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A Method to Estimate Weight and Dimensions of Large and Small Gas Turbine Engines

Final Report

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TABLE OF CONTENTS

		PAGE
	SUMMARY	3
	INTRODUCTION	4
	LIST OF SYMBOLS	5
1.0	METHOD OF ANALYSIS	6
1.1	Large Gas Turbine Engines	13
1.2	Small Gas Turbine Engines	50
1.3	Other Program Capabilities	62
1.4	Program Validation	64
2.0	USER'S GUIDE	66
2.1	Program Structure and Deck Stacking	66
2.2	Input Description and Format	68
2.2.1	Plot-Print Indicators	68
2.2.2	Length Indicators	72
2.2.3	Mechanical Design Indicators	73
2.2.4	Design Values	82
2.3	Output Description and Format	95
2.4	Sample Cases	107
2.5	Program Diagnostics	119
2.6	Program Structure	127
3.0	CONCLUSION AND RECOMMENDATIONS	131
	REFERENCES	132
	DISTRIBUTION LIST	133

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

E. Onat and G. W. Klees

SUMMARY

A method has been developed to estimate engine weight and major envelope dimensions of large axial flow aircraft jet engines and small gas turbine engines. The computerized method, called WATE-2 (Weight Analysis of Turbine Engines), determines the weight of each major component in the engine, such as compressors, burners, turbines and frames. A preliminary design approach is used where the stress level, maximum temperature, material, geometry, stage loading, hub-tip ratio, and shaft mechanical overspeed are used to determine the component weight.

A relatively high level of detail was found to be necessary in order to obtain a total engine weight within the required ±10% accuracy. Component weight data for 29 different engines were used as a data base to develop the method for axial flow aircraft engines. The list of engines includes military and commercial, turbofans and turbojets, augmented and dry, hardware engines and proposed engines, and supersonic and subsonic engines. For small gas turbines, weight correlations were provided through a subcontractor, the Garrett Corporation. Data used in those correlations were proprietary to Garrett and only the selected weight method is shown herein. 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%, on the order of ±5%. The accuracy was verified by applying the method to 9 different engines, some of which were in the original data base and one small gas turbine engine. Engines used in the validation were selected by NASA after completion of the program.

INTRODUCTION

Aircraft and propulsion system studies are frequently conducted by industry and Government. These studies may encompass a wide variety of engine concepts ranging from relatively simple turbofans and turbojets to complicated variable-cycle engines. The industry in general has acquired an adequate computer capability to evaluate the thermodynamic performance of these diverse engine concepts, however, an accurate method of estimating engine weight and dimensions has not previously been available. The engine manufacturers have developed suitable methods, however they are not available to the public.

One method,[1] that has been available to the general industry predicted engine weight by statistical correlations of major cycle characteristics such as airflow, bypass ratio, overall pressure ratio, etc. This method is probably capable of rough estimates for conventional engines; however, it is not applicable to nonconventional engines and could not predict weight within ±5 to ±10% as would be required in typical preliminary design studies.

This program development was initiated to provide a more flexible and more accurate method based on correlations of component weight and physical characteristics, such as compressor airflow size, pressure ratio, hub-tip ratio, etc. This type of approach then would be more capable of estimating nonconventional engines, since the weight of each individual component would be accounted for. As shown in the Methods of Analysis, no adequate correlations could be found and a final method was chosen that is based on a mechanical preliminary design which is responsive to the major engine design variables.

LIST OF SYMBOLS

a	acceleration
A	area
AR	blade aspect ratio
C	blade chord, or convergent nozzle
C-D	convergent-divergent nozzle
C/S	solidity, blade chord to spacing ratio
D	diameter
F	force
g	gravitational constant
h	height, or specific enthalpy
h/t	hub-tip radius ratio
H	Total enthalpy
HP	high-pressure spool
J	778 ft-lb/BTU
K	factor for blade volume
L	length
LP	low pressure spool
M	mass flow, or Mach number
N	number of elements
P	pressure
PTO	power takeoff
R	radius, or gas constant
RPM	revolutions per minute
S	surface area, or blade spacing
T	temperature
t	thickness
TLP	turbine loading parameter
TR	blade taper ratio
U	tip speed
V	volume
W	Weight, or weight flow rate
τ	shear stress
λ	turbine loading parameter
ρ	Density
ω	Rotational Velocity
σ	Stress
γ	ratio of specific heats
ϵ	heat exchanger effectiveness
θ	ratio of local total temp. to std. temp.
δ	ratio of local total pressure to std. pressure

Subscripts:

h	hub
t	tip
b	blade
c	case, or corrected conditions
S	stator
hw	hardware
Stg	Stage
0	stagnation conditions
bp	blade pull
2	Engine inlet station

1.0 METHOD OF ANALYSIS

A thermodynamic simulation of each engine in the data base, Table 1, was made in order to obtain corrected airflows, temperatures, pressures, etc., data on each component. A component weight breakdown was also available for each engine. These computer models contain information that is proprietary to the engine manufacturer, and therefore they are not herein disclosed. These data have been reduced to a nonproprietary form, however, to illustrate the correlation procedure that was used.

Figure 1 shows fan and compressor weight of the data base engines plotted against number of stages. The component weight has been divided by the entry corrected airflow $\frac{W\sqrt{\theta_2}}{\delta_2}$ to normalize the size of each compressor. As can be seen, there is a considerable range of scatter in the data that prevents the definition of a characteristic trend. Some components weigh two to three times as much as other components having the same number of stages.

Table 1 Data Base Engines

Engine	Manufacturer	Manufacturing status [1]	Type of cycle [2]	Augmentation [3]	Primary use [4]
GE4 J4C	GE	P	TJ	AB	C
GE4 J6	GE	X	TJ	AB	C
GE MF 20	GE	X	TF	AB	M
JT11	P&WA	P	TJ	AB	M
[illegible]	GE	S	TJ	AB	C
GE4 J6G	GE	S	TJ	AB	C
GE4 J6H2	GE	S	TJ		C
JT8D 15	P&WA	P	TF		C
JT9D	P&WA	P	TF		C
TF34	GE	P	TF		M
VSCE 502	P&WA	S	TF	DH	C
VCE 201A	P&WA	S	VCE		C
VCE 201B	P&WA	S	VCE		C
VCE 302A	P&WA	S	VCE		C
VSCE 502B	P&WA	S	TF	DH	C
VCE 112B	P&WA	S	VCE		C
VSCE 501	P&WA	S	TF	DH	C
VCE 110B	P&WA	S	VCE		C
ABTF 2	P&WA	S	TF	AB	C
DBTF 2	P&WA	S	TF	DH	C
DSTF 12	P&WA	S	TF	DH	C
JT10D	P&WA	X	TF		C
CFM56	GE SNECMA	P	TF		C
CF6 50	GE	P	TF		C
CF6	GE	P	TF		C
JT8D	P&WA	P	TF		C
CJ805 21	GE	P	TF		C
YJ93	GE	P	TJ	AB	M
JT3D	P&WA	P	TF		C

1 Manufacturing status P = production, S = study proposal, X = experimental
2 TJ = turbojet, TF = turbofan, VCE = variable cycle engine
3 Augmentation type AB = afterburner, DH = ductheater
4 C = commercial, M = military

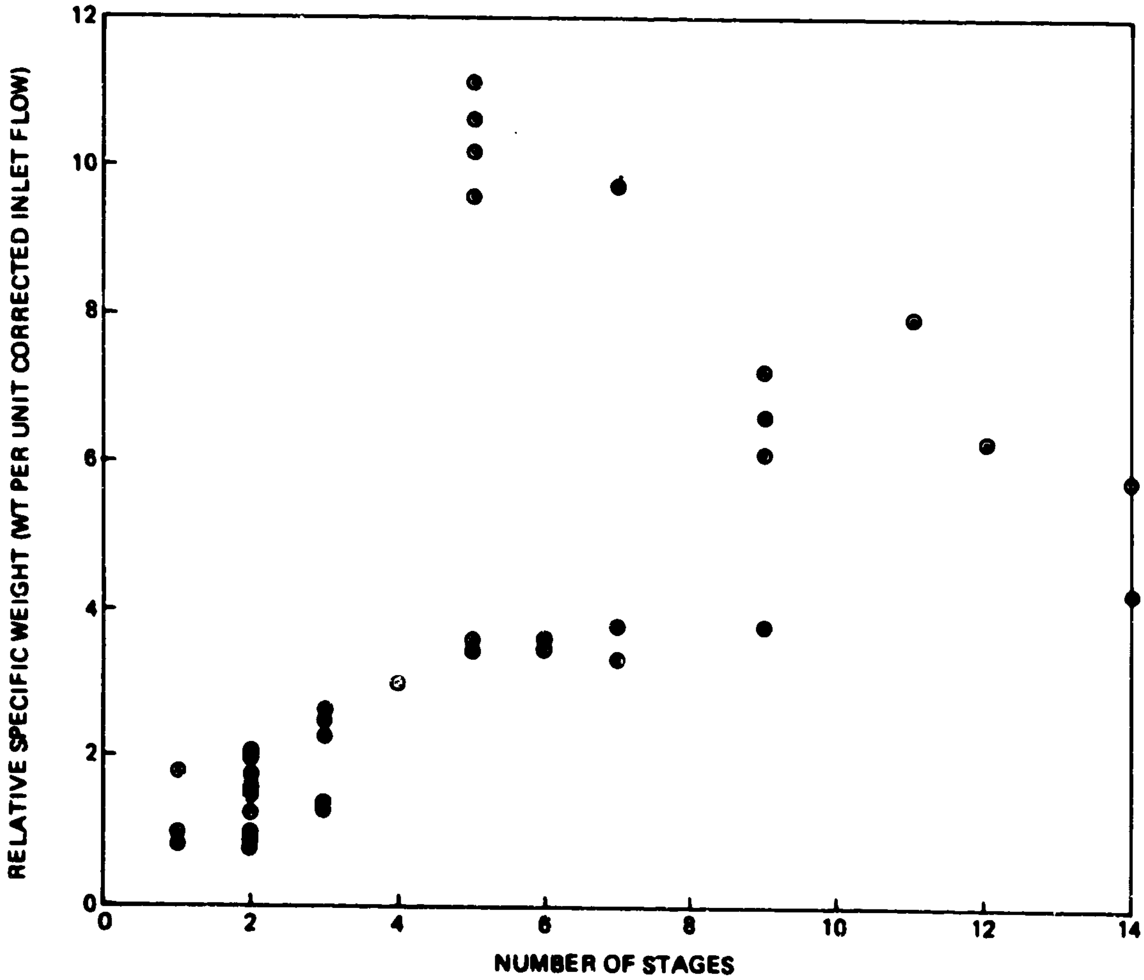


Figure 1. Data Base Engines: Fan and Compressor Specific Weight

Attempts were made to improve this correlation. The data base information was examined to find if there were any mechanical design features (such as h/t, stage loading, etc.) that might account for the large weight difference. It was concluded that there were several different design characteristics that caused the lack of correlation, such as material properties, blade geometry, stage loading, shaft speed, and design life.

A similar problem occurred for turbines (Figure 2), burners and diffusers (Figure 3), augmentors (Figure 4), and duct heaters (Figure 5). Some components, however, did correlate well by this method and these are further discussed in the Methods of Analysis. At this point it was found that the correlation method failed to predict many of the major component weights within the desired accuracy, and another method was adopted.

The adopted method was based on a preliminary mechanical design approach where the design variables are taken into account. In the compressor, for example, rotor blade weight is calculated as a function of specified geometric parameters. Blade pull stress is then found, and the disc weight that will support the blade rotational force is determined. This type of preliminary design approach was also used for the other components (Figures 2 through 5). These methods are also discussed in greater detail in the following secton.

The WATE-2 method is intended to estimate weight for a given engine design. It will not design an engine. This function must be performed external to the program. WATE-2 utilizes component state conditions, flow, work, etc., which are generated in the engine cycle portion of the program (NNEP). NNEP operation is described in reference 2.

In normal use of WATE-2, the desired engine cycle is simulated in NNEP at sea level static conditions for the engine design point. The user of WATE-2 must be cognizant of other conditions in the flight envelope of operation where maximum component temperature, work, speed, or flow occur. If these conditions are greater than the design values, they will

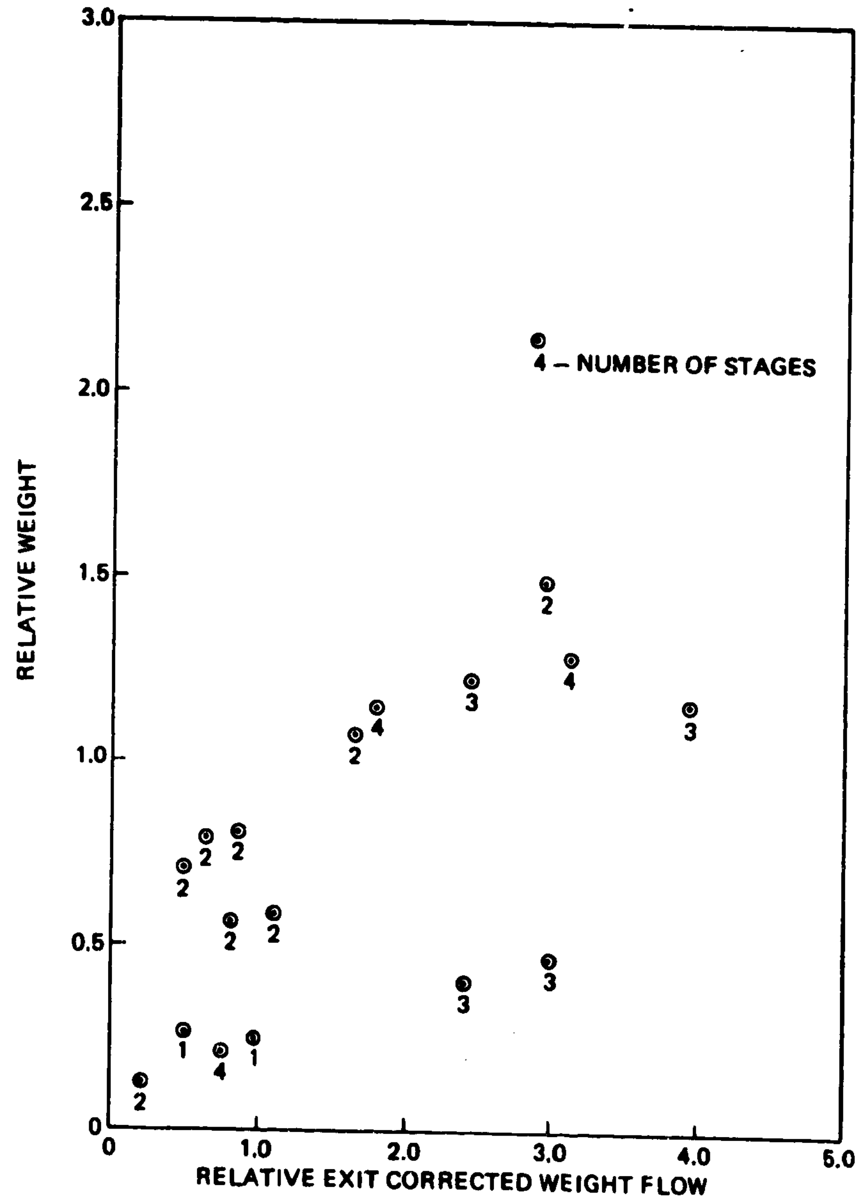


Figure 2. Data Base Engines: Turbine Weight

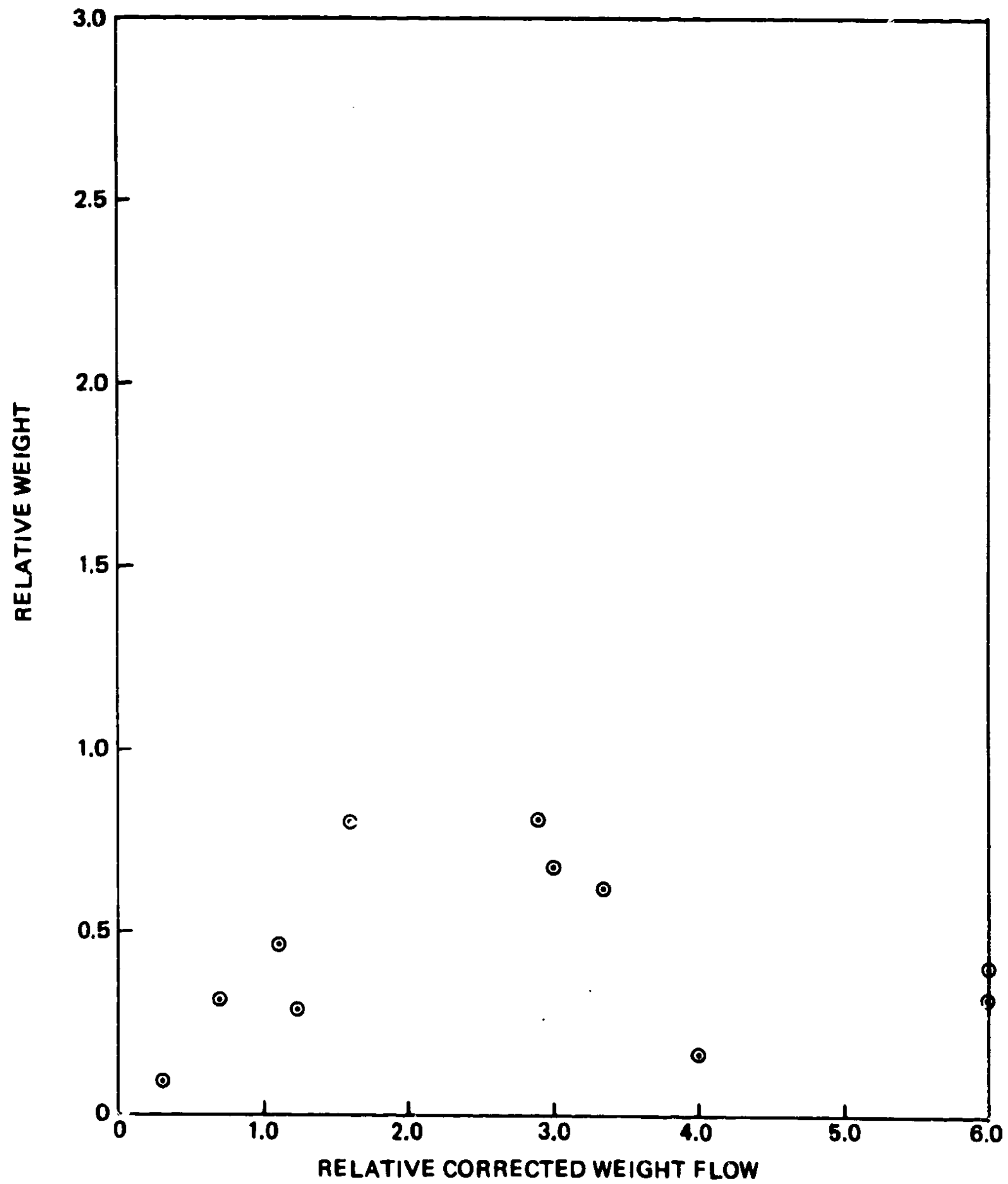


Figure 3. Data Base Engines: Burner and Diffuser Weight

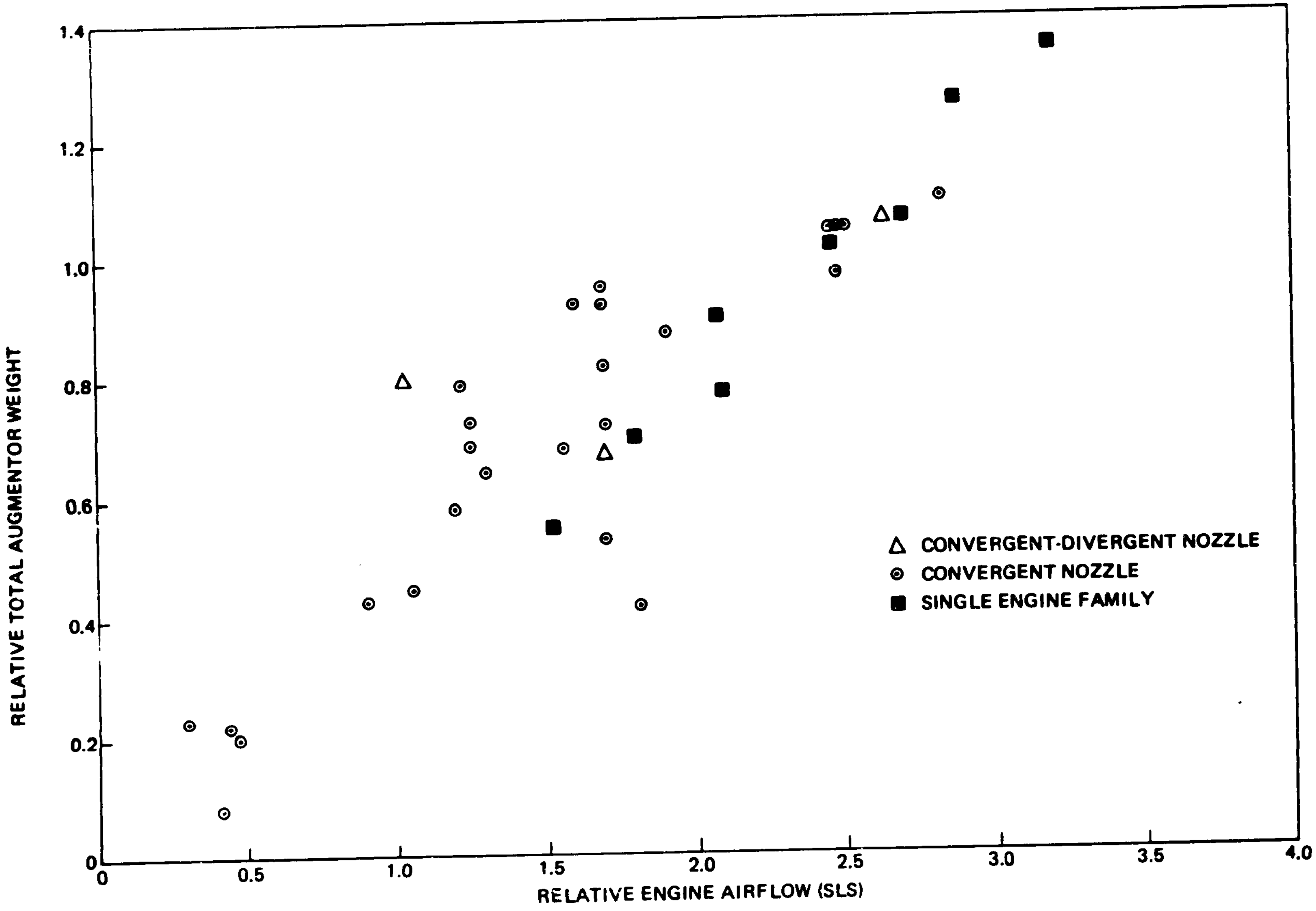


Figure 4. Data Base Engines: Augmentor Weight

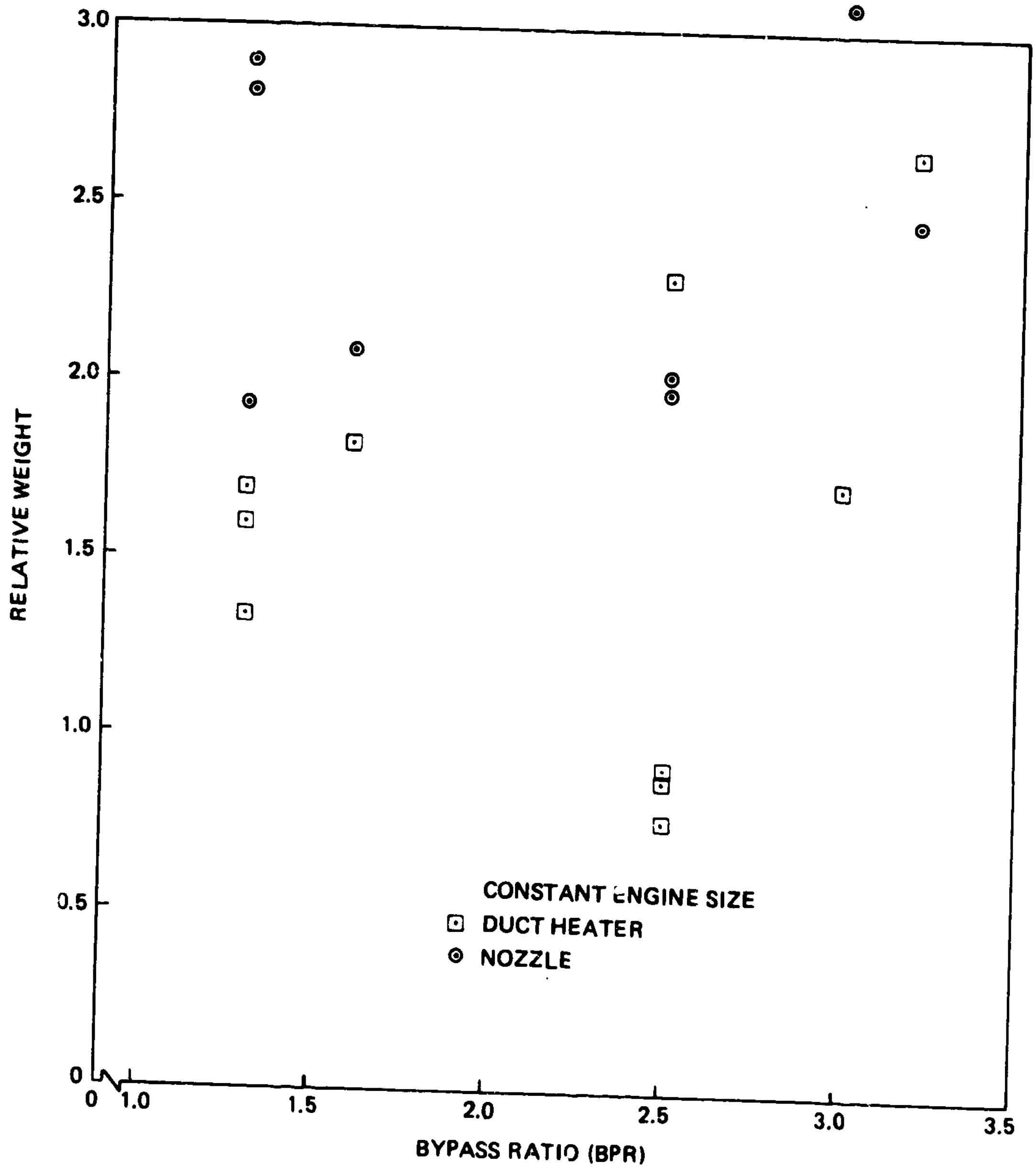


Figure 5. Data Base Engines: Duct Heater and Nozzle Weight

size the component and will have a significant impact on weight. WATE-2 allows input of scalers 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 intended flight envelope. The WATE-2 program will scan the output data of the engine cycle and select the maximum conditions for each component. This automated procedure eliminates the need for scalars to determine maximum component conditions.

The NNEP simulation of the engine may require the use of components that are required mathematically, but are not desired in the engine weight or dimensions. These can be selectively eliminated.

The methods of analysis described for each component in the following section have been developed to achieve an overall accuracy of $\pm 10\%$. Since the rotating components comprise the major part of the total 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 2.0.

1.1 Large Gas Turbine Engines

The methods developed in this section were based on correlations of the data-base family of large gas turbine engines, Table 1. There are certain components that should be equally applicable to small engines such as: annular ducts, burners, rotating splitters, shafts, mixers, nozzles, certain frame types, transmissions or gear boxes, and heat exchangers. Most notable differences between large and small engines are the use of radial-flow components, and relatively thick discs for small axial-flow components. This section should otherwise apply equally well for both large and small engines.

1.1.1 Axial Flow Fans and Compressors

The general procedure used for fan and compressor weight prediction is a stage-by-stage mechanical design as illustrated in Figure 6. Rotor blade volume and weight is determined; then, blade pull stress, disc stress and disc volume are calculated. Connecting hardware, stator, blades, and case are then estimated and summed to give the total component weight. The following input data are necessary:

- An allowable pressure ratio for the first stage which reflects the design approach and technology level. Specific work for this stage will be held constant for additional stages. Number of stages can also be specified as an option.

- The entrance and exit mach number of the component.

- The hub-tip ratio of the first stage.

- Compressor design mode: constant mean-line, constant-hub, or constant-tip diameter.

- Effective density of blade material: defined as total blade weight divided by total volume.

- Maximum inlet and exit temperatures, if not at design.

- Aspect ratios for the first and the last stage blades.

- N_{max}/N_{des} overspeed factor.

- Blade solidity.

- Density of disc material.

