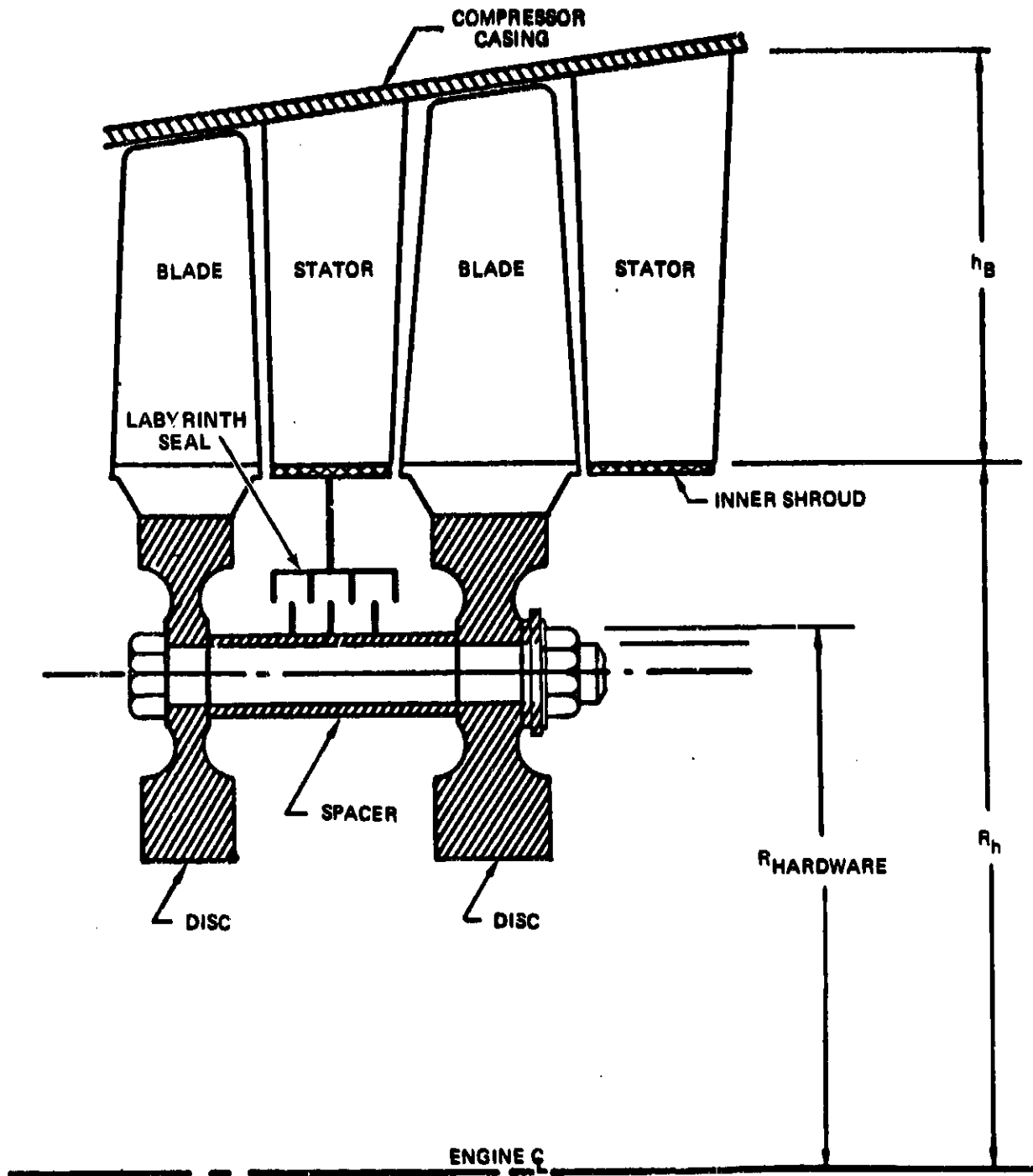
Figure 4. Typical Stage Components.

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give the total component weight. The sum of all stage lengths gives the total compressor length. Inlet guide vanes are not included in the compressor weight, but can be accounted for with a frame (see Section 3.1.9).

Rotational inertia of the compressor is determined by finding the inertia of each stage of the component. It is assumed that blades have uniform weight/area and the disk is of uniform thickness. This method had been applied to several existing engines and the results showed good agreement. The following equations are used for the blades and disk inertias:

$$I_B = \left[\frac{W_B}{g}\left(\frac{h_B^2}{3} + R_h^2\right)\right] N_B \qquad (10)$$

$$I_D = \frac{W_D}{2g} \cdot R_h^2 \qquad (11)$$

The total stage inertia is the sum of blade and disk inertias

$$I_{Stg} = I_B + I_D \qquad (12)$$

The component inertia is the sum of the inertia of each stage.

3.1.2 Rotating Splitter

A rotating splitter, see Figure 5, is a circumferential separator of two flows within the same component. These flows normally have different pressures and temperatures, and the splitter must perform a sealing function. Stages that incorporate rotating splitters are treated the same as compressors; a rotor-stator pair comprises one stage, stator weight and size are assumed to be the same as the rotor blade, and rotor-stator spacing is 17 percent of rotor length.

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SPLITTER

BLADE

R_{SPL}

TYPICAL SECTION
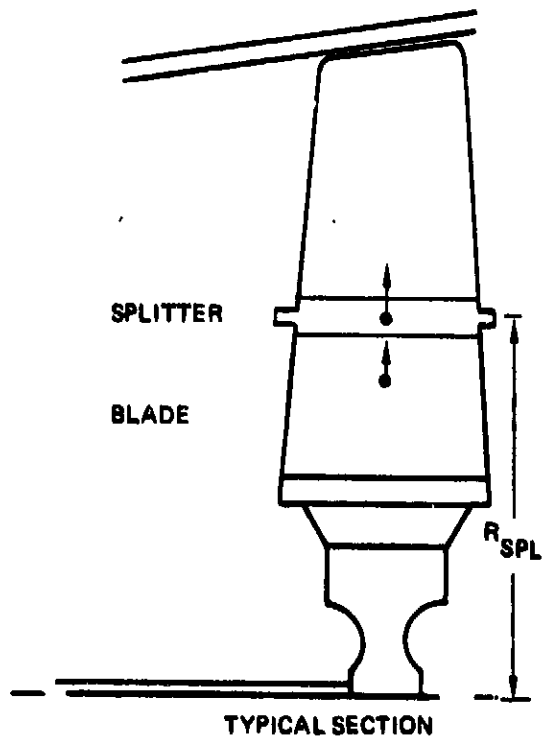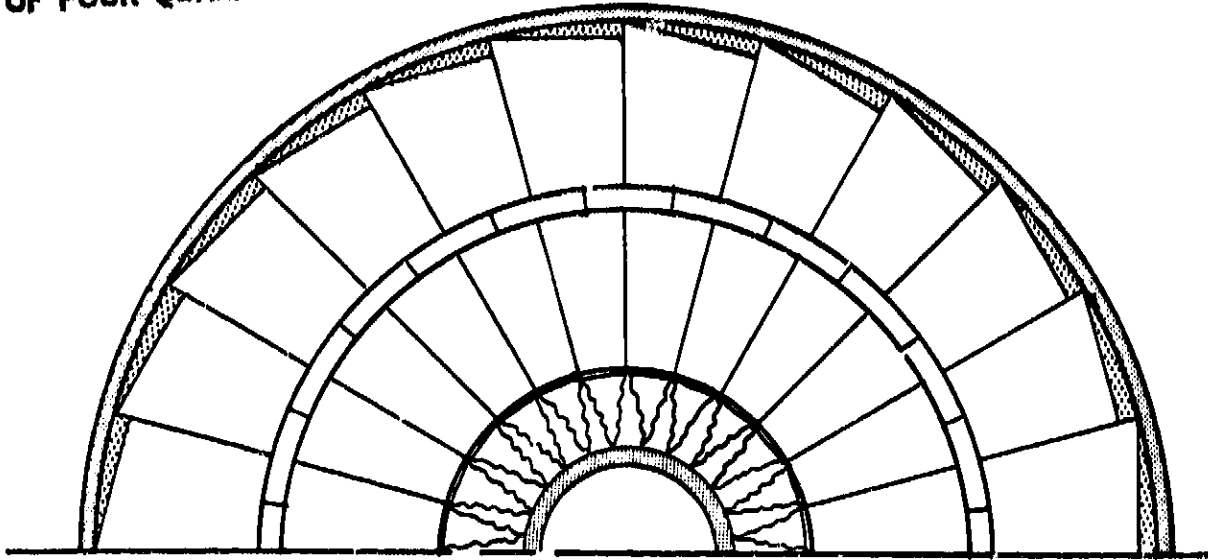
Figure 5.   Rotating Splitter.

The rotating splitter adds weight to the blade and increases the centrifugal blade force. Consequently, the disk must be heavier to carry the added load. Splitter weight per blade is estimated by:

$$W_{SPL} = \frac{2\pi R_{SPL} C^2 \cdot 0.10 \cdot \rho}{N_B} \tag{13}$$

where C is the blade chord found from Equation (3) and R_{SPL} is the radial location of the splitter. Thickness of the splitter is assumed to be 10 percent of the chord, however, this choice was based on only one engine, the General Electric CJ805-23. The CJ805-23 aft-fan blade has a rotating splitter which has a box section. The solid equivalent thickness of the hollow box was approximately 10 percent of the chord. A more accurate estimate could be made by actual design of the cantilevered platform to the desired deflection and/or stress levels.

The centrifugal force contribution of the rotating splitter is:

$$F_{SPL} = \frac{Mr\omega^2}{g} = \frac{W_{SPL}}{100g} \cdot R_{SPL} \cdot \left(\frac{2\pi \cdot RPM}{60.0}\right)^2 \tag{14}$$

where RPM is the shaft speed determined in the same manner as for a compressor.

Blade root centrifugal stress (Equation 7) is increased by the amount

$$\Delta\sigma = \frac{F_{SPL}}{A_B} = \frac{F_{SPL}}{C^2 \cdot t/C} \tag{15}$$

where t/C is the thickness/chord ratio of the blade (which is assumed to be 10 percent). Disk weight is determined with the increased stress level using the procedures described for axial fans and compressors (Section 3.1.1).

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Shaft speed determination (as described in Section 3.1.1) assumes that blade-root stress is subcritical. Use of a rotating splitter will cause the blade centrifugal stress to increase significantly, and the WATE-S output should be inspected to determine whether or not the stress level is acceptable. Reduction of shaft speed may be required to reduce the stress level.

If shaft speed is decreased, additional compressor stages may be required to accomplish the same work. Alternatively, the radius ratio of the compressor can be increased to restore work capacity (due to higher tip speed). Disk weight of each stage will increase for this compromise, however. The final choice must be iterated external to WATE-S and may depend on whether or not the flow path is reasonably well matched to connecting components.

These secondary effects may have a much larger impact on the engine weight than the weight of the splitter material, and they should not be ignored.

3.1.3 Axial Turbines

The methods used for axial turbines are generally the same as those previously described for axial compressors. The following input data is required:

o   The number of stages or the maximum mean diameter of the first stage

o   Inlet Mach number (axial) of the first stage, and exit Mach number (axial) of the last stage

o   Rotor blade aspect ratios of the first and last stages

o   Blade tip solidity

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o   Reference disk stress, 0.2 percent yield point of the
    material selected

o   Cooling indicator, to modify the blade volume calcula-
    tion for cooling passages

o   Turbine design mode; i.e., constant hub diameter, con-
    stant mean line, or constant tip diameter

o   Shaft overspeed factor, RPM_{max}/RPM_{des}

o   Mean work coefficient, $\lambda_m = \dfrac{g \dfrac{\Delta H}{N}}{U_m^2}$

        where $\Delta H/N$ = enthalpy change per stage
        and U_m = mean blade speed

o   Blade material density

o   Blade taper ratio

o   Blade volume factor; ratio of blade volume and total
    annulus volume.

Two alternative procedures may be used to size the turbine:
(1) specify the number of stages, and assuming equal work per
stage, calculate the mean diameter of the first stage based on the
input turbine mean work coefficient; or (2) specify the maximum
mean diameter of the first stage, and assuming equal work per
stage, calculate the number of stages required to satisfy the
input turbine mean work coefficient. Total component work and
state conditions are taken from the engine cycle data.

The flow area required to pass the corrected airflow at the
specified Mach number is calculated at the inlet of each stage.
For the first stage, the hub and tip radii are calculated from
this area and the previously determined turbine mean radius. Sub-
sequent stage dimensions are calculated based on the design mode

selected (constant mean, hub, or tip diameter). When the first-stage inlet Mach number and aspect ratio are different from the last stage values, a proportional change is assumed for the intermediate stages.

Rotor blade chord and number of blades are determined by the same methods used for axial compressors. Blade volume is also determined by the same method, Equation (5), except that K = 0.155 for high-pressure turbines and K = 0.195 for low-pressure turbines. When the blade is a cooled blade, the calculated volume is reduced 20 percent to compensate for cooling-air passages. Blade weight is then found from the specified material density. Blade root centrifugal stress is calculated by Equation (7). The disks are calculated by the preliminary design procedure already discussed for axial compressors.

Each stage of the turbine is treated as a stator-rotor pair (as opposed to rotor-stator pair in the compressor). Stator blades are assumed to have the same number and volume of material as the rotor blades. The stator weight is calculated by Equation (5), with K = 0.155 for high-pressure turbines and K = 0.195 for low-pressure turbines. Stator-rotor spacing is the same as compressors, 17 percent of the rotor length. Stator AR is taken to be 83 percent of the rotor blade AR.

Connecting hardware and case weight are also determined by the same methods used in the compressors. The total weight and length of the turbine component is the sum of disk, blade, stator, connecting hardware, and case. No exit guide vanes (EGV) are assumed in the turbine component. EGV's, if required, can be considered a part of the exit frame weight. Rotational inertia is determined in the same manner as the compressor.

3.1.4 Centrifugal Compressors

The procedure used for centrifugal compressors is a prelim-
inary design approach similar in principle to that used for axial
compressors. Blade volumes and weights are determined and a disk
is sized to support the blades for allowable stress levels based
on inlet and exit flow path temperatures. The following inputs
are required for centrifugal compressors:

o   Inlet Mach number

o   Maximum first-stage pressure ratio, which reflects the
    design approach and technology level. Stage work for
    this stage will be held constant for the second stage.
    Alternatively, the number of stages can be specified.

o   Inlet hub/tip radius ratio

o   Number of blades and splitters

o   Exit Mach number

o RPM_{max}/RPM_{des} overspeed factor

o   Hub $_{inlet}/tip_{exit}$ radius ratio

Only a one- or two-stage centrifugal compressor may be used
in a WATE-S engine simulation. The total enthalpy change for the
component is available from the engine cycle data. Equal work for
each stage is assumed, and the number of stages is calculated to
satisfy the maximum first-stage pressure ratio requirement. When
the number of stages is input, first-stage pressure ratio is cal-
culated based on equal work per stage and the input maximum pres-
sure ratio is ignored.

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The inlet flow area is determined from the specified Mach number and inlet corrected flow from the engine cycle data. The inlet hub (R_{1H}) and shroud (R_{1S}) radii are calculated from the specified inlet/hub tip radius ratio (see Figure 6).
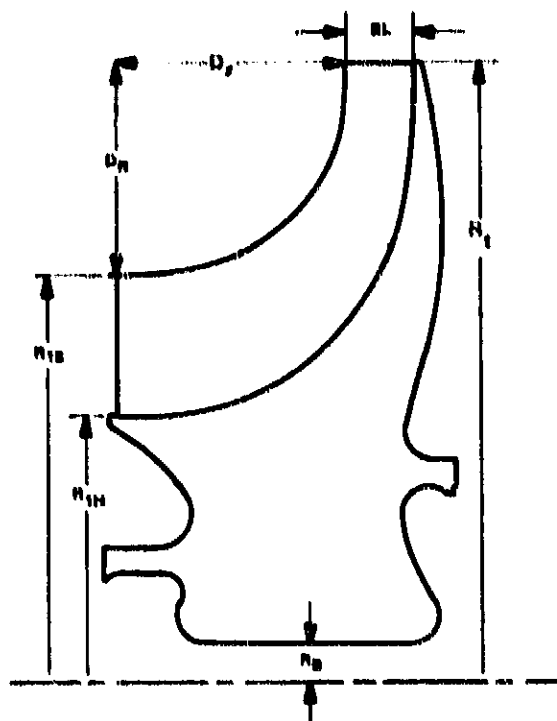
Figure 6. Centrifugal Compressor/Radial Turbine Schematic.

$$R_{1S} = \sqrt{\frac{A_{inlet}}{\pi [1-(h/t)^2]}} \qquad (16)$$

$$R_{1H} = h/t \cdot R_{1S} \qquad (17)$$

The exit tip radius (R_t) is then calculated from the input hub_{inlet}/tip_{exit} radius ratio. The exit flow area is determined from the specified exit Mach number and corrected flow from the engine cycle data. The compressor exit blade length (BL) is calculated from this area and R_t:

$$BL = \frac{A_{exit}}{2\pi R_t} \qquad (18)$$

The ratio of axial length to radial height of the blade at the shroud (D_Z/D_R), is assumed to be 2., and the flow path is assumed to be comprised of two ellipses. Blade volume is computed assuming the blade thickness at the shroud is 0.076 cm and the thickness at the hub results in 15-percent blockage;

$$t_{hub} = \frac{0.15 \ (2\pi R_{1H})}{N_B} \tag{19}$$

where N_B is the number of blades. The compressor material and allowable blade and disk stress levels are selected based on the maximum temperature conditions for the compressor.

The compressor speed is determined from the current (1982) technology design pressure-ratio corrected tip-speed correlation illustrated in Figure 7. Once the material is selected and the rpm is calculated, the blade weight, stress, and natural frequencies are calculated.
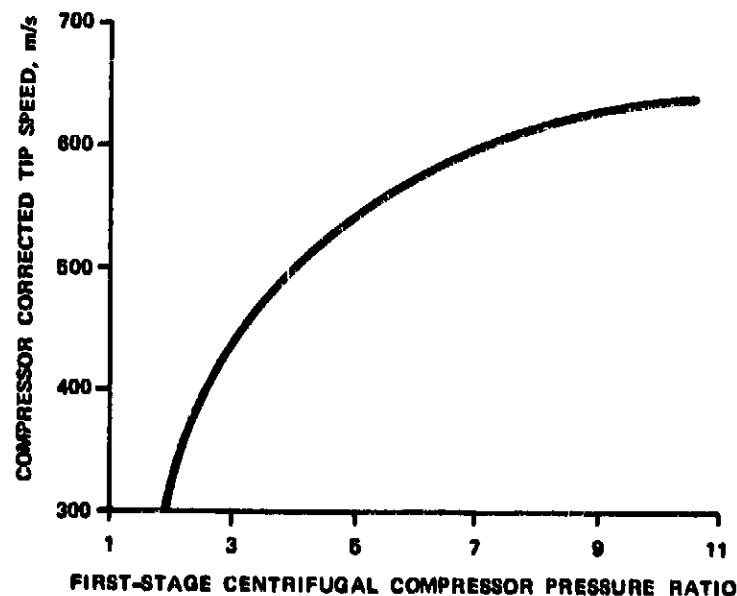
Figure 7. Centrifugal Compressor Tip-Speed Correlation.

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The compressor disk is sized by an iterative preliminary design procedure to support the blades and minimize the stage weight, while maintaining the maximum allowable stress level at the bore. This is done by varying the bore radius and backside geometry of the disk.

Total stage weight is the sum of the blade, disk, shroud, and diffuser weights; and crossover duct weight if a two-stage centrifugal compressor is modeled (see Section 3.1.6, Equation 32).

$$W_{shroud} = 0.1673\rho \left(\frac{R_{1S} + R_t}{2}\right)^3 \tag{20}$$

$$W_{diffuser} = 0.2845\rho \, R_t^3 \tag{21}$$

The diffuser radius is assumed to be 1.6 times the exit tip radius (R_t) and the length equal to 7 percent of its diameter.

The total stage inertia is estimated from the following expression:

$$I_{cent} = 0.1086\rho R_t^5 \tag{22}$$

where ρ is the material density selected.

3.1.5 Radial Turbines

The method described for centrifugal compressors is generally the same for radial turbines. The input data required is;

o   Inlet Mach number

o   Turbine work coefficient, $\lambda_t = \dfrac{g\Delta H/N}{U_t^2}$

o   Number of blades and splitters

o   Exit Mach number

o RPM_{max}/RPM_{des} overspeed factor.

Only a single-stage radial turbine is allowed. The total enthalpy change for the turbine is known from the engine cycle data. The inlet tip radius (R_t) of the turbine is calculated from the input turbine work coefficient and the previously calculated shaft speed. The inlet flow area is determined from the specified Mach number and the corrected flow from the engine cycle data. The inlet blade length is calculated from:

$$BL = \frac{A_{inlet}}{2\pi R_t} \tag{23}$$

The exit shroud radius (R_{1S}) of the turbine is assumed to be 70 percent of the inlet radius (R_t) and the exit hub radius (R_{1H}) is calculated knowing the exit corrected flow and Mach number.

$$R_{1H} = \sqrt{R_{1S}^2 - \frac{A_{exit}}{\pi}} \tag{24}$$

The ratio of axial length to radial height of the blade is assumed to be 2.1, and the flow path is assumed to be comprised of two ellipses. Blade volume is computed the same as for centrifugal compressors. The turbine material is assumed to be a nickel-based superalloy with a density of 0.00792 kg/cm^3 and allowable stress levels for the blade and disk of 51.7 KN/cm^2 and 86.2 KN/cm^2, respectively. Disk weight is calculated the same as for the centrifugal compressors.

Total component weight is the sum of the blade, disk, and shroud weights.

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$$W_{shroud} = 0.1755 \rho \left(\frac{R_{1S} + R_t}{2.} \right)^3 \qquad (25)$$

The total inertia of the radial turbine is estimated from the following expression:

$$I_{rad\ turb} = 0.1687 \rho R_t^5 \qquad (26)$$

3.1.6 Ducts

The design criteria used to size the ducts in WATE-S is assumed to be the internal pressure. Structural loads cannot be addressed in the preliminary design process where WATE-S is intended to be used. Figure 8 illustrates the typical duct geometry assumed. Generally, the outer surface of the OD duct wall is exposed to ambient pressure or fan duct pressure. The inner surface of the ID duct wall can be subjected to fan pressure, LP compressor pressure, or HP compressor exit pressure, etc. For these reasons, ambient pressure is assumed for the calculations of duct wall thickness, this assumption results in conservative weight estimates.
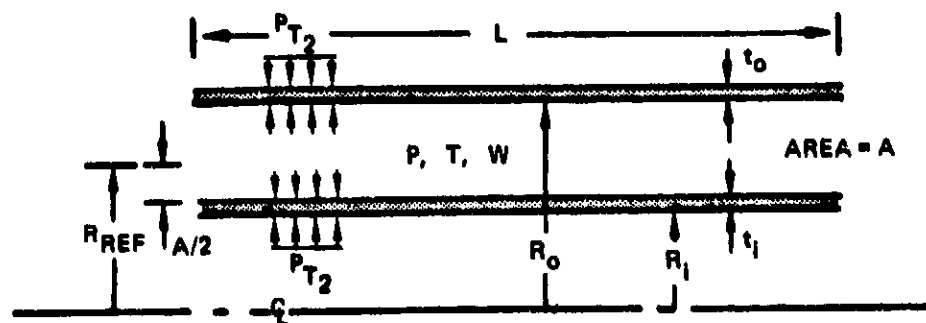
Figure 8. Duct Schematic.

