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Advancements of Gas Turbine Engines and Materials

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ADVANCEMENTS OF GAS TURBINE ENGINES AND MATERIALS

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This thesis starts out with a brief description of gas turbine engines and information on railroad locomotives being the gas-turbine electric locomotives with some comparison of the diesel-electric locomotives in the introduction. Section 1.1 is the research problem looking at the older gas turbine electric locomotives in the 1950's that ran on the rail and the problems they suffered. In section 1.2 titled the purpose of the study takes a look at newer gas turbine locomotives that were being consider or has been built with improvements since the 1950's. The objective of the study being section 1.3 looks at the advantages of new gas turbines engines. Section 1.4 titled the research questions discusses better materials and methods of gas turbine engines. Chapter 2 is the literature review looking at the fuel oil specifications being number 4, number 5, and number 6. This chapter also talks about the use of distillates, types of distillates, composition of distillates, specifications for distillates, residual fuel oil and fuel oil quality dealing with the firing of gas turbine engines. Section 2.3 of chapter 2 being titled power generation looks at power plant gas-turbine engines and the power they produce. Chapter 3, titled the proposed methodology looks at setting up an experiment using a gas-turbine engine and a diesel-electric engine to compare the advantages of along with the disadvantages. Section 3.1 is titled data collected, within this section is discussion on the data collected from the experiment and improvements that could be made to the gas turbine engines. The end of chapter 3, section 3.2 titled data analyzing,

talks about possible the results collected, calculations done, improvements made and rerunning another experiment with the improvements made. Chapter 4 discuss the types of materials using in building the compressor and turbine blades. Last, but not least is chapter 5 which discusses the actual experiment using the gas turbine simulator for aircrafts and how to apply it to the railroad locomotives. After the conclusion which discusses the results, is the appendix a being gas tables, appendix b being trial run 1 and appendix c being trial run 2.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE PAGE

LIST OF TABLES

CHAPTER 1

INTRODUCTION

A gas turbine is a type of constant or continuous combustion, internal combustion engine. The three main parts or elements to this machine which are the upstream rotating gas compressor, the downstream turbine that is on the same shaft and the combustion chamber that is called a combustor. This combustor is in between the rotating gas compressor and the downstream turbine.

A Gas-Turbine Electric Locomotive uses a turbo-electric drivetrain in which a turboshaft engine drives an electrical generator or alternator by way of a system of gears. The electrical output is shared to power the traction motors that drive the locomotive. In overall terms, the system is very similar to a conventional diesel-electric, with the large diesel engine replaced with a smaller gas turbine of similar power. The American Locomotive Company and General Electric built the first Gas-Turbine Electric Locomotive in November 1948 which was numbered 101 and run on a low cost cheap grade Bunker C fuel oil as it was called [1]. This locomotive had 4,500 horsepower built for dual service and was double-ended cabs of a streamlined design [1]. Many lessons were learned from running this locomotive along with changes made while in service. The Union Pacific Railroad would order 10 more with improvements learn from the first locomotive they ran. The rear cab was discontinued along with a change of interior components location permitted an increase in fuel capacity. Other changes that were made was to help upgrade the servicing conditions. No other improvement was made that affected the operation of the turbine motor itself. The Union Pacific Railroad like these Big Blows as they are referred to so much that they order a second set or class from G.E. [1]. The second set that was numbered 61 through 75 included many improvements gained as the result of both experience on the road from part of the first set that was numbered 51 through 56 [1]. Some of the improvement were made because of advancements in engineering. This was the removing of side filters because the air intake was moved to the roof of the locomotives. It also had improvements made to the oil filter system along with no longer needing to run the turbine at full power while going downhill because the dynamic brake, which obtained its excitation current from the auxiliary generator, alleviated this.

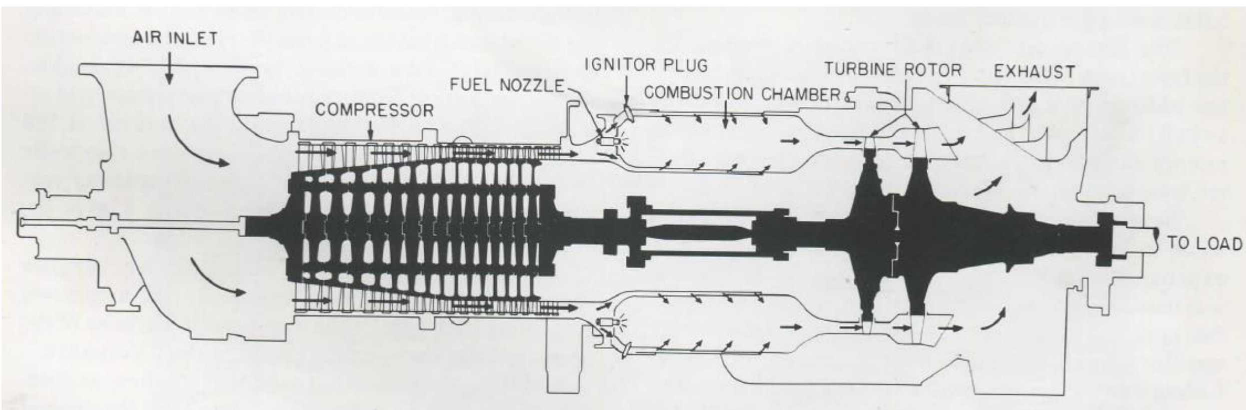

Figure 1 Air flow diagram of the 4,500-horsepower gas turbine engine out of a locomotive. Exhaust gases expelled through the roof aperture at velocity of 150 m.p.h., 850° F with volume of 150,000 cubic feet. [1]

A third class of gas-turbine electric locomotives were built. This locomotive was different from the demonstrator and the two sets of 4,500 horsepower gas-turbine electric locomotive [1]. The major different was the horsepower rating which was increase to 8,500 horsepower and design simplification. The 8,500 horsepower GTEL had two sets of three axle trucks referred to as C trucks [1]. The C-C method running gear eliminated the span bolster trucks used in earlier units, provided a better traction motor ventilating system and improved maintenance accessibility [1].

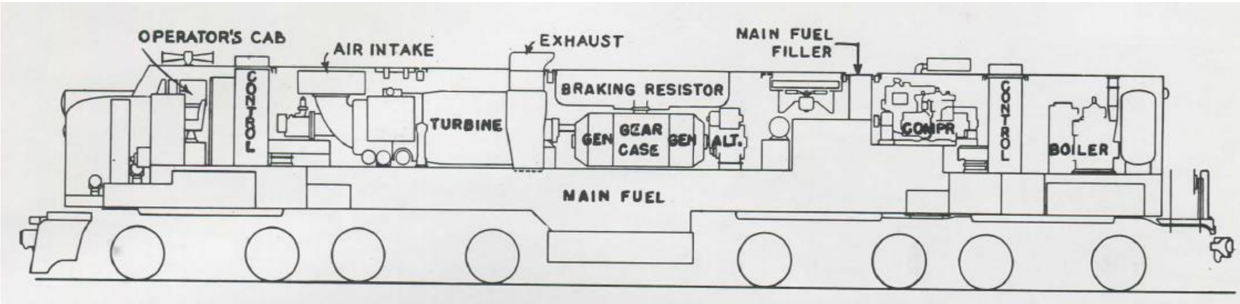

Figure 2 Cutaway side view of the 4,500-horsepower gas turbine electric locomotive shows the layout of the interior equipment while showing the exterior layout of 7,200-gallon fuel formed structural base, carbody rested on two span bolters containing two four-wheel powered trucks.[1]

Chapter 1.1

The Research Problem

When analyzing the performance and prosperity of the gas-turbine electric locomotives, the usual comparison is with the diesel locomotive of the day [1]. They compared favorably on paper of the early years of operation [1]. These gas turbines accommodated either 4,500 horsepower or 8,500 horsepower in one locomotive as compared to a multiple unit diesel [1]. The gas turbine had only one large moving part, the shaft with the turbine buckets. Because of this, the turbine was mechanically much simpler than the diesel engine that has many moving parts such as pistons, connecting rods and valves. This had advantages in servicing and maintenance because of the fewer components' parts. According to author T. R. Lee, "In terms of locomotive length, both classes of turbines produced over 50 horsepower per foot as compared with 30 horsepower for a diesel locomotive of the 1950's. The turbine power plant weighed less than half as much per horsepower as a locomotive type diesel engine of that period.

Due to the smooth rotating motion of the turbine and compressor, one of the outstanding features of gas turbine operation was the absence of the vibration so characteristic with reciprocating diesel engine” [1]. The problems that lead to ending the career of gas-turbine power on the Union Pacific Railroad was the changing fuel situation which was by 1969, the Bunker “C” oil, a one-time surplus of the petroleum industry, now was no longer available as a low-cost fuel [1]. Another problem with the gas turbine electric locomotives is there is no idle mode. It is either full speed of the turbine or off. When a locomotive had to sit in a siding or wait for traffic to clear to continue forward, the turbine was running at full power burning up a lot of fuel. This made the turbine less economic as compared to the diesel-electric locomotive which could idle at slow speeds or when stopped.

Chapter 1.2

The Purpose of the Study

Since the days of 1950’s, gas-turbine motors have come a long way with improvement of materials used for the blades and the setup of these motors has improve with ways of capturing the exhaust. It is put through many stages before sending it back through the turbine to reuse the exhaust gases. While airplanes have made these improvements, which make them run more efficient, there has not been any improvements of railroad locomotives for there is no railroad locomotives using gas-turbine motors to power them and those that have been built were shut down due to a lawsuit. According to the article of Rail People, “Amtrak and Bombardier are in a nasty legal battle over the trouble-plagued Acela Express high-speed electric train recently introduced on the northeast corridor linking Boston, New York and Washington [2].

There has been a rash of train delays and breakdowns with Acela, the first high-speed train service in North America. Amtrak ordered 18 from Bombardier and its French partner Alstom, and 15 have been delivered. Although the train is popular thanks to its speed and comfort, Amtrak has vowed never to buy another" [2]. I want to take the improvements made to the airplanes to apply it to the old gas-turbine electric locomotives and find out the result of these improvements.