- Blade taper ratio

- Blade volume factor, ratio of total volume to blade volume

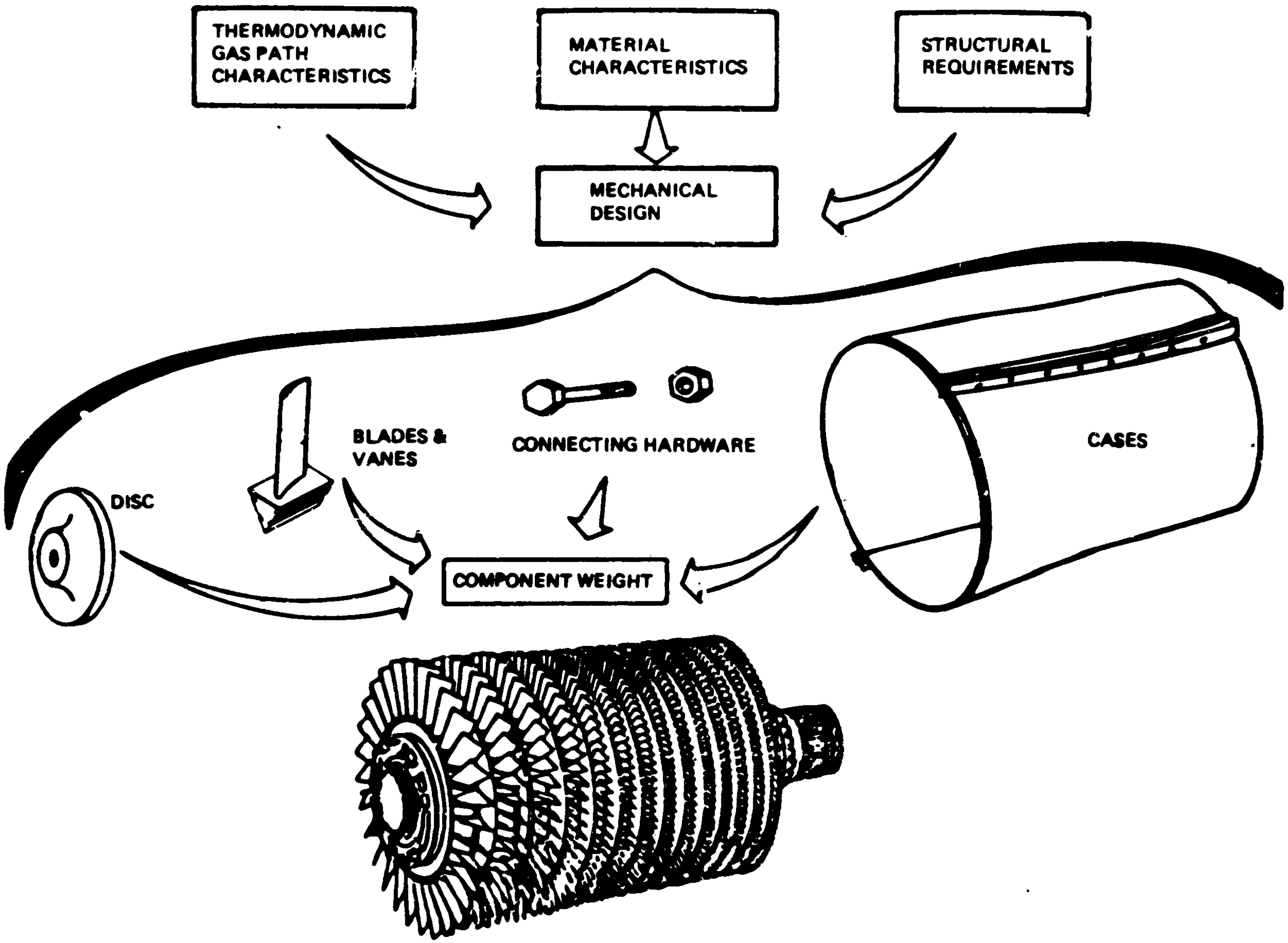


Figure 6. Compressor Weight Method

The total enthalpy change for the component is available in the stored data from the NNEP cycle calculation which precedes the weight method. 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. This iteration is required to obtain equal work per stage with an integer number of stages. When the number of stages is specified, first stage pressure ratio is calculated based on the equal work per stage assumption and the allowable pressure ratio is ignored.

Shaft speed is then estimated by the statistical trend-curve given in Figure 7. This is only an approximation in the event that shaft speed is not known. Shaft speed of additional compressor's driven on the same shaft will be set by the first (upstream) compressor. Turbine blade pull stress and turbine radius ratio are typical fall-outs of this estimated shaft speed. When the WATE-2 process is completed, these typical engine physical constraints may not be satisfied and must be inspected to determine whether the resultant engine design is reasonable.

As an aid in determining if a valid design is made, diagnstic aids will be indicated in the output data which recommend input changes to bring the engine design within limits. In the event that an existing compressor is being weighed, or the shaft speed has previously been determined, a speed scalar can be applied to the shaft speed found from Figure 7 to permit adjustment of the calculated shaft speed to achieve a desired value. The speed scalar can also be used to obtain a more reasonable estimate of shaft speed for hp compressors where the entry temperature significantly effects the pressure ratio capability, or for external iterations of the engine design.

The first stage flow area is determined by the specified Mach number and by the corrected airflow from the cycle data. Inside and outside

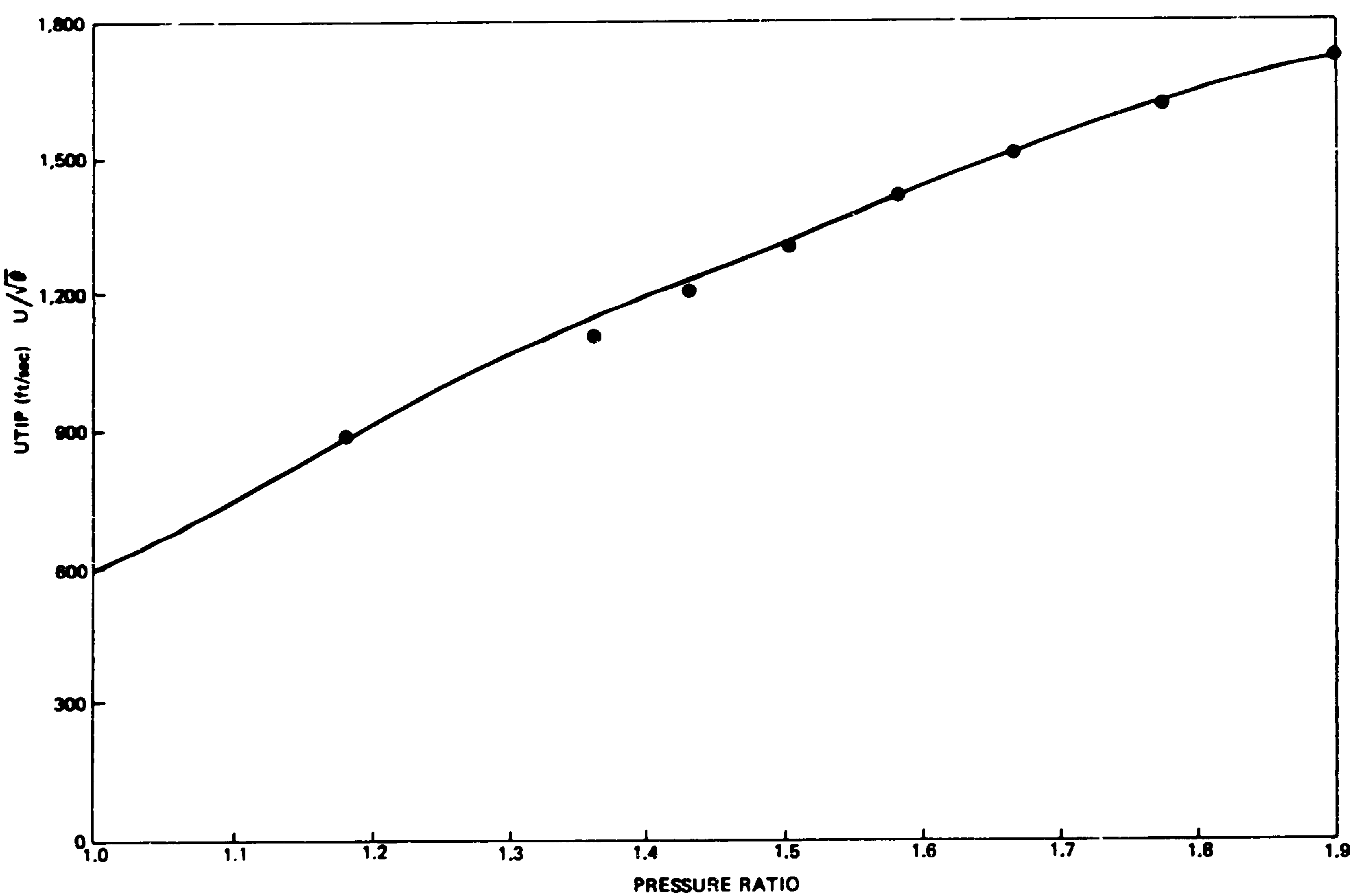


Figure 7. Compressor Tip Speed Estimate for Determination of Shaft Speed

diameters of the flow path are then calculated from the specified radius ratio:

$$D_t = \sqrt{\frac{4A}{\pi(1-h/_t{}^2)}} \tag{1}$$

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

Compressor RPM is determined by dividing the tip speed (found from Figure 7) by the stage radius (R_t).

Dimensions of succeeding stages are based on the design mode selected (constant mean, tip, or hub design). In the constant mean-line method, the mean radius is based on the mean flow area of the first stage. Corrected airflow at the entry of each stage is determined from calculated state conditions. Stage entry Mach number is assumed to vary proportionally to the number of stages when a different entry and exit Mach number are specified. Tip speed for the downstream stages are then calculated from the stage dimensions and shaft speed. Radius of the mean-area location of other stages is set equal to the first stage mean-area radius.

Blade aspect ratio is determined by assuming a proportional change for each stage if entry and exit aspect ratio are different. Volume of metal in the blades is then calculated by:

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

Where K is a volume factor which accounts for fir-tree mount volume, taper ratio, and thickness-to-chord variations in typical blades. For the data base engine, K was found to be 0.055 for fan blades, .12 for compressor blades and for blades with h/t greater than .8:

$$K = .120 + .04\ (^{h}/_{t} - .80) \qquad (4)$$

The rotating blade weight of each stage is determined from the blade volume and material density specified. Material density automatically changes from Ti to steel when the stage temperature exceeds a specified maximum, normally 700°F (371°C). Stage temperature is calculated from the NNEP output data and the specified over-temperature ratio. Stator weight and dimensions are assumed to be equal to the rotor blades and include the inner diameter stator shroud.

Stage length is found in the following manner. Blade chord (C_B) as shown in Figure 8, is the quotient of AR and the blade height:

$$C_B = \frac{h_B}{AR} \qquad (5)$$

For the data base engines, the stator length was found to be equal to the rotor length (or blade chord), with 17% of the rotor length required for clearance between rotor and stator and the same clearance between the stator and next rotor. The sum of all stages gives the total compressor length. Inlet guide vanes are not included in the compressor weight, but can be included as a frame, see Section 1.1.7.

Total number of blades is found from the specified solidity (C/S) and the chord length determined above:

$$N_B = 2\pi \cdot R_t \cdot {}^{C}/_{S} \cdot \frac{AR}{h_B} \qquad (6)$$

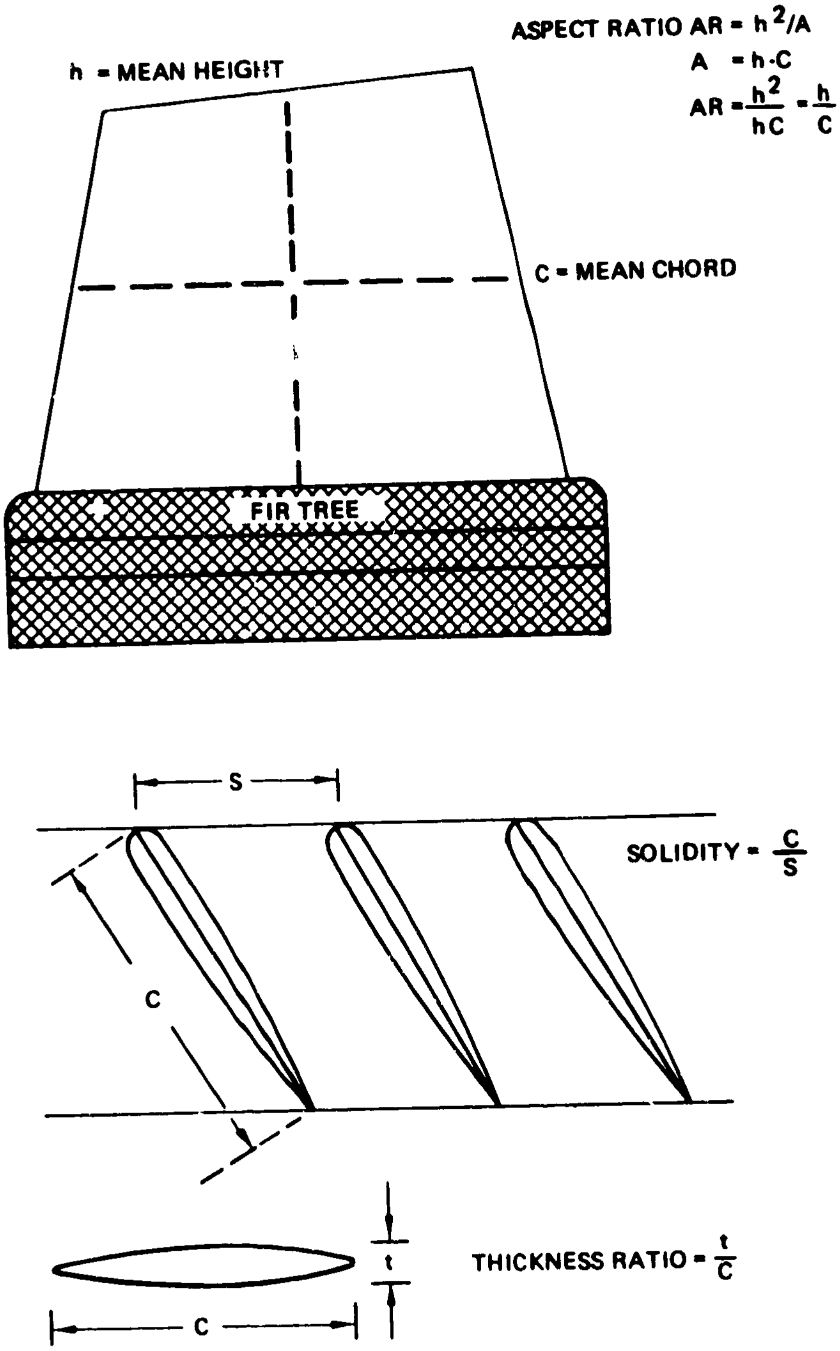


Figure 8. Blade Schematic

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

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

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

where U_t is the product of tip radius, N_{des}, and the overspeed factor N_{max}/N_{des}.

The compressor discs are a large part of the total engine weight and it is therefore necessary to define this weight as accurately as possible. Disc weight is a function of: diameter, blade load carried on the rim of the disc, material type, speed, disc shape (or thickness distribution), and design stress level selected for life considerations. A theoretical functional correlation was developed which showed that disc thickness should vary inversely with the product of blade-pull stress and disc diameter, i.e., the blade load per unit thickness. For those engines in the data base where large-scale drawings were available, several typical discs were measured. Blade-pull stress and disc volume were calculated, and the results were plotted in the form of relative disc thickness versus load per unit thickness, Figure 9.

There is an identifiable trend in these data that show a different characteristic for compressor discs and fan discs. Low hup-tip ratio of the fan probably accounts for the departure from the compressor trend. The allowable stress difference between steel and Ti causes the different trend for the two materials. Further improvements in the accuracy of the disc volume correlations could be made if the number of discs were increased in the data base and the rim loading term was modified by the

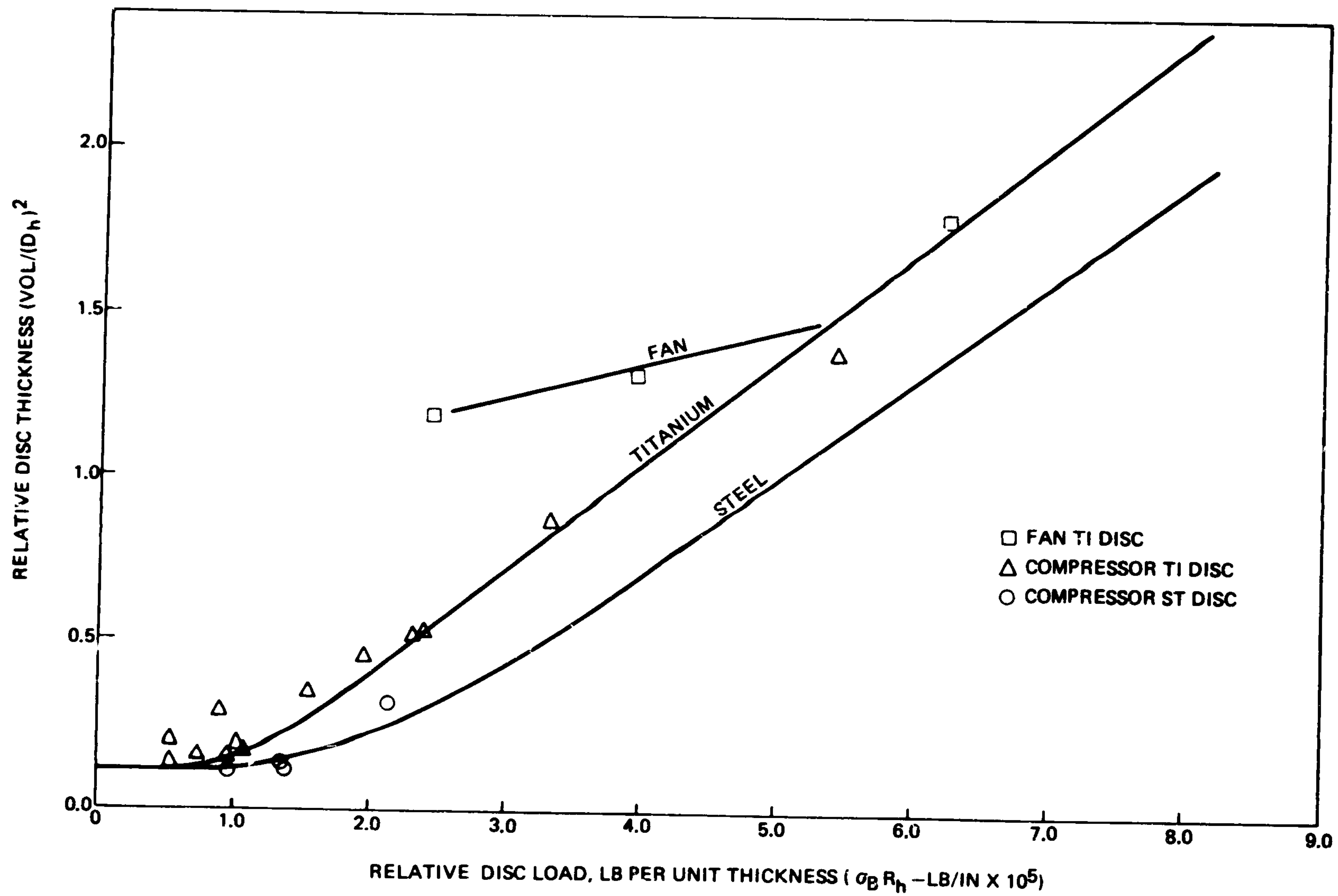


Figure 9. Data Base Engine: Compressor Disk Volume Correlation

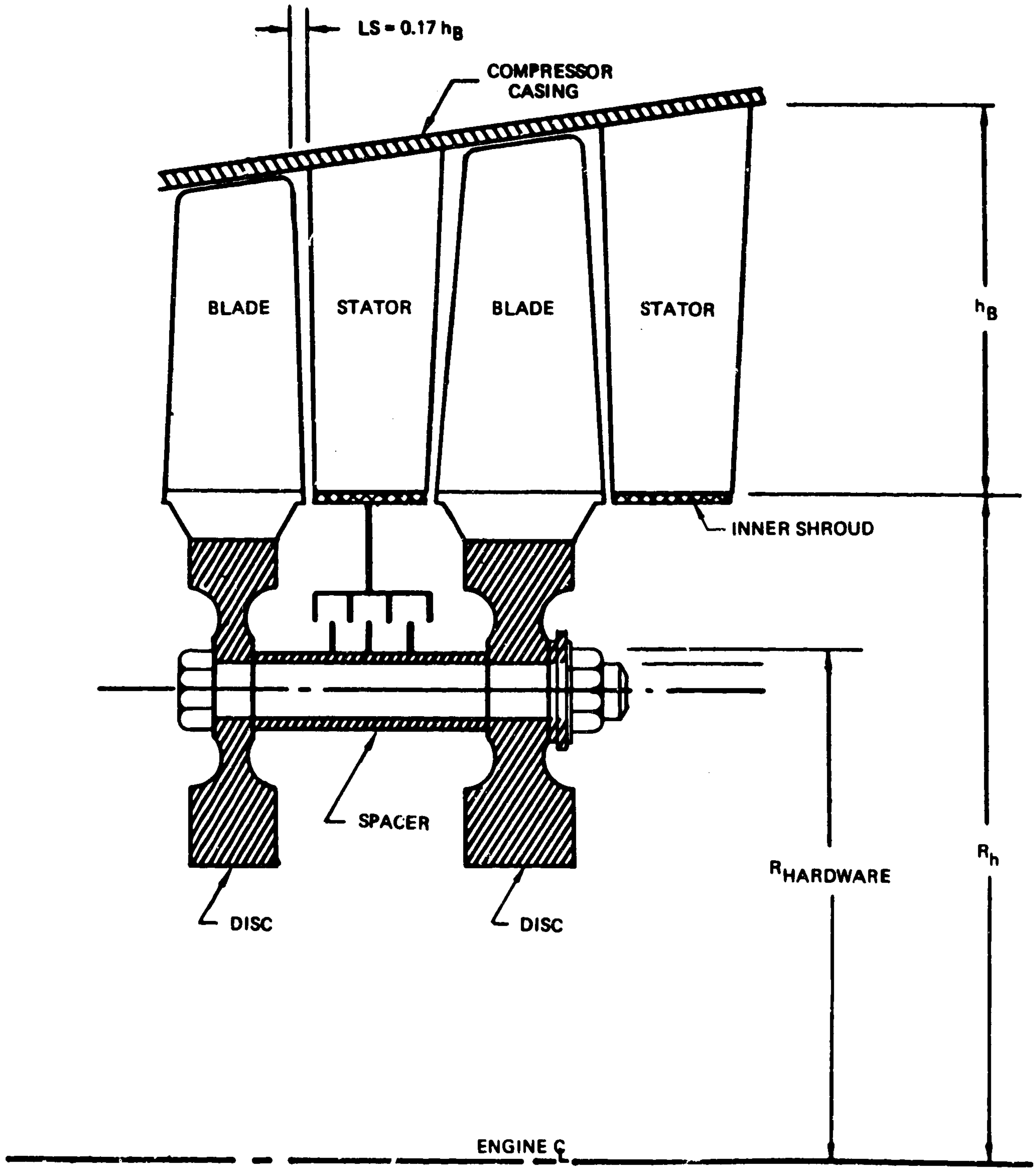


Figure 10. Typical Stage Components

design stress level or maximum allowable. An optional disc preliminary design procedure is also available and is recommended for potential improved accuracy (see sec. 1.2.3).

Figure 10 illustrates a stage coupling method that was used in most of the data base engines. The spacer and nuts and bolts are assumed to be steel, and the spacer was typically a .075-in thick cylinder located at 75% of disc radius. The connecting hardware (W_{hw}) is estimated by the following equation:

$$W_{HW} = .75 \times 2. \times \pi R_h \times .075 \times L_{STG} \times \rho \qquad (8)$$

where R_h is the disc radius (or 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 0.10 in equivalent thickness, including fasteners and flanges. Case weight is calculated stage by stage, and the same material used in the disc is also assumed for the case:

$$W_C = \pi D_t \times L_{STG} \times .10 \times \rho \qquad (9)$$

where D_t is the stage tip diameter.

Total stage weight is the sum of rotor blade, stators, disc, connecting hardware, and case. Stage weights are summed to give the total component weight.

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

$$I_{BLADE} = \frac{WT_{BL}}{g} \times \frac{h_B^2}{3} + R_h^2 \times N_B \qquad (10)$$

$$I_{DISC} = \frac{WT_{DISC}}{8g} \times R_h^2 \qquad (11)$$

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

$$I_{STG} = I_{BLADE} + I_{DISC} \qquad (12)$$

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

1.1.2 Axial Flow Turbines

The method described for compressors is generally the sam for turbines. Input data required are:

- o Maximum tip diameter of the first stage, or number of stages
- o Inlet Mach number (axial) of the first stage, and exit Mach number (axial) of the last stage
- o Rotor blade aspect ratio of the first and last stages
- o Solidity
- o Reference disc stress, 0.2% yield point of the material selected
- o Cooling indicator, to modify the blade volume calculation for cooling holes

- Design mode, constant hub radius, constant mean area or constant tip radius

- Shaft overspeed factor

- Turbine loading parameter, $\lambda = U_t^2 / \frac{\Delta h}{N} \cdot 2gJ$

- Blade material density

- Blade taper ratio

- Blade volume factor

Two alternative procedures can be used to size the turbine: (1) specify maximum diameter of the first stage and find the number of stages from the work loading parameter, or (2) specify the number of stages and the diamter of the first stage is found from the work loading parameter. Shaft speed is transferred from the corresponding compressor; and in the case of (1), the number of stages is found by iteration until the resultant tip diameter is equal to or less than the specified diameter. Equal work per stage is assumed. Total component work and state conditions are taken from the NNEP stored cycle data.

To determine blade height, the flow area necessary to pass the corrected airflow is calculated at the inlet of each stage. When the first stage inlet Mach number is different from the last stage exit Mach number, a proportionate change is assumed for inlet Mach number of the other stages. Hub radius of the first stage is found by subtracting from the stage-projected area the exit-flow area required to satisfy the specified exit Mach number. Dimensions of the remaining stages are then determined from the design mode specification and the calculated exit area.

Aspect ratio and number of blades are determined by the same method used in determining the compressors. Blade volume is also determined by the same method, Equation (3), except that K = 0.195. When the blade is a cooled blade (normally HP turbine blades with relatively low-aspect ratio), the calculated volume is reduced 20% to compensate for cooling-air passages. Blade weight is then found from the specified material density. Blade-pull stress is calculated by Equation (7).

In a manner similar to the compressor discs, turbine discs were measured in the data base engines to produce the results shown in Figure 11. The rim loading parameter $\left(\sigma_{BP} \times R_n\right)$ was modified by dividing by the 0.2% yield strength (at the max. operating temperature) of the particular material used in each disc. There are many different steel alloys and superalloys that have different strength capabilities for which this correction compensates. Each disc has a different operating temperature, maximum allowable stress, and design life. These factors and other unknowns, such as the effect of hub tip ratio, are believed to be the primary cause of the data scatter. The best-fit curve shown in Figure 11 is used in WATE-2, unless the optional procedure is used where the discs are calculated by a preliminary design procedure developed primarily for small engine discs. This method is recommended because it includes the effects of blade aspect ratio and disc stress level.

The relative disc thickness is found from Figure 11 with the calculated independent variable $\left(\sigma_{BP} \times R_n\right)$. Disc volume is found by multiplying the relative thickness parameter (V/D_h^2) by D_h^2. Blade-material density is an input; however, disc material is assumed to be steel or superalloy with 0.286 density. Since all of the data base engines used steel or superalloy discs, correlations of other materials could not be made.

Each stage of the turbine is treated as a stator-rotor pair (as opposed to rotor-stator pair in the compressor. Stator blades are also assumed to have the same number, volume of material, and dimensions as the rotor blades. The stator weight is calculated by Equation (3), with K=0.144. Stator-rotor spacing is the same as compressors, 17% of the rotor length. Stator AR is taken to be 83% of the rotor blade AR.

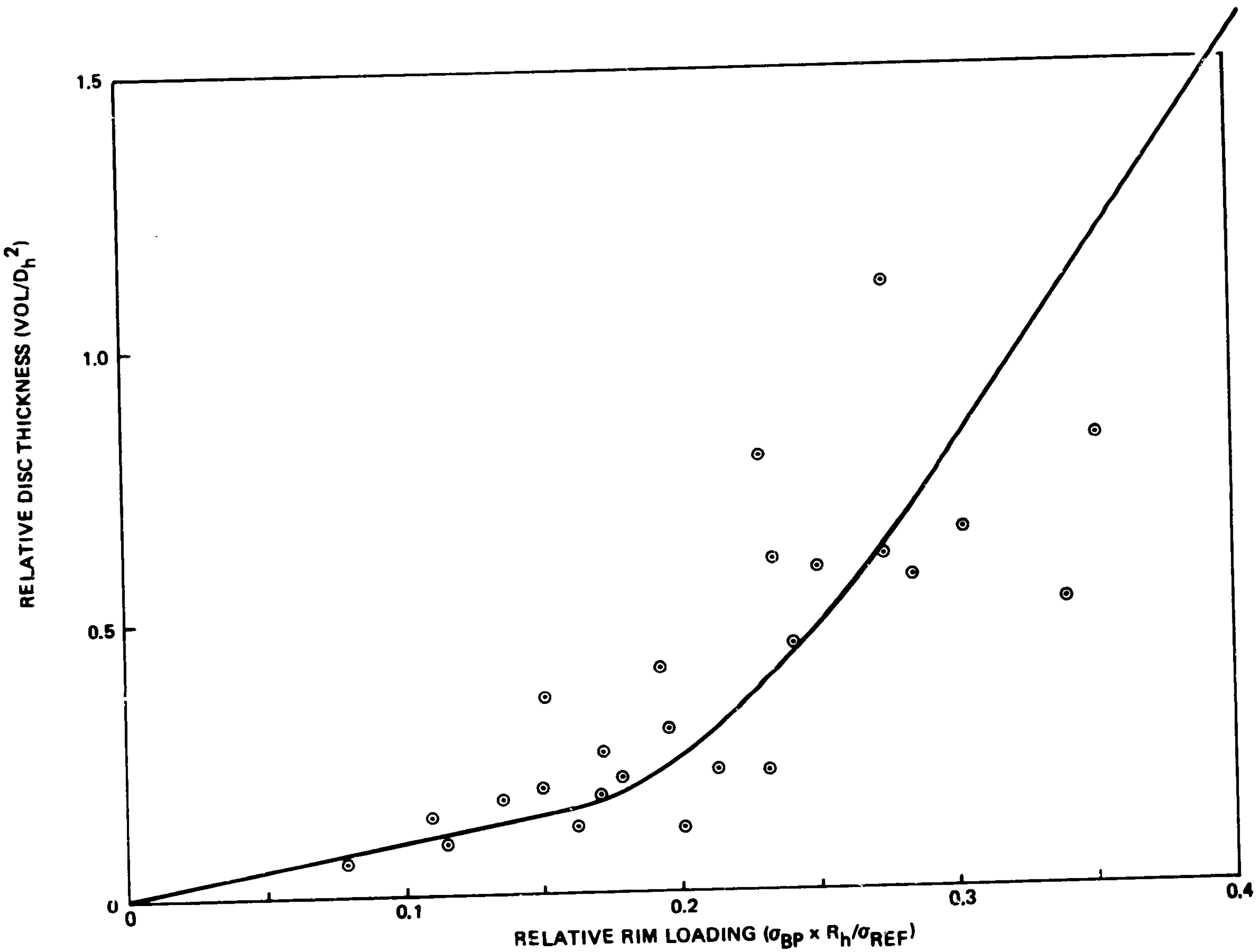


Figure 11. Data Base Engine: Turbine Disc Volume Correlation

Connecting hardware and case weight are also determined by the same method as used in the compressors. The total weight and length of the turbine component is the sum of disc, 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.