The equation for stress on a longitudinal section of a thin-walled cylinder subjected to internal pressure is (ref. 2):

$$\sigma = \frac{PD}{2t} \tag{27}$$

or solving for the minimum thickness, t_{min}:

$$t_{min} = \frac{PD}{2\sigma} \tag{28}$$

where σ is the allowable stress level, P the internal total pressure, and D the duct wall diameter. A minimum gage thickness of 0.127 cm is assumed for all ducts. The assumed materials are titanium ($\sigma = 34.5$ KN/cm^2) below 644°K (1160°R) and stainless steel ($\sigma = 48.3$ KN/cm^2) above 644°K (1160°R). The material is selected based on the total temperature of the duct airflow. The weight is calculated as a function of the duct length (L), the inner diameter (D_i), the outer diameter (D_o), and the calculated wall thicknesses ($t_{min,i}$ and $t_{min,o}$);

$$W_{duct} = \rho \pi L (D_o t_{min,o} + D_i t_{min,i}) \tag{29}$$

Duct Mach number is specified as an input, and corrected airflow is determined from the engine cycle data. The inner and outer diameter are determined as a function of the required flow area and the dimensions of the connecting upstream component.

Care should be taken to ascertain whether these assumptions apply for specific engine configurations. For example, a thin-walled cylinder subjected to an external collapsing pressure will fail at a much lower pressure than it would if it were subjected to an internal bursting pressure, as assumed in the duct weight calculation. If both ID and OD walls of the duct are exposed to ambient pressure, the ID wall should be sized to avoid collapse, such as determined experimentally by Stewart (ref. 2) for lap-welded steel tubes:

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$$P_{max} = 689.5 \left[1 - \sqrt{1-1600\left(\frac{t}{D}\right)^2}\right] \qquad (30)$$

or expressed in terms of minimum wall thickness:

$$t_{min} = \frac{D}{40} \sqrt{1 - \left(1 - \frac{P_{max}}{689.5}\right)^2} \qquad (31)$$

WATE-S does not perform the above calculation to determine whether collapsing pressure sizes the ID wall.

Crossover ducts are required to join two centrifugal compressors, and are calculated in a different manner. The crossover duct diameter is assumed to be 1.6 times the exit tip radius of the upstream centrifugal compressor. The duct length is assumed to be 20 percent of the diameter and the weight is estimated from the following expression:

$$W_{crossover\ duct} = 2.283\ R_t^{\ 3} \qquad (32)$$

where R_t is the exit tip diameter of the upstream centrifugal compressor.

3.1.7 Burners

The methods used for burners are based on a calculated volume of materials, similar to the previously described methods for ducts. However, wall liners, fuel manifolds, and fuel nozzle weights are also calculated as shown in Figure 9. The method described is used for primary burners, both axial and reverse-flow, as well as duct heaters and afterburners.

The required inputs include;

o   Burner residence time

o   Through-flow velocity

o   Burner mean radius for axial primary burners and duct
     heaters, and inner radius for reverse-flow primary bur-
     ners.
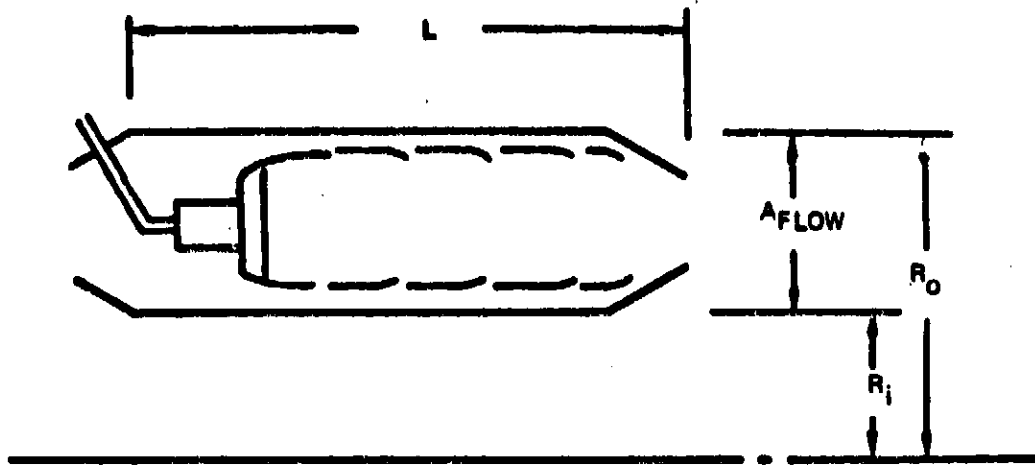
Figure 9. Burner Schematic.

The differences in burner types and configuration are
reflected in the input values. When a primary burner is speci-
fied, a frame weight may be added. Primary burners and duct
heaters require a radius input, while the afterburner is assumed
to have no inner wall.

Burner flow area is determined from the input through flow
velocity, the mean radius, and the inlet-corrected airflow from
the engine cycle data. Burner length is found to give the speci-
fied residence time based on the input velocity and entry condi-
tions. Flow area is used to obtain the inner and outer dimensions
of the burner (R_i and R_o) from the specified mean radius. Inner
and outer case thicknesses are determined from Equation (28). The
assumed material is steel with an allowable stress of 48.3 KN/cm^2. The
we'ght of the inner and outer case is determined from Equa-
tion (29) using the burner length L.

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Liner weight is determined in a similar manner, assuming 0.140-cm thick steel walls, located at 20 percent of passage height from the inner and outer case. The burner dome, fuel manifold, fuel nozzles, and other components are estimated by the following equation developed by Boeing.

$$W_{dome} = 0.1508 \ (R_o{}^2 - R_i{}^2) \tag{33}$$

Total burner weight is the sum of the inner and outer cases and liners, burner dome and fuel nozzle system, and frame when specified.

3.1.8 Shafts

A shaft is assumed to be the power connection component between compressors and turbines, or propellers/propfans and turbines. Figure 10 illustrates the shaft geometry and nomenclature.
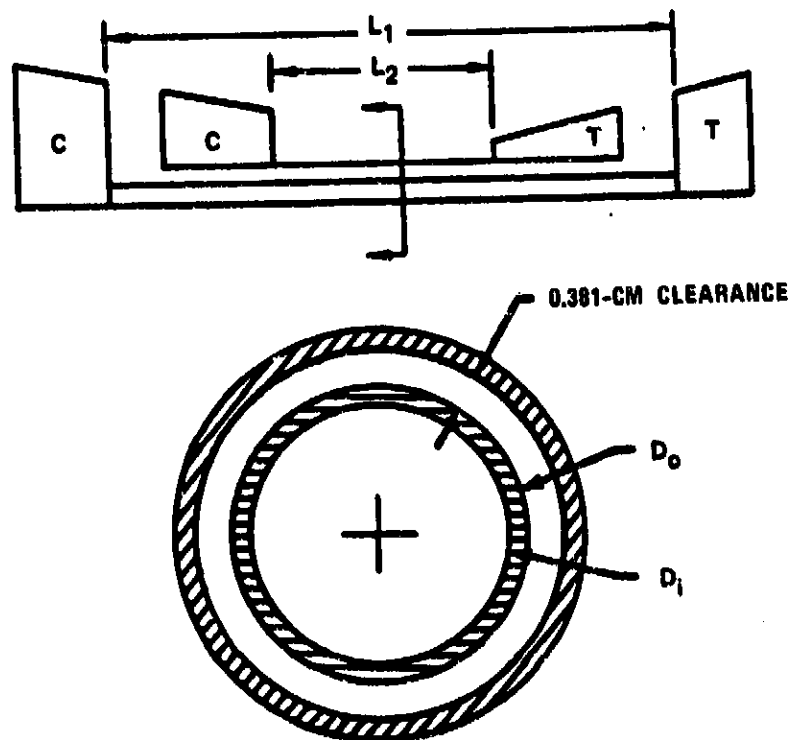
ENLARGED SECTION OF CONCENTRIC SHAFT

Figure 10. Shaft Schematic.

Multiple concentric shafts can also be specified, and will be sized around the inner shaft with 0.381-cm radial clearance. Dimensions of the inner shaft are determined to provide the necessary torque capability at the specified allowable stress. Total shaft power is the summation of work for all turbines on the shaft. Torque is calculated by:

$$T = \frac{10^5}{\omega} \cdot \Sigma PW \tag{34}$$

where ω is the shaft rotational speed.

Shear stress due to the torque load is defined by (ref. 2)

$$\tau = \frac{16 \, T \, D_O}{\pi (D_O{}^4 - D_i{}^4)} \tag{35}$$

or in terms of the input diameter ratio (D_i/D_O)

$$\tau = \frac{16T}{\pi D_O{}^3 \left[1 - \left(\frac{D_O}{D_i}\right)^4\right]} \tag{36}$$

Solving for D_O in terms of allowable stress

$$D_O = \left\{\frac{16T}{\pi \, \tau \left[1 - \left(\frac{D_O}{D_i}\right)^4\right]}\right\}^{1/3} \tag{37}$$

The shaft weight is then found by

$$W = L \rho \pi \frac{D_O{}^2}{4} \left[1 - \left(\frac{D_O}{D_i}\right)^2\right] \tag{38}$$

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A similar procedure is used for concentric shafts. The outer shaft's inner diameter is found by adding 0.762 cm to D_0, and Equation (37) is solved by iteration to satisfy the desired allowable stress.

While it is assumed in the shaft weight estimate that torque determines the shaft dimensions, it should be recognized that other design considerations may dictate shaft dimensions. Shaft critical speeds or longitudinal stiffness may actually design the shaft, but this is a function of bearing arrangement, mount stiffness, location of and stiffness of rotating masses. The calculated shaft weight should be considered to be an absolute minimum, and can possibly be much larger when these other criteria are considered. The rotational inertia of the shaft is not calculated, since it is a negligible quantity compared to the compressors and turbines.

3.1.9 Frames

A structural frame is normally required to span the engine flow path from the outer engine case to the shaft, usually to support a bearing (as shown in Figure 11 for several typical engines). Mechanical design of the frame would require a definition of all loads imposed on the frame under normal operating conditions, transients, and adverse operating conditions, such as a hard landing. This level of detail is normally not available at the preliminary design stage for which WATE-S has been developed.

Boeing had found, however, that the frame weight correlates well with the total frame-projected area. This data is shown in Figure 12 for five types of frames commonly used: single-bearing frames with and without power takeoff (PTO), turbine exit, and intermediate. Frame weight is determined from this data, based on the local diameter and the type of frame specified.
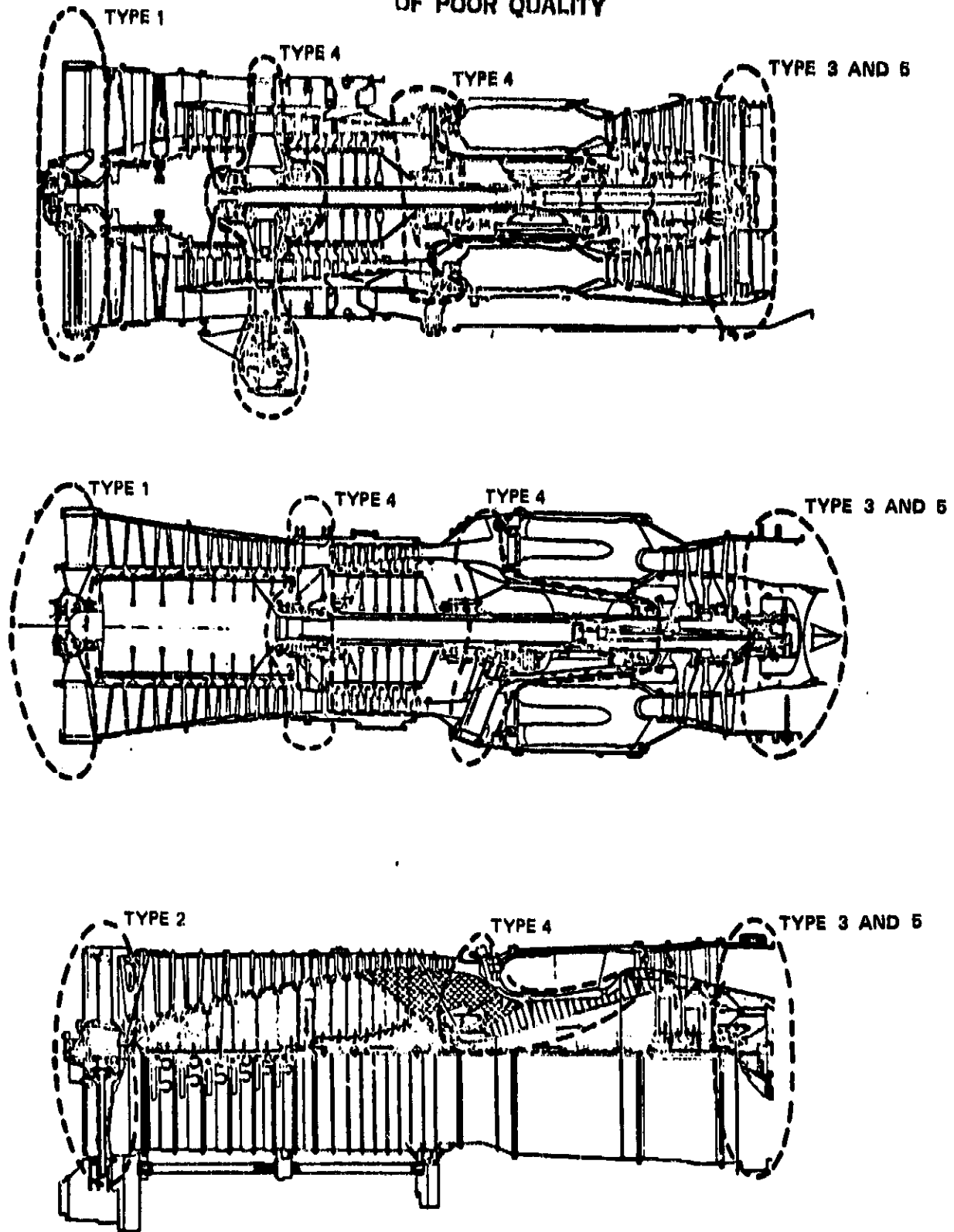
Figure 11. Frame Types.
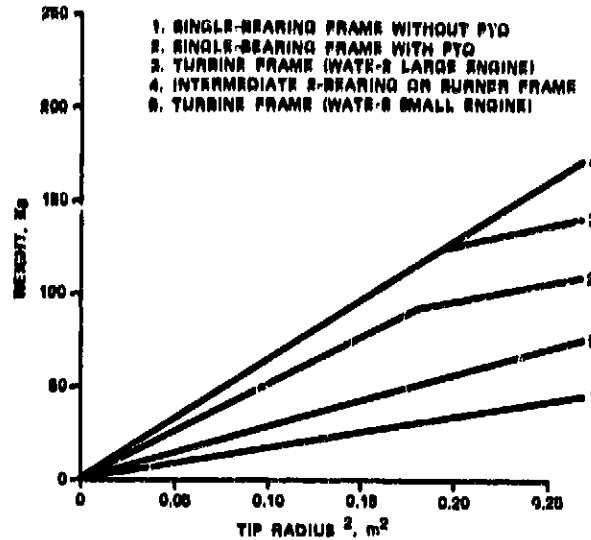
Figure 12. Frame Weight.

3.1.10 Nozzles and Thrust Reversers

Unlike the rotating components, the loads and load paths of nozzles (particularly variable area C-D nozzles) are not readily defined on a general basis. A selected type of nozzle could be subjected to a detailed weight-estimating procedure, however, the trade-offs of internal and external performance with nozzle length and diameter would also be necessary to optimize the design. This type of data is not likely to be available at the level of development for which WATE-S is intended.

A procedure has been developed that shows proper trends for multiple-stream nozzles and for variable geometry and fixed-geometry nozzles. Nozzle length is specified and should be selected to be representative for the type of nozzle. An effective surface area is calculated based on the diameter of the connecting component and the specified length. Only circular, conical nozzles are assumed, and coannular nozzles can be represented by specifying a circular nozzle for each flow path. Plug nozzles can be represented by specifying a larger effective length; e.g., from nozzle entry to end of plug.

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Wall thickness is assumed to be a 0.1626-cm composite of titanium (0.0813-cm) and stainless steel (0.0813-cm) below 644°K (1160°R) and 0.0813-cm stainless steel above 644°K (1160°R). Variable nozzles are calculated in the same manner except that the effective wall thickness is 2.75 times that of the fixed nozzle.

A weight estimating method for thrust reversers previously developed for aircraft preliminary design studies by Boeing was based on the weight of 18 different thrust reversers that are in current use. It had been found in correlations of this data that reverser weight (W) is a function of corrected mass flow ($\frac{W\sqrt{\theta}}{\delta}$) and nozzle pressure ratio (P_R), and is dependent on whether the stream is hot (primary) or cold (fan). The following relationship is included in WATE-S:

$$W = \left[K_1 \, \frac{W\sqrt{\theta}}{\delta} + K_2\right] \left[K_3 \, P_R + K_4\right] \tag{39}$$

	K_1	K_2	K_3	K_4
Hot (primary)	0.52631	191.87	1.0036	-0.5054
Cold (secondary)	2.2222	5.0348	0.23014	0.56091

The WATE-S method will apply the cold stream equation to a fan stream whether or not it is heated by a duct burner. The hot stream equation is used for turbine exit or mixed-flow exhaust streams.

3.1.11 Mixers

A mixer is a mechanical device placed at the confluence of two coannular streams to increase the mixing boundary so that thermal mixing takes place in a minimum length. Figure 13 illustrates a typical example of a mixer. This type of mixer is known as a daisy mixer or forced mixer.

Figure 13. Daisy or Forced Mixer

The required inputs include:

o   Mixer specific length, $L_{sp} = \dfrac{L}{\sqrt{4A/\pi}}$

o   Number of lobes or passages, N

o   Engine core and bypass flow areas, AII and AIO

Engine core and bypass annular flow areas are taken from the
engine cycle data, and the inlet radius (R_i) of the upstream com-
ponent is used as a starting point for locating R_m and R_o, as shown
in Figure 14. R_i normally will be the hub radius of the final
turbine stage.
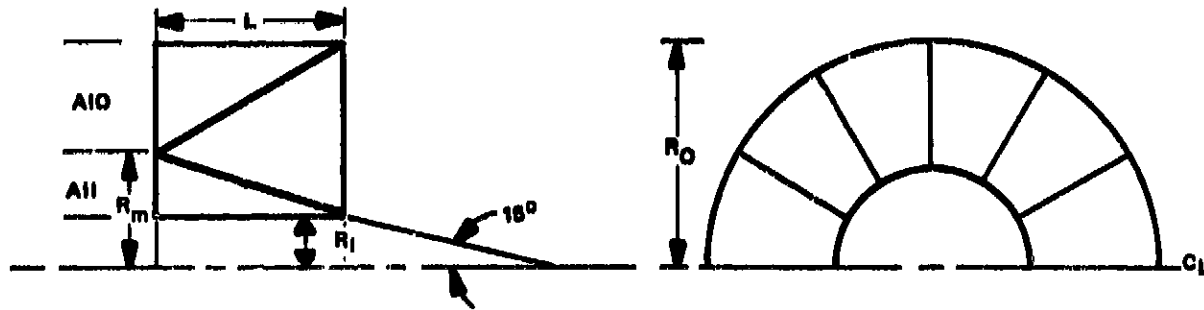
R_m is based on core flow area (AII) and R_i

$A \qquad = (AIO + AII)/2$ where AIO and AII are inputs

$L_{sp} \qquad = L/\sqrt{4A/\pi}$ is an input, calculate L

$N \qquad = $ is the number of lobes or passages input

$W_{mix} \qquad = 1.25 \; N \; (R_o - R_m) \; L \; K_1$

$$W_{plug} = \left[2\pi R_i L + \frac{\pi R_i^2}{\sin 15°} \right] K_2$$

K_1 and K_2 are products of material density and thickness:

$K_1 = (0.127 \text{ cm}) \; (0.00775 \text{ kg/cm}^3) = 0.00098 \text{ kg/cm}^2 \text{(steel)}$

$K_2 = (0.0813 \text{ cm}) \; (0.00775 \text{ kg/cm}^3) = 0.00063 \text{ kg/cm}^2 \text{ (steel)}$

Figure 14.   Mixer Schematic.

The mixer is assumed to consist of two components, the mech-
anical mixer section and the mixer core plug, both fabricated from
stainless steel with a density of 0.00775 kg/cm^3. The average flow

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area of the mixer is used with the input specific length to determine the length of the mechanical mixer section. The mechanical mixer section is assumed to be constructed of 0.127-cm material and the weight estimated from the following expression:

$$W_{mix} = 1.25 \, N \, (R_o - R_m) \, L\rho \, (0.127) \tag{40}$$

The mixer core plug is assumed to be constructed of 0.0813-cm material and has a cylindrical section as well as a conical section. The mixer plug weight is estimated from the following expression:

$$W_{plug} = \left[2\pi R_i L + \frac{R_i^2}{\sin 15°} \right] \rho(0.0813) \tag{41}$$

The total mixer weight is then:

$$W = W_{mix} + W_{plug} \tag{42}$$

3.1.12 Annulus Inverting Valve (AIV)

This device has been used in some variable-cycle engines to invert the annular position of two concentric flow paths. It accomplishes the flow inversion within a constant diameter envelope, and with constant-area duct passages. Figure 15 shows a typical example of an AIV. This AIV was designed to vary the bypass ratio in a JT8D engine.

The AIV weight method assumes a constructon similar to that shown in Figure 15, except that instead of sheet-metal, the material is assumed to be a titanium honeycomb at 5.37 kg/m² below 644°K (1160°R) and steel honeycomb at 9.13 kg/m² above 644°K (1160°R). If desired, different materials can be specified.
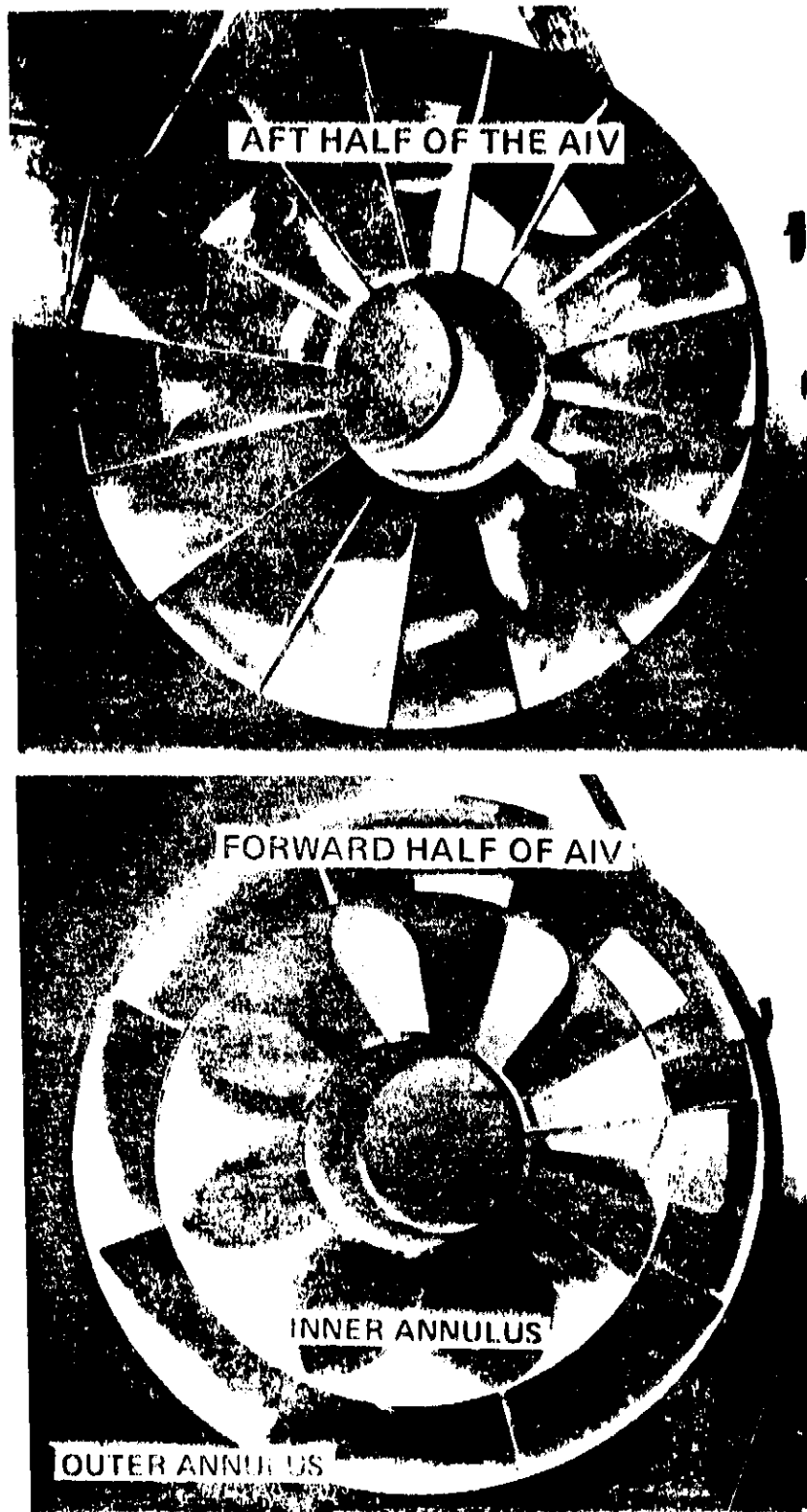
Figure 15.   Typical Annulus Inverting Valve: JT8D
Variable-Bypass Engine Test.