Chapter 1.3

The Objectives of the Study

The objectives of the study are to collect information on the performance of the changes made to the newer gas turbine engines, both that have been done in real life and the simulation model. Look at the results of the model along with documents on newer turbine motor to see what advantages the newer gas turbine motors have. In addition, to look at how those advantages can serve the rail transportation industry. Then see what can be done to make the gas turbine more favorable for rail transportation use.

Chapter 1.4

The Research Questions

- Are companies using better materials to build the turbine blades?
- What new designs are being used to build the turbine blades and new processes being used to create them?
- Which processes can be added after going through the first turbine blades to improve the efficiency of the turbine motor?

- What application can be used for the prediction of gas turbine combustor flow fields?

To answer the first two questions, I will give a brief introduction of knowledge on the blades. This information comes from a book titled Modern gas turbine systems High efficiency, low emission, fuel flexible power generation being Edited by Peter Jansohn. Turbine parts, especially first stage blades, are exposed to high thermal and mechanical loading during operation, and to high thermo-mechanical loading during start-up and shut-down of the gas turbine. High heat transfer at thin-walled blades results in high base material temperature. In the case of thermal barrier coating spallation, the metallic bond coat has to protect the thin-walled blade against environmental attack at elevated temperatures.

CHAPTER 2

LITERATURE REVIEW MATERIALS

One of the areas that gas turbine engine can be improved is in the type of materials they are made from. Over the years, there has been new materials and improved designs in the blades of the compressor and the turbine. They also use different type of materials to improve the performance of the engine. A book titled *Modern gas turbine systems, High efficiency, low emission, fuel flexible power generation* edited by Peter Jansohn talk about alloys for turbine blading which is in chapter 9.2.2. The blades in the compressor and turbine go through 25,000 to 80,000 hours of service with multiple loadings that include high temperatures, vibrations due to expanding combustion gas and the centrifugal force of about 10,000 g[3]. The high temperature can be 700 to 900 degree Celsius (1,292 to 1,652 °F) which is what led to failure being creep, fatigue, oxidation and corrosion, but do to nickel-base (Ni-base) superalloys that change[3]. Superalloys are design to continue on or exist in the conditions describe above. These alloys use nickel-base (Ni-base) alloys which inured or hardened with intermetallic γ phase on a basis of Ni_3Al (40-70 vol-%) and carbides and borides along grain boundaries. Superalloys usually hold ten or more alloying components, assemble according to their functions into three categories:

1. Solid solution elements (Co, Cr, W, Mo, Re) are elements predominantly present in the austenitic γ matrix. W, Mo, Re are effective solid solution strengtheners due to their large atomic diameter: the main role of Cr is to provide corrosion and oxidation resistance through the formation of dense oxide scale; Co, being a minor matrix strengthener,

stabilize γ' phase and increase γ' solvus temperature. These elements also replace Ni atoms in γ' phase lattice with a similar strengthening effect.

2. Gamma prime formers (Al, Ti, Ta, Nb, Hf) form an intermetallic γ' phase, replacing Al and, due to larger atomic diameter, strengthening this phase.

3. Grain boundary strengtheners (C, B, and Zr, Hf, Ti, Ta Nb) form stable carbides and borides along grain boundaries[3].

The three categories above have been successfully installed in the gas turbine throughout the course of the last 50 years because of the special properties of the γ' phase. Within the specified limits of 1,112°F (600°C) to almost 1,472°F (800°C) the toughness of γ' phase becomes greater, meanwhile the bulk of materials lose their toughness. Once the temperature raised above that the strength or toughness slightly reduced, but toward the desired action or solutioning temperature, it stays higher than that of the smaller elements or matrix[3]. The γ' phase has a crystallographic lattice meaning an arrangement of atoms in crystalline solids or the symmetrical three-dimensional arrangement of atoms inside a crystal, coherent being logical and consistent with that of the matrix. An example of the Nickel base (Ni) alloys was being used in the combustor parts for industrial gas turbines (GTs), such as burner or liner, are large, thick-wall components, which are casted or welded Nickel (Ni) or Cobalt (Co) base alloys. Another example of the nickel base (Ni) alloys being coatings is the first stages of the turbine blading which are made out of the Ni-base superalloys, cast as a single crystal, directionally solidified or polycrystalline microstructure[3]. Also used on top of the base material (BM), a layer of MCrAIY which stand for coating composition with M (=Ni and/ or Co, Cr, Al, Y plus other minor elements) is applied by vacuum plasma (VPS) or low pressure (LPPS) as a protective coating[3].

Another material and design change are the directionally solidified and single crystal technology. In present-day Industrial Gas Turbines (IGTs) and Turbine Inlet Temperature (TIT) 2,372°F (1,300°C), efficiency specifications restricted the quantity of the compressor air accessible for cooling, and the wear time or life goal for highly loaded front stage components are 25,000 to 50,000 hours at metal temperature above 1,652°F (900°C) [3]. To fulfill these specifications, present-day Industrial Gas Turbines make use of evolved cooling plan of action, thermal barrier ceramic coatings, and use directionally solidified along with single crystal blades and vanes. An example of the single crystal with improvements started with trials on diffusion welding of two single crystal (SX) blade halves with open cooling configuration which was being done in the 1970. The problem with that process of the days was the lack of adequate non-destructive testing (NDT) techniques and the very high precision specifications for joining the parts[3]. Since those days, advancements of NDT methods and the application of transient liquid phase (TLP) brazing allowed to manufactured of at least prototypes of very heavy blades with complex cooling structures[3]. The transient liquid phase (TLP) brazing, providing more flexibility to connection or joining process, usually results in equiaxed or eutectic cellular structures[3].

CHAPTER 3

LITERATURE REVIEW FUELS

There are a few different types of fuels that a gas turbine engine can run on. To give the reader a background of the fuel types, I have included these pages from the book titled *Fuel Oil Manual* by Paul F. Schmidt. As there are many types of burners and combustion equipment used in different operations, from blast furnaces to small hot-water heaters, the need for various grades of fuel oil is apparent. Fuel oils are separated within five grades.

In order to hang onto the different grades on a constant essence, the American Society for Testing and Materials (ASTM) has adopted five basic grades, classify as Numbers 1, 2, 4, 5, and 6. The five basic grades comes with many differences or variations within each grade, while still having the five original grade numbers are kept. The fuel oil grade number 4 and 5 are split among light and heavy. The oil's thickness tells which subsidiary it is classed.

Table 1 lists the restrictions of the specifications for the different grades. The different refineries along with suppliers do not always conform to the high specification restrictions, but have agreed to those specifications. In Generally, the consumer is getting higher quality fuel oils than is allowable. From time to time the written descriptions or specifications change owing to environmental requirements, refining methods or break down processes, and optimal or ultimate use.

The information in Table 1 are used to figure out which grade an oil is to be classed. These descriptions or identifications are mandatory wide-ranging because of the many variations in fuel oils. The evaluations used to set up the requirements will be described in later chapters. The American Society for Testing and Materials (ASTM) has created and standardized procedures along with plans for evaluating the various properties of oils. These normal tests are used in petroleum laboratories as steady testing methods.

The individual grades of fuel oils are outline to show the oils available. A full comprehensive analysis of these grades is outline throughout the wording in the book.

Table 1. Detailed Requirement for Fuel Oils (Adapted from [4])

	No. 4 (Light)	No. 4	No. 5 (Light)	No. 5 (Heavy)	No. 6
Grade Description	Preheating not usually required for handling or burning	Preheating not usually required for handling or burning	Preheating may be required depending on climate and equipment	Preheating may be required for burning and, in cold climates may be required for handing	Preheating required for handling and burning
Specific	0.8762[g]				
gravity,	(30 max)	…	…	…	…
60/60°F	38 (100)	55 (130)	55 (130)	55 (130)	60 (140)
(deg,API),	-6[c] (20)	-6[c] (20)	…	…	…
max					
Flash point, °C					
(°f) min	2.0	5.8	>26.4	>65	…
Pour point, °C	5.8	26.4[f]	65[f]	194[f]	…
(°f) max	…	5.5	>24.0	>58	…
Kinematic	…	24.0[f]	58[f]	168[f]	>92
viscosity,	…	…	…	(42)	638[f]
mm^2/s (cSt)[d]	…	…	…	(81)	
At 38°C					
(100°F) min					
	(32.6)	(45)	(>125)	(>300)	(>900)
max	(45)	(125)	(300)		(9000)
At 40°C					
(104°F) min	…	…	…	(23)	(>45)
	…	…	…	(40)	(300)
max					
At 50°C					
(122°F) min	…	…	…	…	…
	…	…	…	…	…
max	…	…	…	…	…
Saybolt	…	…	…	…	…
Viscosity[d]	…	…	…	…	…
Universal at	0.05	0.10	0.15	0.15	…
38°C (100°F)					
min	…	…	…	…	…
max					
Furol at 50°C	(0.50)[e]	(0.50)[e]	(1.00)[e]	(1.00)[e]	(2.00)[e]
(122°F)					
min					
max					

Distillation temperature, °C (°F) 10% point man 90% point min max Sulfur content, mass, max Corrosion copper strip, max Sulfated ask, % mass. max Carbon residue, 10% b; % m, max Water and sediment, % vol, max					

Due to the different configurations, fuel oil number 4 could be titled a mixture product being a combination of a distillate and a residual. The book has laid out a more in dept conversation which is added below.

The oil grade does not need to be heated due to its faster flow rate, but has limited service. The number 4 fuel oil are primary used in small boilers in schools and apartment structures, constructing furnaces, low-temperature installations, and functions where the equipment does not deal with the thick oils like number 5 and number 6.

Light oil number 4 was a distillate oil considering its low viscosity. Regular oil number 4 can be any of the supporting types:

1. A concentrated oil, either not cracked or cracked.
2. Unique cuts or components from the crude oil, but a refinery rarely creates this quality of oil due to its small sales quantities.