1.1.3 Ducts

It is assumed that the major structural load in a duct is a result of the internal pressure. Also, it is assumed that the inner wall of the duct is the same gage as the outer wall. In the data base engines the outer surface of the OD walls were typically exposed to ambient pressure. The ID wall was subjected to fan pressure, hp compressor exit pressure, etc., and ΔP for the ID wall could not be generalized. Figure 12 illustrates the duct and nomenclature.

The equation for stress on a longitudinal section of a thin-walled cylinder subjected to an internal pressure is:[3]

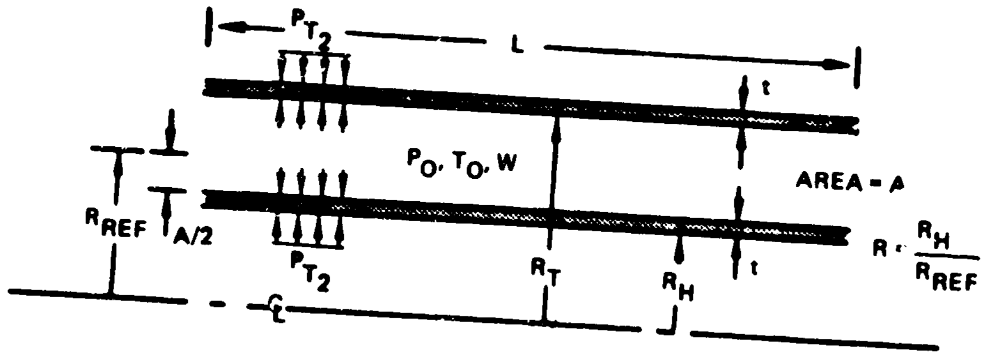
$$\sigma = \frac{P\ D_o}{2t} \tag{13}$$

and for solving for minimum thickness:

$$t_{min} = \frac{P\ D_o}{2\ \sigma} \tag{14}$$

where σ is the allowable for the material, p is the internal total pressure, and D_0 is the duct outside diameter.

Ti is assumed with 50,000 lb/in^2 allowable at temperatures below 700^0F, and steel is assumed at 70,000 lbs/in^2 above this temperature. The appropriate material is selected based on the total temperature of the duct airflow. The weight is calculated as a function



$$A = \frac{W_C}{\left(W_{C/A}\right)} = 2\pi R_{REF}^2 (1 - R^2)$$

SOLVE FOR R_H AND R_T

MATERIAL IS DETERMINED FROM T_O $\quad T_O < 1{,}160^oR - T_i$

$T_O > 1{,}160^oR$ STEEL

$\sigma = \frac{P_O R_T}{t}$ SOLVE FOR t WITH SPECIFIED σ

$$W_{T_{DUCT}} = 2\pi (R_T + R_H)\, t \rho_{MATL} L$$

Figure 12. Duct Schematic

of duct length (L), the inner diameter (D_i), and the outer diameter (D_O):

$$W_{DUCT} = \pi (D_o + D_i) L \rho t_{min} \tag{15}$$

Duct Mach number is specified as an input, and corrected airflow is determined from the NNEP cycle data. ID and OD are determined as a function of 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[3] for lap-welded steel tubes:

$$P_{MAX} = 1000 \left[1 - \sqrt{1\text{-}1600 \left(\frac{t}{D}\right)^2} \right] \tag{16}$$

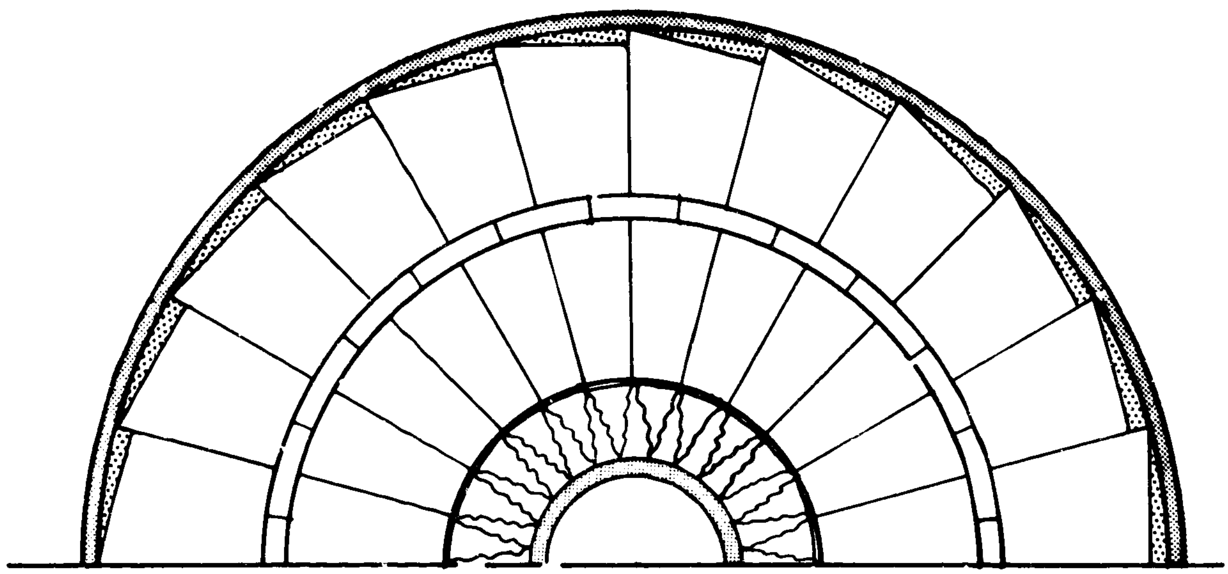
or expressed in terms of minimum wall thickness:

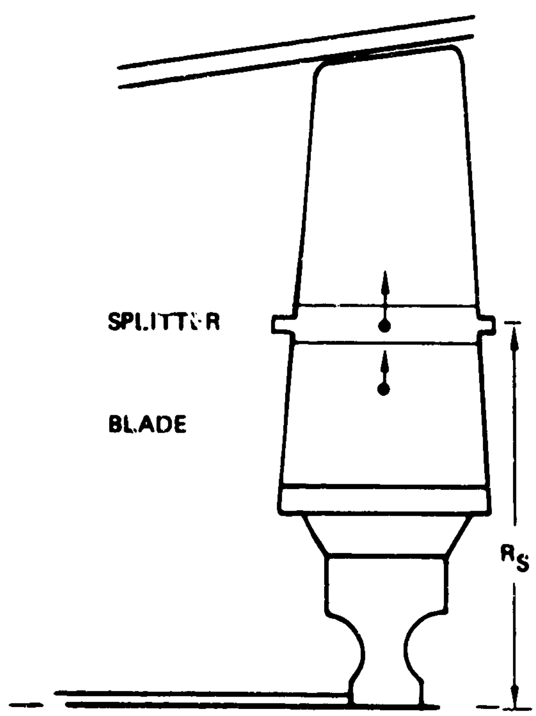
$$t_{min} = \frac{D}{40} \sqrt{1 - \left(\frac{1 - P_{MAX}}{1000} \right)^2} \tag{17}$$

WATE-2 does not perform the above calculation to determine whether collapsing pressure sizes the ID wall. It also does not check to determine whether the gage selected is less than minimum gage.

1.1.4 Rotating Splitter

A rotating splitter, Figure 13, is a circumferential separator of two flows within the same compressor. These flows normally have different pressures and temperatures, and the splitter must perform a sealing





$$F = ma = \sigma A_{ROOT}$$

$$\Delta\sigma_{RIM} = \frac{2\pi}{NB}\,\rho_{MATL}\;U_S^2$$

$$\Delta W_T = 2\pi\left(\frac{T}{C}\right)\frac{b^2}{AR^2}\;\rho_{MATL}\,R_S$$

$\frac{T}{C}$ = .1 FOR WEIGHT

U_S = SPLITTER SPEED
NB = NUMBER OF BLADES
AR = ASPECT RATIO
b = BLADE HEIGHT
ρ_{MATL} = MATERIAL DENSITY

Figure 13. Rotating Splitter

function. Stages that incorporate rotating splitters are treated the same as compressors; a rotor-stator pair comprises one stage, stator weight and size is assumed to be the same as the rotor blade, and rotor-stator spacing is 17% of rotor length.

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

$$W_{SPL} = \frac{2\pi R_S\ C^2 \times .10}{N_B}$$

where C is the blade chord found by Equation (5) and R_S is the radial location of the splitter.

Thickness of the splitter is assumed to be 10% of 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% of chord. A more accurate estimatr can 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:

$$F = MrW^2 = \frac{W_{SPL}}{g} \times R_s \times \left(\frac{2\pi \times RPM}{60.}\right)^2 \tag{18}$$

where RPM is the shaft speed determined in the same manner as compressors. Blade pull stress (Equation 7) is increased by the amount

$$\Delta\sigma_{BP} = \frac{F_{SPL}}{A_B} = \frac{F_{SPL}}{C_B{}^2 \times t/c} \tag{19}$$

where C_B is determined by Equation (5) and t/c is the thickness ratio of the blade (which is assumed to be 10%). Disc weight is determined with the increased stress level using the disc volume correlation, Figure 9.

Shaft speed determination (as described in Section 1.1.1) is only an estimate, and it assumes that blade-root stress is subcritical. Use of a rotating splitter will cause the blade-pull stress to increase significantly, and the WATE-2 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, a larger number of stages will be required to accomplish the same work. Alternatively, the radius ratio of the compressor (or turbine) can be increased to restore work capacity (due to higher tip speed). Disc weight of each stage will increase for this compromise, however. The final choice must be iterated external to WATE-2 and may depend on whether or not the flow path is reasonably well matched to connecting components (such as the HP turbine and LP turbine flow path). These secondary effects may have a much larger impact on engine weight than will the weight of the splitter material, and they should not be ignored.

1.1.5 Burners

This method is based on a calculated volume of materials, similar to the duct method except for the addition of wall liners and fuel manifold and nozzles, as shown in Figure 14. It is used for primary burners, as well as duct heaters, and afterburners. Differences in configuration of these different types of burners are reflected in the specified residence time, through-flow velocity, and type of burner. When a primary burner is specified, a frame weight is added (see Section 3.7). Primary burners and duct heaters require an input mean radius of the annular flow paths while the afterburner is assumed to have no inner wall, i.e., zero radius ratio.

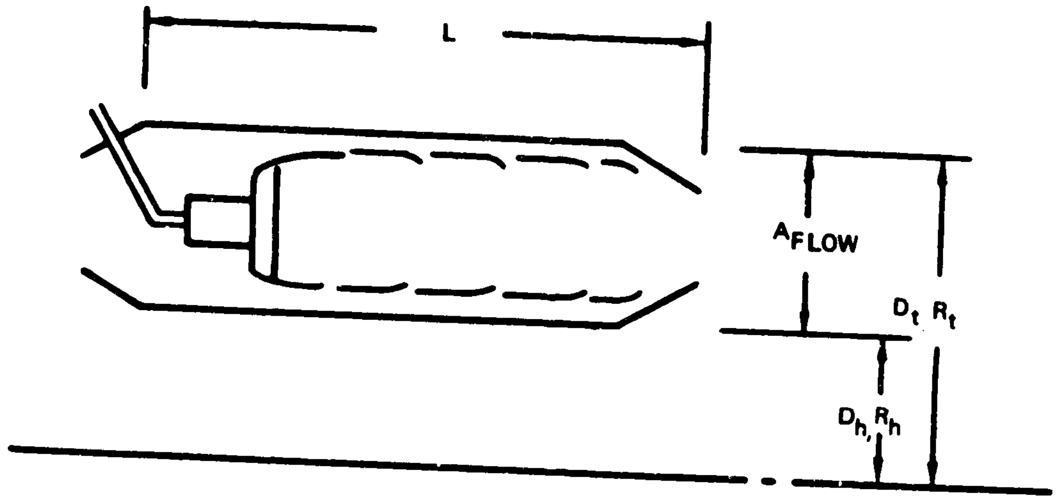


Figure 14. Burner Schematic

Burner flow area is determined from the input velocity, the mean radius, and the entry-corrected airflow from the NNEP cycle data. Burner length is found to give the specified residence time based on the input velocity and entry conditions.

Flow area is used to obtain the inner and outer dimensions of the burner (R_t and R_h) with the specified mean radius located at mid-area. Outer-case thickness is determined by Equation (14). The same thickness is used for the inner case. Material assumed is steel with 70,000 lb/in^2 allowable stress. Weight and volume of material for the inner and outer cases are found by Equation (15), using burner length (L).

Liner weight is determined in a like manner, assuming 0.055-in thick steel walls, located at 20% of passage height from the inner and outer case. The burner dome, fuel manifold, fuel nozzles, and other components are estimated by typical geometry taken from the data base engines as determined by the following equation:

$$W_{DOME} = .0106 \; (R_t^{\,2} - R_h^{\,2}) \qquad (20)$$

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

1.1.6 Shafts

A shaft is assumed to be the power connection between components, see Figure 15. Multiple stages within a compressor or turbine are also connected by a shaft; however, this weight is included in that component's weight buildup.

The required inputs are:

- o The component numbers connected (to determine length, power transmitted and shaft speed).
- o The shaft material density and allowable stress.
- o Radius ratio (of the inner shaft only).

Multiple concentric shafts can also be specified, and will be sized around the inner shaft with 0.20 in radial clearance assumed.

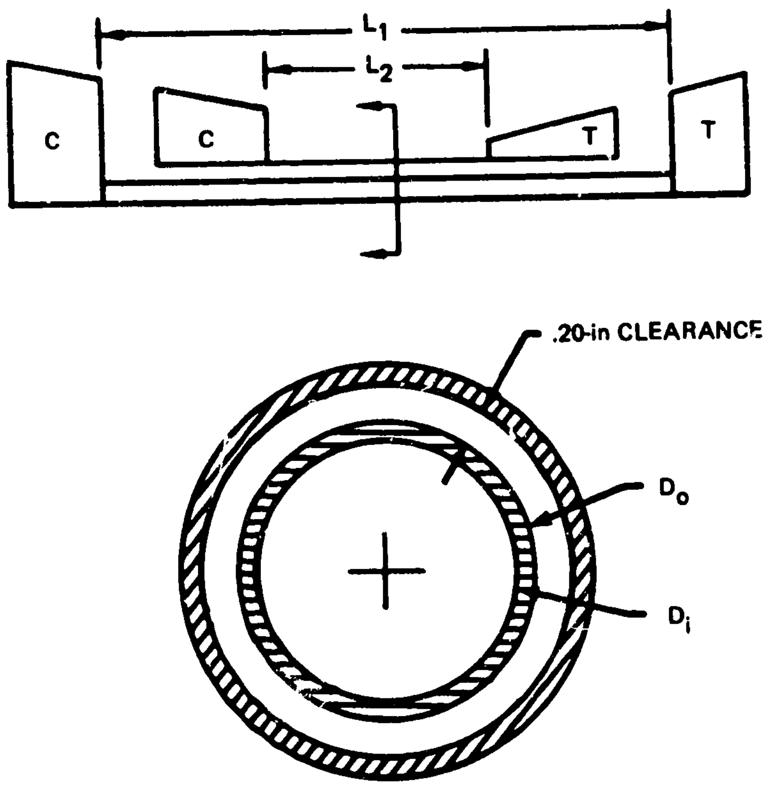
Dimensions of the inner shaft are determined to provided the necessary torque capability at the specified allowable stress. Total shaft power is the summation of work (ΔH) for all turbines on the shaft. Torque is calculated by:

$$T = \frac{\Sigma \Delta H}{\omega} \times J \qquad (21)$$

where ω is the shaft rotative speed, rad/sec.

Shear stress due to the torque load is defined by[3]:

$$\tau = \frac{16\, T\, D_o}{\pi \left(D_o^4 - D_i^4\right)} \qquad (22)$$



ENLARGED SECTION OF CONCENTRIC SHAFT

Figure 15. Shaft Schematic

or in terms of the input diameter or radius ratio (D_i/D_o):

$$\tau = \frac{16T}{\pi D_o^3 \left[1 - \frac{D_o^4}{D_i^4}\right]} \tag{23}$$

Solving for D_0 in terms of allowable stress (σ_{all}):

$$D_o = \left\{ \frac{16T}{\pi \tau \left[1 - \frac{D_o^4}{D_i^4}\right]} \right\}^{1/3} \tag{24}$$

Weight is then found by :

$$W = L \rho \pi \frac{D_o^2}{4} \left[1 - \frac{D_o^2}{D_i^2}\right] \tag{25}$$

A similar procedure is used for concentric shafts. The second shaft's inside diameter is found by adding 0.40 in to D_0, and Equation (24) is solved by iteration.

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.

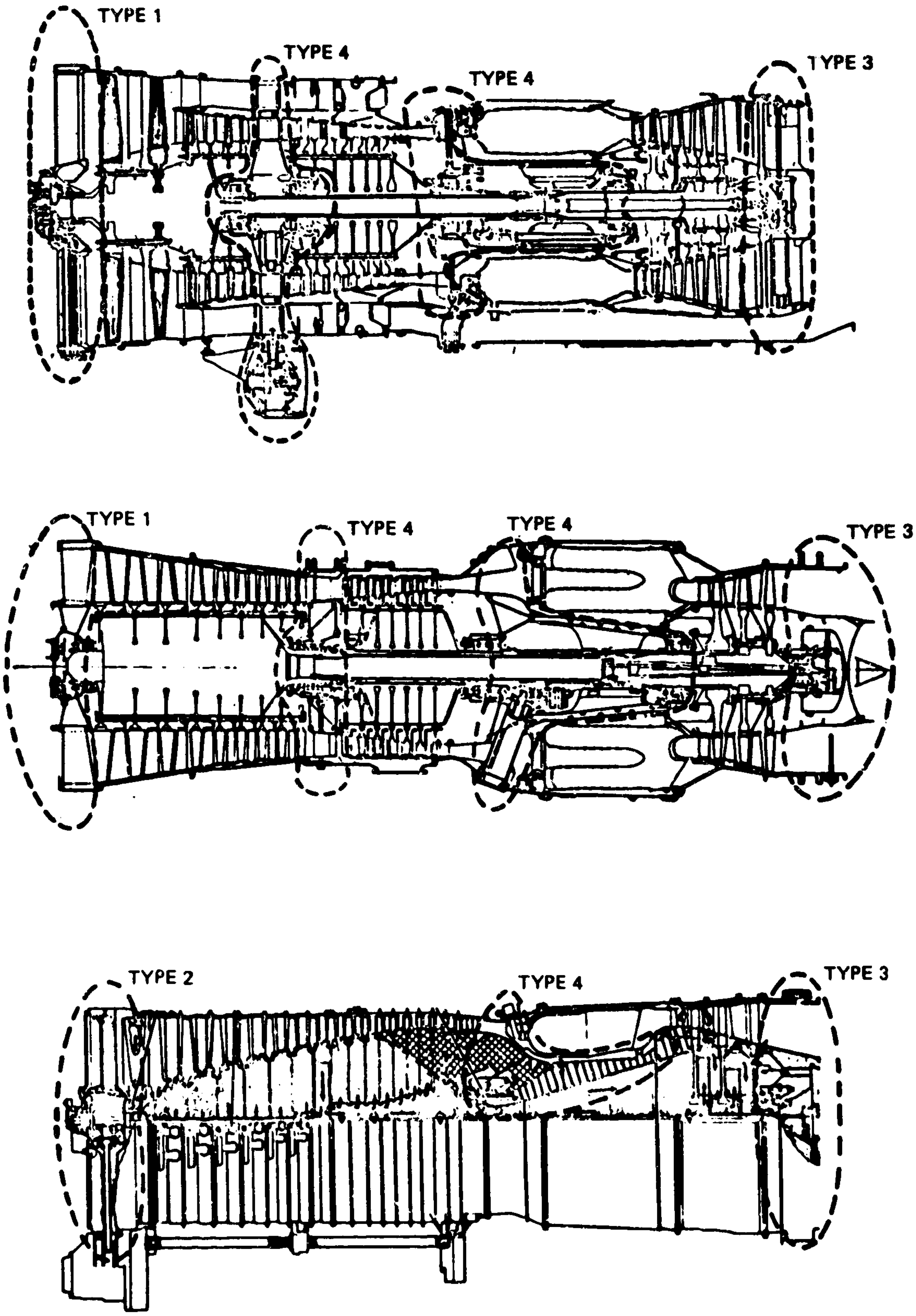


Figure 16. Frame Types

1.1.7 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 16) 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-2 has been developed.

It has been found, however, that the frame weight of the data base engines correlates well with the total frame-projected area. These data are shown in Figure 17 for four types of frames commonly used: single-bearing frames with and without PTO, turbine exit, and intermediate. Frame weight is determined from these data, based on the local diameter and the type of frame specified.

1.1.8 Nozzles

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-2 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, i.e., C or C-D. An effective surface area is calculated based on the diameter of the connecting component and the specified length.

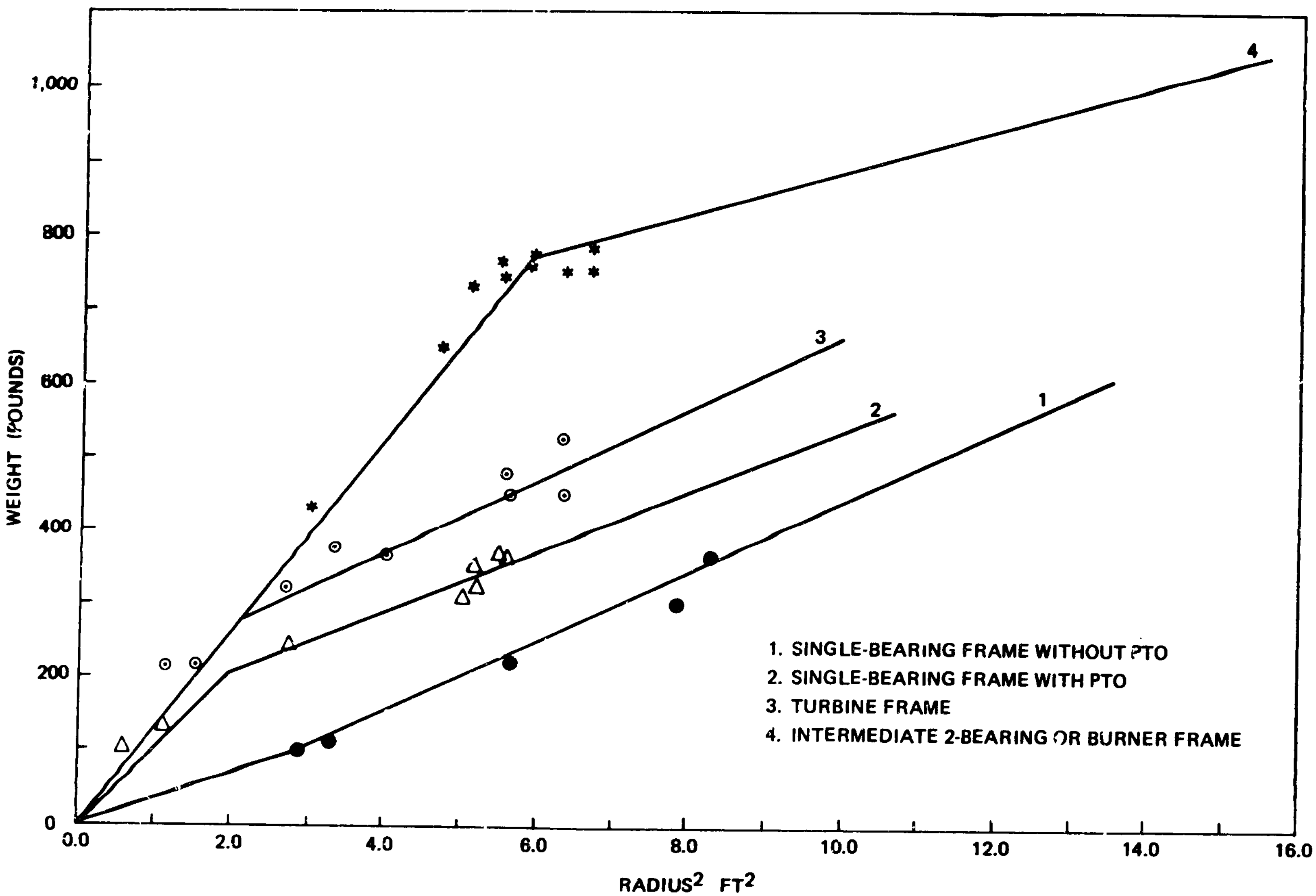


Figure 17. Frame Weight

Only circular, conical nozzles are assumed, however, coannular nozzles could 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. Wall thickness is assumed to be 0.10-in steel above 700°F and Ti below 700°F. Variable nozzles are calculated in the same manner except that the effective wall thickness is 2.75 times that of the fixed nozzle.

1.1.9 Mixers

A mixer is a device placed at the point of confluency of two coannular streams to increase the mixing boundary so that thermal mixing takes place in a minimum length. This type of mixer is sometimes called a daisy-mixer, chute-mixer, or forced-mixer.

Flow area of each annular path is taken from the NNEP cycle data, and the inlet radius (Ri) of the upstream component is used as a starting point for locating R_{mid} and R_0, as shown in Figure 18. Normally Ri will be the hub radius of the last turbine stage.

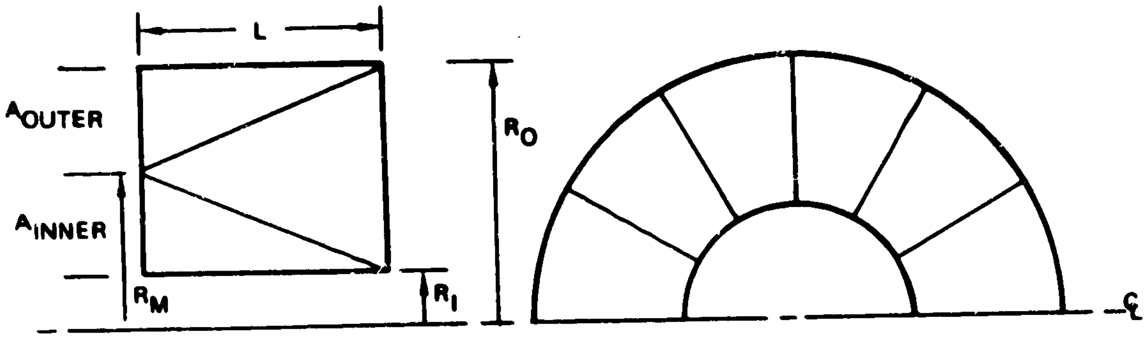
Mixer length (L) and number of passages (N) are required inputs. The following relationship has been developed that is representative of the surface area of typical mixers:

$$S = \left[3.93\ R_M + 1.25\ (R_o - R_i)\right] L \qquad (26)$$

material assumed is 0.10-in thick steel.

1.1.10 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 19 shows a typical example of an AIV. This AIV was designed to vary the bypass ratio in a JT8D engine.