An empirical relationship, similar to the mixer method, had been developed by Boeing for estimation of the AIV weight:

$$W_{AIV} = L \cdot \frac{W}{A} \left[2\pi \left(R_1 + 2. R_0 \right) + 3.93 R_M + 1.25 N (R_0 - R_1) \right] \quad (43)$$

where R_1 is the hub radius of the upstream connecting component, and R_m and R_0 are found to satisfy the input Mach number with the inlet corrected airflow (see Figure 16). The number of passages (N) is an input, and material weight per unit area (W/A) is selected depending on the stream temperature. Length (L) of the AIV is calculated from the input specific length, L_{SP}:

$$L = L_{SP} \sqrt{4A/\pi} \quad (44)$$
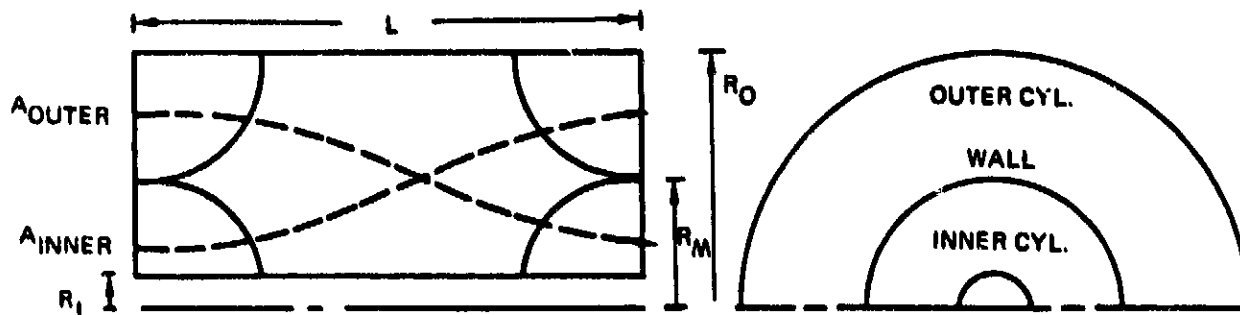
$L_{SP} = L/\sqrt{4A/\pi} \sim$ INPUT A $= \frac{(A_{OUTER} + A_{INNER})}{2.}$

FROM MACH INPUT

A_{INNER} AND A_{OUTER} ARE FOUND

   L IS DETERMINED

WTIC = 2 R_1 L WTSI

WTOC = 2 R_0 L WTSO

WTWALL = (K_1 R_M + K_2 N ($R_0 - R_1$)) L WTSW

WTSI, WTSO AND WTSW ARE MATERIAL WEIGHT PER UNIT AREA

$R_M = \sqrt{A/\pi + R_1^2}$

$K_1 = 3.927$ $K_2 = 1.25$

Figure 16. Annulus-Inverting Valve Schematic.

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Specific length is preferred as an input because it is non-dimensional, and it is a major variable that determines AIV pressure loss. A relatively good compromise between size and performance is achieved when N=8 and L_{sp}=0.8 to 1.0, which results in a pressure loss between 2.5 and 1.5 percent.

If the AIV is of the switching type, where one half indexes in a rotational direction relative to the other half to change flow-path orientation, an actuator weight is estimated at 10 percent of total AIV weight. Additional structure to support the rotating half is not included and should be represented as an additional frame.

3.1.13 Gearboxes and Transmissions

A method of estimating the weight of various types of gear systems has been previously developed by Schmidt (ref. 3). This method has proved applicable for estimating the weight of turbofan engine gearboxes, such as the one in the Garrett TFE731. The equation used for total gearbox weight is

$$\text{Gearbox Wt} = 15.5 \cdot \frac{PW}{GR(RPM)} \cdot (1. + GR)^3 \tag{45}$$

where $\frac{PW}{GR(RPM)}$ defines the maximum torque transmitted

and GR = gear ratio (> 1.)

The gearbox used in turboprop engines is weighed with a different method.

$$\text{Gearbox Wt} = 471.86 \left(\frac{PW}{\text{Prop. RPM}}\right)^{0.8} \tag{46}$$

3.1.14 Heat Exchangers

Both rotary and fixed heat exchanger weights can be estimated. Methods previously developed produce adequate results for preliminary design purposes, see Figure 17.

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FIXED-TUBE HEAT EXCHANGER

ROTARY HEAT EXCHANGER
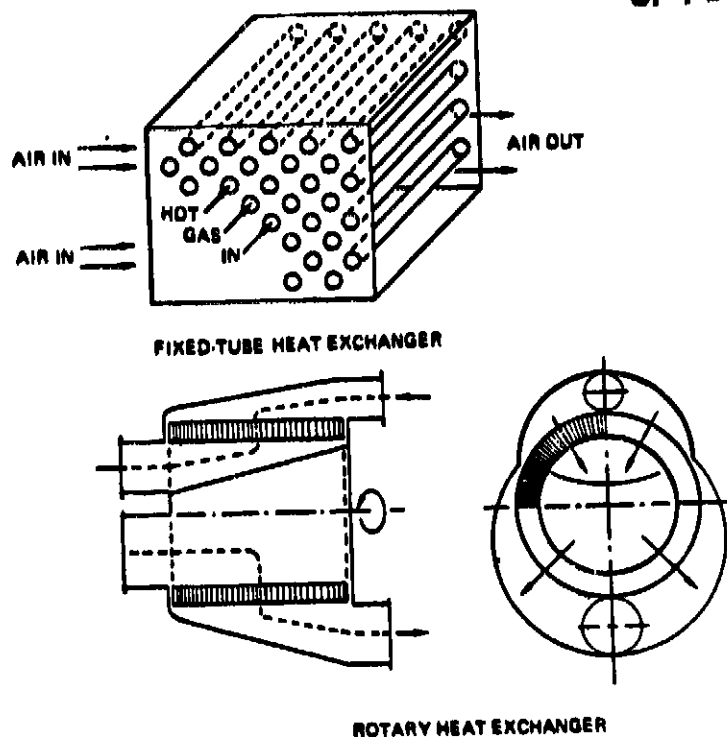
Figure 17. Heat Exchangers.

For rotary heat exchangers, a ceramic core is assumed. Weights of this type of heat exchanger have been determined by the Corning Glass Company (ref. 4) and are represented in Table I for various levels of effectiveness and pressure loss. This data is developed for a total corrected airflow of 90.7 kg/s. For other sizes, these weights are scaled directly with corrected flow.

TABLE I. CERAMIC ROTARY REGENERATOR WEIGHT

90.7 kg/s corrected weight flow						
BPR	3		7		10	
$\Delta P/P$ (%)	5	10	5	10	5	10
Weight (kg)						
ϵ = 80%	305.7	245.8	284.9	201.8	272.2	191.9
85%	440.4	342.0	414.6	290.3	378.3	279.9
90%	735.7	538.9	647.7	492.1	595.6	450.9

Fixed-tube heat exchangers are estimated by a heat-transfer analysis (ref. 5) where the required tube surface area is found to give the specified effectiveness. Flow area of the tubes is found from an input Mach number, number of tubes, and corrected flow. An estimate of the pressure drops is made for the input number of tubes based on input relative roughness values for each flow path. The flow Reynolds number is calculated and the Moody diagram is used to estimate the friction factor, and thus the pressure drop. These calculated $\Delta P/P$'s can be used to ascertain whether the number of tubes selected is reasonable. Wall thickness of the tubes is determined by Equation (28) to satisfy an assumed allowable stress of 34.5 KN/cm^2 and a density of 0.00465 Kg/cm^3 below 644°K (1160°R). A stress of 48.3 KN/cm^2 and a density of 0.00792 Kg/cm^3 is assumed above 644°K (1160°R). Minimum wall thickness of 0.0254-cm is used for the tubes. The length of the tubes is determined to satisfy the surface area requirements. Fixed-tube heat exchanger tube weight (W_{tubes}), is then found by

$$W_{tubes} = \rho L \pi \ (R_o^2 - R_i^2) \tag{47}$$

where R_o and R_i are the tube radii and L is the total length required. A wrap-up factor of 1.85 is used to account for the weight of the casings, mounting hardware, manifolds, and other equipment that may be necessary.

$$W_{HTEX} = 1.85 \cdot W_{tubes} \tag{48}$$

3.1.15 Propellers and Propfans

The following expressions for estimating the weight and diameter of advanced technology propellers and propfans were derived from methods developed by Hamilton Standard (ref. 6). It is noted that these expressions are based upon a conventional blade of the stated materials with a generally rectangular platform shape, and

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a standard flanged shank. The blade weight relations are for common propeller materials; composite and aluminum. If other materials are desired, a density ratio can be used to estimate the weight. However, allowable working stresses and blade stiffness may vary and considerable judgement is required to account for these effects.

The expression used in WATE-S for double acting, advanced technology propellers is

$$\text{Prop Wt} = K \left[\left(\frac{D}{3.048} \right)^2 \left(\frac{N}{4} \right)^{0.7} \left(\frac{AF}{100} \right)^{0.75} \left(\frac{U_t}{319.2} \right)^{0.5} \right.$$

$$\left. (Mn + 1)^{0.5} \left(\frac{PW}{D^2} \right)^{0.12} \right] \tag{49}$$

where K = 42.6 for composite materials

57.6 for aluminum

D = diameter (m)

N = number of blades

AF = blade activity factor

PW = maximum shaft power (KWatt)

Mn = design cruise Mach number

U_t = 100-percent design tip speed (m/s)

The expression for propfans is

$$\text{Propfan Wt} = \left(2.476 + 2.005 \left(\frac{PW}{D^2} \right)^{0.35} \right) D^{2.5} \left(\frac{AF}{231} \right)^{0.75} \left(\frac{U_t}{243.8} \right)^{0.3}$$

$$\left(\frac{N}{8} \right)^{0.65} \tag{50}$$

The input quantities are tip speed, PW/D^2 or D, the number of blades, activity factor, and design cruise Mach number. The calculation procedure determines the diameter if not input, then the propeller RPM is calculated from the tip speed,

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$$RPM = \frac{60 \ U_t}{\pi \ D} \tag{51}$$

and finally the propeller or propfan weight is calculated from the above expressions.

3.1.16 Accessories

Accessory weight data was collected from twelve general aviation aircraft manufacturers and was supplemented with Garrett data for several engines. The data is presented in Table II and includes 22 various turbofan, turboprop, and turboshaft engines ranging in sea level static thrusts from 2.67 KN to 22.46 KN and maximum shaft horsepowers from 0.373 mWatt to 1.163 mWatt.

A tremendous amount of scatter exists in the data, and hence, separate correlations for each accessory were not possible. Battery weights varied and were generally the heaviest accessory. For these reasons, the starter/generator, hydraulic pump, oil pump, and fuel pump were lumped together and a single correlation derived for these accessories (note that the battery is not included).

$$Accs \ Wt = 18.2 + 0.02 \ (bare \ engine \ weight) \tag{52}$$

If this calculation results in an accessory weight fraction less than 10 percent of the bare engine weight, then 10 percent of the bare engine weight is used for the accessories. The bare engine weight where this break point occurs is 198.4 kg.

3.2 Other Program Functions and Capabilities

3.2.1 Flight Envelope Maximization

In the normal use of the WATE-S program, a flight envelope of engine cycle data will be generated. Since the weight of each

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TABLE II. ACCESSORY WEIGHT DATA

Aircraft Manufacturer	Aircraft Model	Engine Model	FN/SHP	Engine Weight	Starter Generator	Hydraulic Pump	Oil Pump	Fuel Pump	Battery	Propeller Pitch Controller	Miscellaneous
Dassault	Falcon 10	TFE731-2	15.57	322	15.2	2.1					
	Falcon 20	CF700	20.02	334	28.6	2.1					
	Falcon 200	AFT3	22.46	494	15.2	2.1					
	Falcon 50	TFE731-3	16.46	334	18.1	2.1					
Piper	Cheyenne 2	PT6-11	0.394	137	11.1	0.8			34.0		2.3
	Cheyenne 3	PT6-41	0.634	136	14.5				34.0		2.3
Lockheed	Jetstar 2	TFE731-3	16.46	324	15.4	4.1					
Rockwell	Sabreliner	TFE731-3	16.46	334	16.6						
		CF700	20.02	334	28.0						
		JT12	14.68	212	28.6						
Gates	Learjet 25	CJ610	13.12	180	24.5	1.0					
	Learjet 35/36	TFE731-2	16.46	334	15.3	1.7					2.3
	Learjet 55/56	TFE731-3A	16.46	334	15.3	2.6					
Cessna	Conquest 411	TPE331	0.645	170	14.5				43.5		
	Corsair 425	PT6-112	0.390	145	14.5				34.0		
	Citation 1	JT15D-1	9.79	231					36.3/2		
	Citation 2	JT15D-4	11.12	253							
	Citation 3	TFE731-3B	16.46	334	17.4						
Gulfstream	Commander	TPE331	0.626	163	14.5	1.4			43.5		0.3
Swearingen	Metro/Merlin 4C	TPE331-11	0.746	170	14.5	2.9			25.3	1.9	
		PT6-45C		192	15.5	3.3			36.7/2*	1.3	
Mitsubishi	Solitaire	TPE331	0.626	163	14.5				43.5		
	Diamond	JT15D-4	11.12	253					36.3(2)		
AiResearch Avn.		TPE331	0.626	154							
		PT6	0.533	145							
		TPE731	16.46	334							
		TT15D	11.12	253							
Bell		PT5	0.671	315/2	13.6						
		T700	1.163	188	16.8						
		LTS101	0.503	105	7.7						
Hughes		250-C30	0.503	131	7.7				17.9		
		T700	1.119	188							
Garrett		TPE331-8		175	15.9		0.78	3.35	18.1	1.3	23.9
		TPE331-11		181			0.78	3.33		1.3	26.7
		TPE331-14/15		238			0.97	3.35		5.44/1.81**	16.8/17.3
		TFE731						3.97			11.8
		AFP3-6						3.97			15.3

*One battery for A/C
**Double-acting/single-acting prop.

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component is affected by its maximum work, flow, temperature, and speed; these maximum values are stored for use in the dimension and weight calculations. The flight condition is given in the output data where the maximum condition occurs for each component.

3.2.2 Design Limits

As an aid to assist the user in achieving a reasonable engine design, the output will provide a warning and suggested corrective action to bring the engine design within reasonable limits. These limits can be specified, or default values will be used if not specified. Table III shows a list of warnings and corrective actions.

3.2.3 Automatic Airflow Scaling

The WATE-S program will automatically scale the engine ±20 percent of the size that is defined by the thermodynamic input. Up to six selected scale factors can also be specified. A scaling exponent (ϵ) is calculated for each scaled engine based on the following expression:

$$W = W_{REF} \left(\frac{W_a}{W_{a_{REF}}} \right)^{\epsilon}$$

(53)

The scaling exponent (ϵ) for each engine size is provided in the output data.

3.2.4 Engine Center of Gravity

The center of gravity of each component, except the rotating components, is assumed to be the midpoint of its length. The moment relative to the front flange of the engine is determined as a function of the position of each component.

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TABLE III. DESIGN LIMITS

Warning Message	Action Recommended	Default Value Tested Against
Blade Centrifugal Stress Exceeded	Reduce shaft speed (by rpm scalar) or increase exit Mach number	$\sigma = 34.5$ KN/cm^2 psi HPT $\sigma = 41.4$ KN/cm^2 psi LPT $\sigma = 55.2$ KN/cm^2 psi fans and axial compressors
h/t Too Large	Reduce hub/tip ratio input	h/t = 0.93 HPC exit
h/t Too Small	Increase hub/tip ratio input	h/t = 0.32 fan, LPC, HPC inlet h/t = 0.50 HPT, LPT exit
Turbine Work Too High	Add turbine stages decrease λ_m input	$\lambda m \frac{\Delta H}{\theta} = 139.6$ KJ/kg HPT, LPT
Stage PR Too High	Reduce stage pressure ratio input	PR = 1.8 fan PR = 1.65 HPC, LPC
Flow Velocity Too High	Decrease stage inlet Mach number input	$Mn_{exit} = 0.60$ all components
Blade Size Too Small	Change overall pressure ratio or reduce h/t input	$h_B = 1.016$ cm all axial compressors
Compressor Work Coefficient Too High	Add compressor stages or increase hub/tip ratio	$\psi = 0.9$ all axial compressors

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For rotating components, the weight of each stage is assumed to act at mid-length of the stage. Moments are summed about the front flange for each stage. The center of gravity of each rotating component and the total engine is calculated. CG locations are shown in the output data for the total engine and each component.

3.3 Program Validation

A verification of the accuracy of the WATE-S method can only be done by applying it to various types of engines and comparing the results with the actual measured engine weight and dimensions, or with those estimated by the manufacturer for proposed engines. Since the manufacturer's estimate of proposed engines also includes some error, the real deviation or error of the WATE-S method can only be found by comparing engines that have been built in production quantities.

In order to demonstrate the accuracy of WATE-S, the NASA Program Manager and Garrett jointly selected four Garrett propulsion engines for comparison. These included both production and proposed engines. Results of this comparison are presented in Figure 18. As can be seen, the predicted engine weight and overall dimensions of the selected engines are within the ±10 percent accuracy goal.
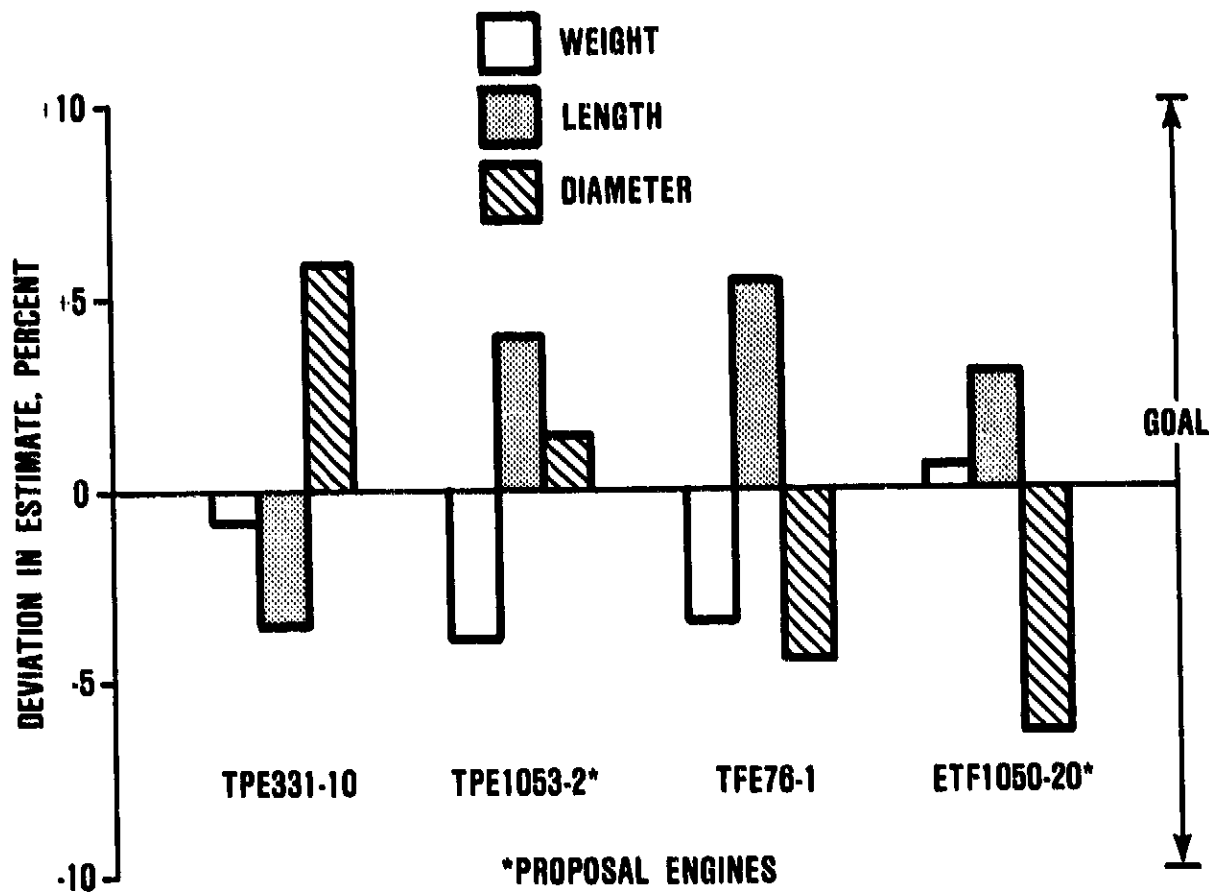
Figure 18. WATE-S Program Results Compared to Garrett Weight Data.

4.0 USERS MANUAL

This section contains a description of the WATE-S input and output data, values of typical inputs, sample cases, and program structure definition. WATE-S is designed to function with a component type thermodynamic engine cycle analysis program. The thermodynamic engine design point may be used to generate the WATE-S inputs, or additional off-design points can be used and the maximum conditions of component work, flow, temperature, and pressure are used to size the turbomachinery components. In order to achieve the most accurate engine weight estimate, the off-design cases should include the maximum performance levels required of each component.

WATE-S will also accept input weight scalars for each component so that components may be selectively eliminated, increased, or decreased in weight to determine sensitivities, etc. Input and output units may be either English or SI.

4.1 Input Description and Formats

The inputs of WATE-S are arranged in three NAMELIST groups: $C for the configuration data, $T for the thermodynamic data, and $W for the aeromechanical design data. The configuration data is input only once per WATE-S execution, whereas the thermodynamic and aeromechanical design inputs are grouped in pairs. Table IV provides a summary of the input variables. Figure 19 illustrates a typical card stacking arrangement to execute WATE-S. The following sections discuss each of these NAMELIST groups in detail and provide typical and default values where appropriate.