3. crediting to many differences in refining functions, a light, off description material can sometimes be sought for this quality.
4. The established process of creating this grade is by mixing residual with distillate. Relying on the thickness of the residual, the proportion of distillate employed can range from 50 to 80%. The controlling element in the identifications is the thickness, which has a range from 45 to 125 seconds, Saybolt Universal Viscosity (SUV) at 100°F (39°C), or 5.8 to 26.4 cSt Kinematic[4].
5. Recovered lubricating oils are applied with small amounts. The types of oils are normally crankcase clear outs from vehicles being cutting, rapid cooling, and modified oils, along with particles of this nature. The discipline was discussed more in dept in Chapter 20.

Table 2 displays the differences in Number 4 examinations and types.

Table 2. Number 4 Fuel Oil Analyses (Adapted from [4])

Sample Types (Blend)	Gravity American Petroleum Institute	Viscosity 100°F (38°C)		Conradson Carbon (%)	- Ramsbottom Carbon (%)
		SSU	cSt		
A (residual & distillate)	18	89	18	4.50	3.75
B (residual & Distillate)	24	110	23	6.00	5.00
C (catalytically cracked distillate)	29	37	3.3	0.010	0.010
D (cracked & straight-run distillate)	33	38	3.6	0.014	0.010
E (Reclaimed lubricating oil)	28	80	16	0.500	0.45

Even though number 5 and number 6 fuel oils also have changing characteristics, number 4 differences are more important due to its employment in compact engines or motors and installations.

Number 5 fuel oil is rarely made in a refinery. It is usually created by mixing number 6 residual with concentrated oils to join established thickness identifications.

Number 5 light fuel oil has low thickness for employment with combustors that have no preheat, while number 5 heavy fuel oil with a higher thickness mandate adequate preheat at the combustor to reduce the viscosity for official atomization.

Relying on the residual thickness, it takes from 20 to 45 percent of concentration to acquire an optimum viscosity within the number 5 fuel oil range. When mixing with concentrations, the mixture oil's features are caused by particularly the gravity, which becomes higher, and thus less British thermal unit per gallon[4].

The number 5 oils are employed in small installations with average rates of usage. The price of number 5 alters, while it is consistently higher than number 6 and fluctuating from 3 to 13 percent higher. Since the handling specifications of number 5 fuel oil are barely less challenging than those for number 6 oil, all the details of the employment of number 5 oil should be examined and assess when differentiated it with the lower-priced and higher thermal energy content number 6 oil.

Caution should be used with number 4 and number 5 oils when not using preheaters have adequately low viscosity in the laboratory test temperature of 100°F (38°C), but the temperature in cold or non-heated storage tanks especially with above ground tanks will drop 30°F to 40°F (19°C to 21°C) below the test center result temperatures. The results of that is high viscosity when the oil arrived at the burner with no warm up becomes poor atomization. For more information on the temperature and viscosity differences, go to Chapter 7 of the *Fuel Oil Manual* book. The flow speed is slow because the oil starts to stiffen and setting above the pour point. Chapter 12 should be reviewed for more information on the subject. When the combustor or burner has no warm up, those two elements should be faithfully reviewed when examining a fuel oil.

The number 6 fuel oil is commonly referred to as Bunker C and residual has the appearance of black, thick, sticky, semi-liquid material at room temperature. This thick, adhesive state was because largely to it viscosity, but occasionally to the flow point. This outcome is the remainder from the crude oil after the light weight oils being gasoline, naphtha, kerosene, and concentrated oils are removed at room temperature and pressure. Even with all that being done, the refinery can still attain more lightweight materials that are the biggest money producers being the remainder called reduced crude, is additionally handled by several techniques.

The optimum employment of residual or leftover oil was in numerous occurrence reliant on costs. It may be mixed straight to heavy weight fuel oil like in the form of asphalt, or billed to other refining sections, such as coking or processing units with the purpose to reduce amount of residual oil (visbreaking) for the refining of other goods, especially light weight concentrates. Being a very thick, slow flowing oil, number 6 fuel oil is restricted to business and manufacturing or industrial use where adequate heat is accessible to make fluidity oil for pumping and burning.

With the diversity of refining procedures, numerous kinds of crude oils, and substantial mixing to create number 6 fuel oil will have changing examinations. In the bulk occurrences, these differences will still allow the oil to drop inside the grade constraints as displayed in Table 1. Regrettably, these descriptions with their wide range of rates can cause complications. These differences will be visible in both national and overseas refined oils, and will enhance as increased foreign crude oils are manufactured in the United States.

The fuels needed to fire gas turbine motors are important to my research. The fuel used for gas turbine motors are treated or refined from cruel oils. Paul F. Schmidt's *Fuel Oil Manual*, Chapter 15: "Fuel Oil Distillates," is important to my research because it talks about heavier fuel oil grades, being number 4, 5 and 6 that are used to power the gas turbine. Petroleum Fuel Oil Distillates meaning concentrated oils are described as being effectively treated or vaporized at temperatures of 650 to 700°F (343 to 371°C) while held at atmospheric pressure[4]. The heavy weight grades of fuel oils being number 4, 5, and 6, require higher heat to vaporize. Distillates or concentrates are liquid enough to flow like water at standard temperatures which is near 70°F (21°C), while the heavy weight grades develop into sticky, adhesive and will hardly flow at this temperature[4].

The capacity and reserve of concentrates will differ a considerable deal which are control by the supply and demand of gasoline, left over fuel oils and by the climate. Modern refining procedures which are about 40 percent of a barrel of crude oil finished up as concentrate. Distillate or concentrate oils are split into two grades that are number 1 and number 2. Grade number 1 houses an inflammable distillate oil for use in combustors that arrange the fuel for burning simple by vaporization and grade number 2 incorporate the fairly volatile distillate oils for use in combustors that arrange the fuel for burning by a merger of vaporization and atomization.

Both grades of concentrate are used in different insertions and equipment being houses or local heating, small businesses-heating installations as in housing accommodation, diesel motors, production of metal (forging) and smelting furnaces, crop drying, air conditioning, and jet motors.

The modern-day number 2 concentrate oils are created by two refining procedures being the straight-run, meaning no cracking and catalytic cracking processes as summarized in Chapter 3 of the book titled *Fuel Oil Manual*. A third process being thermal cracking which builds a concentrate, no longer sells as fuel oil, however used by refineries as charging stock to different cracking units. The number 1 distillate or concentrate fuel oil will be talked about individually.

From the start, straight-run or non-cracked distillates were the only ones accessible. Because of the surge in request for additional and greater gasoline, the catalytic cracking procedure was created which seriously changed the supply picture. The straight-run concentrates or distillates were prefect in creating a high demand for this catalytic cracking process, and generated a shortage in this type of distillate. The refiner, then cracked the residual oils to generate additional demand. As an outcome of events, more straight-run distillate became accessible, distinctly for use in diesel motors.

For ideal efficiency, the type of distillate employed is reliant on the equipment, however, a person can use more than one type in many cases[4]. An example of that is straight-run concentrate can be employed for all national heating equipment along with diesel motors while the cracked distillates are not as efficient in diesel motors. For industrial and business installations like the process of firing and shaping metal along with smelting furnaces, cracked distillates work really well for the reason of the large-size burners and larger combustion chambers. According to the *Fuel Oil Manual* Book, small combustor nozzles and combustion chambers need an additional easily burnable oil, like the straight-run type. The pure catalytically cracked concentrate is regularly employed as number 4 fuel oil, since it is better quality to most mixed oils. The bulk of today's oils retailed for nearly all kinds of installations are mixtures of the two concentrates in varying quantity.

With changes in refinery procedures, the outcome was transformations in the composition and character of the fuel oil concentrates. The quality of straight-run oils is reliant on the primary crude oil, while the increase in the rate of chemical reaction induced by unchanged chemically at the end of the reaction of cracked distillates are reliant on the type of some what refine crude oil used. Again, those are linked to the crude oil and the procedure employed to manufacture the charging stock.

The crucial variance joining catalytically cracked and straight-run distillates is an elevated fragrance or a lower paraffinic (a waxy crystalline flammable substance acquired from concentrate of crude oil) content. This is produced by the removal of hydrogen from a chemical compound in the course of cracking of the paraffinic and naphthenic compounds. The olefinic content, being a synthetic element derived from an alkene, of the cracked oils is vaguely more compare to that of the straight-run distillates. The third type of distillate or concentrate manufactured being thermally cracked oil and has an exceedingly higher olefinic along with a fragrance ratio than is establish in either the straight-run or catalytically cracked oils is no longer marketed today. The thermic cracked oils endure easy oxidation causing acids and sludge to form. In today's refining procedures, the thermic cracked oils are mainly employed as charging stocks to different cracking units.

The variation in their chemical hydrocarbon make up influence the burning of the concentrates to a sizeable degree with local or national like home heating oils compared to with commercial or industrial oils.

Table 1 was adapted to this thesis has detailed essentials for fuel oils which can be found in chapter 4 of *Fuel Oil Manual* Book. The table 1 lists requirements that are widely sufficient to allow nearly all the straight-run and cracked concentrates to drop within the shown ranges.

Table 32 can be found on page 130 of the book and will assist in the comprehension of the differences along with comparisons among identifications of the two basic distillate kinds and mixtures constructed from these types[4]. Additional concentrate identifications can be found in chapter 4 of the *Fuel Oil Manual* Book.

Residual oils are not like distillate oil where there is no one test to regulate the proper employment or efficiency of a concentrate oil. There is an easy rule for choosing the proper kind of concentrate which is the smaller and add delicate to the equipment or installation, the lighter or more inflammable the oil will be. A light weight oil is figured out by high American Petroleum Institute (API) gravity, low carbon-to-hydrogen fraction, low start boiling point, and low finish point.