RM IS BASED ON INNER AREA AND R_I

$L_{SP} \equiv L \quad 2A/\pi$ ~ INPUT

$A = A_{OUTER} + A_{INNER}$

L IS DETERMINED

$WTM = (K_1 \times R_M + 1.25 \times N\ (RO - RI)) \times L \times K_2$

$K_1 = 3.927 \quad K_2 = .028$

Figure 18. Mixer Schematic

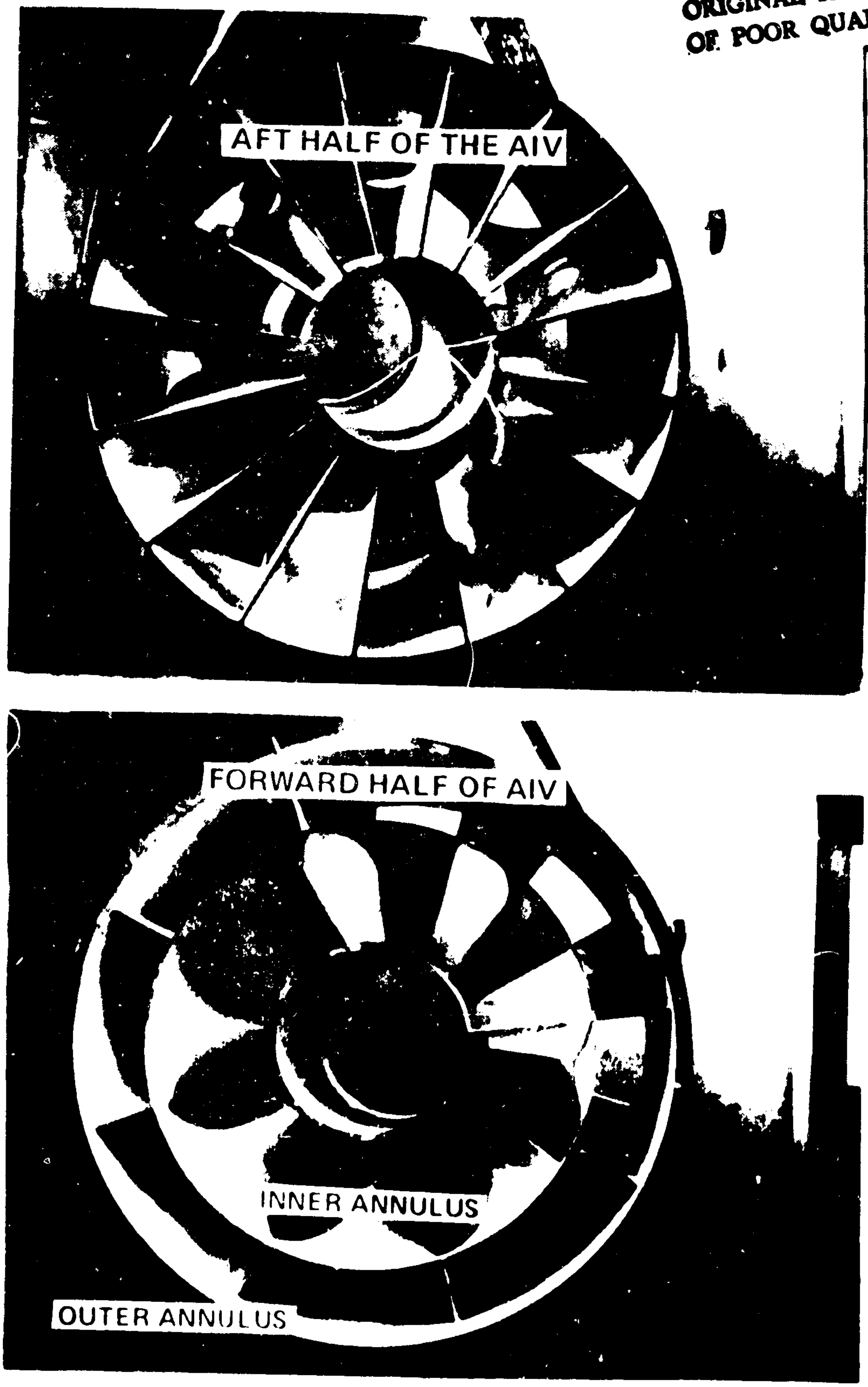


Figure 19. Typical Annulus Inverting Valve: JT8D Variable-Bypass Engine Test

The AIV weight method assumes a construction similar to that shown in Figure 19, except that instead of sheet-metal, the material is assumed to be Ti honeycomb at 1.1 lb/ft^2 below 700^0F and steel honeycomb at 1.87 lb/ft^2 above 700^0F. If desired, different materials can be specified.

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

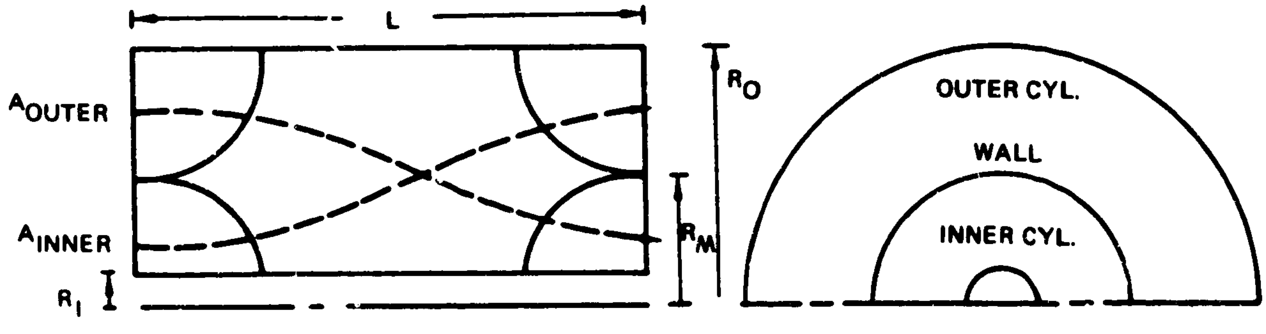
$$W_{AIV} = L \times \frac{W}{A} \left[2\pi R_i + 2\pi R_o + 3.93 R_M + 1.25 (R_o - R_i) \right] \quad (27)$$

where R_i 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 entry corrected airflow (see Figure 20). The number of passages (N) is an input, and material weight per square foot (W/A) is selected depending on the stream temperature. Length (L) of the AIV is calculated from the input specific length, L_{SP}:

$$L = \frac{L_{SP}}{\sqrt{4A/\pi}} \quad (28)$$

Specific length is preferred as an input because it is nondimensional, and it is a major variable that determines AIV pressure loss. A relatively good compromise between size and performance is achieved when N=3 and L_{SP}=0.8 to 1.0, which results in a pressure loss between 2.5% and 1.5%.

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% of total AIV weight. Additional structure to support the rotating half is not incuded and should be represented as an additional frame.



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

FROM MACH INPUT

A_{INNER} AND A_{OUTER} ARE FOUND

L IS DETERMINED

$WTIC = 2 \cdot R_I \cdot L \cdot WTSI$

$WTOC = 2 \cdot R_O \cdot L \cdot WTSO$

$WTWALL = (K_1 \cdot R_M + K_2 N (R_O - R_I)) \cdot L \cdot WTSW$

WTSI, WTSO AND WTSW ARE MATERIAL WEIGHT IN lb/ft^2

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

$K_1 = 3.927 \quad K_2 = 1.25$

Figure 20. Annulus-Inverting Valve Schematic

1.1.11 Transmission

A method of estimating the weight of various types of gear systems has been previously developed by Schmidt.[4] This method is used in WATE-2 for gear sets that are typically used in aircraft.

The equation for the total gear box weight is:

$$W = 324 \left(\frac{SHP}{RPM}\right)^{.80} \tag{29}$$

1.1.12 Thrust Reversers

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

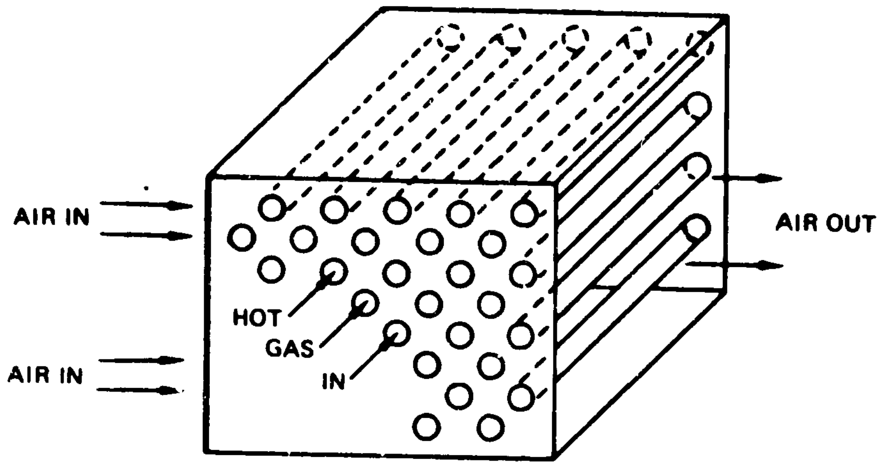
$$W = \left[K_1 \times \frac{W\sqrt{\theta}}{\delta} + K_2 \right] \left[K_3 P_R + K_4 \right] \tag{30}$$

where hot streams $K_1 = .52$, $K_2 = 423$, $K_3 = 1.004$ and $K_4 = -.5054$. For cold streams $K_1 = 2.22$, $K_2 = 11.0$, $K_3 = .23$, and $K_4 = .56$.

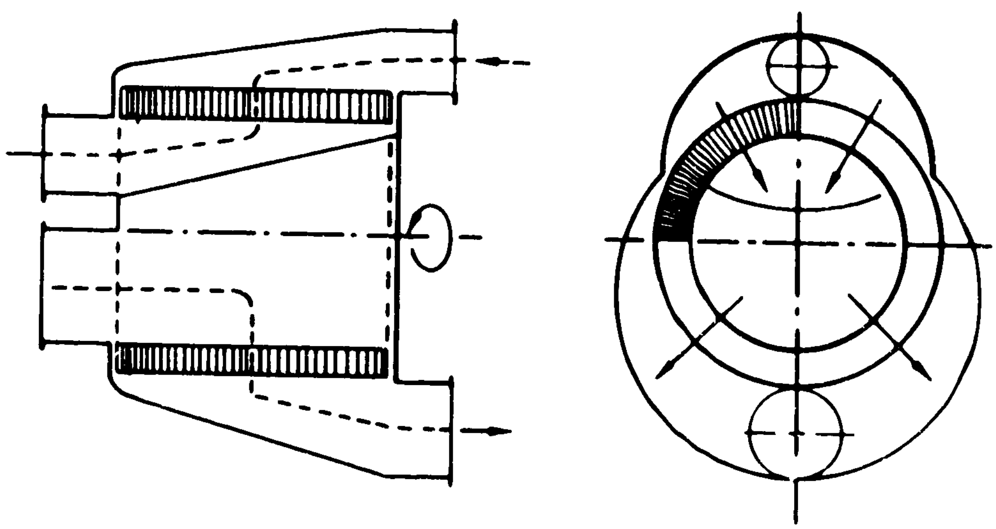
The WATE-2 method will apply the cold stream equation to a fan stream whether or not it is heated by a duct burner. The hot stream equation is used for turbine outlet streams or mixed-flow exhaust streams.

1.1.13 Heat Exchangers

Both rotary and fixed heat exchangers can be estimated. Methods previously developed produce adequate results for preliminary design purposes, see Figure 21.



FIXED-TUBE HEAT EXCHANGER



ROTARY HEAT EXCHANGER

Figure 21. Heat Exchangers

For rotary heat exchangers, a ceramic core is assumed. Weights of this type ofheat exchanger have been determined by the Corning Glass Company[5] and are represented in Table 2 for various levels of effectiveness and pressure loss. These data are developed for a total corrected airflow of 200 lbs/sec. For other sizes, the weights are scaled directly with corrected flow.

Fixed-tube heat exchangers are estimated by a heat transfer analysis[6] whereby 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.

Wall thickness of the tubes is determined by Equation (14) to satisfy an assumed allowable stress of 50,000 lb/in^2 and a density of 0.168 below 700^{o}F. A stress of 70,000 lb/in^2 and a density of 0.286 is assumed above 700^{o}F. The length of tubes is determined to satisfy the surface area requirement.

Table 2. Ceramic Rotary Regenerator Weight

200 lb/sec corrected weight flow						
BPR	3		7		10	
$\Delta p/p$ (%)	5	10	5	10	5	10
Weight (lb)						
ϵ = 80%	674	542	628	445	600	423
85%	971	754	914	640	834	617
90%	1,622	1,188	1,428	1,085	1,313	994

Fixed-tube heat exchanger tube weight (W_t) is then found by

$$W_t = \rho L_t \pi (R_o^2 - R_i^2) \qquad (31)$$

where R_o and R_i are the tube radii and L is the total length required. Casings, mounting hardware, manifolds, and other equipment that may be necessary are assumed to be equal to W_t. Total heat exchanger weight is $2W_t$.

1.2 Small Gas Turbine Engines

Discussed in this section are all of the components that are unique to small gas turbine engines. These include centrifugal compressors, radial turbines, axial compressors, axial turbines, burners, cross-over ducts, diffusers, compressor shroud, gear box, and rear frame. Some components utilize the same methods as used for the large engines, and these are noted in the discussion. A typical small-engine is shown in Figure 22, where the major components are identified.

1.2.1 Centrifugal Compressors

The following input data are required for centrifugal (radial) compressors:

- o Entry axial Mach number
- o Max first stage pressure ratio
- o Radius ratio of the inlet hub to the inlet tip
- o Shaft overspeed factor

If the specified overall pressure ratio is greater than the max allowable first stage pressure ratio, another stage is added and the work is divided equally. Stages are added until the first stage pressure ratio is less than the max allowed. Tip speed of the second stage of multiple stages is taken to be 98% of the first stage tip speed.

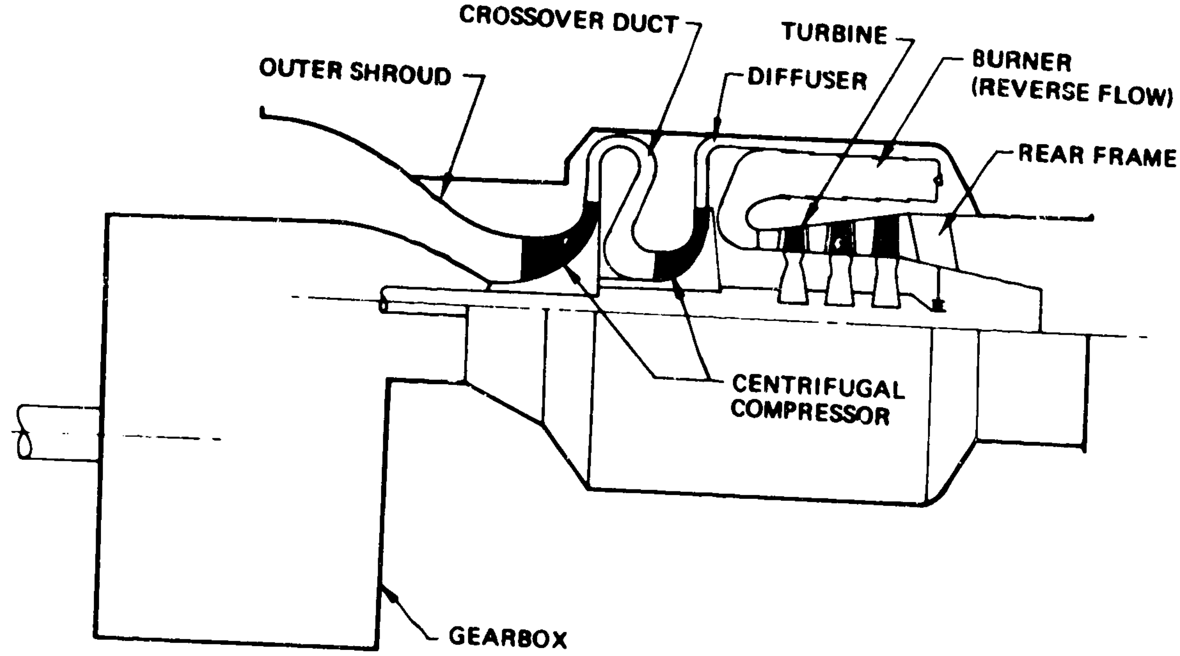


Figure 22. Small Engine Components

Hub and tip radii of the entry are found from the input radius ratio, the entry corrected airflow, and the entry Mach no. The tip radius of the outlet of centrifugal compressors is assumed to be 3 times the hub radius of the entry, which is typical for wheels from 10 to 20 in. diameter.

Corrected tip speed is found from the calculated pressure ratio of the stage, Figure 23, and shaft speed is then found from tip radius and tip speed.

The shaft speed will normally be set by turbine stress. Since turbine stress is a fall-out calculation in WATE-2 (for axial turbines only), it should be checked to see if it is reasonable, and the input radius ratio should be adjusted if necessary to change the calculated shaft speed.

Centrifugal compressors are assumed to be titanium and the weight is found as a function of tip radius, Figure 24. Length and rotational inertia are found similarly, Figures 25 and 26. Figure 26 also compares the inertia of radial turbines.

1.2.2 Radial In-Flow Turbines

The tip radius of radial turbine wheels is found by the inlet corrected airflow, Figure 27. The technology level, current or advanced, must be specified. Length of the impeller is found from Figure 28, as a function of the tip radius.

Steel turbine wheels are assumed, and the weight and rotating inertia are determined from tip radius, Figures 29 and 26, respectively.

1.2.3 Axial Compressors and Turbines

This method is identical to the large gas turbines except for the disc weight calculation procedure. No additional inputs are required, except for the input which activates the optional disc procedure. It was found that the previous disc weight correlations were not applicable to small diameter discs. Typically, the small discs were 3 to 4 times heavier (or