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TABLE IV. WATE-S PROGRAM INPUT

o Configuration Input — Namelist $C =

NCOMP
NOSTAT } This input is only needed once
JTYPE } during WATE-S execution
JCONF

o Thermodynamic Input — Namelist $T =

WTF
TOTEMP
TOPRES
PAR
PERPF } These quantities are generally
DATOUT } calculated from the other $C and $T
DATINP } input and hence, are not required
in all cases

o Aeromechanical Input — Namelist $W =

IWMEC
DESVAL
ACCS
IWT
IPLT
ISII
ISIO
IOUTCD
ILENG
DESLIM
ISCALE
SCALE
ACCARM
DISKWI

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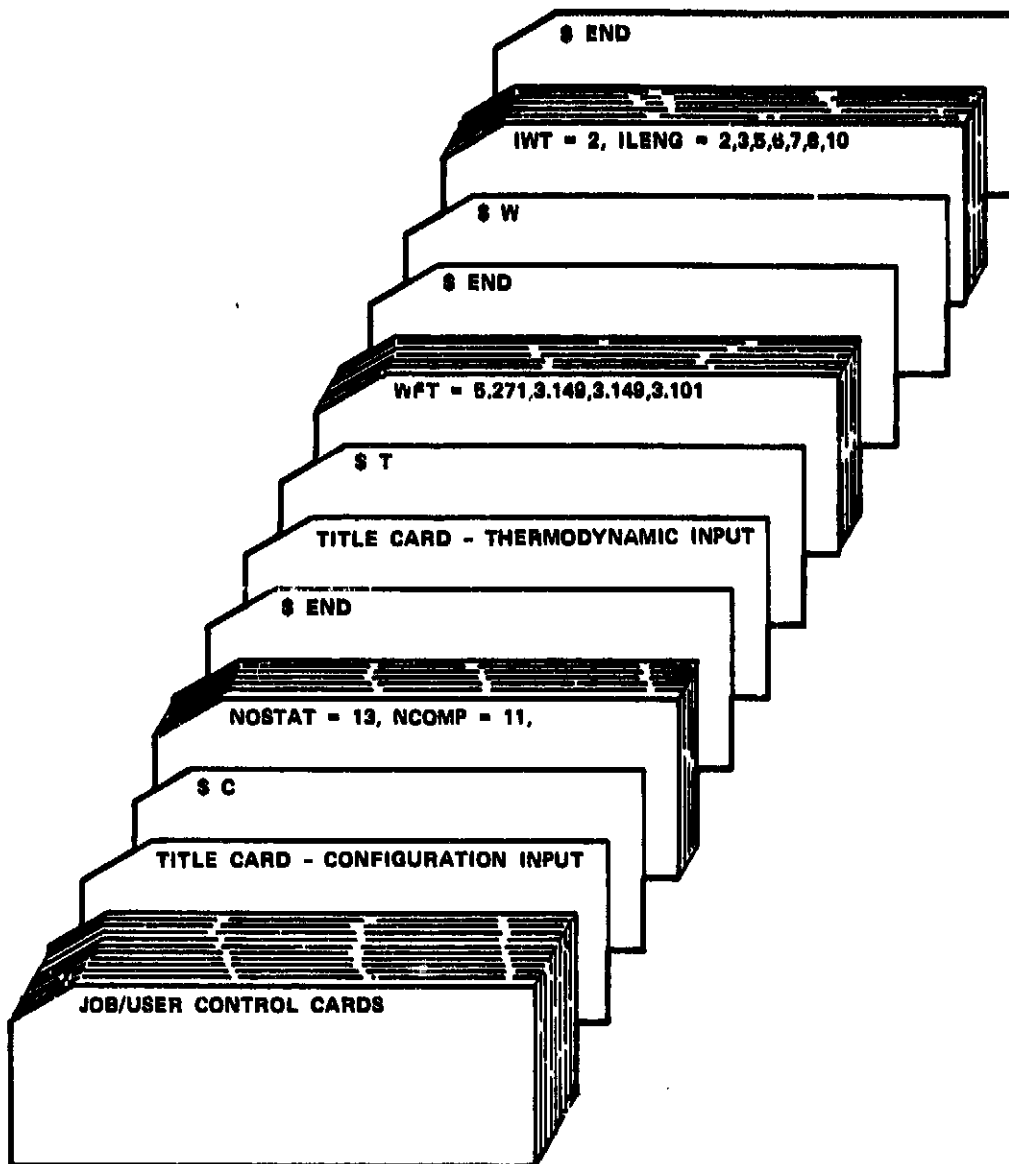
Figure 19.   Deck Stacking.

4.1.1 Configuration Inputs

The engine configuration input is contained in the $C name-
list. It is preceded by a title card describing the engine con-
figuration or any other description the user might desire. The
configuration inputs fully describe the component connectivity and
define the flow stations throughout the engine. The following
variables were originally supplied by NNEP (ref. 7) in WATE-2, but
in WATE-S are required input.

"NCOMP"   is an integer variable defining the total number of
           components used in the WATE-S engine simulation.

"NOSTAT"   is an integer variable defining the total number of
           flow stations used for the thermodynamic simula-
           tion of the engine.

"JTYPE"   is a one-dimensional integer array containing the
           type of component.

1	Inlet	'INLT'
2	Duct	'DUCT'
3	Water Injection	'WINJ'
4	Compressor	'COMP'
5	Turbine	'TURB'
6	Heat Exchanger	'HTEX'
7	Splitter	'SPLT'
8	Mixer	'MIXR'
9	Nozzle	'NOZZ'
10	Propeller	'PROP' (this component known as 'LOAD' in NNEP)
11	Shaft	'SHFT'

"JCONF"   is a two-dimensional integer array defining the
            component connectivity using the flow station
            numbers. It is of the form JCONF(M,N) where M is
            the component number, and N is the variable number
            as described below.

Location   Description

   1   is the primary upstream airflow station number
                for flow components; or the first component
                hooked onto a shaft, or the shaft hooked onto
                a propeller.

   2   is the secondary upstream station number, or
                the second component hooked onto a shaft.

   3   is the primary downstream station number, or
                the third component hooked onto a shaft.

   4   is the secondary downstream station number, or
                the fourth component hooked onto a shaft.

        A default engine configuration has been included in WATE-S.
Figure 20 illustrates this engine; a two-spool turbofan with axial
single-stage fan, axi-centrifugal HP compressor (three-stage
axial), axial single-stage HP turbine, and axial two-stage LPT.
The default $C namelist data corresponding to this engine config-
uration are shown in Table V.
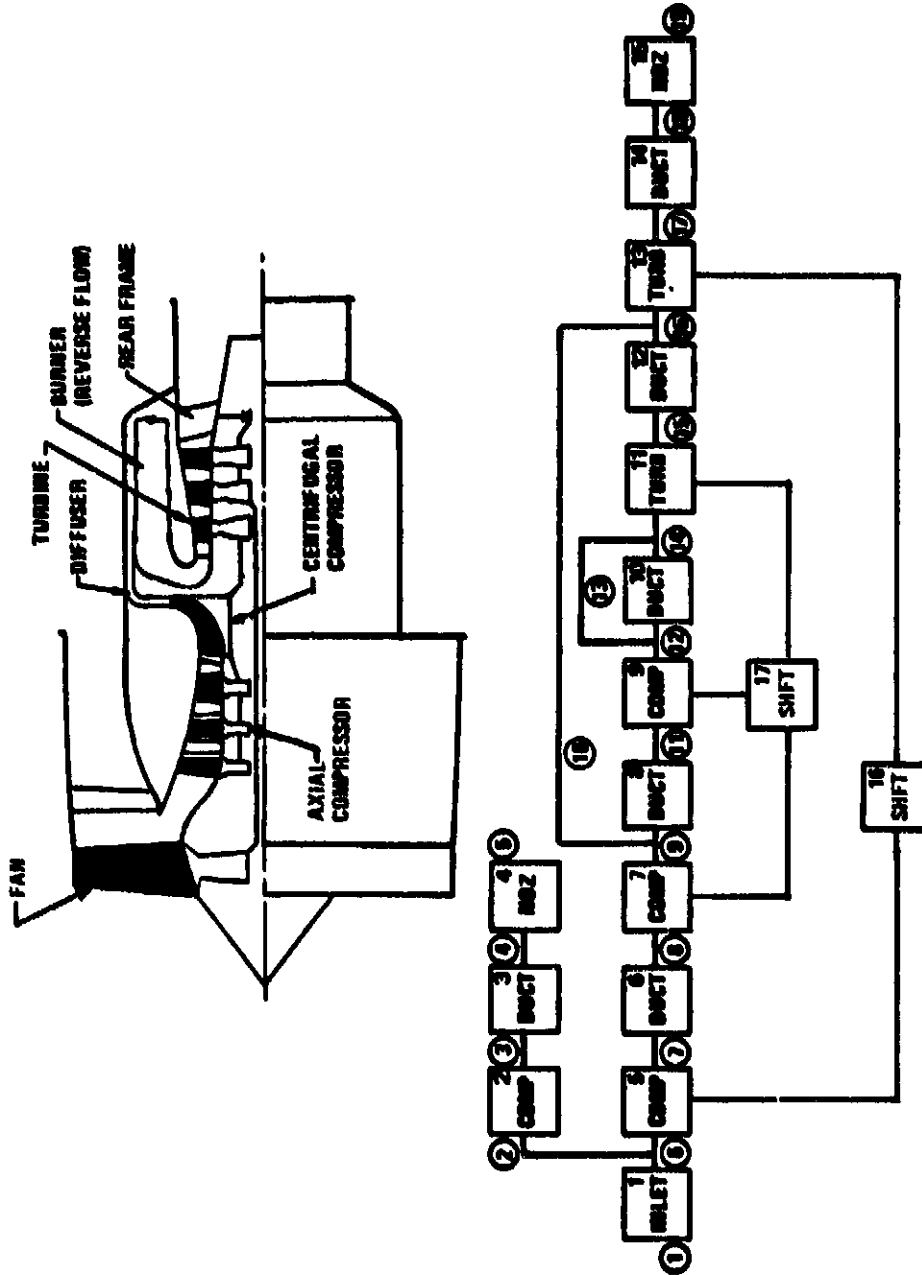
Figure 20. Default Engine Configuration.

TABLE V.   DEFAULT $C VALUES

NCOMP = 17, NOSTAT = 19

Component Number	JTYPE	JCONF			
		1	2	3	4
1	1	1	0	6	2
2	4	2	0	3	0
3	2	3	0	4	0
4	9	4	0	5	0
5	4	6	0	7	0
6	2	7	0	8	0
7	4	8	0	9	10
8	2	9	0	11	0
9	4	11	0	12	13
10	2	12	0	14	0
11	5	14	13	15	0
12	2	15	0	16	0
13	5	16	10	17	0
14	2	17	0	18	0
15	9	18	0	19	0
16	11	5	13	0	0
17	11	7	9	11	0

4.1.2 Thermodynamic Input

The thermodynamic input is contained in the $T namelist. It is preceded by a title card describing the engine being weighed or any other description the user might desire. The thermodynamic input fully describe the properties for each flow station identified in the configuration input. These properties include mass flow rate, total pressure, total temperature, and fuel/air ratio. These inputs are used as component upstream flow conditions.

"WTF" is a one-dimensional array containing the physical mass flow rate at each station (lbm/s).

"TOPRES" is a one-dimensional array containing the total pressure at each station (psi).

"TOTEMP" is a one-dimensional array containing the total temperature at each station (°R).

"FAR" is a one-dimensional array containing the fuel/air ratio at each station.

In addition to the above, three additional arrays of data are required. These arrays were originally filled by the NNEP code in WATE-2, however, since WATE-S is not configured with an engine cycle code, separate input variables were needed.

"PERPF" is a one-dimensional array containing twelve values which describe general performance parameters for the engine.

Location	Description
1	inlet total flow (lbm/s)
2	gross thrust (lbf)
3	fuel flow (lbm/hr)
4	net thrust
5	TSFC

6	net thrust/inlet total flow
7	total inlet drag
8	total brake shaft power (hp)
9	installed thrust
10	installed TSFC
11	spillage and lip drag
12	boattail drag

This data is used for information purposes only, and hence, is considered optional in WATE-S.

"DATINP" is a two-dimensional array containing several miscellaneous component properties. It is of the form DATINP(N,M) where M is the component number, and N is the variable number as described in Table VI. The only required inputs in this array are the shaft gear ratios. The remainder of the inputs are optional. The bleed fractions will be calculated from the "WTF" array input and the Mach number and altitude are for information purposes only.

"DATOUT" is a two-dimensional array containing several other miscellaneous component properties. It is of the form DATOUT(N,M) where M is the component number, and N is the variable number as described in Table VII. The required inputs in this array include the turbine rpm, if the turbine is not connected to a compressor (free-turbine turboprop and turboshaft engines), splitter bypass ratio, and mixer primary and secondary flow areas. The remainder of the array is calculated from the "WTF", "TOPRES", TOTEMP", and "FAR" arrays, if not input.

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TABLE VI. DATINP ARRAY DEFINITIONS.

Component Type	Location								
	1	2	3	4	5	6	7	8	9
Inlet					Mach No.				Altitude
Duct									
Water Inj.									
Compressor		Bleed Fraction							
Turbine		Bleed Fraction							
Heat Exchanger									
Splitter									
Mixer									
Nozzle									
Propeller									
Shaft		Gear (1) Ratio	Gear (1) Ratio	Gear (1) Ratio	Gear (1) Ratio				

NOTE (1): Gear ratio inputs are $RPM_{shaft}/RPM_{compressor}$ and are required input.

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TABLE VII. DATOUT ARRAY DEFINITIONS.

Component Type	Location								
	1	2	3	4	5	6	7	8	9
Inlet							Inlet Recovery		
Duct	Pressure Ratio								
Water Inj.									
Compressor	Horse-power							Effi-ciency	Pressure Ratio
Turbine	Horse-power	Physical* rpm						Effi-ciency	Pressure Ratio
Heat Exchanger	$\Delta P/P$ Primary	$\Delta P/P$ Secondary		Effective-ness					
Splitter	Bypass* Ratio								
Mixer	Main Flow* Area	Secondary* Flow Area							
Nozzle									
Propeller	Horse-power								
Shaft									

*Notes required inputs (see text for turbine rpm)

4.1.3 Aeromechanical Input

The aeromechanical input is contained in the $W namelist. These variables control the aerodynamic and mechanical sizing of the components. The following sections describe the aeromechanical input and give the default values where applicable.

4.1.3.1 Miscellaneous Variables

"ACCARM" is a variable that contains the value of the centroid distance for the accessories component in the CG calculations. If no value is input, accessories are not included in center-of-gravity calculations.

"DISKWI" is a variable that is used as an indicator for the axial compressor disk weight method. (Default = 1.)

- 0 – Do disk weight calculations using the Boeing WATE-2 method.

- 1 – Do disk weight calculations using the Garrett WATE-S method.

"ACCS" is a one-dimensional array containing three values which control the accessory weight calculations. (Default = 40., 0.02, 0.10)

- ACCS(1) = Fixed accessory weight (lbm)

- ACCS(2) = Accessory weight fraction of bare engine weight

- ACCS(3) = Minimum total accessory weight fraction

"ISCALE" is a one-dimensional integer array containing three values which control the engine scaling logic of the program. (Default = 1, 3, 1)

ISCALE(1)   Output indicator for scaled engines. Unscaled engine output set by "IOUTCD".

0 -   Short form engine weight, length, and maximum radius.

1 -   Long form component weights and dimensions.

2 -   Debug option.

ISCALE(2)   Number of scaling points.

ISCALE(3)   Not used.

"SCALE" is a one-dimensional array containing six values. The values correspond to the engine scaling factors desired. The number of "SCALE" values must be equal to the value of ISCALE(2). First value must always equal 1. (Default = 1, 0.8, 1.2, 3*0.)

"IWT" is a integer variable to control the execution of the component weight calculations. (Default = 1)

0 -   Do not do weight calculations.

1 -   Do weight calculations without the thermodynamic parameter maximization feature of the WATE-S code. This is used for design point paramteric weight analysis.

2 -   Do weight calculations using maximum thermodynamic parameter maximization feature.

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3 – Do weight calculation with airflow scaling without the thermodynamic parameter maximization feature.

4 – Do weight calculation with airflow scaling using the thermodynamic parameter maximization feature.

"IPLT" is a logical variable to control the gas path printer plot option of WATE-S. (Default = T)

T – Gas path layout

F – No gas path layout

"ISII" is a logical variable to specify the units of the $W namelist variables. (Default = F)

T – SI units input

F – English units input

"ISIO" is a logical variable to specify the units of the output of the weight calculations. (Default = F)

T – SI units output

F – English units

"IOUTCD" is an integer variable to control the amount of output generated by the component and engine weight calculations. (Default = 2)

0 – Short form engine weight, length, and maximum radius.

1 – Long form component weights and dimensions.

2 – Debug option.

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4.1.3.2 Length Contributing Vector

"ILENG" is a one-dimensional integer array specifying only those components which contribute to the total additive engine length. The component numbers are specified in the order that the components would add in length to achieve the total engine length. This must start with the inlet and end with the furthest downstream nozzle. The default "ILENG" values for the default engine configuration illustrated in Figure 20 are:

$$ILENG = 1, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15,$$

The default "ILENG" input does not include the bypass flow components (COMP 2, DUCT 3, NOZ 4), reverse-flow burner (DUCT 10), or shafts (SHFT 16, SHFT 17) since these components do not contribute to the total engine length.

4.1.3.3 Mechanical Design Indicators

"IWMEC" is a two-dimensional integer array containing the mechanical design indicators. It is of the form IWMEC(N,M), where M is the component number, and N is the variable number as described in the following sections for each component type. The mechanical design indicators must be specified for each component. Table VIII illustrates the default "IWMEC" values, which are representative of the default engine (see Figure 20).

TABLE VIII.   TWMEC DEFAULT VALUES (See Figure 20).

Component Number	Location						
	1	2	3	4	5	6	7
1	'INLT'	0	0	0	0	0	0
2	'FO'	1	0	0	5	0	1
3	'DUCT'	2	0	0	0	0	0
4	'NOZ'	1	0	0	0	0	0
5	'FI'	1	0	1	2	0	1
6	'DUCT'	2	0	0	0	0	0
7	'LPC'	1	0	0	0	0	3
8	'DUCT'	2	0	0	0	0	0
9	'HPC'	2	0	0	0	0	1
10	'PBUR'	1	0	0	0	0	0
11	'HPT'	0	9	9	1	0	0
12	'DUCT'	2	0	0	0	0	0
13	'LPT'	5	5	0	2	0	0
14	'DUCT'	2	0	0	0	0	0
15	'NOZ'	1	0	0	0	0	0
16	'SHAF'	1	0	0	0	0	0
17	'SHAF'	2	0	0	0	0	0

4.1.3.3.1 Compressors

Location		Description

Location   **Description**

1   Type of compressor being weighed

        (1)   'FAN'   – Typical fan

        (2)   'FO'   – Outer portion of nonrotating splitter fan

        (3)   'FI'   – Inner portion of nonrotating splitter fan

        (4)   'RSFO'   – Outer portion of rotating splitter fan

        (5)   'RSFI'   – Inner portion of rotating splitter fan

        (6)   'LPC'   – Low-pressure compressor

        (7)   'HPC'   – High-pressure compressor

2   This indicates if the compressor has stators or if the compressor is a centrifugal compressor.

        0   – Stator weight is not calculated

        1   – Stator weight is calculated

        2   – Centrifugal compressor

3   This is the indicator for 'front' frames in compressors. This input may be:

        0   – No frame

        1   – Single bearing frame without Power Takeoff (PTO)

        2   – Single bearing frame with PTO

        4   – Two bearing frame, such as the frame in front of the HPC in the JT8D or JT9D, which extends outward to the fan outer case and holds two bearings with PTO

Location	Description

Location   **Description**

4   This is the indicator for the 'rear' frame in a compressor

              0   - No frame

              1   - Single bearing frame without Power Takeoff (PTO)

              2   - Single bearing frame with PTO

              4   - Two bearing frame, such as the frame in front of the HPC in the JT8D or JT9D, which extends outward to the fan outer case and holds two bearings with PTO

5   This is the component number connecting to this component for split flow compressors only. If this is the Fan Outer, the Fan Inner must be specified. If this is the Rotating Splitter Outer, the Inner Splitter must be specified, and vice versa. If (-), a dummy compressor is assumed.

6   Gearbox indicator. Input is component number of shaft, 0 for no gearbox.

7   Number of stages; if 0, will calculate number of stages assuming equal work based on the maximum first-stage pressure ratio input [DESVAL(2,M)].

4.1.3.3.2 Turbines

Location   **Description**

1   This is the type of turbine

     (8)   'HPT'   - High-pressure turbine

     (9)   'LPT'   - Low-pressure turbine

2   Indicator for turbine exit frame

              0   - No frame

              3   - Single bearing turbine exit frame for large engines

              5   - Small turbine exit frame

Location	Description
3	Compressor number from which the rpm is determined; if 0, DATOUT(2,M) is used for turbine rpm (axial turbines only).
4	Component number from which the mean radius limit for the turbine is determined. If the component number is positive, the outlet outer dimension is used. If negative, the inlet outer dimension is used. If 0, it will use the outlet of the feeding component.
5	Number of stages; if 0, will calculate number of stages assuming equal work based on turbine mean radius limit and mean work coefficient.
6	Indicator for axial or radial turbine
	0 — Axial turbine
	2 — Radial turbine
7	Not used.

4.1.3.3.3 Burners

Location	Description
1	This is the type of burner being weighed
(10) 'PBUR'	— Primary burner
(11) 'DBUR'	— Duct burner (a mean radius is specified)
(12) 'AUG'	— Augmentor (no inner wall)
2	This is the indicator for frame weight, normally only for primary burners. This frame includes a bearing.
	0 — No frame
	1 — Frame
3-7	Not used.

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4.1.3.3.4 Ducts

Location		Description
1	(20)	'DUCT'
2		Indicator as to type of duct
	1	– Dummy – i.e., no weight or length
	2	– Length input
	3	– Length derived as in a duct connecting a splitter and a mixer
	4	– Crossover duct for centrifugal compressors
3-7		Not used.

4.1.3.3.5 Shafts

Location		Description
1	(13)	'SHAF'
2		Shaft number from inner to outer.
3-7		Not used.

4.1.3.3.6 Mixers

Location		Description
1		Type of mixer
	(14) 'MIX'	– The coannular emergence of two streams without mechanical mixer
	(15) 'FMIX'	– Forced mixer, mechanical, i.e., Daisy lobed mixer
2		Indicator for primary input node
	0	Engine core is inner (primary)
	1	Engine core is outer (secondary)
3-7		Not used.

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4.1.3.3.7 Nozzles

Location		Description

1   (16) 'NOZ'

2   Nozzle type

     1   – Convergent

     2   – C-D variable area

3   Component number from which the nozzle inlet diameter can be determined. If this diameter is taken from the inlet of the component, a (–) component number must be entered. If (+), the exit station will be used. If the previous component determines the diameter, this location may be zero.

4   Thrust reverser type

     0   – None

     1   – Fan

     2   – Primary

5-7   Not used.

4.1.3.3.8 Heat Exchangers

Location		Description

1   (19) 'HTEX'

2   Heat exchanger type

     1   – Fixed tube

     2   – Rotary

3   Flow Direction

     1   – Parallel flow

     2   – Counter flow

4-7   Not used.

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4.1.3.3.9 Splitters

Location		Description
1	(17)	'SPLT'
2		0 — Inner stream is primary
		1 — Inner stream is not primary
3-7		Not used.

4.1.3.3.10 Annulus Inverting Valve

Location		Description
1	(18)	'VALV'
2		Location of Valve
		1 — Inner
		2 — Outer
3		Component number of opposite duct
4		0 if fixed, 1 if movable
5-7		Not used.

4.1.3.3.11 Propellers and Propfans

Location		Description
1	(21)	'PROP'
2		Propeller type
		0 — Hamilton Standard double acting, advanced technology aluminum propeller.
		1 — Hamilton Standard double acting, advanced technology composite propeller.
		2 — Hamilton Standard propfan.
3-7		Not used.

4.1.3.4 Aeromechanical Design Variables

"DESVAL" is a two-dimensional array containing the aero-dynamic and mechanical design inputs. It is of the form DESVAL(N,M), where M is the component number, and N is the variable number as described in the following sections for each component type. The default values are stored in a separate array (DEFAUL) which cannot be altered by program WATE-S input. A summary of these arrays is contained in Table IX. The default values of the "DEFAUL" array are illustrated in Table X. The "DEFAUL" array values are used when the "DESVAL" input is not specified for a given component. Table XI contains typical ranges of the "DESVAL" input variables for each component type.

TABLE IX. DESVAL/DEFAUL ARRAY PARAMETERS.