The portion of the different kinds of hydrocarbons held will change connecting the straight-run and catalytically cracked oils. This variance in chemical make-up affects the carbon-to-hydrogen ratio allowing easier combustion with less oxygen while producing less smoke and soot. The carbon-to-hydrogen fraction of sample A is 6.65 and sample B is 7.41 is in table 32 of the book titled *Fuel Oil Manual* on page 130.

The thickness and slow flow of these distillates is usually adequate to cause no problems even with gravity-feed combustors. The maximum viscosity is 38 SSU at 100°F (38°C), as stated by the standard specifications in table 1 found both in this thesis, an adapted version and the original version found in chapter 4 of the book[4].

The gravity of a concentrate is not in itself a positive evidence of its burning grade, however it is helpful in many of other ways. From the gravity along with the kinds of oil, British thermal units (Btu) content, carbon remains, and carbon-to-hydrogen ratio can be figured out[4]. The subject is talked about in chapter 5 of the book, on gravity, for further information.

One of the greater principal variations between a straight-run concentrate and a cracked one is the British thermal units (Btu) per gallon. As the cracked oil has the lighter weight, it will have considerably more heat release capacity in British thermal units. Table 32 from the book *Fuel Oil Manual* displays how the variation becomes remarkable when magnify by a huge number of gallons [4].

That same book titled *Fuel Oil Manual* has a chapter that addresses issues with dealing with the fuel oil treatments. Chapter 19 which is titled "*Fuel Oil Treatments*" starts out with additives being used to treat various fuel. Fascination in fuel oil additives has enlarged immensely in the past few years. A lot of customers were questioning as to the worth of these treatments when these substances were initial announced and countless are still in disbelief. Like anything else in life, there are good additives and bad additives. Some consumers protest they have no value, while other customers are completely pleased. Surrounded by the causes for disappointment have been inadequate time for the materials to work, techniques of employment, and lack of knowledge of the kind of contaminants that can be eliminated. This has led the subject treatments to become fully debatable for years to come.

Fuel oil grades number 4, 5, and 6, cause problems from the development of sludge, but was tolerated due to the fact it is out of the question and impractical to eliminate the conditions.

The circumstance causing sludge can be minimized, stopped, and even abolished with the right conditions by adding fuel oil additives.

A lot of people are mainly focused on the treatments from the perspective of the applied results and benefits available in their employment. With that said, people should have greater comprehension of the fuel oil treatments, an understanding of the fuel oil's specifications, composition, peculiarities, behavior, and proper storage and handling procedures will be beneficial. This is especially significant in today's world with the difference of fuel oils processed by the countless refiners and current refining techniques.

A great deal of the information conducting with the use of fuel oil treatments in remaining oils is uniformly applicable to concentrate oils and later to come in chapter 19 will be a more complete conversation of the course material. The chemical make-up of these treatments for residual and concentrate oils is rarely the same, because the issues are different. The require for an additive is not as sizable for concentrates as for the heavy weight kinds of fuel oil.

The surged demand for concentrate oils for diesel fuels, furnace oils, and charging stock to increase supply of gasoline means that the refiner must always obtain it from the remaining oil. Present day refining operations turn out a remaining fuel oil that is several times heavier in viscosity compared to once resulted from the straight-run procedure and mild thermal cracking.

The product of leftover oil from a barrel of crude oil has dropped from the beginning 42% to about 9% currently. The leftover oil has been compressed moreover all the time ensuing in reduced quality and a heavy weight oil. All the improvements of technology advances have been headed to expand and idealize all petroleum products except leftover oils.

The grade of fuel oil is hard to explain what may be acceptable for one customer is unfitting for another. Refineries changed the grade and state of many heavy fuel oils that are created before they are ultimately burned should be held in the minds of many people. This is mainly expected to the handling, employment, operation, and kind of equipment employed.

Since the arrival of petroleum refining, the refining operations are now different. There are many differences in the leftovers oils today crediting to the methods of refining and mixing that produce difficulties for the customer and equipment industrialist.

In the beginning, the refineries did not expose the residual oils to very high temperatures and pressures in turn, their make-up was not overly changed. To produce the residuals today, they are exposed to very high temperatures and pressures requiring a reaction call cracking. This cracking generates large chemical differences in the hydrocarbon makeup of a residual oil.

Of the numerous reactions generated by cracking, there are two in which people are mainly focused on starting with:

1. A chemical reaction that transforms light fluids into heavier fluids. This effort is achieved by heat, pressure, or catalyst. In the cracking of an oil, the particles or molecule of oil is broken apart generating both light weight and heavy weight molecules. These molecules then return only except in a larger ratio than earlier. Sadly, that generates hydrocarbons or chemical mixtures that are much heavier, or are of a much higher thickness, developing in various characteristics.
2. The next reaction generates heavier liquid compounds while continuing to produce solid material. The solids give credit to the high viscosity or stability of the oil, either last in suspension or hover in the body of the fluid oil until it eventually settle out[4].

The remaining oil leaving from the refining towers is a very thick, and sticky material which creates a problem to handle. Bulk remaining oils today run about 5,000 to 10,000 seconds at 100°F (38°C), Saybolt Universal: compared to 300 to 1,500 seconds ahead of the arrival of high cracking[4]. Excluding steel mill employ as open-hearth fuel, employed in ship fueling, and use in some sizable installations, this high viscosity is unfitting.

For the previous purposes, the high viscosity of these leftover oil should thus be decreased. This is achieved through “cutting” with light oils[4]. The leftover oil may be mixed with such oils as straight-run, thermally and catalytically cracked concentrate, kerosene, or crude oils[4]. Regularly, the cutter stocks are the materials in surplus at the refinery. Nearly all leftover (residual) oils are mixed. At the time the so-called straight number 6 residual oil is often mixed. This is mandatory in order to make easier in the handling.

Naturally, the heavier the residual, the more the procedure of purifying a fluid by consecutive evaporation and condensation it takes to cut it. Earlier on when the viscosity of the heavy oil was low, only a little blending was required. Occasionally, 5 to 10 percent was all the light oil required to guide it to an acceptable viscosity[4]. The modern-day oils made it required to add 20 to 40 percent light oil to produce a usable product, and this is where the problems began[4]. While mixing residuals will narrow or decrease the viscosity, it will also often create an unstable mix.

This mixing of residual oils with concentrate or light oils introduce two difficulties:

1. When the residual begins to be much thinned, solid mixtures made by cracking and present in suspension are indissoluble or non-mixable with the light oils. This produces the solids to discharge much more simply and faster, crediting to the lighter viscosity of the mix. The residuals also have the trend to become viscous, shaping into big particles of solids. The bigger the particle dimensions, the quicker the settling will be.
2. When the residual is mixed, the liquidly, high-molecular-heavyweight mixtures currently in the residual may be indissoluble in the mixing distillate. This separates solids from the liquid oil, and this reaction is regularly called “organic precipitation”[4].

These two kinds of insolvable solid materials, or particles, falling out of the fluidly oil, discharge to the tank bottom to appear as sludge[4].

The fuel oil distillates and fuel oil treatment were added to this thesis to give the reader a back ground in processes of fuels being the number 4, 5 and 6 oils, mainly the number 6, but some books refer to number 5 oil as being the Bunker ‘C’ fuel oil, because that is used in gas turbine motors to fire them. Gas turbine motors were also supplied with diesel fuel to power them. In chapter 26 of the *Fuel Oil Manual* book, it gives more information on this subject.

Diesel Fuel Oils are nearly linked to heating oils and a lot of times, the same oils are provided along with employed both in diesel engines and for heating reasons. This is not uncommon and is ideally sufficient in a lot of occasion. Consequently, a conversation limited directly to the kinds and grades of diesel fuel oils with trials and descriptions along with their significance is included in the book.

The diesel motor’s capability to burn just about any fuel is its biggest strength. The burning and combustion traits of the numerous diesel fuels change greatly, which averts any one specific engine from financially and efficiently burning all kinds of fuel oils without some changes. Obviously, there should be one fuel that the motor can employ very efficiently. Although, to make a unique fuel for a distinct motor would soar fuel prices, along with cheap quality fuel require expand motor maintenance and need larger fuel usage, all developing in higher operating charges. Hence, nearly all diesel motors are created and constructed that they are achievable of employing a wide range and variation of diesel fuel oils.

Table 44 from the book displays the restricted proportion, temperatures, and factors for three grades. Contrasting these diesel oils with the oils in table 1 of the thesis or chapter 4 of the book, a similarity will be illustrious to those of standard fuel oils. In a lot of cases the diesel fuel oils are the same, or there is only a small change.

There are no descriptions for the heavy diesel oils like the leftovers, as their essentials are limited to a unique kinds of diesel engine being slow speed type and to the directions of the manufacturer.

The kind and grade of diesel fuel oil employed is relying on a lot of factors. The main ones are kind of injection system being bore and stroke of motor along with rotation speed. Other factors are external equipment such as heating and filtering provision wanted for the proper handling of the oils along with extremes of temperature, being hot or cold, and operating conditions as in below-ground mines. A manufacturer's direction occasionally varies from those in table 44 of the book, crediting to a particular operating situation, and then it is jointly agreed upon between the supplier and customer.

The verification of a fitting diesel fuel oil is in the performance of the motor. Test trial will result in the ultimate choice of a fuel oil, while the investigation has shown the rate is below others.

The description for diesel fuel oils are quite wide for the engines are used in many types of environments caused a large varying characteristics of diesel fuels. Because of the difficult essence of diesel fuels and the varying present refining processes along with the number of crude oils employed in the refineries, limiting specifications would tend to drop the accessibility and increase the cost of the fuels.

Choices of the most economical fuel is reliant on a lot of changeable to include operating conditions, fuel accessibility, and fuel price. Thus, it is best to take the manufacturers' endorsement descriptions and have the oil supplier issue a diesel fuel inside their limits. Remember that great fuels are not always overpriced.

Most of the fuel oils, whether employed to create heat under a boiler, or power a diesel engine, have the same results and descriptions. They are filed here with a short statement on each.

The gravity is incidentally related to motor performance. A lower gravity fuel raises power production and lowers fuel usage.