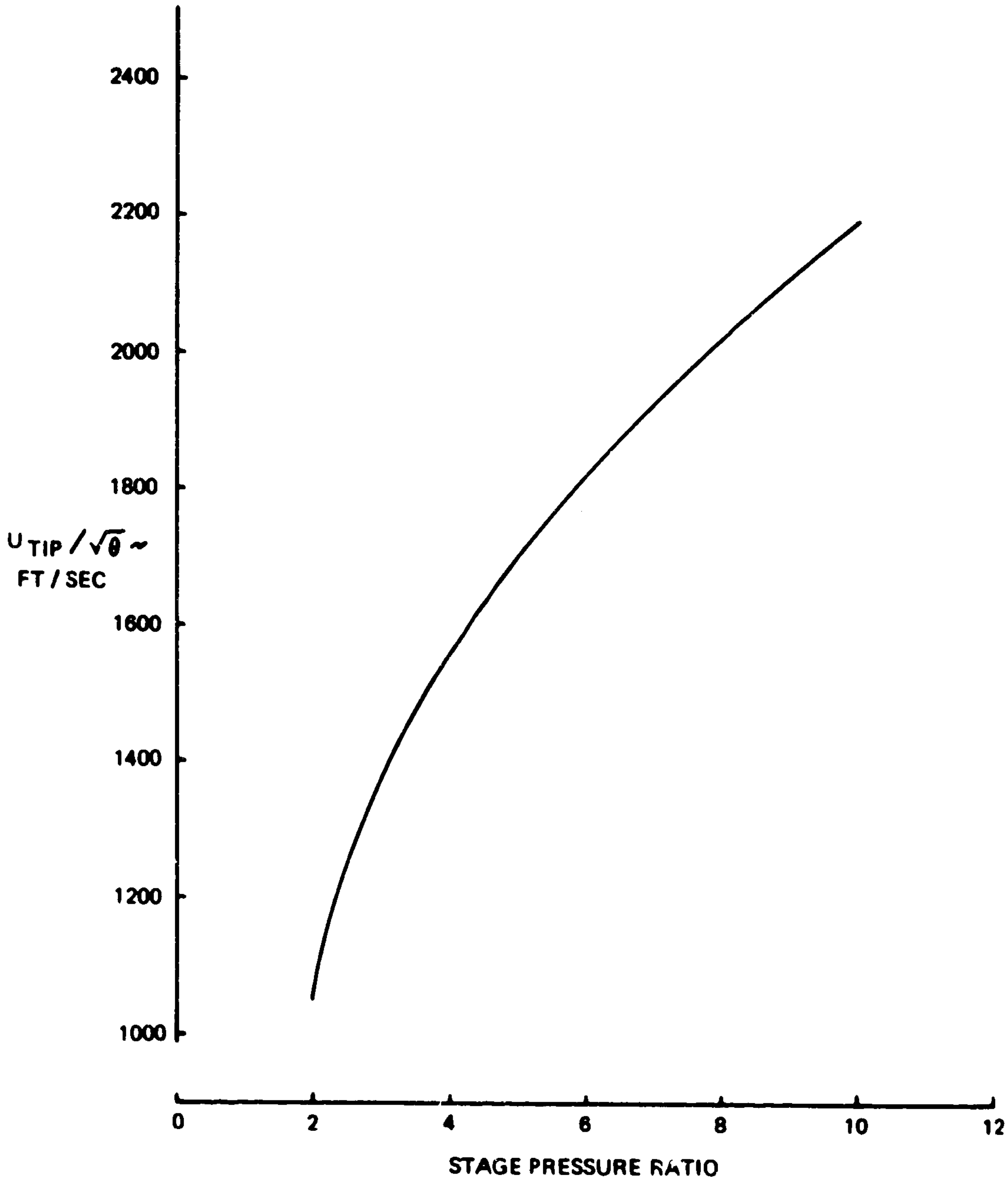


Figure 23. Corrected Speed of Centrifugal Compressors

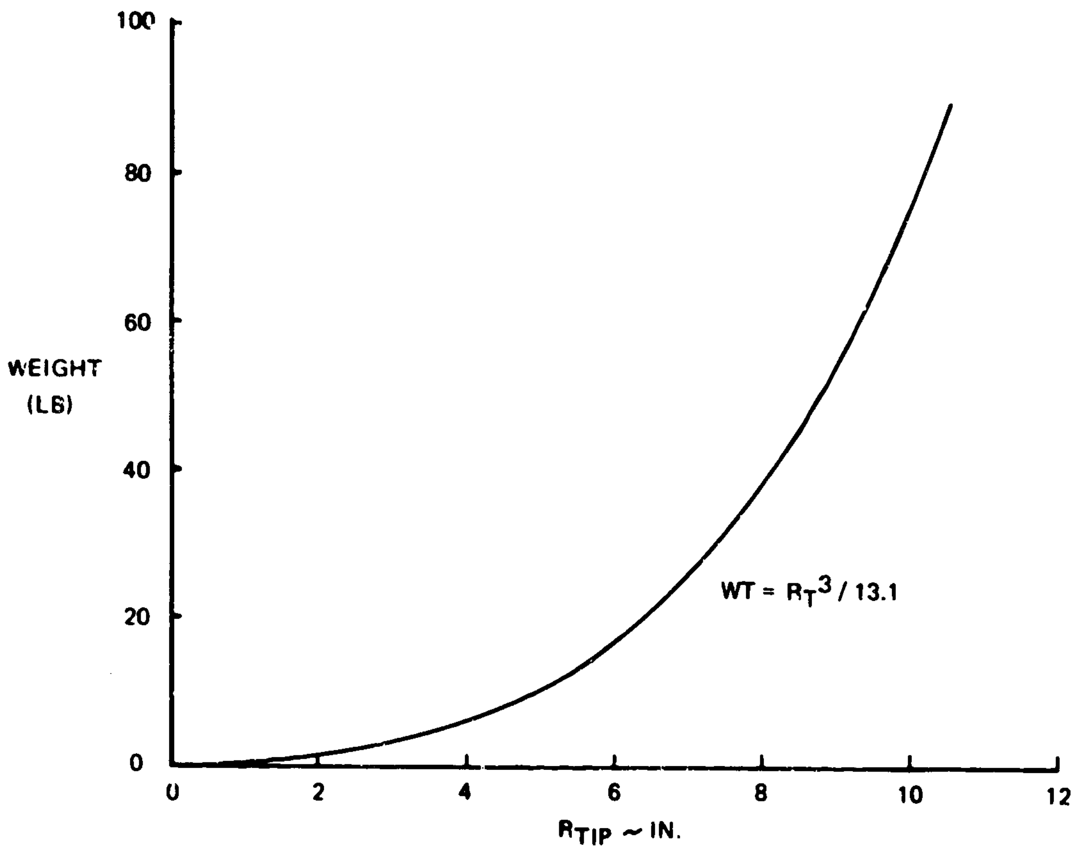


Figure 24. Weight of Titanium Centrifugal Compressors

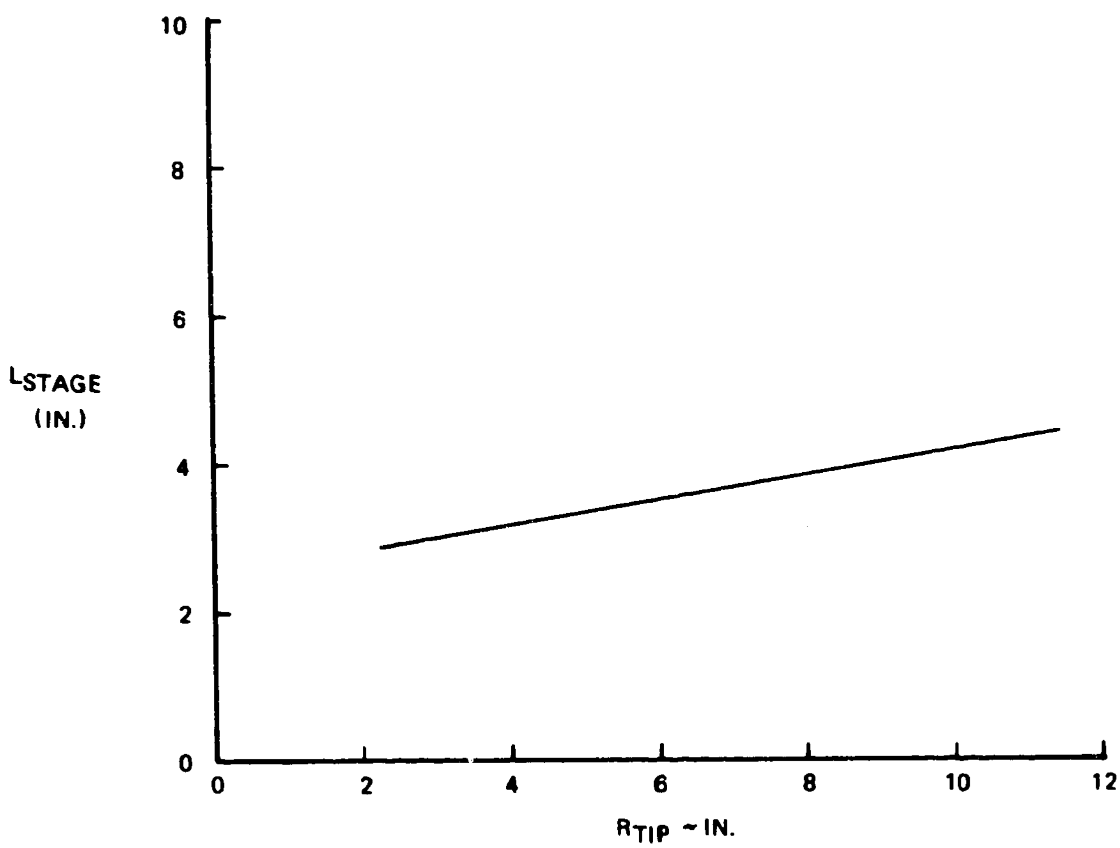


Figure 25. Length of Centrifugal Compressor Stage

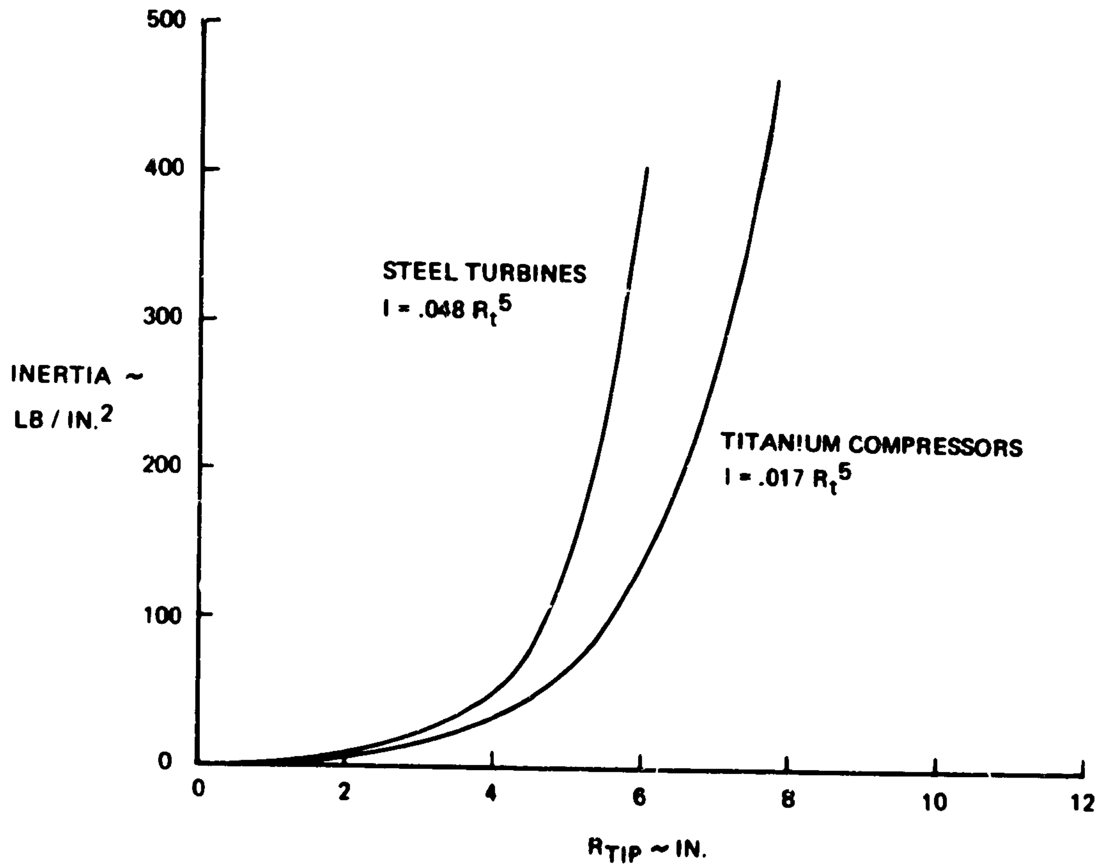


Figure 26. Rotating Inertia of Centrifugal Compressors and Radial Turbines

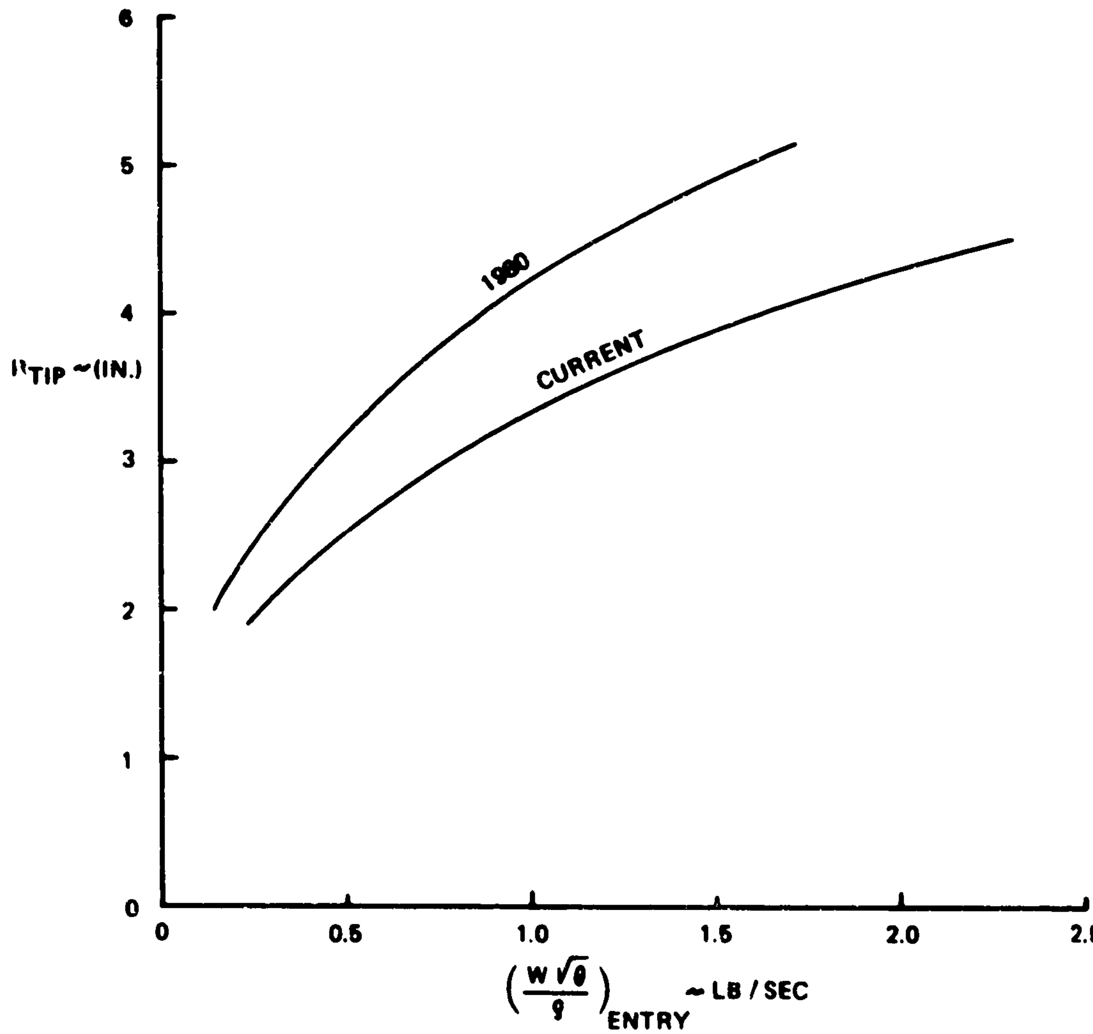


Figure 27. Tip Radius Estimate for Radial Turbines

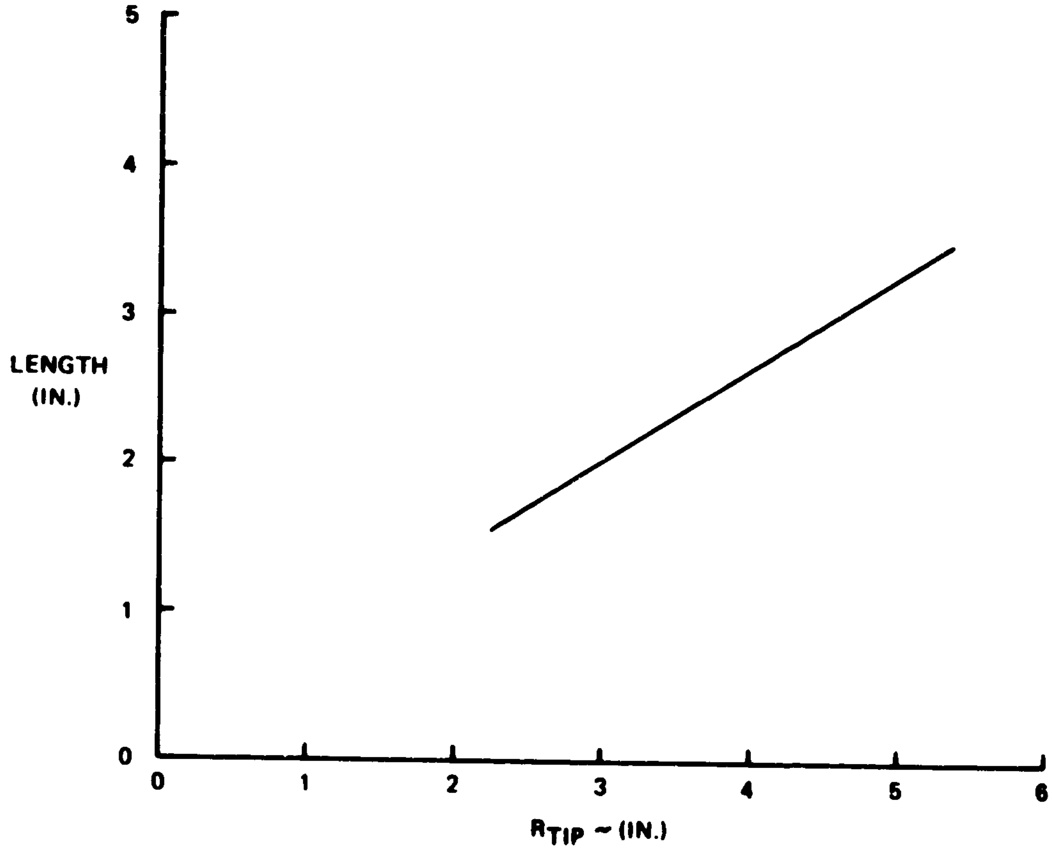


Figure 28. Length Estimate for Radial Turbines

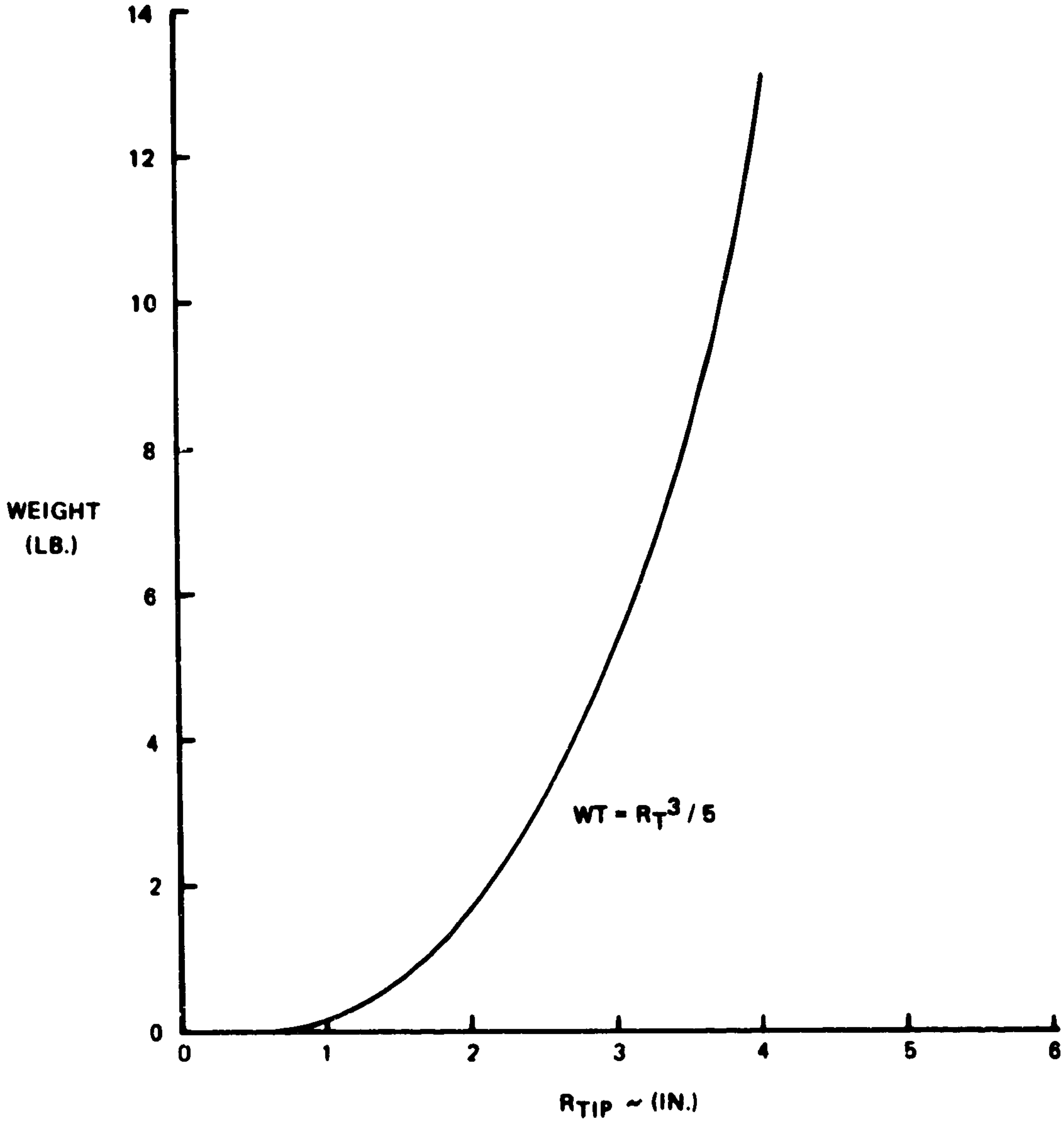


Figure 29. Weight Estimate for Radial Turbines

thicker) than would be predicted by the original method. A new method was developed specifically for small-engines. It is also applicable to large engines, and may provide improved accuracy.

An inserted blade is assumed, and the disc material is assumed to be Ti or steel forgings with ultimate strengths of 120,000 and 160,000 psi respectively. The rim of the disc is assumed to be 10% of the blade hub radius or .75 in, whichever is greater. The remaining disc 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% of the ultimate strength. Thickness of the trapizod at the inner radius is based on 50% of ultimate strength for the tangential stress. This value is selected based on an experimentally determined burst speed margin.

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

Stresses are calculated based on the total blade force acting on the outer circumference of the disc, and it is therefore sensitive to changes in blade aspect ratio and solidity as well as blade pull stress and hub radius. The original method is not sensitive to aspect ratio or solidity.

1.2.4 Crossover Duct Integral with Diffuser

This component is only used to connect two centrifugal compressors, and it has an integral diffuser. The diffuser outside diameter (D_o) is taken to be 1.6 times the first impeller diameter and the length (L) is assumed to be 20% of the diffuser diameter. Weight of the crossover duct is estimated by the following relationship:

$$WT = 33.5\ L \times D_o \qquad (32)$$

where L and D are in ft.

1.2.5 Diffuser

A diffuser is required when only one centrifugal stage is used. It is normally feeding into a burner directly from the compressor. The outside diameter of the diffuser is also 1.6 times the tip diameter of the impeller, and the length is 7% of the diffuser diameter. The weight is expressed by:

$$WT = 32.8\ L \times D_o \tag{33}$$

1.2.6 Rear Frame

For small gas turbines, a turbine exit frame is normally required to support the turbine bearing, radial loads only. The front frame and front bearing take the thrust loads, and this is sometimes an integral part of the gearbox. The following equation is used to estimate the weight of the rear frame, which includes the tailpipe and nose cone:

$$WT = 55.5\ R_t^2 + 6.53 \tag{34}$$

where R_t is the turbine tip radius (ft).

1.2.7 Centrifugal Compressor Housing

This item is similar to the outer case in an axial compressor. Weight is based on the length and the tip radius (R_t) of the impeller:

$$WT = 163 \times L \times R_t \tag{35}$$

1.2.8 Gearbox and Accessories

The existing transmission weight method will give satisfactory results for small engines. Accessory weight however is a significantly higher percentage of total weight. Accessories are typically about 17% of the total engine weight, excluding accessories.

1.3 Other Program Functions and Capabilities

1.3.1 Flight envelope Maximization

In the normal use of the WATE-2 program, a flight envelope of engine performance will be generated. Since the weight of each component is affected by its maximum work, flow, temperature, and speed, these maximized values are stored for use in the dimensions and weight calculations. Thermodynamic output data from NNEP is scanned over all points in the specified flight envelope, and the maximum conditions are stored. The flight condition is given in the output data where the maximum condition occurs for each component.

1.3.2 Design Limits

As an aid to assist the user to achieve a reasonable engine design, the output data 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 3 shows a list of warnings and corrective actions.

1.3.3 Automatic Airflow Scaling

The WATE-2 program will automatically scale the engine to ±20% of the size that is defined in the NNEP simulation. Up to six selected scale factors can also be specified if the default scale factors of .8, 1.0, and 1.2 are not adequate. A scaling exponent (ϵ) is calculated for a best-fit curve between the calculated data points. The curve-fit equation is of the form:

$$WT = WT_{REF} \left(\frac{W_a}{W_{a_{REF}}} \right)^{\epsilon} \qquad (36)$$

The scaling exponent (ϵ) and a short-form output for each engine size is provided in the output data.

1.3.4 Engine Center of Gravity

The center of gravity of each component, except the rotational components, is assumed to be the mid-point of its length. The moment

TABLE 3 DESIGN LIMITS

WARNING MESSAGE	ACTION RECOMMENDED	DEFAULT VALUE TESTED AGAINST
BLADE PULL STRESS EXCEEDED	REDUCE SHAFT SPEED (BY RPM SCALAR) OR INCREASE EXIT MACH NUMBER	σ = 50000 HPT σ = 60000 LPT σ = 80000 FAN & HPC
h/t TOO LARGE	REDUCE HUB-TIP RATIO INPUT	h/t = .93 HPC EXIT
h/t TOO SMALL	INCREASE HUB-TIP RATIO INPUT	h/t = .32 FAN,HPC ENTRY = .50 HPT,LPT EXIT
STAGE LOADING TOO HIGH	INCREASE λ INPUT (WHICH IS 1/LOADING)	λ = .28 HPT,LPT
STAGE PR TOO HIGH	REDUCE STAGE PRES-SURE RATIO INPUT	PR = 1.8 FAN = 1.4 HPC
FLOW VELOCITY TO HIGH	DECREASE STAGE INLET MACH NUMBER INPUT	M_{ex} = .60 ALL COMPONENTS
BLADE SIZE TOO SMALL	CHANGE DES OVERALL PRESSURE RATIO OR REDUCE H/T INPUT	h_B .40 ALL COMPONENTS

relative to the front-flange of the engine is determined as a function of the position of each component.

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.

1.4 Program Validation

A verification of the accuracy of the 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-2 method can only be found by comparing engines that have been built in production quantities.

In order to judge the accuracy of the method, the NASA program manager selected 8 large engines and one small engine for comparison. These included both production and proposed engines. The selection was made after the method was completed and submitted for approval. Results of the WATE-2 estimates for these engines are shown in Figure 30. As can be seen, dimensions and weight of the 9 selected engines are within the ±10% accuracy goal.

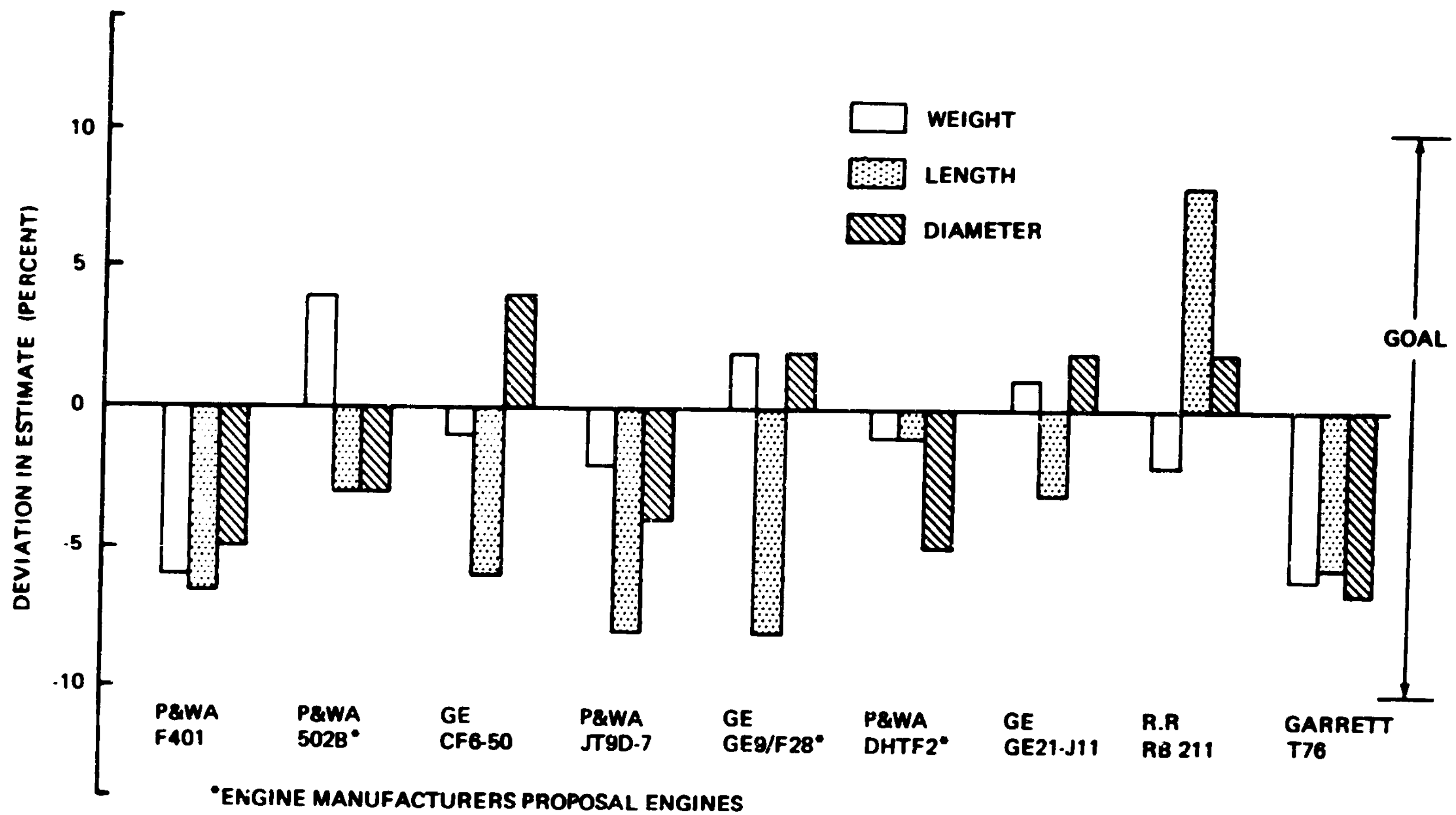


Figure 30. Program Results Compared to Manufacturers Quotations

2.0 USER'S MANUAL

This section contains a description of input-output data, values of typical inputs and sample cases. WATE-2 is designed to function around a component-type engine cycle analysis program, the "NASA-NAVY Engine Program, Reference 7. The calculated thermodynamic output data of NNEP is not described here since it is unchanged from its normal mode of operation.

The thermo design point case of NNEP can be used to generate the WATE-2 inputs or additional NNEP off-design points can be run and the output data will be scanned for maximum conditions of shaft overspeed, work, flow or temperature for each component. In order to produce the most accurate weight estimate, the off-design cases should encompass the maximum performance level required of each component. All components that contribute weight must also be included in the NNEP engine model. WATE-2 will not calculate weight for components which are not included in the NNEP engine simulation.

WATE-2 also will accept an input weight scaler for each component so that selected components can be increased or decreased (or eliminated altogether) to determine sensitivities, etc. Both SI and English units of measure can be used.

2.1 Program Structure and Deck Stacking

The overall program structure is shown in the flow chart, Figure 31. NNEP design point data is stored in the "thermodynamic data" for use in calculating weights and dimensions (W/D) in the WATE-2 part of the program. Computer execution time, core storage, and output print requirements have been increased slightly over the NNEP program.

The order of deck stacking of the Job Control cards and NNEP input data are unchanged from the normal operation of NNEP. Two new inputs have been added to the NNEP indicator set. The indicators, IWT = TRUE and

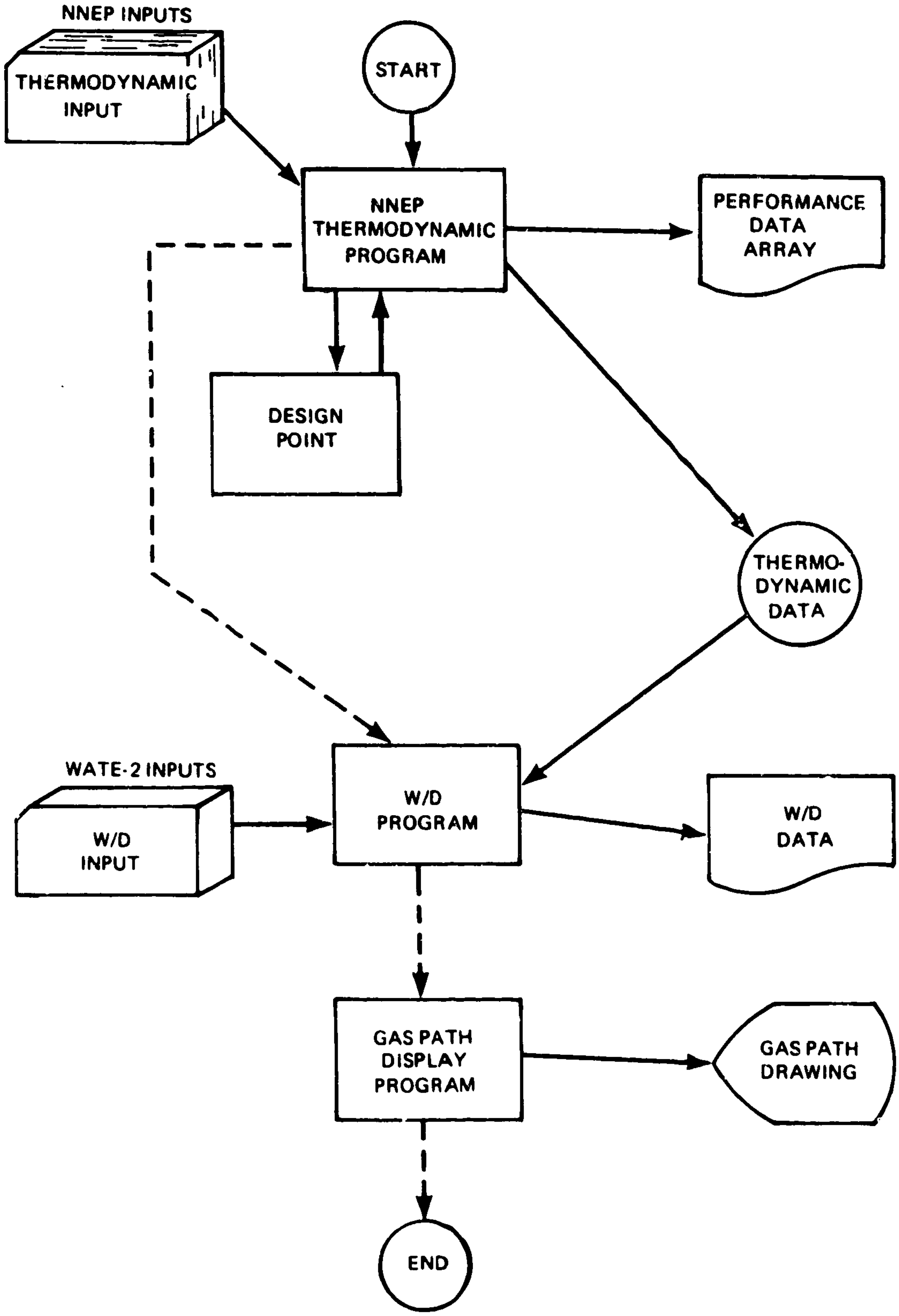


Figure 31. Overall Program Structure

IPLT = TRUE signals that the weight and dimensions calculations are to be performed, and the WATE-2 Data Set is required following the NNEP inputs. Figure 32 shows a typical card-stacking arrangement necessary to operate NNEP and WATE-2.

2.2 Input Description and Format

The WATE-2 inputs are free-field format (NAMELIST), and begin in Column 2. There is no specified order to the inputs; however, for the following discussion they have been grouped into Plot-Print Indicators, Length Indicators, Mechanical Design Indicators, and Design Values. Figure 33 shows a complete input set for a typical case.