Component Type	Location																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Axial compressors	Mn_i	Pr_{MAX}	H/T_i	SOLID.	AR_i	AR_o	Mn_o	T_{MAX_i}	T_{MAX_o}	RPM_R	RBO_B	MODE	RPM_{SC}	T_{METAL}	W_{tsc}	TR	BVF
Axial turbines	Mn_i	TMWC	SOLID	AR_i	AR_o	Mn_o	STRESS	MODE	RPM_R	TCR	RBO_B	BVF			W_{tsc}	TR	SVF
Burners	VEL	TIME	DIA	REF LOC	NO.CANS										W_{tsc}		
Ducts	Mn_i	L/H	DIA	REF LOC											W_{tsc}		
Shaft	STRESS	RBO	H/T												W_{tsc}		
Heat exchanger	NO TUBES	Mn_p	Mn_S	BPR	E/D_p	E/D_S									W_{tsc}		
Mixers	L/H	NO.PASS													W_{tsc}		
AIV	L/H	NO.PASS	Mn_i	Mn_o	Rn	W_{TIC}	W_{TOC}	W_{TW}							W_{tsc}		
Nozzle	L/D	SPR													W_{tsc}		
Centrifugal compressor	Mn_i	Pr_{MAX}	H/T_i	NO.BLD			Mn_o	T_{MAX_i}	T_{MAX_o}	RPM_R		H/T_o	RPM_{SC}		W_{tsc}		
Radial turbine	Mn_i	TMC	NO.BLD			Mn_o	Stress		RPM_R		RBD				W_{tsc}		
Propellers/Propfans	Des Mn	NO.BLD	AP	D_t	HP/D^2										W_{tsc}		

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TABLE X. DEFAUL ARRAY VALUES

COMPONENT TYPE	LOCATION																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ALL FANS(AXIAL)	0.50	1.7	0.5	1.5	2.	1.5	0.45	0.	0.	1.	0.	2.	1.	1160.	1.	1.8	0.06
LPC(AXIAL)	0.45	1.6	0.6	1.7	1.8	1.2	0.40	0.	0.	1.	0.	2.	1.	1160.	1.	1.2	0.12
HPC(AXIAL	0.40	1.5	0.7	1.7	1.2	0.9	0.35	0.	0.	1.	0.	2.	1.	1160.	1.	1.2	0.12
HPT(AXIAL	0.2	1.6	1.6	1.5	1.5	0.4	125000.	2.	1.	0.	0.	0.155			1.	1.	0.155
LPT(AXIAL)	0.3	2.0	1.6	2.	3.	0.55	125000.	2.	1.	0.	0.	0.195			1.	1.	0.195
PRIMARY BURNER	75.	0.01	0.	0.	0.										0.		
DUCT BURNER	150.	0.01	0.	0.											0.		
DUCTS	0.4	1.	0.	-1.											0.		
AUGMENTOR	300.	0.01	0.	0.											0.		
SHAFT	50000.	0.286	0.8												0.		
HEAT EXCHANGER	4000.	0.015	0.035	7.	0.001	0.001		1.1							0.		
MIXERS	1.	8.													0.		
AIV	1.	8.	0.5	0.5	0.	1.2	1.1								1.		
NOZZLE	1.	0.													1.		
CENTRIFUGAL COMPRESSOR	0.45	4.1	0.5	-19.			0.2	0.	0.	1.	0.286	0.3	1.		1.		
RADIAL TURBINE	0.3	0.8	17.	600.		0.45	125000.		1.						1.		
PROPELLER/PROPFAN	0.5	4.	130.	600.	20.										0.		

TABLE XI. TYPICAL RANGE OF INPUT VALUES FOR DESVAL ARRAY

COMPONENT TYPE	LOCATION																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ALL FANS (AXIAL)	0.4-0.6	1.4-1.9	0.3-0.6	1.0-1.5	3.0-1.5	2.0-1.0	0.4-0.6	—	—	—	0.1-0.15	1.0-3.0	0.5-1.2	—	—	1.5-2.0	0.05-0.07
LPC AXIAL	0.35-0.55	1.3-1.7	0.4-0.7	1.0-1.5	2.5-1.5	1.7-0.8	0.3-0.5	—	—	—	0.1-0.10	1.0-3.0	0.5-1.2	—	—	1.0-1.5	0.05-0.15
HPC (AXIAL)	0.35-0.5	1.2-1.6	0.5-0.8	1.0-1.5	2.0-1.2	1.5-0.7	0.25-0.4	—	—	—	0.1-0.10	1.0-3.0	0.5-1.2	—	—	0.5-1.5	0.05-0.15
HPT (AXIAL)	0.1-0.3	1.2-2.0	1.0-1.5	1.0-0.6	1.2-0.8	0.2-0.35	—	1.0-3.0	—	—	0.2-0.3	0.12-0.18	—	—	—	0.8-1.2	0.12-0.18
LPT (AXIAL)	0.15-0.35	1.5-2.0	1.0-1.5	3.5-1.0	2.2-1.0	0.25-0.45	—	1.0-3.0	—	—	0.15-0.3	0.15-0.22	—	—	—	0.8-1.2	0.15-0.22
PRIMARY BURNER	40.0-75.0	0.008-0.015	0.4-0.75	15.0-21.0	—	—	—	—	—	—	—	—	—	—	—	—	—
DUCT BURNER	60.0-150.0	0.01-0.03	0.1-0.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—
DUCTS	0.3-0.5	0.5-10.0	—	—	—	—	0.25-0.4	—	—	—	—	—	—	—	—	—	—
AUGMENTOR	150.0-300.0	0.02-0.05	0.6-1.0	—	—	—	—	—	—	—	—	—	—	—	—	—	—
SHAFT	—	0.2-3	0.6-1.0	1.0-0.8	1.2-0.8	0.2-0.35	—	—	—	—	—	—	—	—	—	—	—
HEAT EXCHANGER	—	0.05-0.3	0.1-0.3	—	0.0-0.001	0.0-0.001	—	—	—	—	—	—	—	—	—	—	—
MIXERS	0.8-1.4	1.0-14.0	—	—	—	—	—	0.5-1.5	—	—	—	—	—	—	—	—	—
A/V	0.3-1.4	1.0-14.0	0.35-0.6	0.25-0.6	—	0.5-1.5	0.5-1.5	—	—	—	—	—	—	—	—	—	—
NOZZLE	0.8-2.5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
CENTRIFUGAL COMPRESSOR	0.3-0.55	4.0-10.0	0.4-0.75	15.0-21.0	—	—	0.15-0.35	—	—	—	0.2-0.3	0.2-0.4	0.8-1.2	—	—	—	—
RADIAL TURBINE	0.1-0.3	0.7-1.5	15.0-23.0	—	—	0.25-0.4	—	—	—	—	—	—	—	—	—	—	—
PROPELLER/PROPFAN	0.3-0.65	3.0-10.0	50.0-140.0	500.0-900.0	15.0-30.0	—	—	—	—	—	—	—	—	—	—	—	—

4.1.3.4.1 Compressor

Array

Location		Description
1		Compressor inlet Mach number.
2		Maximum first-stage pressure ratio, required if IWMEC(7,M) equals 0.
3		Compressor inlet hub/tip ratio.
4	Axial:	Blade tip solidity, ratio of blade tip chord and blade spacing.
	Centri-fugal:	Number of blades. If (-), splitter weight is calculated.
5*		Blade aspect ratio of first stage.
6*		Blade aspect ratio of last stage.
7		Compressor exit Mach number.
8		Maximum compressor inlet temperature. ZERO if design point temperature is to be used for material selection. °R (°K)
9		Maximum compressor outlet temperature. ZERO if desired point temperature is to be used for material selection. °R (°K)
10		Maximum speed ratio - $\text{RPM}_{max}/\text{RPM}_{des}$.
11*		Blade material density. ZERO if WATE-S is to select material. lbm/in^3 (Kg/cm^3)
12	Axial:	Compressor design type
		1. Constant hub radius design.
		2. Constant mean radius design.
		3. Constant tip radius design.
	Centri-fugal:	$\text{Hub}_{inlet}/\text{tip}_{exit}$ radius ratio.

---

*Not used for centrifugal compressors.

Location	Description
13	RPM scaler, normal input is 1. – use to match known rpm or modify tip speed correlations.
14*	Temperature at which a change of material is required. °R (°K)
15	Compressor weight scalar, input ZERO if no scaling is desired.
16*	Blade taper ratio.
17*	Blade volume factor.

*Not used for centrifugal compressors.

4.1.3.4.2 Turbines

Location		Description

1   Turbine inlet Mach number.

2   Axial: First-stage mean work coefficient — $\lambda_m = \dfrac{gJ\,^{\Delta H}\!/_N}{U_m^{\,2}}$

             Radial: Radial turbine work coefficient — $\lambda_t = \dfrac{gJ\,^{\Delta H}\!/_N}{U_t^{\,2}}$

3.   Axial: Blade tip solidity, blade tip chord/blade spacing.

             Radial: Number of blades. If (−), splitter weight is calculated.

4*   Blade aspect ratio of first stage.

5*   Blade aspect ratio of last stage.

6   Turbine exit Mach number.

7   Disk reference stress — 0.2-percent yield, lbf/in2 (Newton/cm2).

8*   Turbine design type

             1. Constant tip radius design.

             2. Constant mean radius design.

             3. Constant hub radius design.

9   Maximum speed ratio — RPM_{max}/RPM_{design}.

10*   Turbine control radius, inch (cm) — blank if transferred from a component. This overrides IWMEC input if nonzero.

---

*Not used for radial turbines.

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Location	Description
11	Density of material in turbine blades, lbm/in^3 (Kg/cm^3).
12*	Blade volume factor.
13-14	Not used.
15	Turbine weight scalar. Input ZERO, if no scaling is desired.
16*	Turbine blade taper ratio.
17*	Stator blade volume factor.

*Not used for radial turbines.

4.1.3.4.3 Burners

Location	Description
1	Burner through-flow velocity, ft/s (m/s).
2	Burner airflow residency time, s.
3	Burner mean diameter, inch (cm). If zero, diameter is calculated to match a connecting component (see below).
4	Component number for calculating burner reference diameter, if other than upstream component. Not used when diameter is specified. If greater than zero, connecting component mean diameter is used for burner mean diameter. If less than zero, connecting component outer diameter is used for burner inner diameter (reverse-flow burners).
5	Number of cans for can burners.
6-14	Not used.
15	Burner weight scalar. Enter ZERO, if no scaling is desired.
16-17	Not used.

4.1.3.4.4 Ducts

Location	Description
1	Duct inlet Mach number.
2	Length to height ratio of duct, required if IWMEC(2,M) equals 2.
3	Duct mean diameter, inch (cm). If 0, duct diameter is calculated to match a connecting component.
4	Component number for calculating mean duct diameter. Not used when mean duct diameter is specified. Enter -1, if upstream connecting component is to be used.
5-14	Not used.
15	Weight scalar. ZERO, if no scaling is desired.
16-17	Not used.

4.1.3.4.5 Shafts

Location	Description
1	Shaft allowable stress, lbf/in^2 ($Newton/cm^2$).
2	Shaft material density, lbm/in^3 (Kg/cm^3).
3	Diameter ratio of shaft, D_{inner}/D_{outer}, not used for outer shafts.
4-14	Not used.
15	Shaft weight scalar. ZERO if no scaling desired.
16-17	Not used.

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4.1.3.4.6 Mixers

Location	Description
1	Effective length-to-diameter ratio of mechanical mixer, $L/\sqrt{A/\pi}$, where L is the mixer length inlet to exit, A is the total flow area. Enter 0, if not a mechanical (forced) mixer.
2	Number of passages (or lobes) in mixer.
3-14	Not used.
15	Weight scalar. Enter ZERO, if no scaling desired.
16-17	Not used.

4.1.3.4.7 Nozzles

Location	Description
1	Length to diameter ratio of nozzle.
2	Bypass ratio for mixed flow nozzle for thrust reverser weight.
3-14	Not used.
15	Weight scalar. Zero, if no scaling desired.
16-17	Not used.

4.1.3.4.8 Heat Exchangers

Location	Description
1	Number of tubes if "Fixed" type.
2	Mach number in primary stream (cold side).
3	Mach number in secondary stream (hot side).
4	Engine bypass ratio if "Rotary" type.
5	E/D for primary stream if "Fixed" type.
6	E/D for secondary stream if "Fixed" type.
7-14	Not used.
15	Weight scalar. Zero if no scaling desired.
16-17	Not used.

4.1.3.4.9 Splitters

Location	Description
1	Only input if first calculated component in flow path. Inlet Mach number.
2	Inlet hub/tip radius ratio.
3-14	Not used.
15	Weight scalar. ZERO, if no scaling desired.
16-17	Not used.

4.1.3.4.10 Annulus Inverting Valve

Location	Description
1	Specific length -- ratio of length to effective diameter of the AIV, $L/\sqrt{4A/\pi}$
2	Number of passages.
3	Mach number of inner passage.
4	Mach number of outer passage.
5	Hub radius in inches (cm); or component number from which hub radius is taken; or blank, if feeding component determines the hub radius.
6	Inner cylinder weight - lb/ft^2, (Kg/m^2).
7	Outer cylinder weight - lb/ft^2, (Kg/m^2).
8	Wall weight - lb/ft^2, (Kg/m^2).
9-14	Not used.
15	Weight scalar. ZERO, if no scaling desired.
16-17	Not used.

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4.1.3.4.11 Propellers and Propfans

Location	Description
1	Design cruise Mach number of aircraft.
2	Number of blades.
3	Activity factor.
4	Tip speed - ft/s (m/s).
5	Ratio of propeller shaft power to diameter squared - hp/ft^2, (KW/m^2).
6-14	Not used.
15	Weight scalar. Zero, if no scaling desired.
16-17	Not used.

4.1.3.5 Design Limits

"DESLIM" is a one-dimensional array containing the design limits for WATE-S. Table XII describes the design limits and the default values currently in the code. These can be changed as desired through the namelist $W input. If these limits are exceeded, the component weight and dimension calculations continue and a warning message is printed out.

4.2 Program Output

The output of WATE-S is contained in three sections, coinciding with the input: configuration, thermodynamic, and aeromechanical. The configuration output contains the $C namelist inputs and a simple configuration layout. The thermodynamic output contains the $T namelist inputs.

The aeromechanical output may be selected in either English or SI units. The units used are presented in Table XIII. The type

TABLE XII. DESIGN LIMIT DEFAULT PARAMETERS AND VALUES.

POSITION	TYPE	VALUE
1	AXIAL COMPRESSOR LOADING PARAMETER $\left(\dfrac{2Jg\ \Delta H/N}{U_m^2} \right)$ CANNOT EXCEED:	0.9
	BLADE CENTRIFUGAL STRESS CANNOT EXCEED:	
2	AXIAL HP TURBINE	50000. psi
3	AXIAL LP TURBINE	60000. psi
4	FANS	80000. psi
5	AXIAL COMPRESSORS	80000. psi
6	HUB/TIP FOR ALL COMPRESSORS CANNOT EXCEED:	0.93
	HUB/TIP CAN NOT BE LESS THAN:	
7	FANS AND AXIAL COMPRESSORS	0.32
8	AXIAL TURBINES	0.50
9	AXIAL TURBINE WORK $\left(\lambda_m \dfrac{\Delta H}{\theta} \right)$ CANNOT EXCEED:	60. Btu/lbm
	MAXIMUM COMPRESSOR FIRST-STAGE PRESSURE RATIO CANNOT EXCEED:	
10	FANS	1.8
11	AXIAL COMPRESSORS	1.65
12	LAST AXIAL COMPRESSOR STAGE EXIT MACH NUMBER CANNOT EXCEED:	0.6
13	AXIAL COMPRESSOR BLADE HEIGHT CANNOT BE LESS THAN:	0.4 inch

TABLE XIII.   OUTPUT UNITS.

VARIABLE	SI UNITS	ENGLISH UNITS
Velocity	m/s	ft/s
Temperature	$°K$	$°R$
Pressure	N/m^2	lbf/ft^2
Area	m^2	ft^2
Stress	N/cm^2	lbf/in^2
Density	Kg/cm^3	lbm/in^3
Weight	Kg	lbm
Length	cm	in
Enthalpy	Joule/Kg	Btu/lbm
Power	KWatt	hp
Weight flow	Kg/s	lbm/s
Weight flow/unit area	Kg/m^2s	lbm/ft^2s
Radius	cm	in

of units in use are noted in the units section of the aero-mechanical output. The level of output is controlled by the $W namelist integer variable "IOUTCD" and has three output options. Examples of these output formats are shown in Section 4.3, Sample Cases for two different engines.

A flow path printer plot is also available when $W namelist logical variable "IPLT" is true. This plot is automatically scaled to fit on one page of output. Examples of this option are also contained in Section 4.3, Sample Cases.

4.3 Sample Cases

Two sample cases are included herein to illustrate the execution and output of WATE-S. The first is a single-spool turboprop and the second a low bypass-ratio mixed-flow turbofan.

4.3.1 Turboprop Engine

Figure 21 illustrates the configuration selected for the sample turboprop test case. The engine has a single spool consisting of a two-stage centrifugal compressor and three-stage axial turbine. A reverse-flow burner and gearbox are also included.

Figure 22 illustrates the WATE-S input necessary to estimate the weight and dimensions of this engine. The first title card is followed by the configuration input contained in the $C namelist. This engine has 11 components and 11 thermodynamic flow stations, thus "NCOMP" and "NOSTAT" are set to 11. The component types are defined by the "JTYPE" array and the component connectivity is specified by the "JCONF" array.

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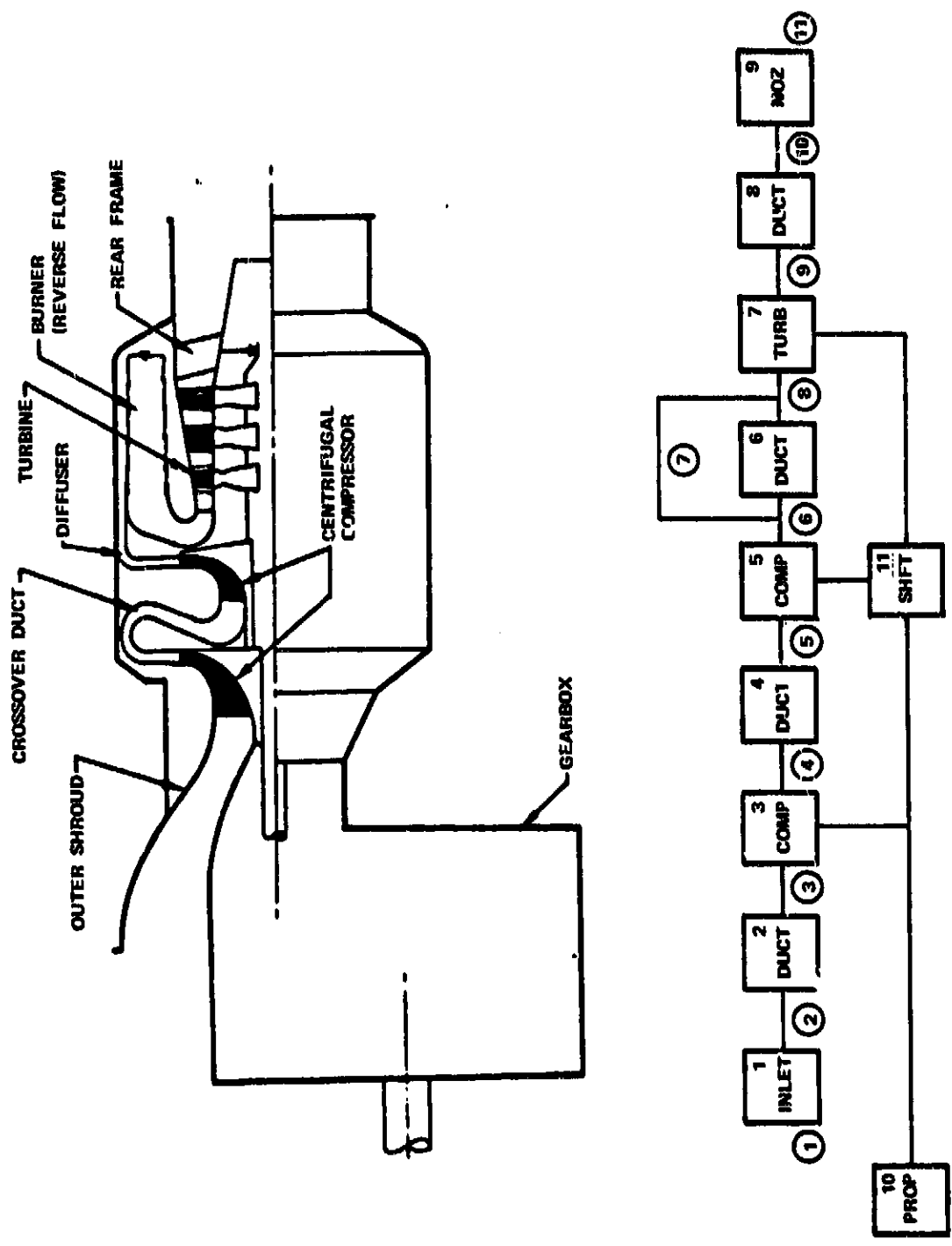
Figure 21. WATE-S Turboprop Sample Case Configuration.

```
4.3.1 TURBOPROP ENGINE SAMPLE CASE
$C
NCOMP=11,NOSTAT=11,JTYPE=1,2,4,2,4,2,5,2,9,10,11,10*0,
JCONF(1,1)=1,2,3,4,5,6,8,9,10,11,3,10*0,
JCONF(1,2)=6*0,7,3*0,5,10*0,
JCONF(1,3)=2,3,4,5,6,8,9,10,11,0,7,10*0,
JCONF(1,4)=4*0,7,16*0,
$END
4.3.1 TURBOPROP ENGINE SAMPLE CASE
$T
WTF=5*7.6502,7.26,.3902,7.4152,3*7.7213,
TOPRES=3*14.696,59.452,59.155,2*155.8077,148.7029,3*14.696,
TOTEMP=3*518.688,2*826.8,2*1135.259,2463.7,1557.319,2*1541.506,
FAR=7*0.,.0214,3*.0205,
PERPF(3)=558.1,4*0.,1000.,
$END
$W
ILENG=1,2,3,4,5,7,8,9,10*0,
IWMEC(1,2)=20,2,5*0,
IWMEC(1,3)=6,2,1,3*0,1,
IWMEC(1,4)=20,4,5*0,
IWMEC(1,5)=7,2,4*0,1,
IWMEC(1,6)=10,1,5*0,
IWMEC(1,7)=8,5,5,0,3,0,0,
IWMEC(1,8)=20,2,5*0,
IWMEC(1,9)=16,1,5*0,
IWMEC(1,10)=21,6*0,
IWMEC(1,11)=13,1,5*0,
DESVAL(1,3)=.49,5.,.356,17.,2*0.,.303,2*0.,1.,0.,.258,1.016,
DESVAL(1,5)=.30,5.,.561,15.,2*0.,.208,2*0.,1.,0.,.318,.969,
DESVAL(1,6)=50.,.012,15.,
DESVAL(1,7)=.196,1.523,1.0,1.2,2.2,.25,125000.,3.,1.,
DESVAL(1,10)=.5,4.,130.,600.,18.,
$END
```

Figure 22. WATE-S Turboprop Sample Case Input.

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Following the second title card, the thermodynamic input is specified in the $T namelist. The mass flow rate, total pressure and temperature, and fuel/air ratio are defined for each flow station. Note that the flow stations represent upstream component conditions. The fuel flow and brake shaft horsepower are entered in the "PERPF" array but this data is for informative purposes only and is not used by the WATE-S code.

The aeromechanical input is next, contained in the $W namelist. Default values are used for all but the "ILENG", "IWMEC", and "DESVAL" arrays. Basically, the default values set both the input and output units to English, turn on the weight estimation code and printer plot option, and provide a complete debug printout. The length contributing vector "ILENG" does not contain DUCT 6, PROP 10, and SHFT 11 since these components do not contribute to the total engine length.