The cloud point which is the temperature at which a fluid being a petroleum oil begins to cloud or vaporize as from the separation of wax on cooling should be below the lowest operating temperature at which the motor will operate so that the filter will not become clogged with wax crystals.

The pour point or flow traits of concentrate diesel oils carry the same relationship to that of burning or heating fuel oils. This description must be at least 10°F (5.6°C) under the lowest operating temperature of the motor.

The flash point or spontaneous ignition is the principal to safe-handling of the fuel, while having no effect on engine operation, exclude if it is extremely low and this is not common.

Ash is the primary cause for engine deposits and extreme wear requiring low ash substance as possible for a diesel fuel.

Sulfur can be linked to engine corrosion especially at low temperatures and with non-continuous operation. Engine manufacturers normally suggest low sulfur oils to solve this problem requesting a 0.75 percent maximum content.

Carbon remains is linked to the amount of deposits found inside the engine. The bigger the carbon remains of the diesel fuel oil, the greater there will be the amount of carbonaceous engine deposits.

Concentrate diesel oil with low initial boiling point can produce smoking, while oils of high distillate range or volatility can produce engine deposits and high fuel usage. The perfect low temp vaporizable is required to allow complete vaporization and clean burning, resulting in low leftover deposits.

The thickness of a diesel fuel, whether a concentrate or leftover type, is of most importance. This description must be correctly managed for sufficient fuel pumping, fuel atomization, and injector operation. It also includes fuel-spray penetration and lubrication of the fuel pump along with injector nozzles.

Concentrate or distillate diesel oils need to have lubricating quality to keep tight contoured parts being the fuel pump and injectors from sticking.

The trial results and descriptions apply to all fuel oils while the three specifications are relevant only to diesel fuel oils being number 1 and number 2 distillates. The specifications are aniline point, diesel index, and cetane number which are related to the calculated Cetane Index.

The aniline point is the lowest temperature for absolute solubility of equivalent volumes of aniline and the distillate specimen under test. The compound is heated until the elements are completely soluble. This mixture is then cooled at which point the temperature reach the aniline and distillate to separate being the aniline point.

Aniline is a non-color fluid that is heavier than water. It is a good dissolving agent while very toxic and can be readily absorbed through the skin. Aniline is made from benzene and is the beginning substance in numerous chemical procedures. Aniline has a chosen dissolving action on petroleum hydrocarbons. Aromatic hydrocarbons are additional solvable in aniline than are naphthenic and paraffinic hydrocarbons, especially as the temperature dropped. The aniline point gives an approximate of the ignition quality along with the type of hydrocarbons present in the oil, but does not at first indicate an oil's performance in a diesel engine.

High aniline point displays paraffinic hydrocarbons of which the biggest percentage are existing in straight-run oils, and are greatly desired in diesel fuel oils. Low aniline point indicates a bigger percentage of aromatic or naphthenic hydrocarbons, which are undesirable and can be discovered in cracked oils. That is to say, the higher the aniline point, the greater the diesel oil.

Normally, the American Petroleum Institute (API) gravity of a concentrate oil will display some relation to the aniline point. A low-gravity oil, designating a cracked oil or a mix of a big percentage of cracked with some straight-run oil, do have a low aniline point. A high-gravity oil displays a straight-run oil or a mix of straight-run with a little percentage of cracked, and do have a high aniline point.

A fascinating relationship between the gravity and aniline point of varying kinds of concentrate oils is shown in table 3 of this thesis.

The diesel index is a calculated numeral or element used to grade diesel fuel oils. It was named, "the poor man's cetane number." Both gradings have almost the same importance. Even though the diesel index numeral is no longer a formal ASTM analysis, it is often listed in diesel oil descriptions. The greater the diesel index number, the superior the diesel fuel.

A measure of the ignition or flame quality of a diesel fuel calculated from a formula involving the gravity or weight of the fuel and its aniline point or the temperature at which the two phases separate out is the definition of diesel index. The equation for calculating the diesel index is list below in this thesis

Equation 1: $$\frac{\text{API gravity x aniline point (°F)}}{100} = \text{diesel index}$$

While the cetane number is the accurate description for a diesel oil, the diesel index number is often substituted, and it is 1 through 5 numbers higher than the cetane numeral. Testing the cetane number requires costly equipment, but the diesel index is effortlessly calculated.

Table 3 Gravity, aniline point (miscible), & diesel index number of various distillate oils (Adapted from [4])

Type of Oil	Gravity	Aniline Point °F(°C)	Diesel Index Number
Thermally cracked distillate	14.5	110 (43)	16
Recycle cracked distillate	27.0	112 (44)	30
Catalytically cracked distillate	28.1	122 (50)	34
Catalytically cracked and straight-run	34.6	140 (60)	48
Catalytically cracked and straight-run	37.1	148 (64)	55
Straight-run distillate	38.1	166 (74)	63

Table 3 graphically displays the gravity, aniline point, and diesel index link between eight separate distillate oils.

The cetane number can be seen in figure 3 was employed to exhibit the ignition quality of a diesel fuel. It is the ratio by volume of usual cetane being the 100 cetane number in a mixture with heptamethylnonane being the 15 cetane number that was same as the ignition quality of the test fuel. This grade of a diesel oil is the greatest key specification in the assessment of the fuel. It can be contrast to the octane rating of gasoline.

In a diesel engine, the fuel is compressed until the air is hot enough to burn it, where as in a gasoline engine employs spark ignition to exploded the fuel. In the gasoline engine, combustion is instantaneous, while in the diesel engine, it is a time-consuming process. Diesel engines have fuel injected into the combustion chamber and ignition does not occur immediately. The time gap between the fuel injection along with its self-ignition is called the ignition delay period. This delay period depends on a lot of variables being the fuel, the motor, its construction, and on the operating conditions. When the delay become too long, the engine will then be hard to start, resulting in accumulated fuel that ignite causing the rate of energy release to be so great that it runs rough or has diesel knock. However, if the delay is short, the engine will run smoothly. These equations are used in calculated Cetane Index and they come from the book titled *Fuel Oil Manual* by Paul F. Schmidt which is in figure 16 on page 223.

Equation 2: Calculated CI = $-420.34 + 0.016\ G^2 + 0.192\ G \log M + 65.01\ (\log M)^2$
Equation 3: Correction for Mid B. Pt. = 1.19 X 6 =7.14
Equation 4: Correction Mid B. Pt. = 550°F + 7.14 =557.14
Equation 5: Calc. Cetane Index (Nomograph) = 48.5
Equation 6: Calc. Cetane Index (Formula) =48.52

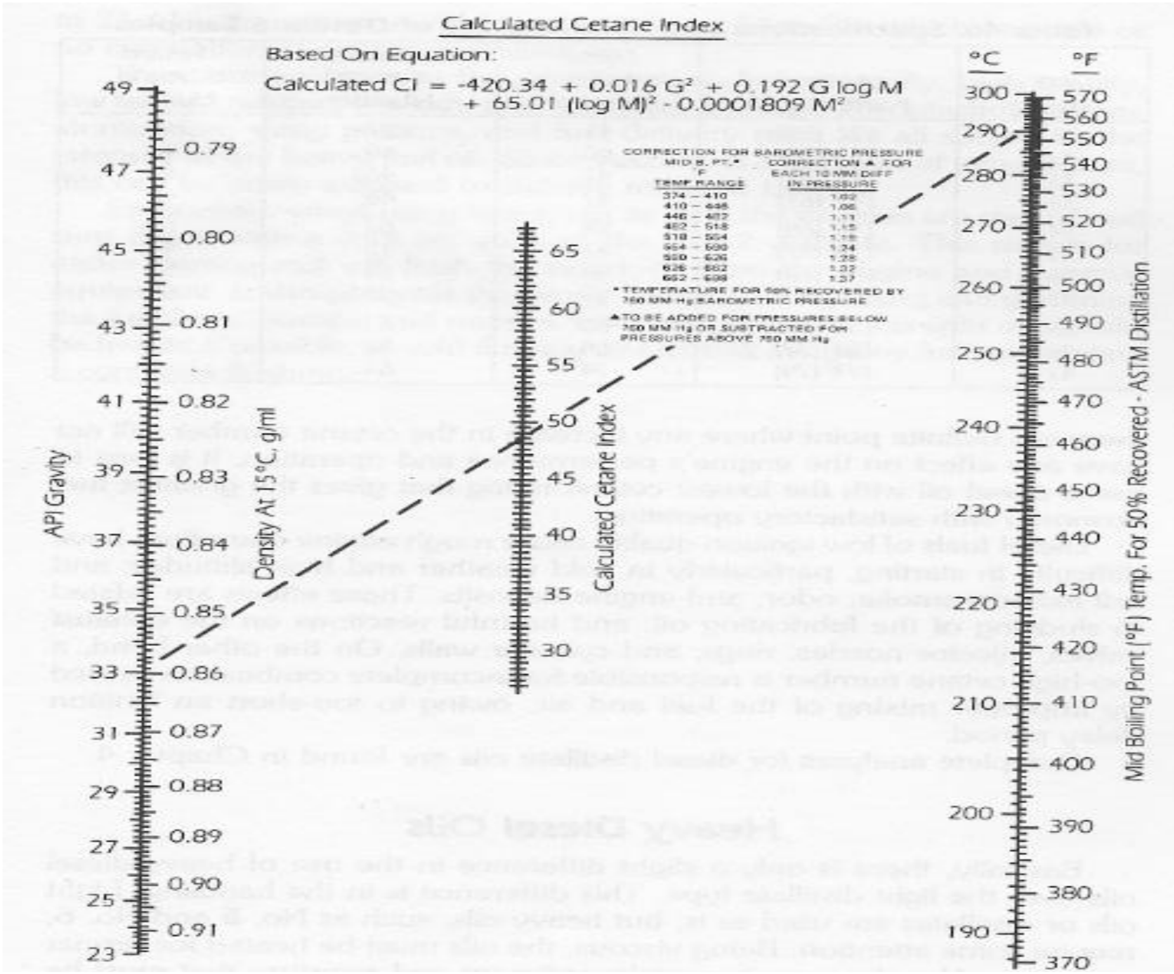

Figure 3. Calculated Cetane Index [4]

The next question the reader might ask them self, is what if you do not have No. 5 or No. 6 Fuel Oils or diesel fuel to power your gas turbine motor with. A book titled *Applied Combustion*, second edition by Eugene L. Keating has an answer for that. In chapter 12, section 5 is a section titled *Gas Turbine Engine Fuel Alternatives* which goes into details to discuss this issue.