2.2.1 Plot-Print Indicators

IWT = 0 - Do not do weight calculation

= 1 - Turn on the thermodynamic parameter maximization of the WATE code. Do not do weight calculation

= 2 - Do weight calculation using maximum thermodynamic parameters

= 3 - Do weight calculation but do not write maximum conditions for the components

= 4 - Do weight calculation with airflow scaling

IPLT = T - Gas path layout

F - No gas path layout

&W - placed at end of NNEP inputs to signal beginning of WATE-2 inputs

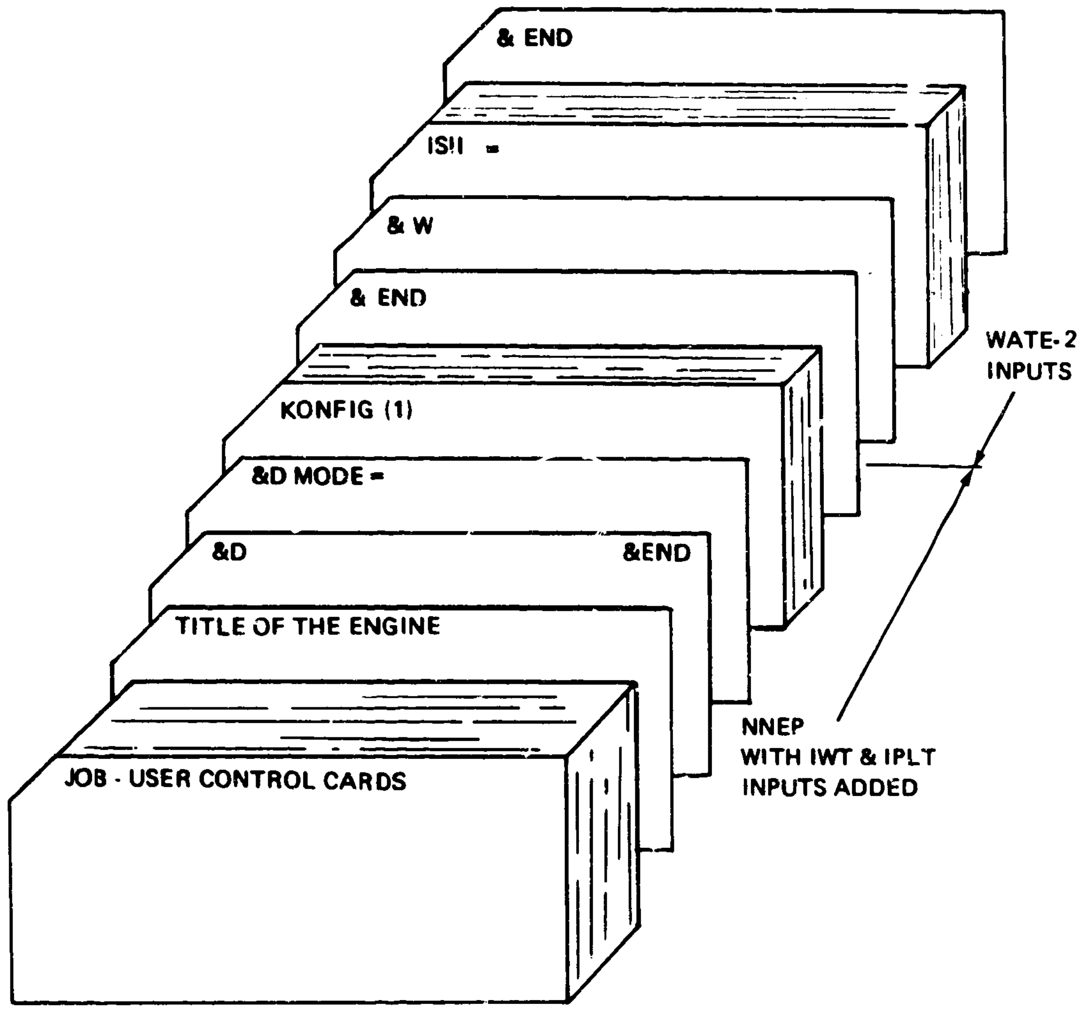


Figure 32. Deck Stacking

```
MODE     1 NOW BEING USED
&W
IPLT=T,
ISII=F,
IS1O=F,
IOUTCO=2,
ILENG(1)=2,3,5,6,7,8,9,10,11,
IWMEC(1,2)='FAN ',1,1,4,3*0,
IWMEC(1,3)='SPLT',6*0,
IWMEC(1,4)='DUCT',0,5*0,
IWMEC(1,5)='LPC ',1,2,4*0,
IWMEC(1,6)='PBUR',1,5*0,
IWMEC(1,7)='HPT ',0,5,-5,3*0,
IWMEC(1,8)='LPT ',1,2,7,3*0,
IWMEC(1,9)='MIX ',6*0,
IWMEC(1,10)='DUCT',2,4*0,
IWMEC(1,11)='NOZ ',1,10,4*0,
IWMEC(1,12)='SHAF',1,8,3*0,2,
IWMEC(1,13)='SHAF',2,7,3*0,5,
DESVAL(1,2)=.524,1.7,.45,1.5,3.5,2.5,.45,0.,0.,1.,0.,2.,1.,
DESVAL(1,3)=15*0.,
DESVAL(1,4)=.45,2*0.,11.,11*0.,
DESVAL(1,5)=.45,1.35,.70,1.2,2.,1.5,.3,0.,0.,1.,0.,2.,1.,
DESVAL(1,6)=100.,.015,
DESVAL(1,7)=.5,.28,1.5,1.5,1.5,.55,150000.,3.,1.,6*0.,
DESVAL(1,8)=.55,.243,1.5,2.,3.,.6,15000.,3.,1.,6*0.,
DESVAL(1,9)=15*0.,
DESVAL(1,10)=.1,2.,
DESVAL(1,11)=1.,14*0.,
DESVAL(1,12)=50000.,.3,.85,12*0.,
DESVAL(1,13)=50000.,.3,13*0.,
&END
```


Figure 33. WATE-2 Input

ISII = T - SI units input

F - English units input

ISIO = T - SI units output

F - English units

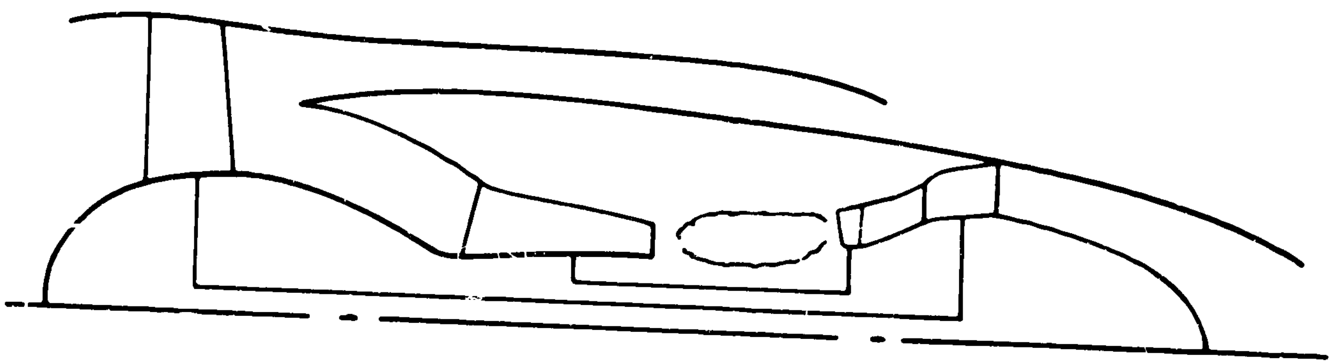
IOUTCD = 0 - Short form-engine weight, length, and maximum radius

1 - Long form-component weights and dimensions and short form

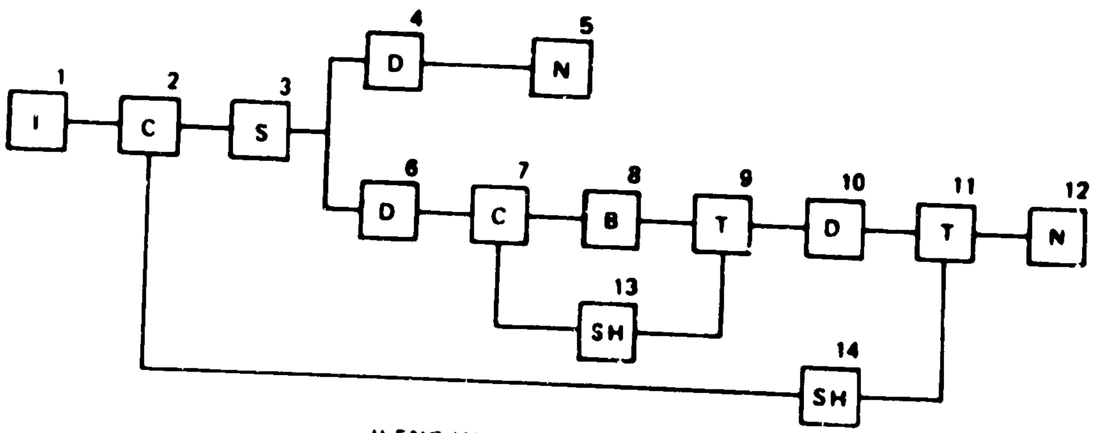
IOUTCD = 2 - Debug option and long and short form

2.2.2 Length Indicators

The ILENG input specifies only those components that contribute to the total additive engine length. The NNEP component number is specified in ILENG in the order that the components would add in length to achieve the total length. This must start with the first compressor and end with the furthest downstream nozzle. Figure 34 shows a typical engine and the ILENG inputs for that engine. The ILENG input does not include duct (4), nozzle (5) or shafts (13) and (14) because these components do not contribute to the total engine length.



ENGINE LAYOUT



ILENG (1) = 1,2,3,6,7,8,9,10,11,12.

FLOW PATH AND COMPONENT NUMBERS

Figure 34. Length Input

2.2.3 Mechanical Design Indicators

The mechanical design indicators (IWMEC) must be specified for each component of the NNEP simulation, with the exception of the NNEP Controls, Inlet, and Water Injection or any other component not represented in WATE-2.

A number of shaft components may be required to simulate an engine in NNEP, as shown in Figure 35. WATE-2 will determine the weight only for connecting shafts of major components, such as the typical HP or LP shaft. In the example of Figure 35, only shaft 15 and shaft 17 would be specified. The smaller component number must always be used on the inner shaft, with increasing component numbers as concentric shafts are added around the inner shaft.

IWMEC is a two-dimensional integer array that contains all of the mechanical design indicators. It is of the form IWMEC (N, M), where M is the component number used in NNEP, and N is the variable number as defined below for each component. Each variable in the IWMEC array for each component is identified as shown in Figure 33 in free-field NAMELIST format.

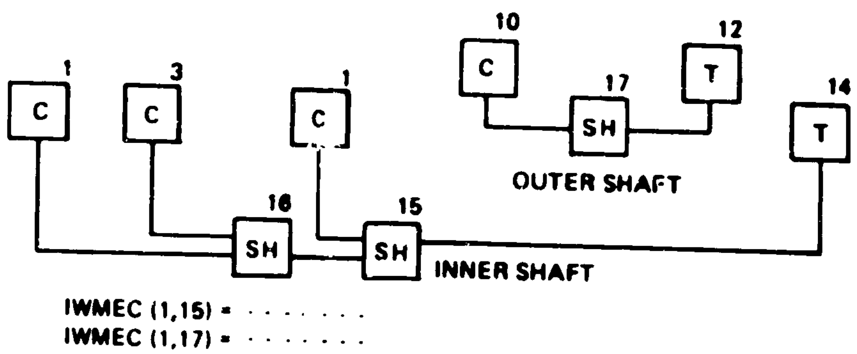


Figure 35. Shaft Input

2.2.3.1 Compressors

IWMEC Array Location	Description	
1	Type of compressor being weighed.	
	'FAN'	- Typical fan
	'FO'	- Outer portion of non-rotating splitter fan
	'FI'	- Inner portion of non-rotating splitter fan
	'RSFO'	- Outer portion of rotating splitter fan
	'RSFI'	- Inner portion of rotating splitter fan
	'LPC'	- Low pressure compressor
	'HPC'	- High pressure compressor
2	This indicates if the fan or compressor has stators or if the compressor is a centrifugal compressor.	
	1	- Stator weight is calculated
	0	- Stator weight is not 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 for turbofans and turbojets with 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
4	This is the indicator for the 'rear' frame in a compressor

0	- No frame
1	- Single bearing frame for turbofans and turbojet without Power Takeoff (PTO)
2	- Single bearing frame with POT
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.
6	Gear box indicator - 0 - No gear or component number of shaft
7	Number of stages

2.2.3.2 Turbines

Location	Description
1	This is the type of turbine 'HPT' - High pressure turbine 'LPT' - Low pressure turbine
2	Indicator for turbine exit frame 0 - No frame 1 - Frame
3	Compressor number from which the RPM is determined
4	Component number from which the outer radius limit for the turbine is determined. If the component number is positive, the outlet dimension is used. If negative, the inlet dimension is used. If 0, it will use the outlet of the feeding component.
5	Number of stages
6	Indicator for axial or radial turbine 0 - Axial turbine 2 - Radial turbine

2.2.3.3 Burners

Location	Description
1	This is the type of burner being weighed. The input is the burner name in four spaces.

'PBUR'	- Primary burner (airframe will be included)
'DBUR'	- Duct burner (a mean radius is specified)
'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

2.2.3.4 Ducts

1 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	- Cross over duct for centrifugal compressors
5	- Diffuser for centrifugal compressors

2.2.3.5 Shafts

Location	Description
1	'SHAF' - Standard shaft
2	Shaft number from inner to outer, i.e., 1, 2, 3, 4, or 5
3-6	Turbine numbers connected to this shaft. The last entry is the furthest downstream turbine. This is used for power summation.
7	First upstream compressor connected to the shaft

2.2.3.6 Mixers

1	Type of mixer 'MIX' - The coannular emergence of two streams without mechanical mixer 'FMIX' - Forced mixer, mechanical, i.e., Daisy lobed mixer
2	Indicator for primary input node 0 - Primary is inner 1 - Primary is outer

2.2.3.7 Nozzles

Location	Description	
1	'NOZ'	- Input
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, the (-) component number must be entered. If (+), the exit node 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

The calculated component weight can be adjusted by an imput scaler, DESVAL (15, M), which is a factor applied to the calculated weight. A zero value, however, denotes that no scaling is used. If it is desired to zero-out the weight of a component, the scaler can be set to a trivial quantity such as .0001.

2.2.3.8 Splitters

Location		Description
1	'SPLT'	- Input
2	1	- If inner stream is not primary

2.2.3.9 Annulus Inverting Valve

1	Input "VALV'	
2	Location of Valve	
	1	- Inner
	2	- Outer
3	Component Number of Opposite Duct	
4	0 if Fixed, 1 if Movable	

2.2.3.10 Heat Exchangers

Location	Description	
1	Input 'HTEX'	
2	Type	
	1	- Fixed tube
	2	- Rotary
3	Flow Direction	
	1	- Parallel flow
	2	- Counter flow

2.2.4 Design Values

This section contains the mechanical and aerodynamic design data necessary to determine the weight and dimensions of each component. A summary of this array is shown in Table 4. If desired, the default values, Table 5, can be used for any component by not specifying the inputs for that component. The data required is in the floating-point two-dimensional array DESVAL (N, M), where M is the component number from NNEP and N is as defined below. A typical range of values is shown in Table 6.

Design limits are built into the program, as shown in Table 7, and cannot be altered by inputs. If these limits are exceeded, the calculation continues and a warning is printed out.

Table 4 DESVAL/DEFAUL Array

TYPE \ POSITION	1	2	3	4	5	6	7	8
COMP	MNI	PRM	H/T	SOLID	ARI	ARO	MNO	TMAXI
TURB	MNI	TLP *	SOLID	ARI	ARO	MNO	REFSTR .2% YIELD STRESS FOR DISK	MODE
BURN	VR	TR	DIA MEAN	REFLOC				
DUCTS	MACH	L/H	DIA MEAN	REFLOC				
TRAN/ SHAFTS	STRESS	RHO	H/T					
MIXERS	L/H	NO. PASS						
AIV	L/H	NO. PASS	MNI	MNØ	RH	WTIC	WTOC	WTW
HEATEX	#TUBE	MNIP	MNIS	BPR				
NOZ	L/D							
SPLT	MNI	H/T						

*TLP = $\dfrac{\mu_T^{2}}{2gJ_{\Delta}\, h/N_{STAGES}}$

TYPE \ POSITION	9	10	11	12	13	14	15
COMP	TMAXO	RPMR	RHO BLADE	MODE	RPMSC	TMET	WEIGHT SCALER
TURB	RPMR						
BURN							
DUCTS							
SHAFTS							
MIXERS							
AIV							
HEATEX							
NOZ							

Table 5 DEFAUL Array

TYPE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FAN	.55	1.7	.45	1.5	4.	3.	.45	0.	0.	1.	2.	1.	0.	0.	0.
LPC	.5	1.5	.4	1.5	4.	3.	.45	0.	0.	1.	0.	2.	1.	0.	0.
HPC	.4	1.4	.7	1.5	3.	1.5	.3	0.	0.	1.0	0.	2.	1.	0.	0.
HPT	.3	.28	1.5	1.5	1.5	.45	125000.	2.	1.	6°0.					
LPT	.45	.28	1.5	2.	4.	.55	125000.	2.	1.	6°0.					
PBUR	100.	.015	13°0.												
DBUR	150.	.015	13°0.												
AUG	300.	.015	13°0.												
DUCT	.4	1.	0.	-1.	11°0.										
SHAFT	50000.	.286	13°0.												
MIXERS	1.	8.	13°0.												
NOZ	1.	14°0.													
AIV	1.	8.	.5	.5	1.1	1.1	1.1								
HTEX	5000.	.5	.5												

Table 6 Typical Range of Input Values for DESVAL/DEFAUL

TYPE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FAN	.5-.6	1.5-1.8	.4-.5	1.-1.5	3.-5.	2.-3.	.45-.55	0.	0.	1.	0.	•	1.	0.	•
LPC	.45-.6	1.5-1.8	.4-.5	1.-1.5	3.-5.	2.-3.	.45-.55	0.	0.	1.	0.	•	1.	0.	•
HPC	.4-.5	1.4-1.7	.6-.8	1.-1.5	2.-5.	1.-2.	.2-.3	0.	0.	1.	0.	•	1.	0.	•
HPT	.3-.4	.2-.3	1.-1.5	1.-2.	1.-2.	.45-.5	100 KSI 150 KSI	• •	1.	0.	0.	0.	0.	0.	
LPT	.4-.5	2-.3	1.-1.5	2.-3.	4.-6.	.55-.6	100 KSI 150 KSI	•	1.						
PBUR	100-150	.01-.02	•	•											
DBUR	150-200	.01-.02	•	•											
AUG	200-300	.01-.02	0.	•											
DUCB	.4-.5	•	•	•											
SHAFB	40-50 KSI	.28-.31	0.-.85												
MIXERS	1.-2.	7.-9.													
NOZ	1.-2.														
AIV	.8-1.2	6.-10.	.4-.6	.4-.6	•	•									
HTEX	5000.	.3-.5	.3-.5	•											

*NOT APPLICABLE SEE TEXT

TABLE 7 DESLIM ARRAY DEFAUL TYPE AND VALUES

POSITION	TYPE	
	BLADE PULL STRESS CAN NOT EXCEED:	
1	FAN AND COMPRESSOR:	80000 PSI
2	HP TURBINE:	50000 PSI
3	LP TURBINE:	60000 PSI
	HUB/TIP FOR ALL COMPRESSORS CAN NOT EXCEED:	
4	0.93	
	HUB/TIP CAN NOT BE LESS THAN:	
5	FAN AND COMPRESSOR:	0.32
6	TURBINE:	0.50
	TURBINE STAGE LOADING INPUT CAN NOT BE LESS THAN:	
7	TURBINE:	0.28
	FIRST STAGE ALLOWABLE PRESSURE RATIO CAN NOT EXCEED:	
8	FAN:	1.8
9	COMPRESSOR:	1.4
	LAST STAGE EXIT MACH NUMBER CAN NOT EXCEED:	
10	FAN AND COMPRESSOR:	0.6
	BLADE HEIGHT CAN NOT BE LESS THAN:	
11	COMPRESSOR:	0.4 INCH
12-13	NOT USED	

2.2.4.1 Compressor

Array Location	Description
1	Compressor face inlet Mach number
2	Maximum first stage pressure ratio
3	Compressor face hub-tip ratio, R_h/R_t
4	Blade solidity, ratio of blade cord to blade spacing
5	Blade aspect ratio at first stage
6	Blade aspect ratio at last stage
7	Compressor exit Mach number
8	Maximum compressor inlet temperature. ZERO if design point temperature is to be used for material selection ^oR, ^oK.
9	Maximum compressor outlet temperature. ZERO if desired point temperature is to be used for materail selection ^oR, ^oK.
10	Maximum speed ratio - RPM_{max}/RPM_{design}
11	Blade material density. ZERO if WATE-2 is to select material. lb/in^3, Kg/cc
12	Compressor design type 1. Constant hub radius design 2. Constant mean radius design 3. Constant tip radius design

Location	Description
13	RPM, scaler, normal input is 1. - use to match known RPM of engine
14	Temperature at which a change of material is required. If ZERO 1160°R will be used, °R, °K.
15	Compressor weight scaler, input ZERO if no scaling is desired
16	Stator blade taper ratio. ZERO input sets 1.8 for fans; 1.2 for compressors
17	Blade volume ratio. ZERO input sets 0.055 for fans; 0.12 for compressors

Centrifugal Compressors

Location	Description
1	Compressor inlet face Mach number
2	Maximum first stage pressure ratio
3	Compressor hub tip ratio
4	RPM ratio
5	Compressor exit Mach number
6	Gear ratio of the power shaft
7	Horse power of power shaft
8-17	Not used

2.2.4.2 Turbines

Location	Description
1	Turbine face inlet Mach number
2	Turbine loading parameter $U_T^2/2g^J\Delta h/N_{stages}$
3	Blade solidity, blade cord/blade spacing
4	Blade aspect ratio of first stage
5	Blade aspect ratio of last stage
6	Turbine exit Mach number
7	Disk reference stress - .2% yield, lb/in^2, Newton's/cm^2
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 inches/cm - blank if transferred from a component
11	Density of material in turbine blades - lb/in^3/Kg/cc
12	Blade volume factor. ZERO input sets 0.155 for high and intermediate turbines; 0.195 for low turbines
13-14	Not used

Location	Description
15	Turbine weight scaler, input ZERO. If no scaling is desired
16	Turbine blade taper ratio. ZERO input sets 1.0 for all turbines
17	Stator blade volume factor. ZERO input sets 0.155 for high and intermediate turbines; 0.195 for low turbines
Centrifugal Turbines	
1	Turbine face inlet Mach number
2-5	Not used
6	Turbine exit Mach number
7-17	Not used

2.2.4.3 Burners

Location	Description
1	Burner through-flow velocity. ft/sec, m/sec.
2	Burner airflow residency time, sec.
3	Burner mean diameter, in. or cm. If zero, diameter is calculated to match connecting component
4	Component number for calculating mean burner diameter. Enter zero if diameter is specified
5	Number of cans for can burners

Location	Description
6-14	Not used
15	Burner weight scaler, enter ZERO. If no scaling is desired
16-17	Not used

2.2.4.4 Ducts

1	Duct Mach number
2	Length to height ratio of duct, required if mode 2 is used in IWMEC
3	Duct mean diameter, in. or cm. If 0., duct diameter is calculated based on node specified below
4	Node number to calculate mean diameter. Enter 0, if mean diameter is specified. Enter -1, if connecting component is to be used
5-14	Not used
15	Weight scaler, ZERO. If no scaling is desired
16-17	Not used

2.2.4.5 Shafts

Location	Description
1	Shaft allowable stress. lb/in^2, $Newton's/cm^2$
2	Shaft material density. lb/in^3, Kg/cc
3	Diameter ratio of shaft D_{inner}/D_{outer}
4-7	Component numbers for total spool inertia
8-14	Not used
15	Shaft weight scaler. ZERO if no scaling desired
16-17	Not used

2.2.4.6 Mixers

1	Effective length to diameter ratio of mechanical mixer, $L/\sqrt{2A/\pi}$, 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 of either hot or cold stream.
3-14	Not used
15	Weight scaler. Enter ZERO. If no scaling is used
16-17	Not used

2.2.4.7 Nozzles

Location	Description
1	Length to diameter ratio of nozzle
2	Bypass ratio for mixed flow nozzle for T/R weight
3-14	Not used
15	Weight scaler. ZERO. If no scaling desired
16-17	Not used

2.2.4.8 Splitters

1	Only input if first calculated component in flow path Mach number in.
2	H/T ratio in.
3-14	Blank
15	Weight scaler
16-17	Not used

2.2.4.9 Annulus Inverting Valve

Location	Description
1	Specific length - $L = \sqrt{4A/\pi}$
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^3, Kg/M^2.
9-14	Blank.
15	Weight scaler.
16-17	Not used.

2.2.4.10 Heat Exchangers

1	Number of tubes if "Fixed" type.
2	Mach number in primary stream.

3	Mach number in secondary stream.
4	Engine Bypass ratio if "Rotary" type.
5-17	Not used.

2.2.4.11 Miscellaneous

"ACCS" is a one-dimensional namelist array that contains the value of the accessory weight scaler. Default value is 0.1.

"DESLIM" is a one-dimensional namelist array that contains the mechanical design limit values for the components. It can have 15 values. First 13 values are defaulted. Range of values is shown in Table 4.

"ISCALE" is a one-dimensional namelist integer array which controls the engine scaling logic of the program.

ISCALE(1) Output indicator

1	Debug option and long and short form for every scaled engine point.
2	Debug option and long and short form for unscaled engine. Long form for each of the scaled engines.

ISCALE(2) Number of scaling points default is three.

ISCALE(3) Not used.

"SCALE" is a one-dimensional namelist array that contains values of scaling factors. It can have six values. First three values are defaulted to 1., .8, 1.2.

"ACCARM" is a namelist array 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 namelist array that is used as an indicator for the new disk weight method.

0 Do disk weight calculations using the old method.

1 Do disk weight calculations using the new method.

2.3 Program Output

The output from WATE-2 may be selected in any of three output formats. Either English or SI units can be selected. Examples of the output are shown for the short output in Figure 36, the long form, Figure 37, and the debug output, Figure 38. This output shows the mechanical design and weight breakdown within the individual component. The units in the output section are shown in Table 8 for English and SI units. The type of units used are noted in the units section of the output.

A flow path layout is also available for conventional type engines. A typical layout is shown in Figure 39. The layout is scaled such that it will fit on one page of the output.

TOTAL BARE ENGINE WEIGHT= 2915. ACCESSORIES= 262.02

ESTIMATED TOTAL LENGTH= 206. ESTIMATED MAXIMUM RADIUS= 29.

Figure 36. Short Output

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

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS RI	UPSTREAM RADIUS RO	RI	RO	DOWNSTREAM RADIUS RI	DOWNSTREAM RADIUS RO	RI	RO	NSTAGE
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0
2	1029.	29.	29.	9.	20.	0.	0.	13.	18.	0.	0.	3
3	0.	0.	29.	0.	0.	0.	0.	15.	16.	16.	18.	0
4	29.	62.	91.	16.	18.	0.	0.	16.	18.	0.	0.	0
5	616.	25.	54.	9.	13.	0.	0.	11.	11.	0.	0.	10
6	250.	18.	72.	9.	13.	0.	0.	9.	13.	0.	0.	0
7	126.	5.	78.	10.	11.	0.	0.	10.	13.	0.	0.	2
8	409.	13.	91.	9.	12.	0.	0.	9.	14.	0.	0.	2
9	0.	0.	91.	4.	16.	16.	21.	4.	21.	0.	0.	0
10	46.	58.	149.	0.	29.	0.	0.	0.	29.	0.	0.	0
11	295.	58.	206.	0.	29.	0.	0.	0.	27.	0.	0.	0
12	40.	0.	0.	9.	20.	10.	11.	0.	0.	0.	0.	0
13	14.	0.	0.	9.	13.	0.	0.	0.	0.	0.	0.	0

TOTAL BARE ENGINE WEIGHT= 2915. ACCESSORIES= 262.02

ESTIMATED TOTAL LENGTH= 206. ESTIMATED MAXIMUM RADIUS= 29.

Figure 37. Long Output

```
*************
*           *
*  FAN   2  *
*           *
************2
DUCT
 M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
0.524  570.  519.    1905.    1579.     6.9517  1.4005

  U TIP  STRESS      DEN   W/AREA    TR       H/T
 1258.9 26757.6    0.168    2.339   1.800    0.450

 COMPRESSOR  2 MECHANICAL DESIGN

 LOADING    N STG    DIAM  U TIP C     RPM    C RPM
   0.874     3.00    39.98  1258.9   7216.9   7216.9

FRAME WT  =    95.67

STAGE      1
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
  65.   59.   59.    0.   26.    7.4 0.168 0.168  3.50
   PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP     STR   WEIGHT TIN
1.4789  16.7 0.524  6.952  8.99  19.99  59 1258.9 26758.  209.  519.

 STAGE      2
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
  91.   34.   34.   51.   21.    6.2 0.168 0.168  3.00
   PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP     STR   WEIGHT TIN
1.4155  16.7 0.499  5.180 11.02  18.95  67 1193.2 20191.  231.  588.

 STAGE      3
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
  97.   23.   23.   46.   19.    5.7 0.168 0.168  2.50
   PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP     STR   WEIGHT TIN
1.3671  16.7 0.475  4.017 12.17  18.23  70 1148.1 15768.  208.  658.

 FRAME WT  =  2[illegible]5.15



  N STG   WEIGHT   LENGTH
     3  1028.68    28.80

 DUCT
  M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
 0.453  582.  727.    5447.    4743.     3.2206  1.3951

   PR     AD EF      PO       TO      HP
 2.8600  0.8700  5447.2    726.9  16910.
   HI      HO       WI       CWI
 123.95  174.07  238.50   265.00

******************** TOTAL COMP WEIGHT IS  1028.680
```

Figure 38. Debug Output

```
*************
*           *
*   HPC   5 *
*           *
*************
DUCT
  M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
 0.450   562.  727.     5447.    4743.    1.8196  1.3951

   U TIP   STRESS      DEN   W/AREA    TR      H/T
  1285.1 23331.5     0.168   0.687    1.200   0.700

  COMPRESSOR  5 MECHANICAL DESIGN

  LOADING     N STG    DIAM  U TIP C     RPM    C RPM
    0.651     10.00    25.58  1085.6 11515.5    9727.5

  FRAME WT  =  118.22

  STAGE      1
    WD    WB     WS     WN    WC     CL    RHOB   RHOD    AR
   24.   14.    14.    36.   10.    4.5 0.168 0.168   2.00
     PR   DEL H   MACH   AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
  1.3603  17.8 0.450   1.320  8.95   12.79  50 1285.1 23331.    99.   727.

  STAGE      2
    WD    WB     WS     WN    WC     CL    RHOB   RHOD    AR
   20.    9.     9.    29.    8.    3.6 0.168 0.168   1.94
     PR   DEL H   MACH   AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
  1.3241  17.8 0.435   1.442  9.42   12.45  60 1250.7 18516.    75.   800.

  STAGE      3
    WD    WB     WS     WN    WC     CL    RHOB   RHOD    AR
   16.    6.     6.    25.    7.    3.0 0.168 0.168   1.89
     PR   DEL H   MACH   AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
  1.2943  17.8 0.420   1.171  9.75   12.19  70 1225.3 15046.    59.   873.

  STAGE      4
    WD    WB     WS     WN    WC     CL    RHOB   RHOD    AR
   13.    4.     4.    21.    6.    2.6 0.168 0.168   1.83
     PR   DEL H   MACH   AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
  1.2704  17.8 0.405   0.970  9.98   12.00  81 1206.2 12477.    49.   946.

  STAGE      5
    WD    WB     WS     WN    WC     CL    RHOB   RHOD    AR
   11.    3.     3.    18.    5.    2.2 0.168 0.168   1.78
     PR   DEL H   MACH   AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
  1.2499  17.8 0.390   0.818 10.15   11.86  93 1191.5 10527.    41.  1017.

  STAGE      6
    WD    WB     WS     WN    WC     CL    RHOB   RHOD    AR
   10.    3.     3.    16.    4.    2.0 0.168 0.168   1.72
     PR   DEL H   MACH   AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
  1.2324  17.8 0.375   0.701 10.28   11.74 104 1180.1  9018.    36.  1089.
```

Figure 38. Cont.