The "IWMEC" values follow the "ILENG" array. The inlet, component 1, is not entered since inlet calculations are not performed in WATE-S. Components 3 and 5 are specified as one-stage centrifugal compressors with a front frame associated with compressor 3. Component 4 is a crossover duct, IWMEC(2,4)=4 and component 6 is a burner. The HP turbine, component 7, derives its rpm from compressor 5, IWMEC(3,7) = 5; and is a three-stage axial turbine, IWMEC(5,7) = 3 and IWMEC(6,7) = 0. The propeller type is a Hamilton Standard double acting, advanced technology aluminum propeller, IWMEC(2,10) = 0.

The "DESVAL" values follow the "IWMEC" inputs. "DEFAUL" values are used for all but the compressors, burner, turbine, and propeller. Compressor 3 has an inlet Mach number of 0.49, inlet hub/tip radius ratio of 0.356, and exit Mach number of 0.303. The number of blades is 17 and no splitters are used. DESVAL(4,3) = 17. The design point pressure-ratio tip-speed correlation is

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being modified 1.6 percent to match a known compressor rpm. DESVAL(13,3) = 1.016. Burner 6 has an airflow velocity of 50. ft/s, residency time of 0.012 seconds, and a mean diameter of 15.0 inch.

Turbine 7 has an inlet Mach number of 0.196, a mean work coefficient of 1.523, and an exit Mach number of 0.25. The tip solidity is 1.0 and the aspect ratios of the first and last stages are 1.2 and 2.2, respectively. A constant hub radius design is specified, DESVAL(8,7) = 3. The disk material is a high strength superalloy with a reference stress of 125,000 psi.

The design cruise Mach number of propeller 10 is 0.5 and the propeller has 4 blades. The activity factor is 130. and the tip speed is 600. ft/s. The propeller loading is 18. hp/ft^2, DESVAL(5,10) = 18.

Figure 23 illustrates the complete debug output for the turboprop sample case. This includes the configuration, thermodynamic, aeromechanical, and printer plot sections. Figures 24 and 25 illustrate the long and short form outputs of the aeromechanical calculations of WATE-S.

```
$C
NCOMP=11,NOSTAT=11,JTYPE=1,2,4,2,4,2,5,2,9,10,11,10*0,
JCONF(1,1)=1,2,3,4,5,6,8,9,10,11,3,10*0,
JCONF(1,2)=6*0,7,3*0,5,10*0,
JCONF(1,3)=2,3,4,5,6,8,9,10,11,0,7,10*0,
JCONF(1,4)=4*0,7,16*0,
$END
```

4.3.1 TURBOPROP ENGINE SAMPLE CASE

CONFIGURATION DATA   11 STATIONS   11 COMPONENTS

COMPONENT NUMBER	NKIND	COMPONENT TYPE	UPSTREAM STATIONS		DOWNSTREAM STATIONS	
1	1	INLET	1	0	2	0
2	2	DUCT B	2	0	3	0
3	4	COMPRESR	3	0	4	0
4	2	DUCT B	4	0	5	0
5	4	COMPRESR	5	0	6	7
6	2	DUCT B	6	0	8	0
7	5	TURBINE	8	7	9	0
9	2	DUCT B	9	0	10	0
9	9	NOZZLE	10	0	11	0
10	10	PROP	11	0	0	0
11	11	SHAFT	3	5	7	0

```
              1
         INLT    1
              2
         DUCT    2
              3
         COMP    3
              4
         DUCT    4
              5
         COMP    5          COMP    5
              6                     7
         DUCT    6          TURB    7
              8
         TURB    7
              9
         DUCT    8
              10
         NOZZ    9
              11
```

SHAFT (11) IS CONNECTED TO COMP(3) AND COMP(5) AND TURB(7) AND

Figure 23.   WATE-S Turboprop Sample Case Debug Output.

C-2

ᴬᵀ
WT=447.6502,7.25,3302.7,4152,3*7.7213,
TDPRES=3*14.696,59.452,59.155,2*155.5077,148.7029,3*14.696,
TDTEMP=3*518.693,2*826.8,2*1135.259,2463.7,1557.319,2*1541.506,
FA2=740.,.0214,3*.0235,
PE2PF(3)=558.1.440.,1000.,
SEND

CASE IDENTIFICATION   4.3.1 TURBOPROP ENGINE SAMPLE CASE

COMPONENT NO. TYPE	DATINP1	DATINP2	DATINP3	DATINP4	DATINP5	DATINP6	DATINP7	DATINP8	DATINP9
1 INLET	0.	0.	0.	0.	0.	0.	0.	0.	0.
2 DUCT 8	0.	0.	0.	0.	0.	0.	0.	0.	0.
3 COMPRESSR	0.	0.	0.	0.	0.	0.	0.	0.	0.
4 DUCT A	0.	.51005E-01	0.	0.	0.	0.	0.	0.	0.
5 COMPRESS	0.	0.	0.	0.	0.	0.	0.	0.	0.
6 DUCT B	0.	0.	0.	0.	0.	0.	0.	0.	0.
7 TURBINE	0.	0.	0.	0.	0.	0.	0.	0.	0.
8 DUCT B	0.	0.	0.	0.	0.	0.	0.	0.	0.
9 NOZZLE	0.	0.	0.	0.	0.	0.	0.	0.	0.
10 PROP	0.	0.	0.		0.			0.	0.
11 SHAFT	0.	0.							0.

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

CASE IDENTIFICATION   4.3.1 TURBOPROP ENGINE SAMPLE CASE

STATION PROPERTY OUTPUT DATA

FLOW STATION	WEIGHT FLOW	TOTAL PRESSURE	TOTAL TEMPERATURE	FUEL/AIR RATIO	REFERRED FLOW	MACH NUMBER	STATIC PRESSURE	INTERFACE FLOW	CORRECTED ERROR
1	.75502E+01	.14696E+02	.51869E+03	0.	.76502E+01	-1	-1	-1	-1
2	.76502E+01	.14696E+02	.51869E+03	0.	.76502E+01	-1	-1	-1	-1
3	.75502E+01	.14696E+02	.51869E+03	0.	.76502E+01	-1	-1	-1	-1
4	.75502E+01	.53452E+02	.82680E+03	0.	.23876E+01	-1	-1	-1	-1
5	.75502E+01	.59155E+02	.92680E+03	0.	.23995E+01	-1	-1	-1	-1
6	.72400E+01	.15581E+03	.11353E+04	0.	.10131E+01	-1	-1	-1	-1
7	.39020E+00	.15581E+03	.11353E+04	0.	.54449E-01	-1	-1	-1	-1
8	.74152E+01	.14870E+03	.24637E+04	.21400E-01	.15971E+01	-1	-1	-1	-1
9	.77213E+01	.14696E+02	.15573E+04	.20500E-01	.13379E+02	-1	-1	-1	-1
10	.77213E+01	.14696E+02	.15415E+04	.20500E-01	.13311E+02	-1	-1	-1	-1
11	.77213E+01	.14696E+02	.15415E+04	.20500E-01	.13311E+02	-1	-1	-1	-1

COMPONENT OUTPUT DATA

COMPONENT NO. TYPE	DATOUT1	DATOUT2	DATOUT3	DATOUT4	DATOUT5	DATOUT6	DATOUT7	DATOUT8	DATOUT9
1 INLET	0.	0.	0.	0.	0.	0.	.10000E+01	0.	0.
2 DUCT B	.1000CE+01	0.	0.	0.	0.	0.	0.	.82099E+00	.40455E+01
3 COMPRESS	-.83527E+03	0.	0.	0.	0.	0.	0.	0.	.26330E+01
4 DUCT A	-.99500E+00	0.	0.	0.	0.	0.	0.	.82370E+00	0.
5 COMPRESS	-.32858E+03	0.	0.	0.	0.	0.	0.	0.	.26330E+01
6 DUCT B	.95440E+00	0.	0.	0.	0.	0.	0.	.86630E+00	.10119E+02
7 TURBINE	-.27328E+04	0.	0.	0.	0.	0.	0.	0.	0.
8 DUCT B	.1000CE+01	0.	0.	0.	0.	0.	0.	0.	0.
9 NOZZLE	0.	0.	0.	0.	0.	0.	0.	0.	0.
10 PROP	-.10989E+04	0.	0.	0.	0.	0.	0.	0.	0.
11 SHAFT	0.	0.	0.	0.	0.	0.	0.	0.	0.

MACH= 0.00   ALTITUDE=   0.   RECOVERY= 1.000

AIRFLOW (LB/SEC)	7.65	GROSS THRUST	0.00
NET THRUST	0.00	TSFC	0.0000
TOTAL INLET DRAG	0.00	TOTAL BRAKE SHAFT HP	1000.00
INSTALLED THRUST	0.00	INSTALLED TSFC	0.0000

FUEL FLOW (LB/HR)	558.10
NET THRUST/AIRFLOW	0.0000
BOATTAIL DRAG	0.00
SPILLAGE + LIP DRAG	0.00

FOR COMPRESSOR 5 THE BLEED FRACTION IS   .0510

Figure 23.   WATE-S Turboprop Sample Case Debug Output (Contd).

```
$W
ILENG=1,2,3,4,5,7,8,9,10*0,
IWMEC(1,2)=20,2,5*0,
IWMEC(1,3)=6,2,1,3*0,1,
IWMEC(1,4)=20,4,5*0,
IWMEC(1,5)=7,2,4*0,1,
IWMEC(1,6)=10,1,5*0,
IWMEC(1,7)=8,5,5,0,3,0,0,
IWMEC(1,8)=20,2,5*0,
IWMEC(1,9)=16,1,5*0,
IWMEC(1,10)=21,6*0,
IWMEC(1,11)=13,1,5*0,
DESVAL(1,3)=.49,5.,.356,17.,2*0.,.303,2*0.,1.,0.,.258,1.016,
DESVAL(1,5)=.30,5.,.561,15.,2*0.,.209,2*0.,1.,0.,.318,.969,
DESVAL(1,6)=50.,.012,15.,
DESVAL(1,7)=.196,1.523,1.0,1.2,2.2,.25,125000.,3.,1.,
DESVAL(1,10)=.5,4.,130.,600.,18.,
$END
```

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

COMPONENT DESIGN INPUT DATA (*=INPUT)

ITEMS = 1, 2, 3, 4, 5, 7, 8, 9

COMPONENT NO.	TYPE	IVMEC1	IVMEC2	IVMEC3	IVMEC4	IVMEC5	IVMEC6	IVMEC7
1	INLET	INLT	0	0*	0*	0	0*	0
2	DUCT R	DUCT*	2*	1*	0*	0*	0*	1*
3	COMPRESR	LPC	2*	0*	0*	0*	0*	1*
4	DUCT R	DUCT*	4*	0*	0*	0*	0*	1*
5	COMPRESR	HPC	2*	0*	0*	0*	0*	0*
6	DUCT R	DUR*	1*	5*	0*	3*	0*	0*
7	TURBINE	HPT	5*	0*	0*	0*	0*	0*
8	DUCT R	DUCT*	2*	0*	0*	0*	0*	0*
9	NOZZLE	NOZ	1*	0*	0*	0*	0*	0*
10	PROP	PROP*	0*	0*	0*	0*	0*	0*
11	SHAFT	SHAF*	1*	0*	0*	0*	0*	0*

COMPONENT NO.	TYPE	DESVAL 1	DESVAL 2	DESVAL 3	DESVAL 4	DESVAL 5	DESVAL 6	DESVAL 7	DESVAL 8	DESVAL 9
1	INLET	0.	0.	0.	-.1000E+01	0.	0.	0.	0.	0.
2	DUCT B	.4000E+00*	.1000E+01	0.	.1700E+02*	0.	0.	.3030E+00*	0.	0.
3	COMPRESR	.4900E+00*	.5000E-01*	.3560E+00*	-.1000E+01*	*	*	0.	0.	0.
4	DUCT B	.4000E+00*	.1000E+01	0.	.1500E+02*	*	*	*	*	*
5	COMPRESR	.3000E+00*	.5000E+01*	.5610E+00*	.1500E+02*	*	*	.2080E+00*	*	*
6	DUCT B	.5000E+02*	.1200E-01*	.1500E+02*	0.	0.	0.	0.	0.	0.
7	TURBINE	.1960E+00*	.1523E+01*	.1000E+01*	.1200E+01*	.2200E+01*	.2500E+00*	.1250E+06*	.3000E+01*	.1000E+01*
8	DUCT B	.4000E+00	.1000E+01	0.	-.1000E+01	0.	0.	0.	0.	0.
9	NOZZLE	.1000E+01	0.	.1300E+03*	.6000E+03*	.1800E+02*	*	*	*	*
10	PROP	.5000E+00*	.6000E+01*	.8000E+00*	0.	0.	0.	0.	0.	0.
11	SHAFT	.5000E+05	.2860E+00	*	*	*	*	*	*	*

COMPONENT NO.	TYPE	DESVAL10	DESVAL11	DESVAL12	DESVAL13	DESVAL14	DESVAL15	DESVAL16	DESVAL17
1	INLET	0.	0.	0.	0.	0.	0.	0.	0.
2	DUCT B	.1000E+01*	0.	.2580E+00*	.1016E+01*	0.	0.	-1*	-1*
3	COMPRESR	0.	*	.2580E+00*	.1016E+01*	*	*	-1*	-1*
4	DUCT B	0.	0.	0.	0.	0.	0.	*	*
5	COMPRESR	.1000E+01*	*	.3190E+00*	.9690E+00*	*	*	*	*
6	DUCT B	0.	*	*	0.	0.	0.	-1*	-1*
7	TURBINE	0.	0.	0.	0.	0.	0.	*	*
8	DUCT B	0.	0.	0.	0.	0.	0.	0.	0.
9	NOZZLE	*	*	*	*	*	.1000E+01	*	*
10	PROP	0.	0.	0.	0.	0.	0.	0.	0.
11	SHAFT	0.	0.	0.	0.	0.	0.	0.	0.

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

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CASE IDENTIFICATION   4.3.1 TURBOPROP ENGINE SAMPLE CASE

```
***************
*             *
*   DUCT  2   *
*             *
************"*2

MAX CONDITIONS OCCUR AT
****************************
       ALT        MN
PTOT       0.     0.000
TTOT       0.     0.000
****************************
R4=    0.00 RT=    3.36 LENG=    3.36
AREA=   .246 RHO= .168
         CAS WT    INC WT    WTOT
          .60       0.00      .60




************
*          *
*  CENC  3 *
*          *
************2

MAX CONDITIONS OCCUR AT
*************************************
       ALT        MN       VALUE
PTOT       0.     0.000    14.7 LB/SQIN
TTOT       0.     0.000    519.7 DEG R
CWIN       0.     0.000     7.7 LB/SEC
*************************************
DUCT
  M NO   VEL   T TOT   P TOT   P STAT   AREA   GAM
  .490   534.   519.   2116.    1796.   .210  1.401

BORE RADIUS LIMIT

STAGE   1
  WDISK   WBLD   WSHRD   WDIFF      CL    RHO
   5.1     .6    1.7      4.6     3.06   .134
   SPR     RPM    RTIP   NB    UTIPC    OSTR    BSTR   WEIGHT  STAGE I
  4.045  41728.   4.59   17   1322.7  22263.  48175.    5.7    29.5

FRAME WT =    5.04


  N STG  WEIGHT  LENGTH  CENGRA  INERTIA
    1     17.12   4.72    2.68     29.5

DUCT
  M NO   VEL   T TOT   P TOT   P STAT   AREA   GAM
  .303   422.   827.    8561.    8036.   .098  1.391

   PR    AD EF    PO      TO      HP
  4.045  .8210   8561.    827.    805.
   HI     HO      WI      CWI
  123.96 198.35   7.65    7.65


**************** TOTAL COMP WEIGHT IS    17.1
```

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

```
************
*          *
*  DUCT  4  *
*          *
***********2
```

```
MAX CONDITIONS OCCUR AT
*********************
        ALT        MN
PTOT      0.      0.000
TTOT      0.      0.000
************************
***CROSSOVER DUCT***
LENGTH= 2.935 WEIGHT=    6.1
```

```
*************
*           *
*  CENC  5  *
*           *
***********2
```

```
MAX CONDITIONS OCCUR AT
*********************************
        ALT        MN        VALUE
PTOT      0.      0.000      59.2 LB/SQIN
TTOT      0.      0.000      826.8 DEG R
CWIN      0.      0.000       2.4 LB/SEC
**********************************
DUCT
  M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
  .300   418.   827.   8518.    8006.   .099   1.391
```

```
***** RECALCULATE UPSTREAM DUCT CONDITIONS, SPECIFIED RPM
DUCT
  M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
  .307   427.   827.   8518.    7982.   .097   1.391
```

BORE RADIUS LIMIT

```
STAGE   1
  WDISK    WBLD    WSHRD   WDIFF      CL      RHO
   8.0      .5      1.2     4.3      4.26    .134
   SOR      RPM     RTIP    NB      UTIPC   DSTR     BSTR    WEIGHT   STAGE I
  2.634   41725    4.50     15     1106.5  21462.   30691.    8.4      26.7
```

```
  N STG   WEIGHT   LENGTH   CENGRA   INERTIA
    1     14.01     4.34     4.34     26.7
```

```
DUCT
  M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
  .203   339.  1135.  22436.   21793.   .062   1.372
```

```
   PR     AD EF    PO       TO      HP
  2.634   .9237   22436.   1135.    829.
   HI      HO      WI      CWI
 193.34  274.89   7.65     2.40
```

```
****************** TOTAL COMP WEIGHT IS    14.0
```

```
*************
*           *
*           *
```

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

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```
*  HPT   7  *
*            *
*************2

MAX CONDITIONS OCCUR AT
*********************************************
      ALT        MN        VALUE
PTOT      0.      0.000     148.7 LB/SQIN
TTOT      0.      0.000     2463.7 DEG R
CWOUT     0.      0.000     13.4 LB/SEC
*********************************************
DUCT
 M NO  VEL  T TOT   P TOT   P STAT   AREA   GAM
 .196  458. 2464.   21413.  20887.   .101  1.300

 UTIPMAX STRESS    DEN  WGHT/A   TR    H/T
 1323.4 32829.     .286  .202  1.00   .805

 TURBINE  7  MECHANICAL DESIGN
    H/T   N STG  M WRK C   AREA
   .805    3.0    1.523    .101
    UT    RTIP   RHUB   DEL H    RPM    MAXRPM   TORQ
  1323.4  3.63   2.93   260.5   41728.  41728.   4128.

STAGE   1
 DISK  BLADE VANE  HWD   CASE   AR
 3.7    .4    .6   1.4   1.0   1.20
 SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR    WEIGHT  LENGTH  STG I
 1.250 85.3  .196  .101  2.93   3.63   38  1323.4 32829.   7.06    1.52    19.

STAGE   2
 DISK  BLADE VANE  HWD   CASE   AR
 4.5    .8   1.2   1.5   1.2   1.70
 SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR    WEIGHT  LENGTH  STG I

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
BLADE ROOT STRESS IS  55081.7 DES LIMIT IS  50000.0
**STRESS IS TOO HIGH REDUCE SHAFT SPEED OR INCREASE EXIT MACH NUMBER**
 2.158 85.8  .214  .170  2.93   4.04   38  1472.6 55062.   9.21    1.69    26.

STAGE   3
 DISK  BLADE VANE  HWD   CASE   AR
 5.7   2.1   3.0   2.0   1.9   2.20
 SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR    WEIGHT  LENGTH  STG I

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
BLADE ROOT STRESS IS 101798.9 DES LIMIT IS  50000.0
**STRESS IS TOO HIGH REDUCE SHAFT SPEED OR INCREASE EXIT MACH NUMBER**
 2.486 85.9  .232  .314  2.93   4.79   35  1744.8101799.  15.64    2.19    49.

FRAME WT =    21.51


 N STG  LENGTH  WEIGHT   CENGRA   INERTIA
   3     6.30   53.42     4.9      95.

DUCT
 M NO  VEL  T TOT   P TOT   P STAT   AREA   GAM
 .250  469. 1557.   2116.   2030.   .666  1.333

  PR     TR    AD EF    PO      TO      TO.1
 10.117  1.503  .8663  2116.2  1556.1  1557.3
  H IN   H OUT  ANOZ   FLOW    HP
 552.59 392.24  .581   7.42   2733.
```

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

```
****************** TOTAL TURB WEIGHT IS    53.4

***************
*             *
*  DUCT  8    *              ORIGINAL PAGE IS
*             *              OF POOR QUALITY
***********2

MAX CONDITIONS OCCUR AT
************************
        ALT        MN
PTOT      0.      0.000
TTOT      0.      0.000
*************************
RH=    3.30 RT=    5.57 LENG=    2.27
AREA=    .440 RHO= .286
        CAS WT       INC WT      WTOT
        1.14          .67        1.81



*************
*           *
*  NOZ   9  *
*           *
***********2

MAX CONDITIONS OCCUR AT
***********************
        ALT        MN
PTOT      0.      0.000
TTOT      0.      0.000
***********************
WEIGHT=    3.50 LENGTH=    11.15 TR WT=   0.00


*************
*           *
*  PBUR  6  *
*           *
***********2

MAX CONDITIONS OCCUR AT
****************************************
        ALT        MN       VALUE
PTOT      0.      0.000     155.8 LB/SQIN
TTOT      0.      0.000    1135.3 DEG R
CWIN      0.      0.000       1.0 LB/SEC
****************************************
   RIN      ROUT     LENGTH     MACH     WSPEC
   5.58     9.08      7.20      .031     2.587
        CAS WT   LIN WT   NOZ WT   INC WT   FRAME   WTOT
        5.5      11.2      1.4      4.7     59.2    82.0



*************
*           *
*  PROP 10  *
*           *
***********2

MAX CONDITIONS OCCUR AT
```

Figure 23.   WATE-S Turboprop Sample Case Debug Output (Contd).

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```
*********************
      ALT        MN
PTOT      0.    0.000
TTOT      0.    J.000
*********************

   POWER       RPM      DIA     WPROP      GBWT
   1098.9     1467.     7.81    159.0      214.9

**************
*            *
*   SHAF 11  *
*            *
************2

MAX TORQUE CONDITION
**********************
 TORQUE
    944.0
**********************
SHAFT  11
   OD      OI    LENG     ON      WT
  1.13    .90   14.48    1.19    1.48

TOTAL INERTIA OF THIS SPOOL IS       151.

**************
*            *
*  ACCS 4T   *
*            *
************2

  ACCS WT=    38.53
```

CASE IDENTIFICATION   4.3.1 TURBOPROP ENGINE SAMPLE CASE

      WEIGHT INPUT DATA IN ENGL UNITS
      WEIGHT OUTPUT DATA IN ENGL UNITS

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS				DOWNSTREAM RADIUS				NSTAGE
				RI	RO	RI	RO	RI	RO	RI	RO	
2	.6	3.4	3.4	0.0	3.4	0.0	0.0	0.0	3.4	0.0	0.0	0
3	17.1	4.7	8.1	1.2	3.3	0.0	0.0	1.2	4.6	0.0	0.0	1
4	6.1	2.9	11.0	4.6	7.3	0.0	0.0	4.6	7.3	0.0	0.0	0
5	14.0	4.3	15.4	1.4	2.5	0.0	0.0	1.4	4.5	0.0	0.0	1
6	32.0	7.2	22.6	6.9	8.1	0.0	0.0	6.9	8.1	0.0	0.0	0
7	53.4	6.3	21.7	2.9	3.6	0.0	0.0	2.9	6.2	0.0	0.0	3
8	1.8	2.3	23.9	3.3	5.6	0.0	0.0	3.3	5.6	0.0	0.0	0
9	3.5	11.1	35.1	0.0	5.5	0.0	0.0	0.0	5.0	0.0	0.0	0
11	1.5	0.0	15.4	1.2	3.3	1.4	2.5	0.0	0.0	0.0	0.0	0

```
  BARE ENGINE WEIGHT =    176.9     TOTAL ENGINE LENGTH =    35.1
    ACCESSORY WEIGHT =     38.5           MAXIMUM RADIUS =     8.1
    HEAT EXCH WEIGHT =      0.0      CENTER OF GRAVITY =      8.1
   EXHAUST SYSTEM WT =      3.5
       GEARBOX WEIGHT =   214.9      PROPELLER WEIGHT =     159.0
  TOTAL ENGINE WEIGHT =    433.4
```

Figure 23.   WATE-S Turboprop Sample Case Debug Output (Contd).