Synthetic fluid fuels extracted from coal, shale oil, and tar sands have serve as lasting fuel substitutes for the crude oil-derived gas turbine fuels currently being employed. Alcohol fuels being most likely methanol will also find some future use in land and or marine gas turbine engines. Trading out for an alcohol fuel in a distinct hydrocarbon distillate fueled combustor would result in greater fuel usage and may partially degrade the gas turbine engine. Alcohol fuel traits as well as combustion characteristics of alcohols, for an example being viscosity, latent heat of vaporization, specific heats, flame speed, and flammability limits, does not prevent seeking modifications for optimizing use of alcohol fuels in improved combustor ideas for specific applications. Water dissolvable of alcohol would seriously affect its use in a marine environment. Aircraft employment would be tough since the constant-temperature boiling properties of alcohols.

Gas turbine arrangements have been developed that burn solid fuels like coal and wood. Methods for burning solid fuels involve straight combustion, slurry combustion, fluidized bed combustion, and indirect combustion. Chapter 6 in a book titled *Applied Combustion* outlines these combustion methods as they apply to coal fired steam generating systems. One problem needed to be solved is the fuel-engine interface issues of gas turbine combustors for burning solid fuels like pulverized coal. Coal powder is different than most of the solid fuel equipment outlined in chapter 6 which is introduced into high-pressure and high gas flow rate operating authority of the gas turbine environment. Observe that some of the solid fuel would need to totally burn during the short time it stays within the combustor in order to verify no tar depositing arises during solid fuel result gas expansion through the hot turbine division.

Chapter 8 explained the mechanics of scientific knowledge for the gasification of coal. Successful scientific knowledge that created clean energy from coal fired gasification will provide an employable fuel resource for gas turbines assisting electric power generation-distribution systems. Burning solid fuels individually and employing heat exchangers rather than using customary or improved combustor components to transfer released energy to the gas turbine airstream might develop a means of protecting the turbine divisions from damaging solid combustion products types.

Aeroderivative was a light weight variant of a gas turbine. This machinery that burns high grade kerosene gas-turbine fuels was originally presented into the marine world of industrial and stationary power generation fields. Greater application of improved aeroderivative gas turbine technology by the stationary power generating industry employing systems having the ability of cleanly burning low emission natural gas, heavy oil, and coal resources, along with supplied benefits beyond simply increasing peak load. Special land-based burner-fuel combinations supply increasing fuel alternatives operation, increasing utility power result, increasing thermic efficiencies, increasing plant flexibility and operability, along with increasing flexibility in design.

Figure 4 shows achievable arrangements of advanced gas turbine technology founded on use of fuel alternatives. In one combined cycle arrangement a steam generator being the Fluidized Bed Combustion (FBC) coal combustor creates a gas product that can be used as gas turbine fuel for firing in the gas turbine department of the combined plant. In another integrated cycle difference, a gas turbine burning a clean fuel being natural gas can use the turbine exhaust gas with additional firing as the heat source in the heat recovery boiler department of a combined plant.

Hydrogen’s traits as a future lasting fuel resource are studied in chapter 8 of the book. Some properties make hydrogen an appealing candidate as a lasting aviation fuel replacement which include: considerably larger clearly defined energy than kerosene fuels, atomization and vaporization are not required when burned as a gas, good heat sink to help cool engine parts when stored as a liquid, wide combusting range and fast flame speeds, which are both compatible with small combustor diagrams, no presence of carbon decreases radiant heat loss, smoke, soot, and particles[5]. Also included in that list is no formation of carbon, carbon dioxide, unburned hydrocarbons, absence of eroding or corroding containments, and no carbon buildup on critical engine components[5].

Remember that any of the suggested alternative along with synthetic turbine fuels, and any of their needed system modifications would still be required to meet the same performance and environmental conditions authorized that present fuels must meet [5].

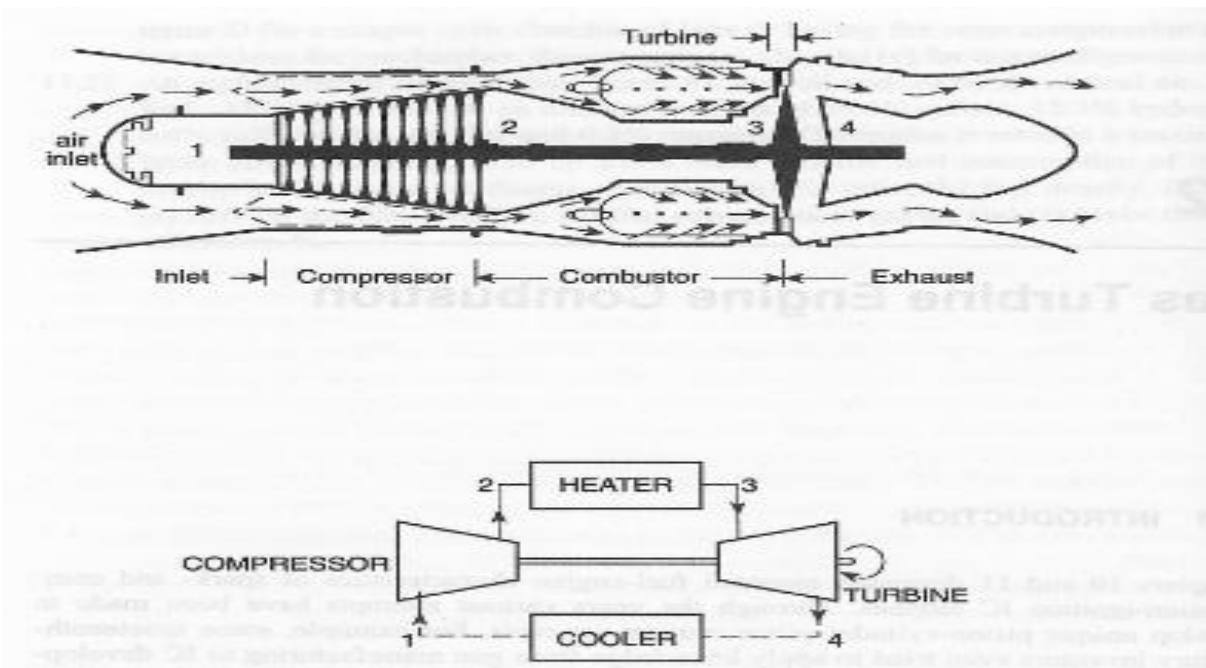

Figure 4. Gas turbine diagram and power system [5]

Chapter 12.5 mentions chapter 6 which talks about combustion techniques of coal and other solid fuels that apply to coal fired steam generating systems. To give the reader a closer look at chapter 6, I will include parts of it as well.

Any public engineering foundation in combustion along with in addition to introducing fundamentals of thermochemistry should assess some specific fuel science topics including energy properties of different important fuel resources. Numerous causes come to thought for choosing solid fuels as the first fuel science subject studied in this book along with including the historical role the solid fuel coal took part in the birth of the Industrial Revolution. The other causes are the relevance today solid fuels take part in industrial heat and power generation along with established pollution issues associated with solid fuel combustion. To add to that solid fuel resources along with coal have become usable in the future as raw material for making varying synthetic liquid and gaseous fuels.

A remarkable quantity of information has been written and published that addresses varying subjects linking to solid fuels including the beginnings, the worlds supplying, as well as the possible environmental impact and economics of rising use of coal. This conversation will concentrate mainly on those specific engineering subjects that are relevant to industrial combustion-generated power or heat transfer applications. The next material will be restricted thus to taking into account technical aspects of solid fuels along with the combustion machinery required to burn these selected reactants, and their common emissions properties and pollution control.

The bulk of naturally occurring solid fuel resources are mainly hydrocarbon-based compounds. The important solid phase element in the fuels is carbon. From table

B.1 in Appendix B of the book titled *Applied Combustion*, the heat of combustion of solid carbon is establish to equal

Equation 7:

$\Delta\overline{H}_c$= 393,804 kJ/kgmole (169,307 Btu/lbmole) (6.1)

or

Equation 8:

ΔH_c= 32,817 kJ/kg carbon (14,109 Btu/lbm) (6.2)

The heating usefulness of hydrocarbon-solid fuels must be about 32,800 kJ/kg fuel (14,110 Btu/lbm).

Difficult solid fuel resources like coal can change in their local material and energy characteristics. The energy produced by coal acquire from different mine locations will be noticeably incompatible from the perfect heat of combustion for carbon. The actual method for figuring out the real heating value of a specific solid or liquid fuel source employs the use of a constant-volume reaction vessel and this can be seen in figure 5.