C-2

```
STAGE      7
  WD     WB     WS     WN     WC     CL     RHUB    RHOD     AR
  9.     2.     2.    14.     4.     1.8  0.168  0.168    1.67
  PR    DEL H   MACH    AREA   R HUB    R TIP   NB U TIP      STR      WEIGHT TIN
1.2173   17.8 0.360   0.608  10.39   11.65 115 1171.0   7829.     32.  1159.

STAGE      8
  WD     WB     WS     WN     WC     CL     RHUB    RHOD     AR
 12.     3.     3.    13.     3.     1.6  0.286  0.286    1.61
  PR    DEL H   MACH    AREA   R HUB    R TIP   NB U TIP      STR      WEIGHT TIN
1.2042   17.8 0.345   0.534  10.47   11.58 126 1163.6  11712.     39.  1229.

STAGE      9
  WD     WB     WS     WN     WC     CL     RHUB    RHOD     AR
 15.     3.     3.    12.     3.     1.5  0.286  0.286    1.56
  PR    DEL H   MACH    AREA   R HUB    R TIP   NB U TIP      STR      WEIGHT TIN
1.1926   17.8 0.330   0.475  10.53   11.52 136 1157.7  10407.     36.  1299.

STAGE     10
  WD     WB     WS     WN     WC     CL     RHUB    RHOD     AR
 15.     2.     2.    11.     3.     1.4  0.286  0.286    1.50
  PR    DEL H   MACH    AREA   R HUB    R TIP   NB U TIP      STR      WEIGHT TIN
1.1824   17.8 0.315   0.426  10.59   11.47 146 1152.8   9343.     33.  1367.

 N STG    WEIGHT   LENGTH

   10    616.43    25.43

DUCT
 M NO    VEL    T TOT    P TOT    P STAT    AREA     GAM
0.300    544.  1436.   51236.   48251.    0.3874  1.3539

  PR      AD EF      PO       TO       HP
9.4060   0.8700  51235.9   1435.6   33965.
  HI       HO       W1       CW1
174.07   352.23   134.75    61.97

******************* TOTAL COMP WEIGHT IS    616.477

*************
*           *
*  PBUR  6  *
*           *
*************2
BURNER NUMBER      6
  RIN      ROUT       LENGTH       MACH       WSPEC
  8.756    12.909     18.000      0.055      4.596
  CAS WT    LIN WT    NOZ WT     INC WT      FRAME      WT OT
   24.2      40.4      17.8       16.4       151.3      250.2
```

Figure 38. Cont.

```
*************
*           *
*  HPT   7  *
*           *
************2
DUCT
 M NO  VEL   T TOT   P TOT   P STAT   AREA    GAM
0.500 1106. 2621.  46112.  39327.    0.3977  1.2908

  U TIP   STRESS      DEN   W/AREA    TR       H/T
 1106.0  9819.5    0.286   0.246    1.000    0.922

 TURBINE   7  MECHANICAL DESIGN
    H/T    N STG LOADING     AREA
  0.922    2.000   0.280   0.398
     UT     RTIP    RHUB    DEL H      RPM    TORQ
 1106.0     11.0    10.1    174.5 11515.5 185913.

 STAGE     1
  DISK    BLADE   VANE    HWD    CASE    AR
    6.4     2.3    8.4    21.7    4.0   1.50
   PR   DEL H  MACH   AREA  R HUB  R TIP  NB  U TIP    STR    WEIGHT   LENGTH
1.8453  87.3 0.500   0.398 10.14   11.01 180 1106.0  9820.    42.84     2.02

 STAGE     2
  DISK    BLADE   VANE    HWD    CASE    AR
  10.8     6.4    23.7    35.5    6.8   1.50
   PR   DEL H  MACH   AREA  R HUB  R TIP  NB  U TIP    STR    WEIGHT   LENGTH
2.0095  87.3 0.525   0.666 10.14   11.55 116 1160.9 16456.    83.19     3.29

  N STG   LENGTH   WEIGHT
    2       5.31   126.03

 DUCT
  M NO   VEL   T TOT    P TOT    P STAT    AREA    GAM
 0.550 1149. 2028.   12436.   10243.     1.2074  1.3127

   PR        TR      AD EF      PO        TO       TO.1
 3.7081   1.2928   0.8600  12435.6   2027.7   2027.7
 H IN     H OUT      AREA     FLOW      HP
 699.28   524.74     5.17   137.56   33969.

 ******************** TOTAL TURB WEIGHT IS   126.028

 *************
 *           *
 *  LPT   8  *
 *           *
 ************2
 DUCT
  M NO   VEL   T TOT    P TOT    P STAT    AREA    GAM
 0.550 1149. 2028.   12438.   10245.     1.2072  1.3127
```

Figure 38. Cont.

```
  U TIP   STRESS      DEN   W/AREA    TR      H/T
  727.0 11706.5    0.286   0.777    1.000   0.765

 TURBINE  6  MECHANICAL DESIGN
    H/T    N STG LOADING     AREA
  0.765    2.000    0.243    1.207
     UT      RTIP     RHUB    DEL H      RPM     TORQ
  727.0     11.5      8.8     86.9   7216.9 147693.

 STAGE      1
  DISK    BLADE  VANE    HWD     CASE    AR
    5.0    22.4    66.0   38.9     9.9   2.00
   PR   DEL H  MACH   AREA  R HUB  R TIP  NB  U TIP    STR    WEIGHT  LENGTH
 1.4664   43.4 0.550  1.207  8.83  11.54  80  727.0 11709.  142.18    4.77

 STAGE      2
  DISK    BLADE  VANE    HWD     CASE    AR
    6.9    27.6    81.4   34.0     9.3   3.00
   PR   DEL H  MACH   AREA  R HUB  R TIP  NB  U TIP    STR    WEIGHT  LENGTH
 1.5156   45.4 0.575  1.652  8.83  12.59  98  780.6 16019.  159.21    4.17

 FRAME WT  =  167.79


  N STG  LENGTH  WEIGHT
    2     13.41   469.18

 DUCT
  M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
 0.663 1154. 1722.    5594.    4436.     2.3313  1.3249

   PR        TR      AD EF      PO       TO      TO.1
  2.2236   1.1779   0.8600   5593.7   1721.5   1721.5
  H IN     H OUT     AREA     FLOW      HP
  524.77   437.87   16.80   137.56   16912.

 ******************** TOTAL TURB WEIGHT IS   469.184


 *************
 *           *
 *  AUG  13  *
 *           *
 ************2
 BURNER NUMBER   10
   RIN     ROUT       LENGTH      MACH      WSPEC
   0.0      24.120    48.000     0.143     11.899
   CAS WT   LIN WT    NOZ WT    INC WT    WTOT
    23.7    120.0     296.1       0.0     439.8
```

Figure 38. Cont.

```
*************
*           *
*  NOZ  11  *
*           *
************2
NOZZLE    11
WEIGHT =     568.95 LENGTH=    48.239 TR WT=     0.0

*************
*           *
*  DUCT  4  *
*           *
************2
DUCT ,    4
RH=    15.78 RT=    17.69 LENG=    62.16
AREA=    1.401 RHO=.168
         CAS WT          INC WT        WTOT
        15.5408          13.8556        29.3964


*************
*           *
*  SHAF 12  *
*           *
************2
SHAFT  12
    DO      DI     LENG      DN      WT
   3.54    3.01   48.74     0.65    40.03


*************
*           *
*  SHAF 13  *
*           *
************2
SHAFT  13
    DO      DI     LENG      DN      WT
   4.35    3.94   18.00     1.27    14.33


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

  ACCS WT= 501.414
```

Figure 38. Cont.

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

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS RI	UPSTREAM RADIUS RO	UPSTREAM RADIUS RI	UPSTREAM RADIUS RO	DOWNSTREAM RADIUS RI	DOWNSTREAM RADIUS RO	DOWNSTREAM RADIUS RI	DOWNSTREAM RADIUS RO	NSTAGE
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0
2	1132.	29.	29.	9.	20.	0.	0.	13.	18.	0.	0.	3
3	0.	0.	29.	0.	0.	0.	0.	13.	16.	16.	18.	0
4	32.	62.	91.	16.	18.	0.	0.	16.	18.	0.	0.	0
5	678.	25.	54.	9.	13.	0.	0.	11.	11.	0.	0.	10
6	275.	18.	72.	9.	13.	0.	0.	9.	13.	0.	0.	0
7	139.	5.	78.	10.	11.	0.	0.	10.	13.	0.	0.	2
8	516.	13.	91.	9.	12.	0.	0.	9.	14.	0.	0.	2
9	0.	0.	91.	4.	16.	16.	21.	4.	21.	0.	0.	0
10	484.	48.	139.	0.	24.	0.	0.	0.	24.	0.	0.	0
11	626.	48.	187.	0.	24.	0.	0.	0.	22.	0.	0.	0
12	44.	0.	0.	9.	20.	10.	11.	0.	0.	0.	0.	0
13	16.	0.	0.	9.	13.	0.	0.	0.	0.	0.	0.	0

TOTAL BARE ENGINE WEIGHT= 3941. ACCESSORIES= 301.41

ESTIMATED TOTAL LENGTH= 187. ESTIMATED MAXIMUM RADIUS= 24.

Figure 38. Cont.

UPDATED INPUT DATA TO REFLECT CALCULATED INPUT

COMPONENT NO.	TYPE	DATINP1	DATINP2	DATINP3	DATINP4	DATINP5	DATINP6	DATINP7	DATINP8	DATINP9
1	INLET	0.238500D 03	0.0	0.146960D 02	0.0	0.0	0.900000D 00	0.0	0.0	0.0
2	COMPRESSOR	0.150000D 01	0.0	0.400000D 04	0.376100D 04	0.265900D 05	0.376200D 04	0.101130D 01	0.376300D 04	0.992220D 00
3	SPLITTER	0.770000D 00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	DUCT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	COMPRESSOR	0.130000D 01	0.260000D-01	0.514550D 04	0.373700D 04	0.614190D 02	0.370800D 04	0.909090D 00	0.370900D 04	0.132460D 01
6	DUCT	0.100000D 00	0.0	0.0	0.265000D 04	0.940000D 00	0.183000D 05	0.0	0.0	0.0
7	TURBINE	0.400000D 01	0.100000D 01	0.467330D 00	0.385100D 04	0.736450D 00	0.380200D 04	0.967270D 00	0.902440D 00	0.100000D 01
8	TURBINE	0.250000D 01	0.0	0.335770D 03	0.380300D 04	0.726330D 00	0.380400D 04	0.940120D 00	0.815580D 00	0.100000D 01
9	MIXER	0.757730D 03	0.639250D 03	0.240000D 02	0.0	0.0	0.0	0.0	0.0	0.0
10	DUCT	0.600000D-01	0.0	0.0	0.0	0.900000D 00	0.183000D 05	0.0	0.0	0.0
11	NOZZLE	0.472500D 03	0.150000D 01	0.0	0.0	0.980000D 00	0.100000D 01	0.0	0.0	0.100000D 01
12	SHAFT	0.400000D 04	0.100000D 01	0.170000D 01	0.100000D	0.100000D 01	0.100000D 01	0.100000D 01	0.100000D 01	0.100000D 01
13	SHAFT	0.600000D 04	0.100000D 01	0.100000D 01	0.100000D	0.100000D 01	0.100000D 01	0.100000D 01	0.100000D 01	0.100000D 01

CASE IDENTIFICATION   SIMPLE MODEL

STATION PROPERTY OUTPUT DATA

FLOW STATION	WEIGHT FLOW STATP1	TOTAL PRESSURE STATP2	TOTAL TEMPERATURE STATP3	FUEL/AIR RATIO STATP4	REFERRED FLOW STATP5	MACH NUMBER STATP6	STATIC PRESSURE STATP7	INTERFACE CORRECTED FLOW ERROR STATP8
1	0.238500D 03	0.146960D 02	0.518570D 03	0.0	0.238500D 03	0.0	0.0	0.0
2	0.238500D 03	0.132260D 02	0.518670D 03	0.0	0.264990D 03	0.0	0.0	0.0
4	0.238500D 03	0.378280D 02	0.726870D 03	0.0	0.179690D 03	0.0	0.0	0.0
5	0.134750D 03	0.378200D 02	0.726870D 03	0.0	0.619700D 02	0.0	0.0	0.0
6	0.131240D 03	0.355410D 03	0.145550D 04	0.0	0.901830D 01	0.0	0.0	0.0
7	0.350340D 01	0.355310D 03	0.143560D 04	0.0	0.0	0.0	0.0	0.0
8	0.134050D 03	0.320220D 03	0.275030D 04	0.214250D-01	0.139060D 02	0.0	0.0	0.0
9	0.137560D 03	0.883700D 02	0.272760D 04	0.208680D-01	0.462760D 02	0.0	0.0	0.0
10	0.137560D 03	0.380490D 02	0.172160D 04	0.208680D-01	0.948010D 02	0.240000D 00	0.374010D 02	0.0
11	0.103750D 03	0.378280D 02	0.726870D 03	0.0	0.477170D 02	0.0	0.0	0.0
12	0.241310D 03	0.374010D 02	0.131570D 04	0.117900D-01	0.151010D 03	0.0	0.0	0.0
13	0.241310D 03	0.351570D 02	0.131570D 04	0.117900D-01	0.160650D 03	0.100000D 01	0.187800D 02	0.0
14	0.241310D 03	0.351570D 02	0.131570D 04	0.117900D-01	0.160650D 03	0.117290D 01	0.146960D 02	0.0
15	0.103750D 03	0.378280D 02	0.726570D 03	0.0	0.477170D 02	0.127340D 00	0.374010D 02	0.0

COMPONENT OUTPUT DATA

COMPONENT NO.	TYPE	DATOUT1	DATOUT2	DATOUT3	DATOUT4	DATOUT5	DATOUT6	DATOUT7	DATOUT8	DATOUT9
1	INLET	0.0	0.0	0.0	0.100000D 01	0.100000D 01	0.0	0.900000D 00	0.100000D 01	0.0
2	COMPRESSOR	-0.169120D 05	0.400000D 04	0.0	0.180000D 01	0.400000D 04	0.100000D 01	0.265900D 03	0.870000D 00	0.286000D 01
3	SPLITTER	0.770000D 00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	DUCT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	COMPRESSOR	-0.339090D 05	0.600000D 04	0.0	0.130000D 01	0.514550D 04	0.985000D 00	0.614180D 02	0.870000D 00	0.940600D 01
6	DUCT	0.0	0.100000D 00	0.0	0.214250D-01	0.0	0.101230D 05	0.0	0.940000D 00	0.265000D 04
7	TURBINE	0.339090D 05	0.600000D 04	0.100000D 01	0.400000D 01	0.467330D 00	0.568000D 04	0.706450D 00	0.860000D 00	0.370730D 01
8	TURBINE	0.169120D 05	0.400000D 04	0.100000D 01	0.250000D 01	0.335770D 00	0.524400D 04	0.726330D 00	0.860000D 00	0.222340D 01
9	MIXER	0.757730D 03	0.639250D 03	0.113870D 01	0.101140D 01	0.472740D 03	0.167730D 03	0.0	0.949900D-16	0.100000D 01
10	DUCT	0.0	0.600000D-01	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	NOZZLE	0.137850D 05	0.133790D 04	0.239230D 01	0.483930D 03	0.472830D 03	0.100000D 01	0.980000D 00	0.187210D 01	0.239230D 01
12	SHAFT	0.0	0.400000D 04	0.400000D 04	0.400000D 04	0.0	0.0	0.0	0.0	0.0
13	SHAFT	[illegible]	0.600000D 04	0.600000D 04	0.600000D 04	0.0	0.0	0.0	0.0	0.0

MACH NO. 0.0   ALTITUDE= 0.0   RECOVERY FACTOR   ITERATIONS   PASSES

AIRFLOW (LB/SEC)	[illegible]	GROSS THRUST	[illegible]	FUEL FLOW (LB/HR)	[illegible]
NET THRUST	[illegible]	TSFC	[illegible]	NET THRUST/AIRFLOW	[illegible]
TOTAL RAM DRAG	[illegible]	TOTAL BRAKE SHAFT HP	[illegible]	BOATTAIL DRAG	[illegible]
INSTALLED THRUST	[illegible]	INSTALLED TSFC	[illegible]	SPILLAGE + LIP DRAG	[illegible]

Figure 38. Cont.

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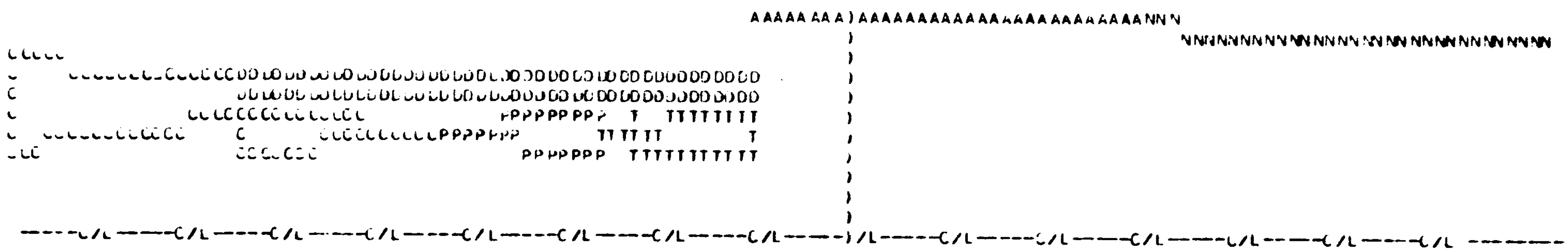

Figure 39. Flow Path

Table 8. Output Units

VARIABLE	SI UNITS	ENGLISH UNITS
Velocity	m/sec	ft/sec
Temperature	^oK	^oR
Pressure	n/m^2	lb/ft^2
Area	M^2	ft^2
Stress	N/cm^2	lb/in^2
Density	kg/cm^3	lb/in^3
Weight	kg	lb
Length	cm	in
Enthalpy	kwatts	btu/sec
Horsepower	kwatts	hp
Weight flow	kg/sec	lb/sec
Weight flow/unit area	$kg/m^2 sec$	lb/ft^2 sec
Radius	cm	in

2.4 Sample Cases

2.4.1 Large Engine

A simple mixed flow augmented turbofan is used as an example for the WATE-2 input and execution. Figure 40 shows a schematic and a block diagram of the engine. From this block diagram, the component numbers are determined.

To construct the input deck the indicator section must first be set, Figure 41. In this example, the units in and out are English, so ISII and ISIO are set false. Since the weight and gas path layout are desired, IWT and IPLT are set true. The debug option is turned on with IOUTCD set equal to 2. The length inputs are then entered in ILENG. Since the duct (4) and shaft (12) and (13) do not contribute to the total length, they are not entered. Also, the components are entered as the flow would progress through the engine.

The IWMEC values are now entered. Since no inlet weight calculations are done, the inlet is not entered. This is true with any component entered in the NNEP KONFIG section; it is not entered in IWMEC if no routine exists to weigh it. In the example, the IWMEC (1,2) card says a "fan" is being weighed. The weight will include stators, IWMEC (2,2)=1, a front frame, IWMEC (3,2)=1, and an intermediate frame, IWMEC (4,2)=4. The IWMEC (1,8) card says a "LPT" is being weighed. It has a turbine exit frame, IWMEC (2,8)=1, and it is connected to component 2, (IWMEC (3,8)=7. The nozzle has variable area capability, IWMEC (2,11)=2, and its diameter will be taken from the inlet to the augmentor, IWMEC (3,11)=10. Since the augmentor has constant diameter, the node position for taking the diameter is of no consequence.

The DESVAL inputs follow the IWMEC inputs. Component numbers used in DESVAL must agree with those used in IWMEC. Input of DESVAL data will override the default values. For the example case, the fan design card DESVAL (1,2) indicates that the compressor inlet Mach number is 0.524,

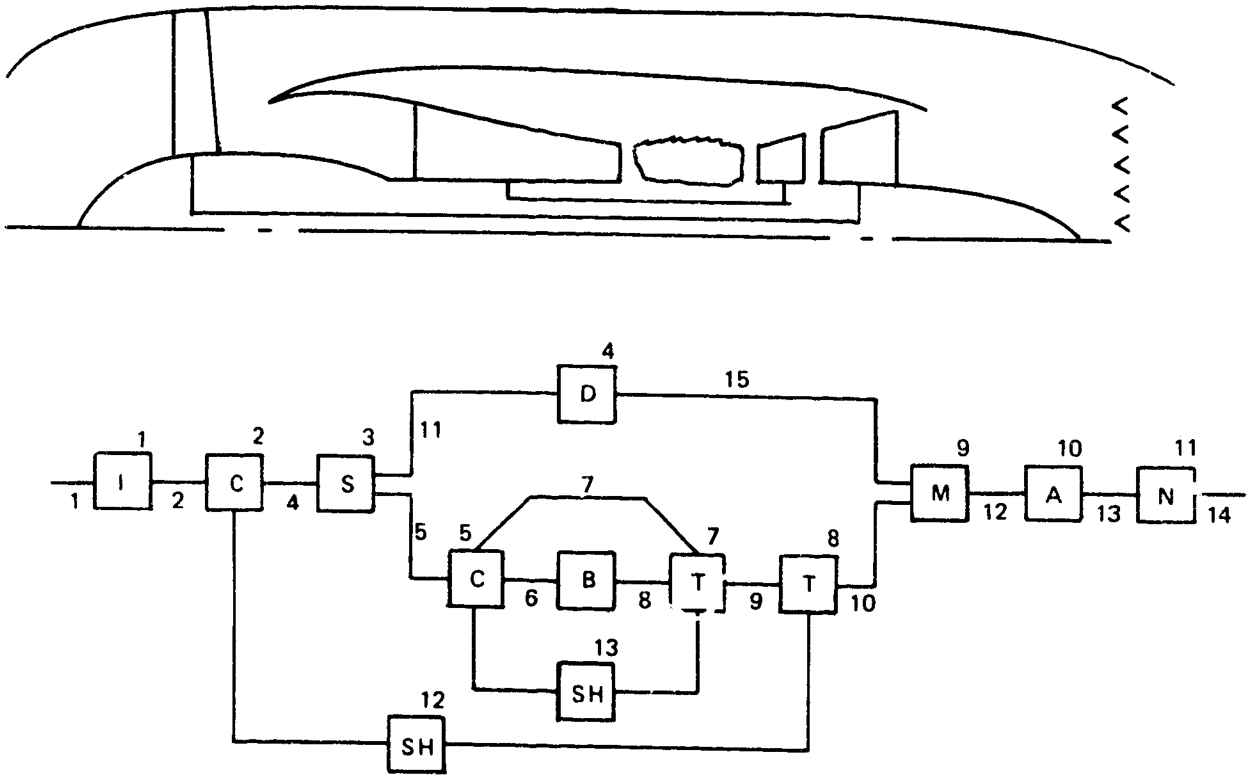

Figure 40. Engine Schematic

```
MODE      1 NOW BEING USED
&W
IPLT=T,
ISII=F,
ISIO=F,
IOUTCD=2,
ILENG(1)=2,3,5,6,7,8,9,10,11,
IWMEC(1,2)='FAN ',1,1,4,3*0,
IWMEC(1,3)='SPLT',6*0,
IWMEC(1,4)='DUCT',3,5*0,
IWMEC(1,5)='HPC ',1,2,4*0,
IWMEC(1,6)='PBUR',1,5*0,
IWMEC(1,7)='HPT ',0,5,-5,3*0,
IWMEC(1,8)='LPT ',1,2,7,3*0,
IWMEC(1,9)='MIX ',6*0,
IWMEC(1,10)='AUG ',6*0,
IWMEC(1,11)='NOZ ',2,-10,4*0,
IWMEC(1,12)='SHAF',1,8,3*0,2,
IWMEC(1,13)='SHAF',2,7,3*0,5,
DESVAL(1,2)=.524,1.7,.45,1.5,3.5,2.5,.45,0.,0.,1.,0.,2.,1.,0,1.1,
DESVAL(1,3)=14*0.,1.1,
DESVAL(1,4)=.45,2*0.,11.,10*0.,1.1,
DESVAL(1,5)=.45,1.35,.70,1.2,2.,1.5,.3,0.,0.,1.,0.,2.,1.,0,1.1,
DESVAL(1,6)=100.,.015,0.,5.,10*0.,1.1,
DESVAL(1,7)=.5,.28,1.5,1.5,1.5,.55,150000.,3.,1.,5*0.,1.1,
DESVAL(1,8)=.55,.243,1.5,2.,3.,.6,150000.,3.,1.,5*0.,1.1,
DESVAL(1,9)=14*0.,1.1,
DESVAL(1,10)=250.,.016,12*0.,1.1,
DESVAL(1,12)=50000.,.3,.85,11*0.,1.1,
DESVAL(1,11)=1.,13*0.,1.1,
DESVAL(1,13)=50000.,.3,12*0.,1.1,
&END
```

Figure 41. WATE-2 Input Example

the maximum first stage pressure ratio is 1.7 and the inlet hub/tip ratio is 0.45. The compressor has a blade solidity of 1.5 with a first blade aspect ratio of 3.5. The last stage has an aspect ratio of 2.5 and an exit Mach number of 0.45. The inlet and exit temperatures calculated in NNEP will be used for disk material determination, DESVAL (8,2) and DESVAL (9,2) are 0.; the RPM ratio between maximum and design is 1.0. The blade material will also be chosen by the code because DESVAL (11,2) is 0. The design of the fan is a constant mean line since the mode, DESVAL (12,2) equals 2. Also, no speed scaling or weight scaling will be done since DESVAL (13,2) is 1.0 and DESVAL (15,2) is 0. A material change temperature of 1160^{o}R will be used since DESVAL (14,2) is 0.

The HP turbine DESVAL (1,7) has an inlet Mach number of 0.5 and a turbine loading of 0.28. It has 1.5 solidity with inlet and exit blade aspect ratio equal to 1.5. The exit Mach number is 0.55. The disk material is a high strength super/alloy with a reference stress of 150,000 psi. A constant tip radius is used in the design, DESVAL (8,7)=3., and a speed ratio of 1. is specified for stress calculations.

To end the inputs, a "&END" is entered. This will initiate execution of WATE-2. The output of WATE-2 is shown in Figure 42 for the example case.

```
*************
*           *
*   FAN   2 *
*           *
************2
DUCT
 M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
0.524  570.  519.    1905.    1579.     6.9517  1.4005

  U TIP  STRESS     DEN   W/AREA   TR      H/T
 1258.9 26757.6   0.168   2.339   1.800   0.450

 COMPRESSOR  2 MECHANICAL DESIGN

 LOADING    N STG   DIAM  U TIP C    RPM    C RPM
   0.874     3.00   39.98  1258.9  7216.9  7216.9

FRAME WT  =   95.67

STAGE     1
  WD    WB    WS    WN    WC    CL    RHOB   RHOD   AR
  65.   59.   59.    0.   26.    7.4 0.168 0.168  3.50
   PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP     STR    WEIGHT TIN
1.4789  16.7 0.524  6.952  8.99  19.99  59 1258.9 26758.  209.   519.

STAGE     2
  WD    WB    WS    WN    WC    CL    RHOB   RHOD   AR
  91.   34.   34.   51.   21.    6.2 0.168 0.168  3.00
   PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP     STR    WEIGHT TIN
1.4155  16.7 0.499  5.180 11.02  18.95  67 1193.2 20191.  231.   588.

STAGE     3
  WD    WB    WS    WN    WC    CL    RHOB   RHOD   AR
  97.   23.   23.   46.   19.    5.7 0.168 0.168  2.50
   PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP     STR    WEIGHT TIN
1.3671  16.7 0.475  4.017 12.17  18.23  70 1148.1 15768.  208.   658.

FRAME WT  =  285.15


 N STG   WEIGHT  LENGTH
    3   1028.68   28.80

DUCT
 M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
0.450  582.  727.    5447.    4743.     3.2266  1.3951

  PR     AD EF      PO      TO      HP
 2.5600  0.8700  5447.2   726.9   16910.
  HI      HO      WI     CWI
 123.95  174.07  238.50  265.00

******************* TOTAL COMP WEIGHT IS  1028.680
```

Figure 42. WATE-2 Output Example

```
*************
*           *
*   HPC   5 *
*           *
*************
DUCT
 M NO   VEL   T TOT    P TOT    P STAT   AREA      DIAM
0.450   582.  727.     5447.    4743.     1.8196  1.3951

  U TIP  STRESS      DEN   W/AREA    TR       H/T
 1285.1 23331.5    0.168    0.687   1.200    0.700

 COMPRESSOR  5 MECHANICAL DESIGN

 LOADING    N STG    DIAM  U TIP C     RPM    C RPM
   0.651    10.00    25.58  1085.6 11515.5   9727.5

FRAME WT  =  118.22

STAGE     1
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
 24.   14.   14.   36.   10.    4.5 0.168 0.168   2.00
  PR    DEL H  MACH  AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
1.3603  17.8 0.450  1.320  8.95   12.79  50 1285.1 23331.    99.   727.

STAGE     2
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
 20.    9.    9.   29.    8.    3.6 0.168 0.168   1.94
  PR    DEL H  MACH  AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
1.3241  17.8 0.435  1.442  9.42   12.45  60 1250.7 18516.    75.   800.

STAGE     3
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
 16.    6.    6.   25.    7.    3.0 0.168 0.168   1.89
  PR    DEL H  MACH  AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
1.2943  17.8 0.420  1.171  9.75   12.19  70 1225.3 15046.    59.   873.

STAGE     4
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
 13.    4.    4.   21.    6.    2.6 0.168 0.168   1.83
  PR    DEL H  MACH  AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
1.2704  17.8 0.405  0.970  9.98   12.00  81 1206.2 12477.    49.   946.

STAGE     5
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
 11.    3.    3.   18.    5.    2.2 0.168 0.168   1.78
  PR    DEL H  MACH  AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
1.2499  17.8 0.390  0.818 10.15   11.86  93 1191.5 10527.    41.  1017.

STAGE     6
  WD    WB    WS    WN    WC    CL    RHOB   RHOD    AR
 10.    3.    3.   16.    4.    2.0 0.168 0.168   1.72
  PR    DEL H  MACH  AREA  R HUB   R TIP  NB U TIP     STR    WEIGHT TIN
1.2324  17.8 0.375  0.701 10.28   11.74 104 1180.1  9018.    36.  1089.
```