Figure 23. WATE-S Turboprop Sample Case Debug Output (Contd).

CASE IDENTIFICATION   4.3.1 TURBOPROP ENGINE SAMPLE CASE

WEIGHT INPUT DATA IN ENGL UNITS
WEIGHT OUTPUT DATA IN ENGL UNITS

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS				DOWNSTREAM RADIUS				NSTA?
				RI	RO	RI	RO	RI	RO	RI	RO	
2	.6	3.4	3.4	0.0	3.4	0.0	0.0	0.0	3.4	0.0	3.0	0
3	17.1	4.7	8.1	1.2	3.3	0.0	0.0	1.2	4.6	0.0	0.0	1
4	6.1	2.9	11.0	4.6	7.3	0.0	0.0	4.6	7.3	0.0	0.0	0
5	14.0	4.3	15.4	1.4	2.5	0.0	0.0	1.4	4.3	0.0	3.0	1
6	82.0	7.2	22.6	6.9	8.1	0.0	0.0	6.9	8.1	0.0	0.0	0
7	53.4	6.3	21.7	2.9	3.6	0.0	0.0	2.9	6.2	0.0	0.0	2
8	1.8	2.3	23.9	3.3	5.6	0.0	0.0	3.3	5.6	0.0	3.0	0
9	3.5	11.1	35.1	0.0	5.6	0.0	0.0	0.0	5.0	0.0	0.0	0
11	1.5	0.0	15.4	1.2	3.3	1.4	2.5	0.0	0.0	0.0	0.0	0

```
BARE ENGINE WEIGHT  =    176.5      TOTAL ENGINE LENGTH =    35.1
ACCESSORY WEIGHT    =     38.5             MAXIMUM RADIUS =     8.1
HEAT EXCH WEIGHT    =      0.0        CENTER OF GRAVITY =     8.1
EXHAUST SYSTEM WT   =      3.5
GEARBOX WEIGHT      =    214.9        PROPELLER WEIGHT =   159.0
TOTAL ENGINE WEIGHT =    433.4
```

Figure 24.   WATE-S Turboprop Sample Case Long Output.

CASE IDENTIFICATION   4.3.1 TURBOPROP ENGINE SAMPLE CASE

WEIGHT INPUT DATA IN ENGL UNITS
WEIGHT OUTPUT DATA IN ENGL UNITS

```
BARE ENGINE WEIGHT  =    176.5      TOTAL ENGINE LENGTH =    35.1
ACCESSORY WEIGHT    =     28.5             MAXIMUM RADIUS =     8.1
HEAT EXCH WEIGHT    =      0.0        CENTER OF GRAVITY =     8.1
EXHAUST SYSTEM WT   =      3.5
GEARBOX WEIGHT      =    214.9        PROPELLER WEIGHT =   159.0
TOTAL ENGINE WEIGHT =    433.4
```

Figure 25.   WATE-S Turboprop Sample Case Short Output.

4.3.2 Turbofan Engine

Figure 26 illustrates the configuration of the sample turbofan test case. The engine has two spools. The low-pressure spool consists of a two-stage axial fan, T-stage, and two-stage axial low-presure turbine. The high-pressure spool consists of a single-stage centrifugal compressor driven by a single-stage axial high-pressure turbine. The engine has a reverse-flow burner and a mixer-compound exhaust system.

Figure 27 illustrates the input required to estimate the weight of this engine. The first title card is followed by the configuration input, namelist $C. This engine configuration is nearly identical to the default and requires few changes. Component 15 is a mixer instead of a nozzle, and shaft 16 contains the fan, T-stage, and LP turbine.

Following the second title card, the thermodynamic input is specified in the $T namelist. The mass flow rate, total pressure and temperature, and fuel/air ratio are specified for each station. The thrust and fuel flow are entered in the "PERPF" array, but these are optional inputs and are not required for execution. However, the mixer flow areas, DATOUT(1,15) and DATOUT(2,15) are required and must be input for the mixer weight and dimension calculations.

The aeromechanical inputs are next, and are contained in the $W namelist. Default values have been used for most of the "IWMEC" array since the sample turbofan configuration is so close to the default configuration. However, IWMEC(7,2) and IWMEC(7,5) are set equal to 2 for the two-stage fan, and IWMEC(7,7) is set equal to 1 for the single-stage t-stage LP compressor. A two-stage LP turbine is input, IWMEC(5,13) = 2 and component 15 is specified as a forced mixer.
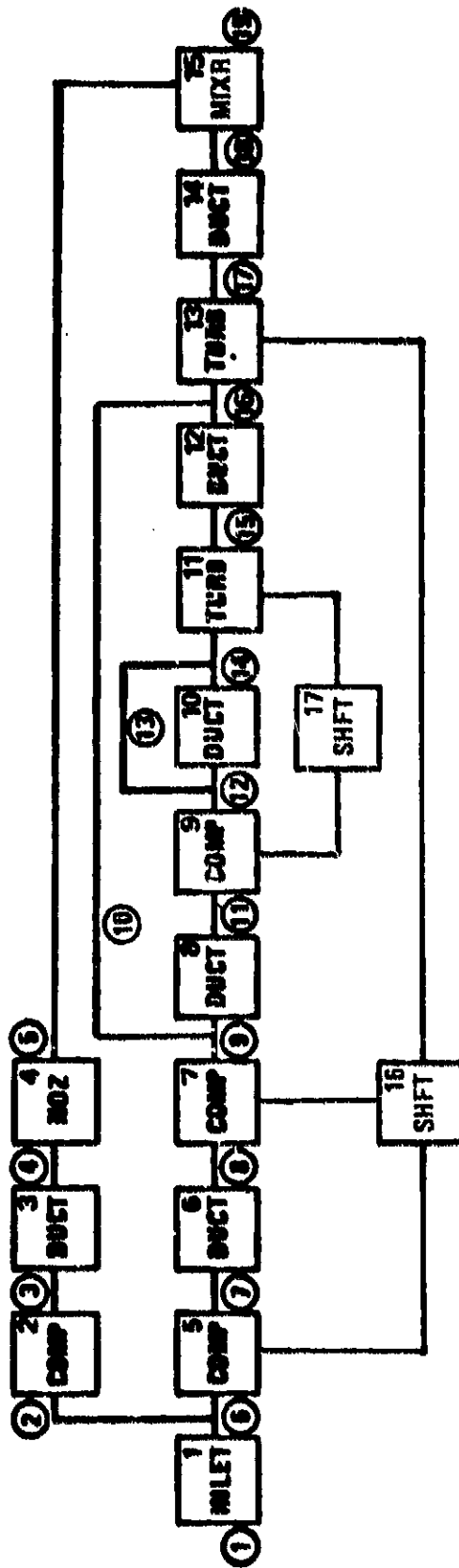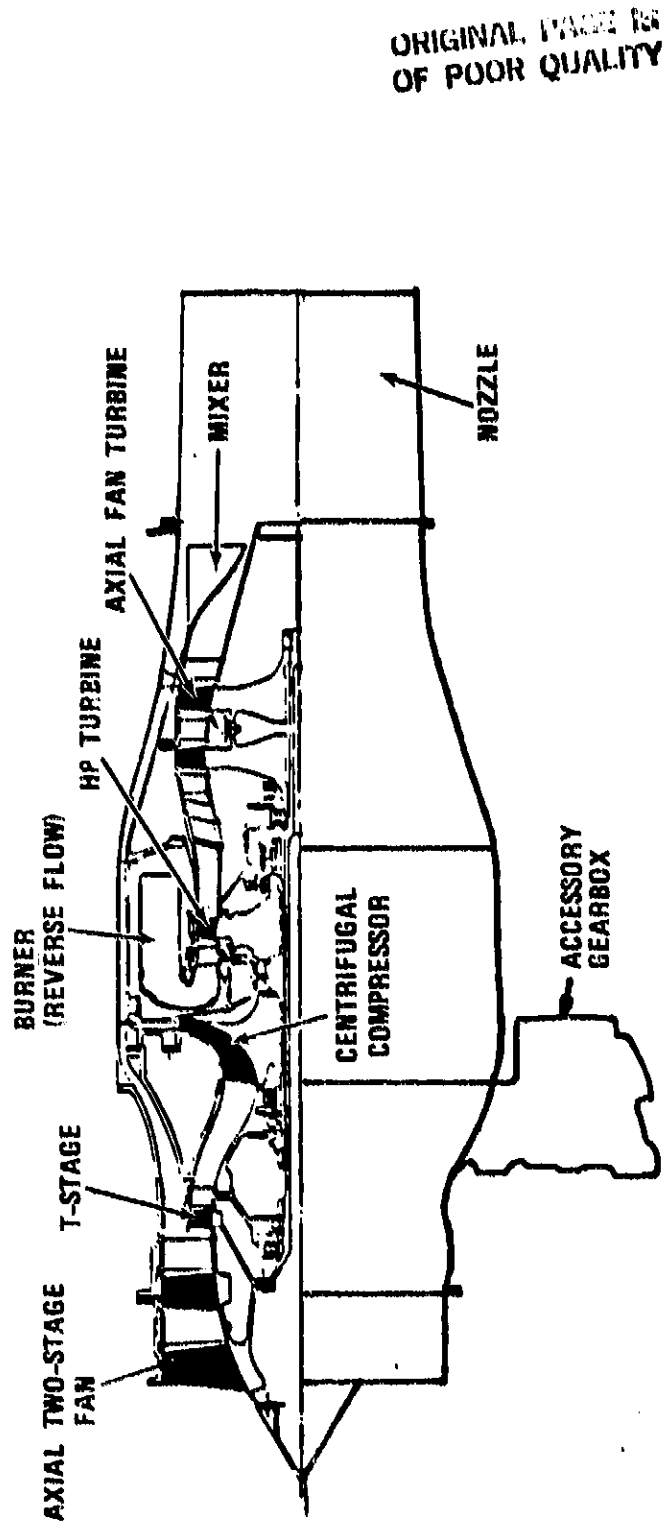
Figure 26. NNEP-3 Turbofan Sample Case Configuration.

```
4.13.2 TURBOFAN ENGINE SAMPLE CASE
$C
JTYPE(15)=8,
JCONF(17,1)=9,JCONF(15,2)=5,7,11,JCONF(16,3)=13,0,
$END
4.3.2 TURBOFAN ENGINE SAMPLE CASE
$T
WTF=17.886,8.879,3*8.812,3*9.007,8.969,.038,8.969,8.759,.210,8.931,
2*9.010,3*9.154,
TOPRES=14.696,18.145,43.537,42.178,14.696,18.145,2*43.531,2*58.780,
59.193,2*310.694,296.269,104.530,102.125,40.837,40.426,37.347,
TOTENP=518.7,562.5,791.9,2*756.6,562.5,2*739.8,3*817.6,2*1395.6,2579.7,
2077.1,2071.5,1694.4,2*1687.7,
FAR=13*0.,.0192,.0192,.0191,.0191,.0188,.0188,
PERPF(2)=651.2,618.3,
OATINP(5,1)=.65,
DATOUT(1,15)=31.88,16.55,
$END
$W
IWMEC(1,2)=2,1,2,0,5,0,2,
IWMEC(1,5)=3,1,2,0,2,0,2,
IWMEC(1,7)=6,1,4*0,1,
IWMEC(1,13)=9,5,5,12,2,0,0,
IWMEC(1,15)=15,6*0,
DESVAL(1,2)=.56,1.7,.4,1.5,2.,1.5,.43,0.,0.,1.,0.,3.,.965,
DESVAL(1,3)=.4,30.,0.,-1.,
DESVAL(1,5)=.56,1.7,.4,1.5,2.,1.5,.43,0.,0.,1.,0.,3.,.965,
DESVAL(1,7)=.43,1.7,.8,1.5,1.5,1.6,.40,0.,0.,1.,0.,2.,.861,
DESVAL(1,8)=.4,4.,0.,-1.,
DESVAL(1,9)=.42,4.1,.59,20.,2*0.,.19,2*0.,1.,0.,.37,.97,
DESVAL(1,10)=55.,.008,0.,-9.,
DESVAL(1,11)=.16,1.24,1.6,2*1.2,.31,125000.,2.,1.,
DESVAL(1,12)=.4,5.,0.,-1.,
DESVAL(1,13)=.23,1.2,1.6,1.5,2.0,.31,125000.,1.,1.,
DESVAL(1,15)=.8,8.,13*0.,
$END
```

Figure 27. WATE-S Turbofan Sample Case Input.

The "DESVAL" values follow the "IWMEC" inputs. In this case, most "DESVAL" values are specified, the "DEFAUL" values used for the compressor duct (component 4), intercompressors duct (component 6), turbine exit duct (component 14), and shafts (components 16 and 17). The fan, (components 2 and 5) has an inlet Mach number of 0.56, inlet hub/tip radius ratio of 0.4, and exit Mach number of 0.43. The tip solidity is 1.5 and the first and last stage aspect ratios are 2.0 and 1.5, respectively. The fan utilizes a constant tip radius design mode, DESVAL(12,2) =3.; and a 3.5 percent scalar is applied to the design-point pressure-ratio corrected tip-speed correlation, DESVAL(13,2) = 0.965. The intercompressor duct, component 8, has an inlet Mach number of 0.4 and a length-to-height ratio of 4.0. The inlet mean radius is determined from the upstream component, LP compressor 7. The burner through-flow velocity is 55. ft/s and a burner residency time of 0.008 seconds is specified. The inner diameter of the burner is specified as the outer diameter of component 9, the HP turbine (DESVAL(4,10) = -9.). This is how reverse-flow burners are handled when the mean diameter is not known.

The HP turbine, component 11, has an inlet Mach number of 0.16, turbine mean work coefficient of 1.24, and an exit Mach number of 0.31. The tip solidity is 1.6 and the aspect ratio is 1.2. A disk reference stress of 125,000 psi is specified, DESVAL(7,11) = 125,000. The forced mixer has a length to hydraulic diameter ratio of 0.8 and has 8 lobes.

Figure 28 illustrates the complete debug output for the turbofan sample case. This includes the configuration, thermodynamic, aeromechanical, and printer plot sections.

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```
$C
JTYPE(15)=8,
JCCNF(17,1)=9,JCCNF(15,2)=5,7,11,JCUNF(14,3)=13,0,
$END
```

4.3.2 TURBOFAN ENGINE SAMPLE CASE

CONFIGURATION DATA   19 STATIONS   17 COMPONENTS

COMPONENT NUMBER	NKINC	COMPONENT TYPE	UPSTREAM STATIONS		DOWNSTREAM STATIONS	
1	1	INLET	1	0	6	2
2	4	COMPRESR	2	0	3	0
3	2	DUCT B	3	0	4	0
4	9	NOZZLE	4	0	5	0
5	4	COMPRESR	6	0	7	0
6	2	DUCT B	7	0	8	0
7	4	COMPRESR	8	0	9	10
8	2	DUCT B	9	0	11	0
9	4	COMPRESR	11	0	12	13
10	2	DUCT B	12	0	14	0
11	5	TURBINE	14	13	15	0
12	2	DUCT B	15	0	16	0
13	5	TURBINE	16	10	17	0
14	2	DUCT B	17	0	18	0
15	8	MIXER	18	5	19	0
16	11	SHAFT	5	7	13	0
17	11	SHAFT	9	11	0	0

```
                          1
                      <INLT  1>        <INLT   1>
                          6                2
                      <COMP  5>        <COMP   2>
                          7                3
                      <DUCT  6>        <DUCT   3>
                          8                4
    <COMP   7>        <COMP  7>        <NOZZ   4>
        10                9                5
    <TURB  13>        <DUCT  8>
                         11
                      <COMP  9>
                         12
                      <DUCT 10>                        <COMP    9>
                         14                               13
                      <TURB 11>                        <TURB   11>
                         15
                      <DUCT 12>
                         16
                      <TURB 13>
                         17
                      <DUCT 14>
                         18
                      <MIXR 15>
                         19
```

SHAFT (16) IS CONNECTED TO COMP(5) AND COMP(7) AND TURB(13) AND
SHAFT (17) IS CONNECTED TO COMP(9) AND TURB(11) AND

Figure 28.   WATE-S Turbofan Sample Case Output.

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Figure 28. WATE-S Turbofan Sample Case Output (Contd).

CASE IDENTIFICATION   4.3.2 TURBOFAN ENGINE SAMPLE CASE

STATION PROPERTY OUTPUT DATA

COMPONENT OUTPUT DATA

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

```
$b
IhMEC(1,2)=2,1,2,C,5,C,2,
IbMEC(1,5)=3,1,2,C,2,C,2,
IhMEC(1,7)=6,1,4*C,1,
IhMEC(1,13)=9,5,5,12,2,0,0,
IhMEC(1,15)=15,6*C,
CESVAL(1,2)=.56,1.7,.4,1.5,2,.1.5,.43,0.,0.,1.,C.,3.,.965,
CESVAL(1,3)=.4,30.,0.,-1.,
CESVAL(1,5)=.56,1.7,.4,1.5,?.,1.5,.43,C.,0.,1.,C.,3.,.965,
CESVAL(1,7)=.43,1.7,.6,1.5,1.5,1.5,.40,0.,0.,1.,0.,2.,.661,
CESVAL(1,8)=.4,4.,0.,-1.,
CESVAL(1,9)=.42,4.1,.59,20.,2*0.,.19,2*0.,1.,0.,.37,.97,
CESVAL(1,1C)=55.,.008,0.,-9.,
CESVAL(1,11)=.16,1.24,1.6,2*1.2,.31,125000.,2.,1.,
CESVAL(1,12)=.4,5.,0.,-1.,
CESVAL(1,13)=.23,1.2,1.6,1.5,2.C,.31,125000.,1.,1.,
CESVAL(1,15)=.6,8.,13*0.,
$END
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

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Figure 28. WATE-S Turbofan Sample Case Output (Contd).

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CASE IDENTIFICATION   4.3.2 TURBOFAN ENGINE SAMPLE CASE

```
**************
*            *
*  FI    5   *
*            *
**************2
DLCT
 P NO  VEL  T TOT   P TOT   P STAT  AREA    GAM
 .560  631.  563.   2613.    2112.  .379  1.400

 LTIPMAX STRESS     DEN   WGHT/A   TR     H/T
  1382.1 33788.     .168    .580  1.60    .400

 CCMPRESSOR  5 MECHANICAL DESIGN

 LCADING   N STG   DIAM   U TIP C   RPM    C RPM   MAX RPM
  1.161     2.0    9.09   1327.2   34841.  33456.  34841.

FRAME WT =    14.54


STAGE    1
  WD    WB    WS    WN    WC    CL   RHCB   RHOD    AR
  1.8   1.6   1.6   C.0   2.6   3.2   .168   .168   2.00
  SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR   WEIGHT  TIN  TMAX  STG I

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
STAGE WORK COEFFICIENT IS 1.18 DES LIMIT IS  .90
**STAGE WORK COEFFICIENT TO HIGH, ADD STAGES OR INCREASE H/T INPLT**
  1.592  22.1  .560   .379  1.82   4.55  31  1382.1 33788.   7.6  963.  563.   12.

STAGE    2
  WD    WB    WS    WN    WC    CL   RHUB   RHOD    AR
  3.1   .9    .9    .9    2.2   2.7   .168   .168   1.50
  SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR   WEIGHT  TIN  TMAX  STG I
  1.497  22.1  .495   .279  2.80   4.55  36  1382.1 25445.   7.9  654.  651.   20.

 N STG  WEIGHT  LENGTH  CENGRA  INERTIA
   2     30.46   7.35    3.06     31.9

DUCT
 P NO  VEL  T TOT   P TOT   P STAT  AREA    GAM
 .430  564.  746.   6269.    5523.  .219  1.394

   PR    AD EF    PC      TO      HP
  2.355  .8698   6269.   746.   1117.
   HI     HD      WI     CWI
 134.47 178.60  17.89   15.09


****************** TCTAL COMP WEIGHT IS   90.9

************
*          *
*  DUCT  6 *
*          *
************2

MAX CONDITIONS OCCUR AT
***********************
      ALT      PN
PTCT    0.    .650
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

```
TTCT        0.      .650
***************************
RP=    3.20 RT=    3.55 LENG=     .75
AREA=    .117 RHC= .160
        CAS WT      INC WT      WTOT
         .16         .13         .28



*************
*           *
*  LPC   7  *
*           *
************2

MAX CONDITIONS OCCUR AT
*********************************************
        ALT         MN        VALUE
PTOT        0.      .650      43.5 LB/SQIN
TTCT        0.      .650      739.8 DEG R
ChIN        0.      .650      3.6 LB/SEC
*********************************************
DUCT
 M NO  VEL  T TOT  P TOT  P STAT  AREA   GAM
 .430  562.  740.  6268.  5523.  .110  1.395


***** RECALCULATE UPSTREAM DUCT CONDITIONS, SPECIFIED RPM
DUCT
 M NO  VEL  T TOT  P TOT  P STAT  AREA   GAM
 .435  566.  740.  6268.  5508.  .110  1.395

 UTIPMAX STRESS    DEN  WGHT/A   TR    H/T
 1135.4 12081.    .168   .134  1.20  .800

 CCMPRESSOR  7 MECHANICAL DESIGN

 LOADING  N STG  CIAM  U TIP C  RPM   C RPM   MAX RPM
  .907    1.0    7.47   950.7  34841. 29173.  34841.

STAGE    1
 WD   WB   WS   WN   WC   CL   RHOB  RHOD   AR
 1.4  .3   .3  1.1   .8  1.2  .168  .168  1.50
SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR   WEIGHT TIN  TRAX  STG I

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
STAGE WORK COEFFICIENT IS  .91 DES LIMIT IS  .90
**STAGE WORK COEFFICIENT TO HIGH, ADD STAGES OR INCREASE H/T INPUT**
1.350  18.9  .435   .110  2.99   3.73   70 1135.4 12866.  3.8  740.   740.    9.

 N STG  WEIGHT  LENGTH  CENGRA  INERTIA
  1      3.79    1.17    1.17     8.8

DUCT
 M NO  VEL  T TOT  P TOT  P STAT  ARFA   GAM
 .400  550.  816.  8464.  7566.  .091  1.391

 PR    AD EF    PC     TO     HP
1.350  .6392   8464.   818.   241.
 HI     HO      WI     CWI
177.20 196.10  9.01   3.63


**************** TOTAL COMP WEIGHT IS    3.8
```

Figure 28. WATE-S Turbofan Sample Case Output (Contd).

```
*************
*           *
*  DUCT  8  *
*           *
*************2

MAX CONDITIONS OCCUR AT
******************************
         ALT        MN
PTCT      0.        .650
TTCT      0.        .650
******************************
RH=    3.04 RT=    3.66 LENG=    2.40
AREA=    .091 RHO= .168
         CAS WT       INC WT      WTOT
          .46          .40        .88



*************
*           *
*  CENC  9  *
*           *
*************2

MAX CONDITIONS OCCUR AT
*************************************
         ALT        MN       VALUE
PTCT      0.        .650     58.2 LB/SQIN
TTCT      0.        .650     817.6 DEG R
CWIN      0.        .650     2.8 LB/SEC
*************************************
DUCT
  P NO  VEL  T TOT   P TOT    P STAT   AREA    GAM
  .420  577.  818.   8380.    7428.    .088   1.391

STAGE 1 BLADE STRESS EXCEEDS ALLOWABLE, STRESS = 51099.  ALLOWABLE = 46143.