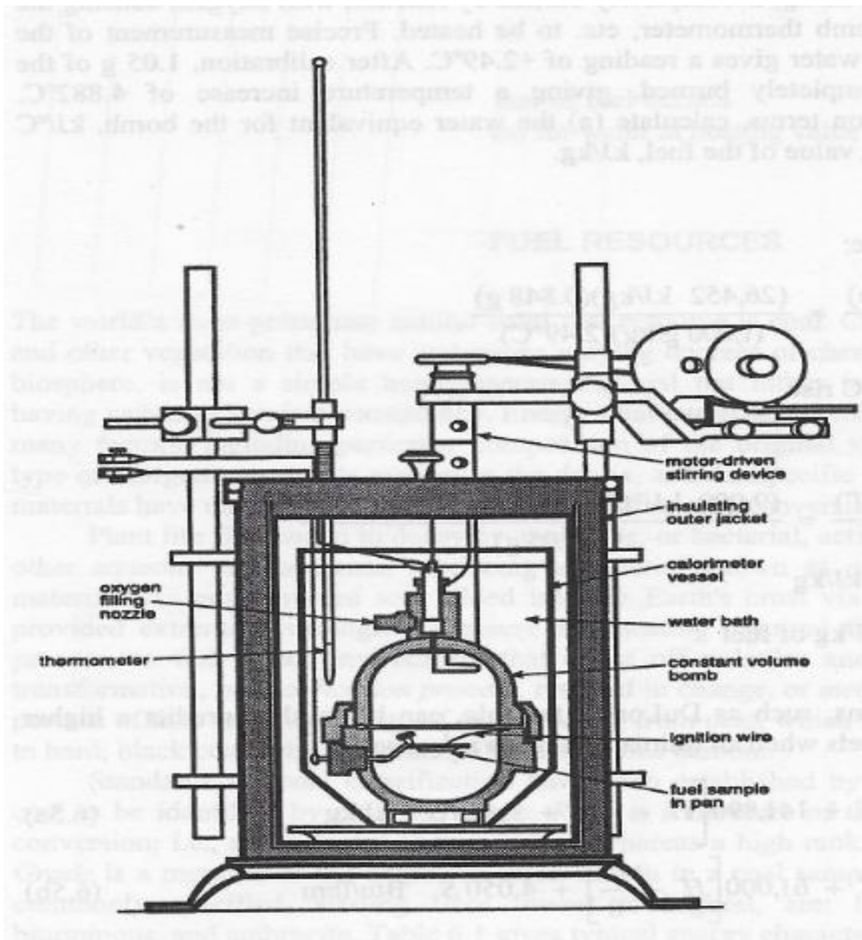

Figure 5 Constant-volume oxygen bomb calorimetry diagram [5]

The outcomes are acquired by deducing the energy released from the total combustion of a sample of source material inside the vessel. The experimental methods used to figure out the heat of combustion are based on fundamentals of calorimetry. In order to verify accurate measurements of energy in a fuel specimen, the bomb calorimetry needs the use of common methods being those confirmed by the American Society for Testing Materials (ASTM), expert calibration, and reproducible operation with the facilities.

A reaction vessel holding a fuel and surplus pure oxygen mixture is submerged in a water bath originally at ambient conditions referring to standard temperature and pressure (STP) being temperature of 25°C. Energy discharged by the full combustion of the reactants within the vessel is absorbed by the encircle water bath which produce the water temperature in the jacket to increase. By burning a pure compound with a familiar heating value like benzoic acid that has a thermic reaction, or a water equivalence of the equipment can be established from the heat given off by the calibration sample. After adjusting the unit, any fuel specimen that releases about the same total energy would also affect the water jacket temperature to increase approximately the same, and by employing the water equivalence, the fuel heating value can thus be figured out. Employing a constant-volume oxygen bomb calorimeter, heating values of solid and definite fluid fuels can be experimentally calculated using Equation 9 as

Equation 9: $$HV = \frac{W\Delta T - E_1 - E_2 - E_3 - E_4}{m} \qquad (6.3)$$

Below is a key for what the different variables represent:

Equation 10: W = water equivalent, kJ/°C (Btu/°F)

Equation 11: ΔT = temperature rise, °C (°F)

E_1 = rectification for heat of formation of nitric acid, E_2 = rectification for heat of formation of sulfuric acid, E_3 = rectification for combustion of gelatin capsule (used with fluid fuel testing), E_4 = rectification for heat of combustion of firing wire, M = weight of fuel specimen, kg (lbm), HV = heat value of fuel, kJ/kg (Btu/lbm)

Precision needs mass measurement of the fuel specimen to within ± 0.002°C. Combustion of premeasured fuel and surplus of pure oxygen is achieved by current flowing through an ignition wire. Some corrections are added in Equation 9 (6.3) to account for irrelevant experimental factors such as energy given off by burning any ignition wire and energy connected with the formation of any nitric and or sulfuric acid. Laboratory mistakes can appear because of unacceptable fuel sizing or contamination with impurities during provision. Remember that to guarantee equal water equivalents, adjustment and experimental runs require that fuel specimen weight be carefully overseen. Laboratory errors are caused by unsuitable ignition for instance from an inadequate ignition current, misalignment or grounding of the ignition wire, and insufficient oxygen for full combustion. Lack of standard adjustment or testing can result in inaccurate water equivalence and or predicted heating value.

The bulk of natural solid fuels exist in the environment as compounded organic chemicals and mineral compounds that have gone through varying degrees of aging and chemical conversion. Solid hydrocarbon fuel materials starting with wood through coal are actually vegetation in various stages of decay and consist mainly of carbon, hydrogen, oxygen, moisture, sulfur, carbon monoxide and methane, along with ethane, sulfuric acid, tars, and ammonia.

Description of the correct energy characteristics of these solid fuels would require a full knowledge of all components expressed in terms of each element mass fraction, for example of an ultimate analysis. Frequently for engineering consideration a nearly accurate or fixed carbon analysis is adequate to define the fuel's combustion characteristics shown as a fixed carbon, C, analysis or

Equation 12: $\%C = 100\% - \%moisture - \%\ volatiles - \%\ ash$

Condensation is water trapped within a fuel specimen. Volatiles are components that evaporate during low-temperature heating of the fuel, while ash is man-made mineral impurity or residue left when a fuel has been fully burned. The fixed carbon is a coke-like leftover fuel material left after water vapor, volatiles, and ash are taken out.

This last part of section 6.2 having the molecule make-up of the different solid fuel helps with the understanding of the combustion processes which take place in many types of motors including the turbine motor. An idea to improve the efficiency of the turbine motor was to use the exhaust gases to heat a boiler that would convert steam to electricity.

It is important for the reader to have a back ground on specification for number 4, 5, and 6 fuel oils along with the alternate fuels which are used to fire the gas turbine motors and the chemical makeup for the combustion process. The reader should know these terms as well, being uses of distillates, types of distillates, composition of distillates, specifications for distillates, and residual fuel oil along with the “cracking” reactions. Knowing these terms or information being viscosity, blending residuals, blending problems helps in understanding what type of fuels are best for various gas turbine motors. Diesel Fuel Oils and specifications for diesel fuel oils is also important for in some of the first gas turbine engines, these fuels were used to fire them. Now that you have a back ground and understanding of the types of fuels, it is time to move onto the types of gas turbine systems. This book will help with that. A book titled *Modern gas turbine systems High efficiency, low emission, fuel flexible power generation* edited by Peter Jansohn has a chapter 2.2 called *Gas turbine types by application*.

Gas turbine engines are used in the transportation sector being land, sea and air applications of commercial, along with military purposes. The mechanical power result for such gas turbine products ranges from a few 10 to 100 kilowatts that is for use in passenger cars being the Volvo of 1992, multiple 10 megawatts for use in jet engines and ship propulsion[3].

The results at the low-power scope of microturbines are employed in stationary equipment for joint heat and power (CHP) systems for apartment house, community heating networks, and hotel resorts[3]. Also included in that list is campgrounds and farming along with greenhouses[3].

However, CHP systems are well liked in plants in the low megawatts thermal range being maximum up to around 100 megawatts thermal for local and or regional heating networks and for consolidated solutions in industrial processes like paper mills, refineries, chemical industries, and so on. This require remarkable amounts of heat in the configuration of steam and or hot water for their operation. Only in astonishing cases do such networks contain huge scale gas turbines even in the multiple hundred-megawatt range[3].

The territory of gas turbine products with 5 to 50 MW mechanical shaft power output is mainly now called aeroderivative turbine systems, which are small changes of individual aero-engine designs accurately adjusted to more rugged stationary operational employments. The industrial gas turbine category is a popular drive for fluid-mechanical machines such as pumps, compressors of along gas and or oil pipelines and large blower or fans in industrial production plants[3]. The aeroderivative gas turbine designs grant themselves primarily to changes of the simple cycle gas turbine configuration towards more experienced being higher efficiency system arrangements. This would include compressor inter-cooling and or exhaust heat recuperation. To learn more on the details of thermodynamics of advanced cycles, go to chapter 3 of the books[3].

Electric power generation established on gas turbine systems covers the full range of output from the kilowatt of single simple cycle machine to the gigawatt scale of multi-turbine arrangement in an incorporated cycle plant[3]. While the smaller dimension gas turbine arrangement below 10 megawatts are mostly operated in a simple cycle configuration, this one is using an added of a bottoming steam cycle which makes use of the gas turbine exhaust heat for additional electricity generation. This is the most universal set-up for large scale plants of more than 100 megawatts. Todays combined cycle arrangement do provide world record electric efficiencies of beyond 60 percent. The high efficiencies also benefit from increased production and lowered costs effects that come about with single gas turbine unit sizes on the order of 300 megawatts.

Gas turbine established procedures for electric power generation cross the whole dimension range from a few 10 kilowatts microturbines to multiple hundred megawatts for large combined cycle power plants which is large heavy-duty gas turbine manufacturers. The biggest power output for a single unit gas turbine engine only extends close to 400 megawatts which makes a combined cycle plant size well past 500 megawatts. Due to appealing increasing production and lowering costs effects, the so-called 2-in-1 plant arrangement being the exhaust gas heat from two gas turbines is guided into one bottoming steam cycle and steam turbine are fairly popular and deliver up to almost 1 gigawatt.

The electric efficiency accomplished with such big power plants has now exceeded the 60 percent spot. All major original equipment manufacturers like GE, Siemens, Mitsubishi, and Alstom of such large turbine engines have announced 60 plus percent efficiency levels with their latest products. That is only with one of the original equipment manufacturers having it already demonstrate and certified by an independent company [3].