Figure 42. Cont.

```
STAGE     7
  WD    WB    WS    WN    WC    CL   RHUB  RHOD   AR
  9.    2.    2.    14.   4.    1.8 0.168 0.168  1.67
  PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP    STR   WEIGHT TIN
1.2173  17.8 0.360  0.608 10.39  11.65 115 1171.0  7829.   32. 1159.

STAGE     8
  WD    WB    WS    WN    WC    CL   RHOB  RHOD   AR
 16.    3.    3.    13.   3.    1.6 0.286 0.286  1.61
  PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP    STR   WEIGHT TIN
1.2042  17.8 0.345  0.534 10.47  11.58 126 1163.6 11712.   39. 1229.

STAGE     9
  WD    WB    WS    WN    WC    CL   RHOB  RHOD   AR
 15.    3.    3.    12.   3.    1.5 0.286 0.286  1.56
  PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP    STR   WEIGHT TIN
1.1926  17.8 0.330  0.475 10.53  11.52 136 1157.7 10407.   36. 1299.

STAGE    10
  WD    WB    WS    WN    WC    CL   RHOB  RHOD   AR
 15.    2.    2.    11.   3.    1.4 0.286 0.286  1.50
  PR   DEL H  MACH  AREA  R HUB  R TIP  NB U TIP    STR   WEIGHT TIN
1.1824  17.8 0.315  0.426 10.59  11.47 146 1152.8  9343.   33. 1367.

 N STG   WEIGHT   LENGTH

   10    616.43    25.43

DUCT
 M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
0.300   544.  1436.   51236.  48231.     0.3874  1.3539

  PR     AD EF      PO      TO      HP
 9.4060  0.8700 51235.9  1435.6  33965.
  HI       HO       WI      CWI
 174.07   352.23   134.75   61.97

******************** TOTAL COMP WEIGHT IS   616.477

*************
*           *
*  PBUR  6  *
*           *
*************2
BURNER NUMBER      6
  RIN      ROUT      LENGTH      MACH      WSPEC
  8.756    12.909    18.000      0.055     4.596
  CAS WT   LIN WT    NOZ WT    INC WT     FRAME      WTOT
   24.2      40.4      17.8      16.4     151.3      250.2
```

Figure 42. Cont.

```
*************
*           *
*  HPT   7  *
*           *
************2
DUCT
 M NO   VEL   T TOT    P TOT    P STAT   AREA    GAM
0.500 1186. 2621.  46112.  39327.    0.3977  1.2968

  U TIP   STRESS     DEN  W/AREA    TR      H/T
 1106.0  9819.5   0.286   0.246   1.000   0.922

 TURBINE  7  MECHANICAL DESIGN
    H/T    N STG LOADING     AREA
  0.922   2.000   0.280    0.398
     UT     RTIP    RHUB    DEL H      RPM     TORQ
 1106.0     11.0    10.1    174.5 11515.5 185913.

STAGE     1
 DISK    BLADE  VANE    HWD     CASE    AR
   6.4     2.3     8.4   21.7     4.0  1.50
   PR  DEL H  MACH  AREA  R HUB  R TIP  NB  U TIP   STR   WEIGHT  LENGTH
1.8453  87.3 0.500  0.398 10.14  11.01 180 1106.0  9820.   42.84    2.02

STAGE     2
 DISK    BLADE  VANE    HWD     CASE    AR
  10.8     6.4    23.7   35.5     6.8  1.50
   PR  DEL H  MACH  AREA  R HUB  R TIP  NB  U TIP   STR   WEIGHT  LENGTH
2.0065  87.3 0.525  0.666 10.14  11.55 116 1160.9 16456.   83.19    3.29

 N STG   LENGTH  WEIGHT
    2      5.31  126.03

 DUCT
  M NO   VEL   T TOT    P TOT    P STAT   AREA    GAM
 0.550 1149. 2028.  12436.  10243.    1.2074  1.3127

   PR        TR       AD EF      PO        TO       TO.1
  3.7081   1.2928   0.8600 12435.6   2027.7   2027.7
  H IN     H OUT     AREA    FLOW      HP
  699.28   524.74     5.17  157.56   55969.

 ******************** TOTAL TURB WEIGHT IS   126.028

 *************
 *           *
 *  LPT   8  *
 *           *
 ************2
 DUCT
  M NO   VEL   T TOT    P TOT    P STAT   AREA    GAM
 0.550 1149. 2028.  12438.  10245.    1.2072  1.3127
```

Figure 42. Cont.

```
 U TIP   STRESS      DEN   W/AREA    TR      H/T
 727.0 11708.5    0.286    0.777   1.000    0.765

TURBINE   6  MECHANICAL DESIGN
   H/T     N STG LOADING     AREA
 0.765    2.000    0.243    1.207
    UT     RTIP     RHUB     DEL H      RPM     TORQ
 727.0     11.5      8.8     86.9   7216.9 147693.

STAGE      1
 DISK     BLADE   VANE     HWD      CASE     AR
   5.0    22.4    66.0    38.9      9.9    2.00
   PR   DEL H   MACH   AREA  R HUB   R TIP   NB   U TIP     STR    WEIGHT  LENGTH
1.4669   43.4  0.550   1.207   8.83   11.54  80   727.0  11709.   142.18    4.77

STAGE      2
 DISK     BLADE   VANE     HWD      CASE     AR
   6.9    27.6    81.4    34.0      9.3    3.00
   PR   DEL H   MACH   AREA  R HUB   R TIP   NB   U TIP     STR    WEIGHT  LENGTH
1.5156   43.4  0.575   1.652   8.83   12.39  98   780.6  16019.   159.21    4.17

FRAME WT   =   167.79



 N STG   LENGTH   WEIGHT
    2     13.41   469.18

DUCT
 M NO   VEL   T TOT    P TOT    P STAT   AREA     GAM
0.600 1154. 1722.    5594.    4436.    2.3313  1.3249

   PR       TR       AD EF      PO       TO       TO.1
2.2256   1.1779    0.8600   5593.7   1721.5   1721.5
 H IN     H OUT     AREA     FLOW       HP
524.77   437.87    16.80   137.56   16912.

******************** TOTAL TURB WEIGHT IS    469.184


*************
*           *
*  AUG  10  *
*           *
************Z
BURNER NUMBER    10
  RIN      ROUT        LENGTH        MACH       WSPEC
   0.0      24.120     48.000      0.143      11.899
  CAS WT    LIN WT     NOZ WT      INC WT      WTOT
    23.7     120.0      296.1        0.0       439.8
```

Figure 42. Cont.

```
*************
*           *
*  NOZ  11  *
*           *
************2
NOZZLE    11
WEIGHT=    568.95 LENGTH=   48.239 TR WT=    0.0


*************
*           *
*  DUCT  4  *
*           *
************2
DUCT ,    4
RH=   15.78 RT=   17.69 LENG=   62.16
AREA=   1.401 RHO=.168
      CAS WT        INC WT       WTOT
     15.5408        13.8556       29.3964



*************
*           *
*  SHAF 12  *
*           *
************2
SHAFT  12
    DO       DI    LENG      DN      WT
   3.54    3.01  48.74    0.65  40.03



*************
*           *
*  SHAF 13  *
*           *
************2
SHAFT  13
    DO       DI    LENG      DN      WT
   4.35    3.94  18.00    1.27  14.33



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

  ACCS WT= 501.414
```

Figure 42. Cont.

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

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS RI	UPSTREAM RADIUS RO	UPSTREAM RADIUS RI	UPSTREAM RADIUS RO	DOWNSTREAM RADIUS RI	DOWNSTREAM RADIUS RO	DOWNSTREAM RADIUS RI	DOWNSTREAM RADIUS RO	NSTAGE
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0
2	1132.	29.	29.	9.	20.	0.	0.	13.	18.	0.	0.	3
3	0.	0.	29.	0.	0.	0.	0.	13.	16.	16.	18.	0
4	32.	62.	91	[illegible]	18.	0.	0.	16.	18.	0.	0.	0
5	678.	25.	[illegible]	[illegible]	13.	0.	0.	11.	11.	0.	0.	10
6	275.	18.	72.	9.	13.	0.	0.	9.	13.	0.	0.	0
7	139.	5.	78.	10.	11.	0.	0.	10.	13.	0.	0.	2
8	516.	13.	91.	9.	12.	0.	0.	9.	14.	0.	0.	2
9	0.	0.	91.	4.	16.	16.	21.	4.	21.	0.	0.	0
10	484.	48.	139.	0.	24.	0.	0.	0.	24.	0.	0.	0
11	626.	48.	187.	0.	24.	0.	0.	0.	22.	0.	0.	0
12	44.	0.	0.	9.	20.	10.	11.	0.	0.	0.	0.	0
13	16.	0.	0.	9.	13.	0.	0.	0.	0.	0.	0.	0

TOTAL BARE ENGINE WEIGHT= 3941. ACCESSORIES= 301.41

ESTIMATED TOTAL LENGTH= 187. ESTIMATED MAXIMUM RADIUS= 24.

Figure 42. Cont.

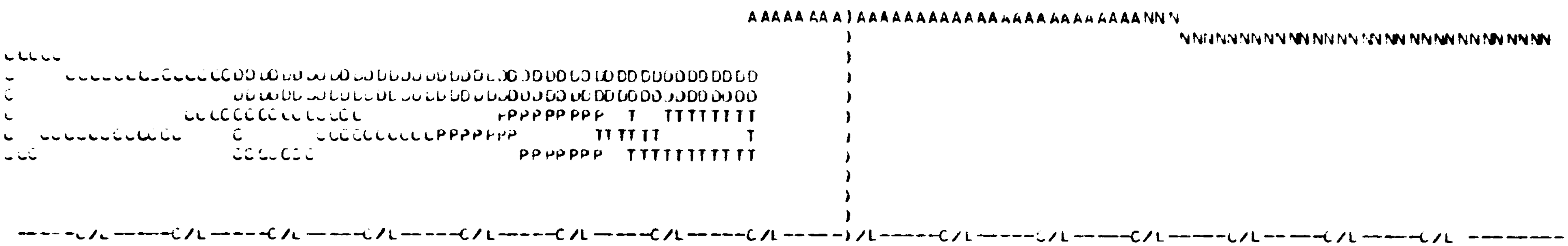

Figure 42. Cont.

2.4.2 Small Engine

A typical turboshaft engine as illustrated in Figure 22 has been represented by the inputs shown in Figure 43. The general input format for small engines is the same as for large engines. Major differences are the IWMEC inputs that call for centrifugal stages instead of axial, and the IWMEC input that calls for the optional disc weight procedure for the axial-flow turbine.

Component input data should be selected to be representative of this type of engine. For example, blade volume factors may be significantly larger because of the small-size blades. Blade geometry also may be considerably different than the default values. Samll engines generally have larger blade taper than large engines.

Output data for the sample case is shown in Figure 44. Since the engine geometry and component arrangement does not generalize for small engines, it is not possible to automate a computer drawn flow path layout as was done for the large engines. Radial component dimensional data also is not readily defined, except for the major envelope dimensions which are shown in the output. The same output options also are available for the small engines.

2.5 Program Diagnostics

The WATE-2 program contains error printout to aid the user in trouble shooting an input deck. A listing of the error messages and their meanings are shown in Table 9. None of these errors will cause termination of the program. The component routine in which the error occurred will be terminated and the program will continue its calculations. The components calculated after an error may or may not be in error.

```
$W
IWT=2,IP_T=T,
ISII=F,ISIO=F,IOUTCD=2,
ILENG(1)=2,3,4,
DISKWI=1.,
ACCS=.17
IWMEC(1,2)='HPC ',2,0,0,0,1,0,
IWMEC(1,3)='PBUR',0,5*0,
IWMEC(1,4)='HPT ',5,2,2,3,0,0,
IWMEC(1,5)='NOZ ',1,5*0,
IWMEC(1,6)='SHAF',1,4,3*0,2,
DESVAL(1,2)=.74,5.,.48,.7296,.3,15.,1438.,10*0.,
DESVAL(1,3)=39.,.037,12.9,0.,13*0.,
DESVAL(1,4)=.2,.42,1.2,.9,3.1,.3,150000.,3.,1.,6*0.,3.,1.5,
DESVAL(1,5)=1.,14*0.,
DESVAL(1,6)=50000.,.3,.85,2.,4.,10*0.,
$END
```

Figure 43. Small Engine Inputs

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

MAX CONDITIONS OCCUR AT
****************************************
       ALT          MN         VALUE
PTOT        0.      0.000        14.7 LB/SQIN
TTOT        0.      0.000       518.7 DEG R
CWIN        0.      0.000        12.0 LB/SEC
****************************************
DUCT
 M NO  VEL   T TOT    P TOT    P STAT   AREA     GAM
 .740  784.   519.    2116.    1471.     .2594  1.4005


STAGE      1
STPR      RPM       RTIP       INERTIA    LENGTH     WEIGHT
 8.0 30352.6       5.7         106.9       3.5         13.8

STAGE      2
STPR      RPM       RTIP       INERTIA    LENGTH     WEIGHT
 3.3 30352.6       5.5          91.2       3.5         13.8

***COMP HOUSING   ***
WEIGHT=   21.7

***CROSSOVER DUCT***
LENGTH=  .3?2 WEIGHT=  15.3

***DIFFUSER***
LENGTH=  .1?4 WEIGHT=   5.0

***GEAR BOX***
SHP    = 143?. GEAR R=  15.0 SHAFT RPM= 2.24.
WEIGHT= 2?5.9

 N STG  WEIGHT  LENGTH  CENGRA  INERTIA
    2    58.54    7.34    3.7     192.1

DUCT
 M NO  VEL   T TOT    P TOT    P STAT   AREA     GAM
 .330  465. 1.35.   16930.   15920.     .?680  1.37?4

  PR      AD EF      PO        TO       HP
 8.0000   .8??? 15923.8  1036.2    214?.
  HI       HO       WI      CWI
 123.95   25?.?    12.??   12.00
```

Figure 44. Small Engine Output

```
*************
*           *
*  PBUR  3  *
*           *
************2

MAX CONDITIONS OCCUR AT
*************************************
        ALT        MN        VALUE
PTOT      0.      0.000      117.6 LB/SQIN
TTOT      0.      0.000     1036.2 DEG R
CWIN      0.      0.000        2.1 LB/SEC
*************************************
BURNER NUMBER     3
  RIN     ROUT     LENGTH     MACH     WSPEC
   3.421    8.456    13.32      .019     1.625
  CAS WT   LIN WT   NOZ WT   INC WT    FRAME     WTOT
     2.5     16.4      8.6      1.0      0.0     28.6


*************
*           *
*  HPT   4  *
*           *
************2

MAX CONDITIONS OCCUR AT
*************************************
        ALT        MN        VALUE
PTOT      0.      0.000      112.2 LB/SQIN
TTOT      0.      0.000     2100.0 DEG R
CWOUT     0.      0.000        0.0 LB/SEC
*************************************
DUCT
 M NO   VEL   T TOT   P TOT   P STAT   AREA    GAM
 .200   434.  2100.  16151.  15734.    .1990  1.3130

 UTIPMAX STRESS     DEN   W/AREA   TR      H/T
 1205.2 13423.5     .286    .547   3.000    .748

 TURBINE  4  MECHANICAL DESIGN
    H/T    N STG LOADING    AREA
   .748    3.000    .420    .199
     UT     RTIP    RHUB    DEL H     RPM    MAXRPM    TORQ
 1205.2      4.6     3.4    207.3  30352.6  30352.6    7429.
```

Figure 44. (continued)

```
STAGE      1
 DISK    BLADE   VANE    HWD     CASE    AR
   8.2    [illegible]   12.[illegible]     5.4     3.7    .90
  PR   DEL H   MACH   AREA   R HUB   R TIP  NB MAXUTIP   STR     WEIGHT  LENGTH  STAGE I
1.8729  69.1  .2[illegible]    .199   3.40    4.55  26 1235.2 18424.    50.93    4.47     297.

STAGE      2
 DISK    BLADE   VANE    HWD     CASE    AR
   5.5    21.7   12.5     3.5     2.6   2.90
  PR   DEL H   MACH   AREA   R HUB   R TIP  NB MAXUTIP   STR     WEIGHT  LENGTH  STAGE I
2.0475  69.1  .233    .372   3.40    5.04  46 1335.6 27668.    45.85    2.88     303.

STAGE      3
 DISK    BLADE   VANE    HWD     CASE    AR
   5.9    33.2   22.0     3.4     3.0   3.10
  PR   DEL H   MACH   AREA   R HUB   R TIP  NB MAXUTIP   STR     WEIGHT  LENGTH  STAGE I
2.3144  69.1  .267    .506   3.40    5.90  55 1562.4 45676.    72.44    2.83     555.

FRAME WT  =   14.81


 N STG  LENGTH  WEIGHT   CENGRA  INERTIA
   3     13.57  183.14    8.2     1155.

DUCT
 M NO  VEL   T TOT   P TOT   P STAT  AREA    GAM
 .300  527. 1353.   1808.   1702.     .9676  1.3471

  PR      TR      AD EF    PO      TO      TO.1
 3.9345  1.5519   .8500  1807.7  1353.2  1353.2
 H IN    H OUT    AREA   FLOW     HP
 543.09  335.84   1.17   12.29   3578.

******************** TOTAL TURB WEIGHT IS   183.135
```

Figure 44. (continued)

```
*************
*           *
*   NOZ  5  *
*           *
************2

MAX CONDITIONS OCCUR AT
***********************
       ALT         MN
PTOT        0.     0.000
TTOT        0.     0.000
***********************
NOZZLE     5
WEIGHT=     19.79 LENGTH=    14.918 TR WT=     0.00


*************
*           *
*   SHAF  6 *
*           *
************2

MAX TORQUE CONDITION
***********************
 TORQUE
   .9
***********************
SHAFT    6
    DO      DI    LENG      DN      WT
  1.65    1.4[illegible]  13.32    1.27    2.37


TOTAL INERTIA OF THIS SPOOL IS      1348.

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

  ACCS WT=  [illegible]
```

Figure 44. (continued)

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

COMP NO	WT EST	COMP LEN	ACCU LEN	UPSTREAM RADIUS RI	RO	RI	RO	DOWNSTREAM RADIUS RI	RO	RI	RO	NSTAGE
1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0
2	230.	7.	7.	0.	0.	0.	0.	2.	6.	0.	0.	2
3	29.	13.	21.	3.	8.	0.	0.	3.	8.	0.	0.	0
4	153.	14.	34.	3.	5.	0.	0.	3.	7.	0.	0.	3
5	20.	15.	49.	0.	7.	0.	0.	0.	5.	0.	0.	0
6	2.	0.	0.	0.	0.	3.	5.	0.	0.	0.	0.	0

TOTAL BARE ENGINE WEIGHT= 514. ACCESSORIES= 84.01 ESTIMATED TOTAL LENGTH= 34.
ESTIMATED CENTER OF GRAVITY= 15.
ESTIMATED MAXIMUM RADIUS= 8.

Figure 44. (concluded)

Table 9 Error Messages

1. "Compressor, I, pressure ratio is too high" - more than 20 compressor stages calculated. First stage maximum pressure ratio too small.

2. "Compressor, I. stage and blade parameters, meaningless" - stage inlet Mach number less than or equal to zero, or hub radius of compressor equals zero.

3. "Duct is not converging - error only called for rotating splitter fan component. Inlet or exit Mach numbers of fan may be input incorrectly.

4. "Error in shaft" - iteration for shaft diameter not converging. Check shaft inputs.

5. "Turbine, I, work or radius too high, RC = , X.XX" - more than 9 turbine stages calculated - turbine loading parameter too small or control radius improperly input.

6. "Turbine, I, stage and blade parameters meaningless" - Mach number or hub radius less than or equal to zero.

2.6 Program Structure

The execution flow was designed to minimize the interaction of the basic NNEP program and the weight estimation routines. The only data flowing between the two is via the common blocks SNGL and DBL and the variables IWT and IPLT. The subroutine THERM is used to obtain thermodynamic properties of the fluid. An assumption is made that the thermodynamic properties are established at each station prior to calling WTEST subroutine, which is flow charted in Figure 45.

WTEST calls the component routines. These component routines are independent of each other, and some use the same lower level routines as some other components. After all weights and dimensions have been estimated ENGPLT is called to make the printer plot. For a description of subroutine connectivity, see Figure 46.

The code is in FORTRAN IV and has been checked out on IBM 370/168. The code is single precision except for the values in the Navy-NASA Engine Program (NNEP). The code was designed to minimize conversion requirements to other machines. No subroutines are required beyond those in the IBM FORTRAN IV manual, and there is no character manipulation, only full word tests are used when testing BCD input.

The NNEP/WATE-1 code requires $75B48_{16}$ core (482120_{10} bytes) to run without buffers. The execution of a design point followed by a weight estimation and printer plot is 4 seconds CPU time, using an existing load module (all data reference 370/168).

The following variables in NNEP 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, NFINIS. In no case is any value changed by the weight estimation code. Each call to WTEST routine will cause a NAMELIST read of "W" data. This is the one and only read in weight estimation code. Based on the information in NCOMP and JTYPE the proper component routine is called

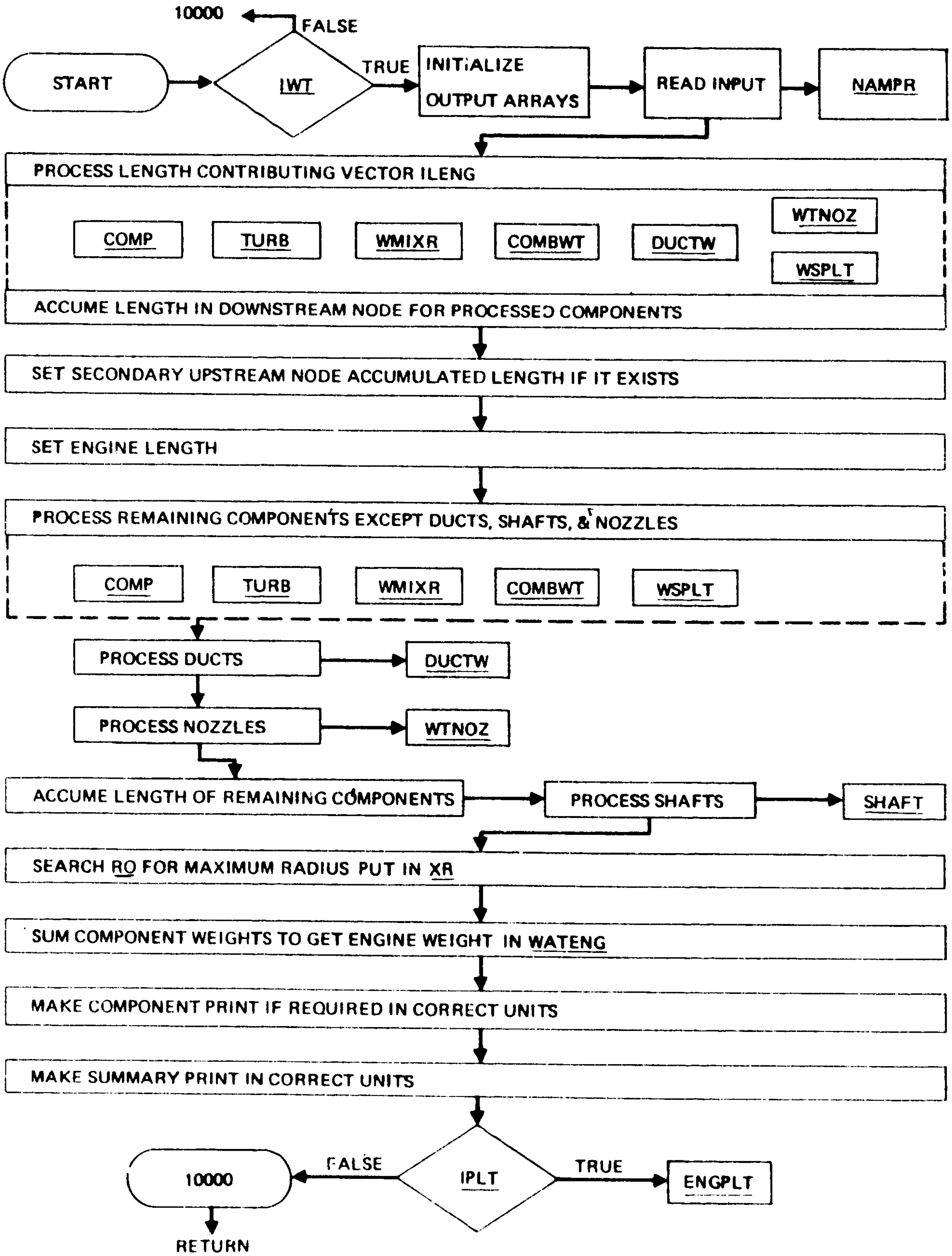

Figure 45. Functional Flow Chart of WTEST

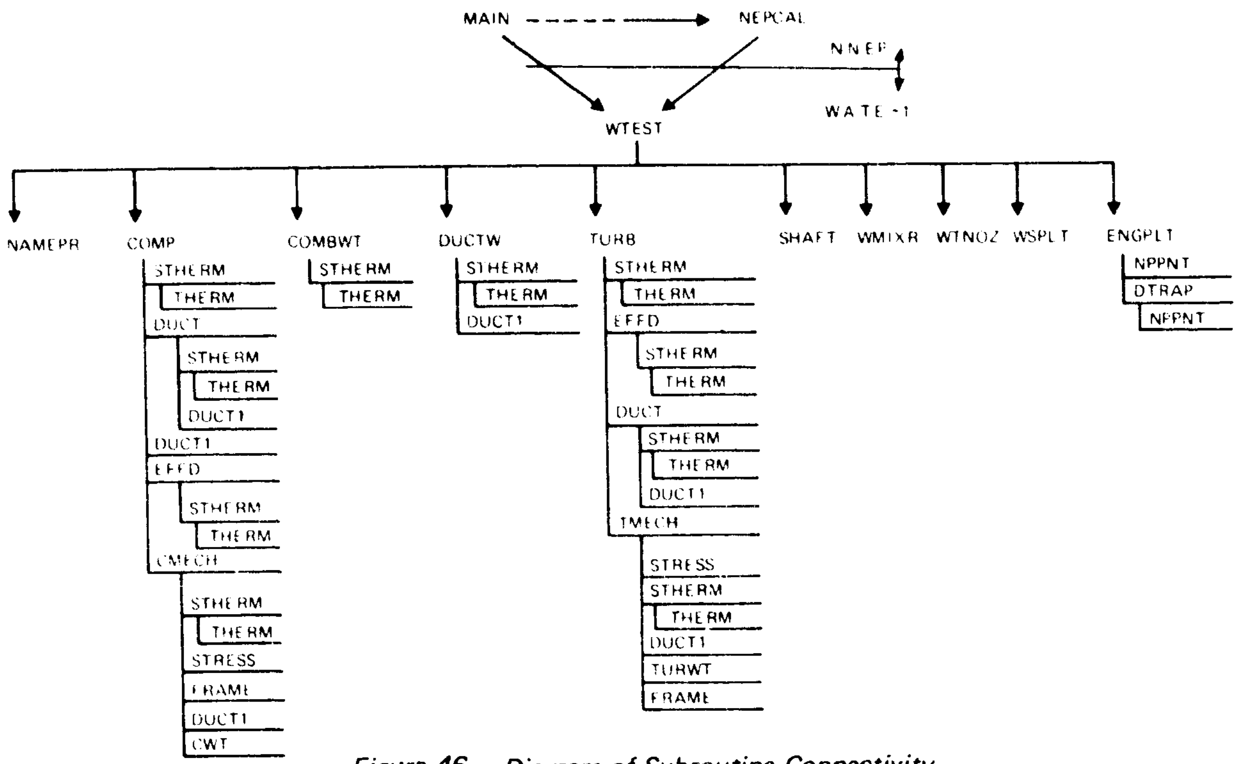

Figure 46. Diagram of Subroutine Connectivity

with the compoent 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 units to SI units:

ARRAY #	VALUE	UNITS ENGLISH	to	UNITS SI
1	2.54	inch		cm
2	.3048	feet		meter
3	.4536	lb_m		K_g
4	.0929	ft^2		$meter^2$
5	.02768	lb_m/in^3		K_g/cm^3
6	.689475	lb_f/in^2		$Newton/cm^2$
7	4.882	lb_m/ft^2		K_g/m^2
8	.555	^oR		^oK
9	1.05435	BTU/sec		K WATTS
10	.07457	HP		K WATTS
11	47.88	lb_f/ft^2		$Newton/m^2$

8.0 CONCLUSIONS AND RECOMMENDATIONS

The WATE-2 method can provide a reasonable level of accuracy in predicting weight and dimensions of large and small gas turbine engines. Flexibility of modeling the engine cycle and gas-path allows virtually any conventional or non-conventional gas turbine engine to be analyzed. Normally, all components can be sized from the stage by stage calculation of state conditions that are accomplished internally.

A number of new capabilities have been added to the original program that will also make it more useful: small gas turbines, rotating interia, airflow scaling, center of gravity, engine design diagnostic aids, and flight envelope maximization of component size. Accuracy of the program has also been improved with the addition of a new preliminary design procedure for discs. The disc weight correlations that were previously developed did not include the effects of blade aspect ratio or disc stress; it was only sensitive to blade pull stress and disc radius. Both methods are available as options, however it is recommended that the new disc design procedure be used for all types of engines rather than the disc weight correlation procedure.

Further improvements to the program are also recommended. An engine design procedure similar to that described in Reference 8 could be built into the program to eliminate external iterations of the engine design. Exit Mach number in turbines should be used to establish blade sizes rather than the entry Mach number as now used. Since there is usually less variation in the exit angle and exit Mach number than there is at the entry of turbines, this would provide a better blade sizing criteria. The program could also be changed to a constant-mean radius design procedure rather than the constant-area area definition that is currently used. The former method is more commonly used in the industry.

REFERENCES

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