STAGE    1
  WDISK    WBLD    WSHRD   WDIFF      CL      RHO
   5.2      .4      .9      3.0      3.26     .134
  SPR      RPM     RTIP     NB      UTIPC    DSTR     BSTR   WEIGHT  STAGE I
  5.339   63690.   3.97     20     1345.8   49682.   51099.   5.6    14.4

  N STG   WEIGHT  LENGTH  CENGRA   INERTIA
    1      9.56    3.34    3.34     14.4

DUCT
  P NO  VEL  T TOT   P TOT    P STAT   AREA    GAM
  .190  341. 1396.   44740.   43661.   .045   1.356

   PR     AD EF     PO      TO      HP
  5.339   .8201   44740.   1396.   1849.
   HI      HO      WI      CWI
 196.10  341.76   8.57    2.84


****************** TOTAL COMP WEIGHT IS     9.6


*************
*           *
*  HPT  11  *
*           *
```
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).
```

```
************2

MAX CONDITIONS OCCUR AT
*******************************
         ALT        MN      VALUE
PTOT       0.       .650     298.3 LB/SQIN
TTOT       0.       .650    2579.7 DEG F
CHCUT      0.       .650       2.9 LB/SEC
*************************************
DUCT
 M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
 .160   383.  2560.   42951.   42244.   .076   1.299

 LTIPMAX STRESS      DEN  WGHT/A   TR    H/T
 1880.6  57168.      .286  .160   1.00   .835

 TURBINE 11  MECHANICAL DESIGN
     H/T    N STG   M WRK C   AREA
    .835    1.0     1.240     .076
     UT     RTIP    RHUB      DEL H      RPM    MAXRPM   TORQ
   1860.6   3.38    2.82      147.4     63690.  63690.   1844.

 STAGE    1
   DISK   BLADE  VANE   HWD    CASE   AR
   5.0     .4     .6    1.0     .7   1.20
   SPR   DEL H  MACH   AREA   R HUB  R TIP  NR UTIPMAX  STR   WEIGHT  LENGTH  STG I

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
BLADE ROOT STRESS IS   57167.7 DES LIMIT IS   50000.0
**STRESS IS TOO HIGH REDUCE SHAFT SPEED OR INCREASE EXIT MACH NUMBER**
2.900 147.4  .160  .076   2.82   3.38   73  1880.6 57168.    7.67    1.20    23.

 N STG  LENGTH  WEIGHT   CENGRA  INERTIA
   1     1.20    7.67     1.2      23.

 DUCT
 M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
 .310   665.  2077.   15052.   14139.   .105   1.312

   PR      TR     AD EF     PO      TO      TO.1
  2.853   1.242   .8963   15052.3  2077.1   2077.1
   H IN    H OUT   ANGZ    FLOW    HP
  669.39  537.97   .357    8.93    1863.

****************** TOTAL TURB WEIGHT IS    7.7

**************
*             *
*  DUCT 12   *
*             *
************2

MAX CONDITIONS OCCUR AT
*********************
       ALT        MN
PTOT     0.      .650
TTOT     0.      .650
*************************
RH=   2.78  RT=   3.40  LENG=    3.12
AREA=   .084  RHO=  .286
       CAS WT      INC WT      WTOT
        .95         .78        1.73
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

```
*************
*           *
*  LPT  13  *
*           *
*************2

MAX CONDITIONS OCCUR AT
**************************************
         ALT        MN      VALUE
PTQT       0.      .690     102.1 LB/SQIN
TTCT       0.      .690     2071.5 DEG R
CHCUT      0.      .690       6.0 LB/SEC
**************************************
CLCT
 P NO  VEL  T TOT  P TOT  P STAT  AREA   GAM
 .230  495. 2072. 14706.  14206.  .140  1.312

 UTIPMAX STRESS     DEN  WGHT/A   TR    H/T
 1196.4 31757.     .286   .289  1.00   .764

 TURBINE 13  MECHANICAL DESIGN
    H/T   N STG  P WRK C   AREA
    .764   2.0   1.200    .140
     UT    RTIP   RHUB   DEL H     RPM    MAXRPM  TORQ
   1196.4  3.93   3.01   106.8    34841.  34841.  2462.

STAGE   1
 CISK  BLADE  VANE   HWD   CASE   AR
 3.6   1.2    1.4    1.9   1.1   1.50
 SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR    WEIGHT LENGTH STG I
 1.549 53.4 .230  .140   3.01   3.93   69 1196.4 31757.   8.90   1.60   28.

STAGE   2
 CISK  BLADE  VANE   HWD   CASE   AR
 3.0   1.7    1.9    1.2   1.1   2.00
 SPR  DEL H  MACH  AREA  R HUB  R TIP  NB UTIPMAX  STR    WEIGHT LENGTH STG I
 1.622 53.4 .270  .178   2.70   3.93   64 1196.4 40332.   8.90   1.59   24.

FRAME WT =    12.50


 N STG LENGTH WEIGHT  CENGRA  INERTIA
   2   3.78   30.25    3.0     52.

CLCT
 P NO  VEL  T TOT  P TOT  P STAT  AREA   GAM
 .310  604. 1694.  5881.   5520.  .244  1.327

  PR    TR    AD EF    PO      TO     TO.1
 2.501 1.223  .9143  5880.5  1694.4  1694.4
 H IN  H OUT  ANO2   FLOW     HP
 536.29 429.53 .941   9.01   1361.

**************** TOTAL TURB WEIGHT IS    30.3

*************
*           *
*  DUCT 14  *
*           *
*************2

FAN CCNDITIONS OCCUR AT
**************************
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

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```
         ALT          MN
PTCT      0.         .650
TTCT      0.         .650
*************************
RI=    2.15 HT=    3.69 LENG=    1.54
AREA=    .196 RHO=  .266
         CAS WT       INC WT      WTOT
          .51          .30         .81



***************
*             *
*   FMIX 15   *
*             *
***************2

MAX CONDITIONS OCCUR AT
*************************
         ALT          MN
PTCT      0.         .650
TTOT      0.         .650
*************************

MIX WT    PLUG WT    WTOT    LENGTH    OUTER RAD
 1.9       1.0       2.9      4.4         4.41

***************
*             *
*   FC    2   *
*             *
***************2

***************
*             *
*   PBUR 10   *
*             *
***************2

MAX CONDITIONS OCCUR AT
*****************************************
         ALT          MN        VALUE
PTCT      0.         .650      310.7 LB/SQIN
TTCT      0.         .650     1395.6 DEG R
CHIN      0.         .650        .7 LB/SEC
*****************************************
 RIN      ROUT     LENGTH     MACH      WSPEC
 3.97     5.28      5.28      .031      2.567
 CAS WT   LIN WT   NGZ WT    INC WT    FRAME    WTOT
  2.0      5.1       .7       2.0      25.3     35.7



***************
*             *
*   DUCT  3   *
*             *
***************2

MAX CONDITIONS OCCUR AT
*************************
         ALT          MN
PTCT      0.         .650
TTCT      0.         .650
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

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```
*************************
RH=    3.93 RT=    4.55 LENG=   16.74
AREA=    .115 RHO= .166
       CAS WT      INC WT      WTOT
        4.50        3.66        8.38
              .
```

```
*************
*           *
*  NOZ   4  *
*           *
*************2

MAX CONDITIONS OCCUR AT
***************************
       ALT         MN
PTOT       0.      .650
TTOT       0.      .650
****************************
WEIGHT=     3.16 LENGTH=     9.10 TR WT=    0.00


**************
*            *
*  SHAF 16   *
*            *
**************2

MAX TORQUE CONDITION
****************************
 TORQUE
   205.2
****************************
SHAFT  16
    DO      DI    LENG    DN      WT
   .95     .76   12.06   .84     .87

TOTAL INERTIA OF THIS SPOOL IS        92.

**************
*            *
*  SHAF 17   *
*            *
**************2

MAX TORQUE CONDITION
****************************
 TORQUE
   153.6
****************************
SHAFT  17
    DO      DI    LENG    DN      WT
  1.31    1.25    5.28   2.11    .10

TOTAL INERTIA OF THIS SPOOL IS        37.
THE DN VALUE OF 2.11 MILLION IS HIGH
```

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

```
**************
*            *
*  ACCS WT   *
*            *
************2
```

ACCS WT = 37.61

CASE IDENTIFICATION   4.3.2 TURBOFAN ENGINE SAMPLE CASE

WEIGHT INPUT DATA IN ENGL UNITS
WEIGHT OUTPUT DATA IN ENGL UNITS

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS				DOWNSTREAM RADIUS				NSTAGE
				RI	RO	RI	RO	RI	RO	RI	RO	
2	15.1	7.4	7.4	3.5	4.5	0.0	0.0	4.0	4.5	0.0	0.0	0
3	8.4	18.7	26.1	3.9	4.5	0.0	0.0	3.9	4.5	0.0	0.0	0
4	3.2	9.1	35.2	0.0	4.5	0.0	0.0	0.0	4.1	0.0	0.0	0
5	15.3	7.4	7.4	1.8	3.5	0.0	0.0	3.2	4.0	0.0	0.0	2
6	.3	.8	8.1	3.2	4.0	0.0	0.0	3.2	4.0	0.0	0.0	0
7	3.8	1.2	9.3	3.0	3.7	0.0	0.0	3.0	3.7	0.0	0.0	1
8	.9	2.5	11.8	3.0	3.7	0.0	0.0	3.0	3.7	0.0	0.0	0
9	9.6	3.3	15.1	1.5	2.5	0.0	0.0	1.5	4.0	0.0	0.0	1
10	35.7	5.3	20.4	4.0	5.3	0.0	0.0	4.0	5.3	0.0	0.0	0
11	7.7	1.2	16.3	2.8	3.4	0.0	0.0	2.7	3.5	0.0	0.0	1
12	1.7	3.1	19.4	2.8	3.4	0.0	0.0	2.8	3.4	0.0	0.0	0
13	30.3	4.0	23.4	3.0	3.9	0.0	0.0	2.1	3.9	0.0	0.0	2
14	.8	1.5	25.0	2.1	3.7	0.0	0.0	2.1	3.7	0.0	0.0	0
15	2.5	4.4	29.4	2.0	3.8	3.8	4.4	2.0	4.4	0.0	0.0	0
16	.9	0.0	15.1	3.8	4.4	3.2	4.0	0.0	0.0	0.0	0.0	0
17	.2	0.0	0.0	3.0	3.7	1.5	2.5	0.0	0.0	0.0	0.0	0

BARE ENGINE WEIGHT   =   130.6   TOTAL ENGINE LENGTH =   29.4
ACCESSORY WEIGHT   =   37.6   MAXIMUM RADIUS =   5.3
HEAT EXCH WEIGHT   =   0.0   CENTER OF GRAVITY   =   15.0
EXHAUST SYSTEM WT   =   5.7
TOTAL ENGINE WEIGHT =   173.9

Figure 28.   WATE-S Turbofan Sample Case Output (Contd).

Figure 28. WATE-S Turbofan Sample Case Output (Contd).

4.4 Program Diagnostics

The WATE-S program contains several error checks to aid the user in obtaining an acceptable engine design. A listing of these errors, and the subroutines they occur in, are included in Table XIV. None of these errors will cause the execution of WATE-S to stop. The subroutine the error occurred in may be terminated and subsequent component calculations can be in error.

4.5 Program Structure

The WATE-S code is written in FORTRAN IV and has been checked out on the IBM 370 computer. However, the code was developed at Garrett on a CDC 170 machine in an overlay structure. The code is written in single precision and requires no subroutines beyond those in the IBM FORTRAN IV manual. There is no character manipulation and only full word tests are used when testing BCD input.

The main program is called WATES and in turn calls INPUT and WTEST as shown in Figure 29. Subroutine INPUT reads the configuration ($C) and thermodynamic ($T) data. Subroutine WTEST reads the aeromechanical ($W) data and calls the component routines. These component routines are independent of each other, and some use the same lower level routines as others. After all weights and dimensions have been estimated, ENGPLT is called to make the printer plot.

The following variables in the common blocks may be referenced by a component weight estimating routine depending on the component type: DATOUT, WTF, TOPRES, TOTEMP, FAR, CORFLO, JCONF, JTYPE, NCOMP, NOSTAT. In no case is any value changed by the weight estimation code.

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TABLE XIV. WATE-S ERROR MESSAGES

SUBROUTINE FIGURE-

   MAIN FLOW PATH DIDNT END, RETURN

   FLOWPATH II+1 DIDNT END, CHECK LOGIC

SUBROUTINE DISK-

   ******AVERAGE DISK STRESS GREATER THAN ALLOWABLE STRESS***** XXXXXXX.

SUBROUTINE DUCT1-

   DUCT IS NOT CONVERGING

SUBROUTINE CENCOM-

   STAGE II DISK STRESS EXCEEDS ALLOWABLE, STRESS = XXXXXXX. ALLOWABLE = XXXXXXX.

   STAGE II BLADE STRESS EXCEEDS ALLOWABLE, STRESS = XXXXXXX. ALLOWABLE = XXXXXXX.

   STAGE II BLADE FREQUENCY LESS THAN 2/REV

SUBROUTINE CMECH-

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   BLADE ROOT STRESS IS XXXXXXX. DES LIMIT IS XXXXXXX.
   STRESS IS TOO HIGH REDUCE SHAFT SPEED OR INCREASE EXIT MACH NUMBER

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   STAGE HUBTIP RATIO IS X.XX DES LIMIT IS X.XX
   HUB TIP RATIO IS TOO HIGH REDUCE HUB TIP RATIO INPUT

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   STAGE HUBTIP RATIO IS X.XX DES LIMIT IS X.XX
   HUB TIP RATIO IS TOO LOW INCREASE HUB TIP RATIO INPUT

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   1ST STAGE PRATIO IS XX.XX DES LIMIT IS XX.XX
   STAGE ALLOWABLE PRESSURE RATIO IS TOO HIGH REDUCE INPUT

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   LAST STAGE MACH NO IS X.XX DES LIMIT IS X.XX
   LAST STAGE MACH NO IS TOO HIGH REDUCE STAGE EXIT MACH NO INPUT

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   STAGE BLADE HEIGHT IS XX.XX DES LIMIT IS XX.XX
   STAGE BLADE HEIGHT IS TOO SMALL CHANGE DES OPR OR REDUCE H/T INPUT

   **** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED *****
   STAGE WORK COEFFICIENT IS XX.XX DES LIMIT IS XX.XX
   STAGE WORK COEFFICIENT TO HIGH. ADD STAGES OR INCREASE H/T INPUT

   COMPRESSOR II PRESSURE RATIO IS TOO HIGH

   COMPRESSOR II STAGE AND BLADE PARAMETERS, MEANINGLESS

TABLE XIV. WATE-S ERROR MESSAGES (CONTD)

SUBROUTINE SHAFT-

ERROR IN SHAFT II

THE DN VALUE OF XX.XX MILLION IS HIGH

SUBROUTINE RADTUD-

DISK STRESS EXCEEDS ALLOWABLE, STRESS = XXXXXXX. ALLOWABLE = XXXXXXX.

BLADE STRESS EXCEEDS ALLOWABLE, STRESS = XXXXXXX. ALLOWABLE = XXXXXXX.

BLADE FREQUENCY LESS THAN 2/REV

SUBROUTINE TMECH-

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED*****
BLADE ROOT STRESS IS XXXXXX. DES LIMIT IS XXXXXXX.
STRESS IS TOO HIGH REDUCE SHAFT SPEED OR INCREASE EXIT MACH NUMBER

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED*****
STAGE HUBTIP RATIO IS X.XX DES LIMIT IS X.XX
HUB TIP RATIO IS TOO LOW INCREASE TURBINE CONTROL RADIUS

**** WARNING FOLLOWING STAGE DESIGN LIMIT EXCEEDED*****
STAGE WORK IS X.XXX DES LIMIT IS X.XXX
**STAGE WORK IS TO HIGH, ADD STAGES OR DECREASE INPUT MEAN WORK COEFFICIENT

TURBINE II WORK OR RADIUS TOO HIGH, RC = XXX.XX

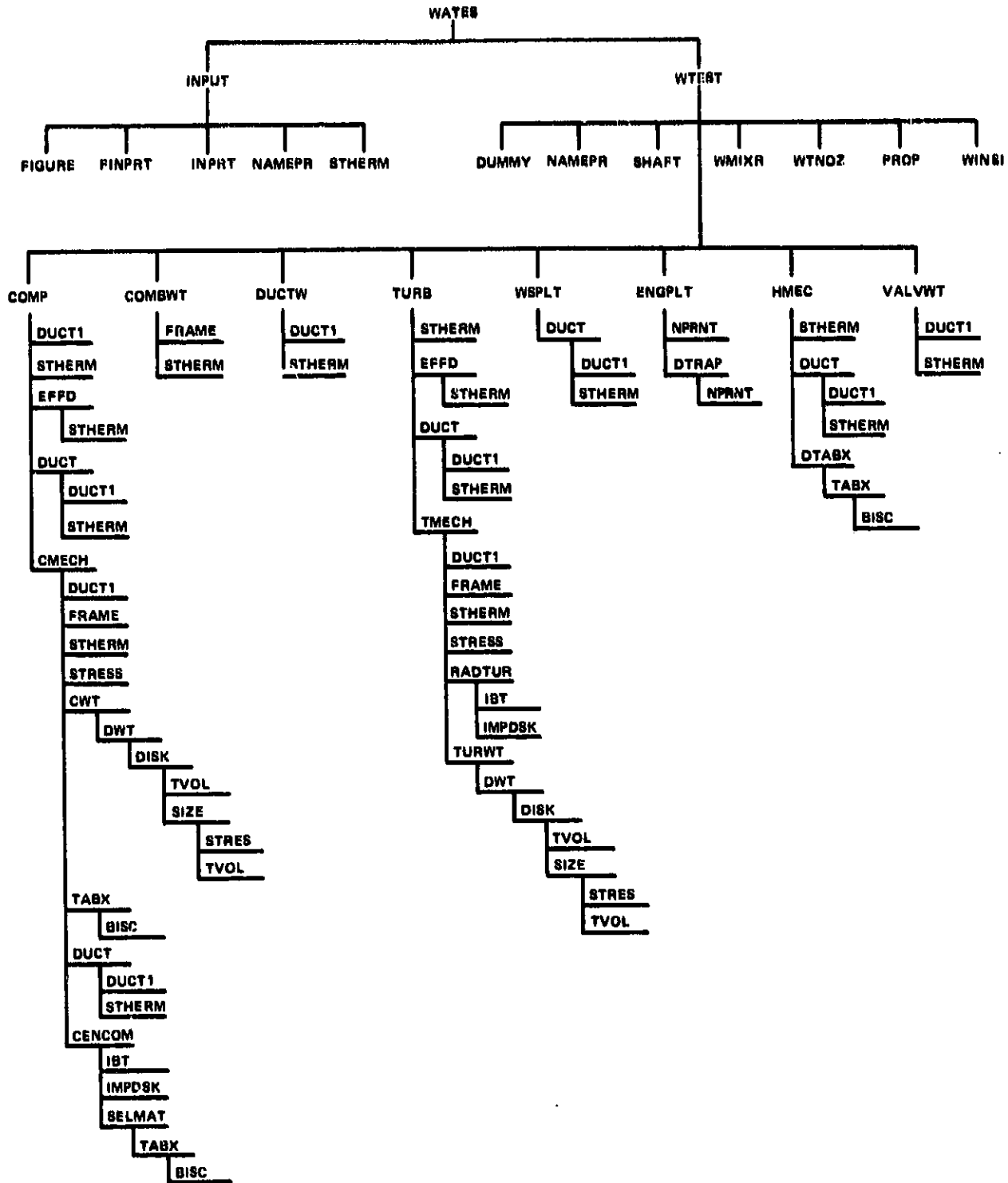TURBINE II STAGE AND BLADE PARAMETERS MEANINGLESS

Figure 29. Diagram of Subroutine Connectivity.

Based on the information in NCOMP and the JTYPE array, the proper component routine is called with the component number (I) as an argument. Each component is expected to fill WATE(I), ALENG(I), TLENG(I), RO(1,I), RO(2,I), RI(1,I), RI(2,I). Rotating components also fill RPMT(I). The shaft component fills DSHAFT(N) where N is the shaft count from the inside out.

The array "CONVER" in common CONVER are conversion factors to convert English to SI units for output, or SI to English units for input. However, all internal calculations in WATE-S are performed in English units.

LOCATION	VALUE	UNITS ENGLISH	to	UNITS SI
1	2.5400	inch		cm
2	0.30480	feet		meter
3	0.45359	lb_m		Kg
4	0.092903	ft^2		$meter^2$
5	0.027680	lb_m/in^3		Kg/cm^3
6	0.68948	lb_f/in^2		$Newton/cm^2$
7	4.8824	lb_m/ft^2		Kg/m^2
8	0.55556	°R		°K
9	2326.0	Btu/lbm		Joule/Kg
10	0.074570	hp		KWatt
11	47.880	lb_f/ft^2		$Newton/m^2$

5.0 CONCLUSIONS AND RECOMMENDATIONS

The WATE-S program can provide the level of accuracy in predicting weight and dimensions of both small and intermediate propulsion gas turbine engines that is required for preliminary engine cycle selection studies. On an absolute basis, the calculated weights and dimensions have been demonstrated to be within ±10 percent for six reference engines. On a relative basis, between engines of the same generic family and configuration, the accuracy is much better, estimated at less than ±2 percent.

The flexibility of modeling the engine allows virtually any conventional or nonconventional gas turbine engine to be analyzed given the thermodynamic performance of the engine components. WATE-S is viewed as an extension of the Boeing WATE-2 code, that is, the structure of the basic program was not altered. Hopefully, this should allow users of the WATE-2 code to easily adapt WATE-S to their design system, if desired.

The following improvements to the program are recommended:

(a) Exit Mach number should be used to size the blades for axial turbines instead of inlet Mach number as is currently in use. Exit Mach number is a more fundamental parameter in turbine design and the code should reflect this.

(b) The heat exchanger calculation should be made to "close the loop" on fixed tube number. Currently, WATE-S estimates the pressure drops through the heat exchanger for the input number of tubes. This could be compared against the thermodynamic data, and the number varied until the results agree. For nonpropulsion engines, e.g. auxillary power units, stationary power units, and vehicular engines, the heat exchanger can be the largest and heaviest component in the engine, and hence, should be modeled as accurately as possible.

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(c)   For ducts, burners, and duct burners where the ID wall is
        subjected to collapsing pressure rather than internal burst-
        ing pressure, the calculations outlined in Section 3.1.6
        should be included. Duct weights are typically a small frac-
        tion of total engine weight but a definite component accuracy
        improvement could be obtained. In addition, the duct model
        could be improved to radially match both the upstream and
        downstream components.

(d)   Blade mean solidity should be used to determine the blade
        count for axial components instead of the blade tip solidity.
        Blade mean solidity generally has more significance and con-
        sistency than does blade tip solidity.

APPENDIX A
LIST OF SYMBOLS

A	area (cm^2)		U	wheel speed (m/s)
AF	activity factor		V	volume (cm^3)
AR	aspect ratio		W	weight (kg)
C	blade chord (cm)		τ	shear stress (N/cm^2)
C-D	convergent-divergent nozzle		λ	turbine work coefficient
C/S	solidity, blade chord to spacing ratio		ρ	density (kg/cm^3)
D	diameter (cm)		ω	rotational velocity (rad/s)
F	force (Newton)		σ	normal stress (N/cm^2)
g	gravitational constant $\frac{Kg-M}{N-S^2}$		ϵ	heat exchanger effectiveness
			θ	ratio of local total temperature to standard temperature
GR	gear ratio			
h	height (cm)		δ	ratio of local total pressure to standard pressure
h/t	hub/tip radius ratio			
H	total enthalpy (Joule/kg)			
HP	high-pressure spool		ψ	compressor work coefficient
I	rotational inertia (cm^2-kg)			
J	778.16 ft-lbf/Btu		**Subscripts:**	
K	factor for blade volume			
L	length (cm)		h	hub
LP	low-pressure spool		t	tip
Mn	Mach number		B	blade
N	number of elements		c	case or corrected conditions
P	pressure (N/cm^2)		S	stator
PTO	power takeoff		hw	hardware
PW	power (KWatt)		Stg	stage
R	radius (cm)		D	disk
RPM	revolutions per minute		SPL	splitter
S	blade spacing (cm)		2	engine inlet station
T	temperature (°K) or torque (cm-N)		m	mean
t	thickness (cm)		i	inner
TR	blade taper ratio		o	outer

APPENDIX B
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