There are many different theses out there, but very few on the topic I am doing. One example of a thesis that touches the topic is *Improving Efficiency in the SIUC Campus Chilled Water System Using Exergy Analysis,* where the turbine is use to power a shaft, but in this thesis, it does not talk about or conduct experiments to improve the turbine motor. A technical paper that does relate to my thesis and works to improve the turbine efficiency is titled *A Recuperated Gas Turbine Incorporating External Heat Sources in the Combined Gas-Steam Cycle*. Within this technical paper or journal is an article titled *Recuperated Gas Turbine Process and Efficiency Definitions*, that came from a website titled *Double-Jet Ejection of Cooling Air for Improved Film Cooling*, which says “A simplified gas turbine process without heat recuperation (a simple cycle) and with heat recuperation, both with an internal source (exhaust gases from a turbine), as well as with an external source, is shown on the entropy diagram”, of figure 6.

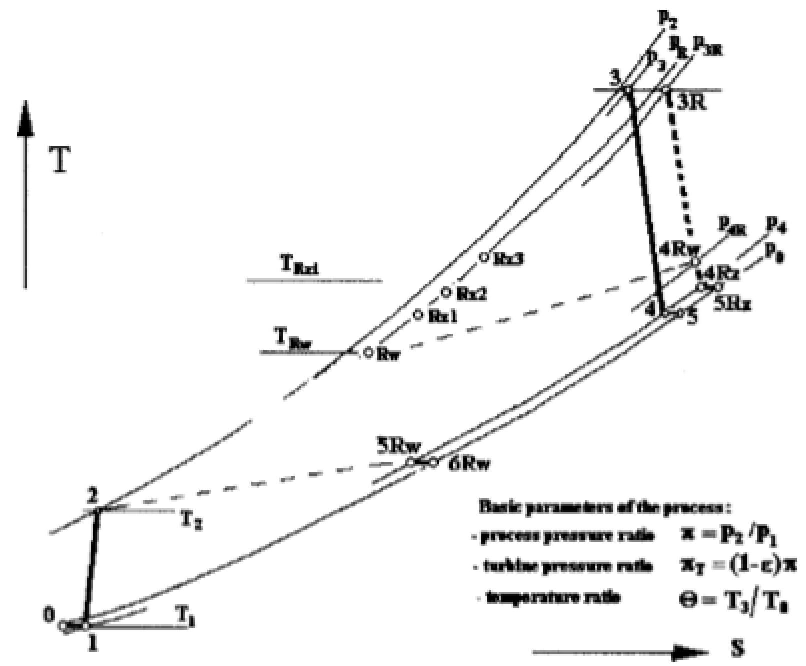

Fig. 1 Entropy diagram of gas turbine processes. Simple cycle: 0-1-2-3-4-5; cycle with heat recuperation with turbine exhaust gases: 0-1-2-Rw-3R-4Rw-5Rw-6Rw; cycle with heat recuperation with an external source 0-1-2-Rzi-3R-4Rz-5Rz, *i*=1, . . . – *n*.

Figure 6. Gas turbine process for entropy diagram [4]

As can be seen in Fig. 6, an introduction of heat recuperation in the gas turbine process brings about (on the assumption of the constant cycle pressure ratio

Equation 13: π=p2 /p1, and the constant temperature ratio

Equation 14: Θ=T3 /T0):

• a decrease in fuel consumption of the gas turbine owing to an increased air temperature upstream the combustion chamber in comparison with a simple cycle

• a decrease in the gas turbine power resulting from additional flow resistance in air and gas paths leading to a decrease in the turbine pressure ratio

Equation 15: $\pi T = (1-\varepsilon)\pi$;

• an increase in the turbine exhaust gas temperature ($T_{4RZ}>T_4$, $T_{4RW}>T_4$).

It can also be seen in figure 6 that as against the recovery of the turbine exhaust gases, the recuperation with outside heat sources to preheat the compressed air before the combustor permit one to employ fully the exhaust gases in the bottoming steam cycle with a steam turbine. In such a combined gas and steam procedure with two diverse heat origins as fuel energy and process waste heat, the effectiveness of electric power production must be sufficiently defined, specifically

• gas turbine fuel efficiency, acknowledge as the effective thermal efficiency on the generator clamps

Equation 16: (1) $\eta_F \equiv \eta_{the} = P_{el\ GT}/Q^{\cdot}{}_F;$

• incorporate gas and steam cycle fuel efficiency

Equation 17: (2) $\eta_{F\ COMB} = (P_{e1\ GT} + P_{e1\ ST})/Q^{\cdot}{}_F;$

• final thermal efficiency of the energy [3].

Equation18: (3) $\eta_0 \equiv \eta_{the0} = (P_{e1\ GT} + P_{e1\ ST} + P_{e1\ EX})/\,(Q^{\cdot}{}_F + Q^{\cdot}{}_P),$

when in the energy system besides gas and steam turbines, the gas expansion turbines being expanders are used, and the Q_{dot} p variable is the total waste heat output from the industrial process[6]. This journal has information on improving the efficiency of gas turbine while using the exhaust gases most like what I am proposing to use to improve a railroad locomotive. However, instead of using graphs and charts, I will be using a simulator to show the results of making changes to the gas turbine motor [7].

Another importance in the simulator is the change in blade design, but before you can change the design you need to understand how the basics of blade cooling works in a turbine. A book titled, *Modern gas turbine systems High efficiency, low emission, fuel flexible power generation* by Peter Jansohn has a section that does just that. As you burn fuel, an engine is going to expand and a gas turbine does that too. As it goes through the expansion process, it is supposed to be adiabatic, where no heat enters the system or leaves the system. The section of the book being 3.6, *Basics of blade cooling*, points out it is completely restricting to accept as true, considering the turbine inlet temperature levels currently used in commercial gas turbines, which are several hundred degrees higher than the maximum temperature that metal alloys can stand. Technological restriction would be too great for the metal of the nozzles and blades, if it was not for the cooling technology to prevent the maximum metal temperature. The turbine inlet temperature has a minimal of three exact meaning and is of great significance to understand. First is the combustor outlet temperature or COT, being the temperature produced within combustion area in front of or before first nozzle of the gas turbine. Manufacturers will not provide a data sheet for the outlet temperature of a gas turbine even though the turbine inlet temperature is identical to the COT while the turbine is adiabatic. Second, which is significant in nearly all cycle calculations and simulations, and is the COT lowered by the mixing of the gases exiting the combustor with the cooling air of the first nozzle, is the first rotor inlet stagnation temperature, the turbine inlet temperature (TIT). Third is the ISO turbine inlet temperature (TIT_{ISO}) which is describe as the temperature acquired following mixing the gases exiting the combustor with the overall nozzle and blade cooling flowrate. Allowing air to flow inside the nozzles and blades is the usual way to cool high temperature nozzles and blades by draining air from the compressor at the discharge temperature which is normally lower than 350°C. The cooling air is combined with the hot gases once passing through the blades. The thermodynamics operation is totally difficult to understand due to the nonadiabatic expansion and combining involves a full understanding of the turbine arrangement in series and the heat transfer properties of the blades and nozzles. A simplified calculation can be carried out by concluding the cooled turbine as a series of adiabatic expansions accompanied by mixing of colder air with the hot gases.

A cooled expansion is conceptually worse than a process occurs without transferring heat or mass between a thermodynamic system and its surroundings being an adiabatic one. It is not accurate to compare a cooled expansion turbine along with an adiabatic turbine with the same inlet temperature. This is because it would be pointless to cool a turbine from temperatures where an adiabatic turbine would be operated cautiously and, at the same time. It would be out of the question to use an adiabatic turbine at temperatures where cooling is required.

Thus, when differentiate an adiabatic turbine with a turbine inlet temperature (TIT) of 900°C with a cooled turbine with an inlet temperature of 1500°C, it is clear that the particular work and efficiency of the cooled turbine will be much larger than that of the adiabatic turbine.

Learning the process of the gas turbine, it is clear that the successful transformations have primarily been in the components, and only in one case being in the thermodynamics cycle.

The evolution of the gas turbine has needed important efforts in research, and gas turbine builders have always been fully conservative in accepting proposals involving major changes of the system. Thus, the advancements were primarily made in the compressor and making turbine streamlined, combustion efficiency and cut down of pollutant emissions, high temperature materials and nozzles along with blades cooling.

The bulk of the technologies have come to a very thorough level of design and work, awaited advancements are slow, and only unexpected break throughs will be able to pass from today's development paths. These trends are established to gas turbine scientists and manufacturers.

Viewing the thermodynamics cycles, there has been a serious fascination in the last two decades for wet cycles employing air and water, or a mixture of them as working fluids. This was primarily credit to outstanding improvements in the abilities in terms of efficiency and specific power.

Combined cycles of the last creation with steam cooling of the nozzles have portrayed an important transformation that still needs development and may produce further advancements in the performance.

The true revolution for the future may come from the incorporation of gas turbines and high temperature fuel cells in the alleged hybrid cycles. Although, the main problem to be worked out in this technology are on the fuel cell side. The anticipated efficiencies for that kind of plant may reach 70 percent, which is currently a future goal for combined cycles and with the extra advantage of being able to reach such performance levels even for small power plants[3].

A thesis titled JET FUEL THERMAL STABILITY has an article titled APPLIED RESEARCH AND TEST SIMULATORTS talks about approaches used for fuel system simulator studies of jet fuel stability. One method it talked about involves parametric studies in a general design type of simulator whose objective would be to provide parametric design data under near real-world conditions. This data collected would be used to project fuel consumption in a diversification of aircraft systems. In this same article it talked about a second approach would involve systematic studies in a complex simulator constructed to reflect the specific conditions in a single, given aircraft system. The reasoning for this is to bridge the gap between small scale laboratory test device results and performance in actual fuel systems using the parametric simulator studies. They will also provide a predictive design variable data base for aircraft fuel system designers analogous to those routinely developed in the chemical and petroleum industry via pilot plant process variables studies whose results are used to establish commercial production unit process designs. Traditional, specifically designed simulators would be used to demonstrate individual aircraft fuel system designs and to study specific flight parameters in more detail where needed. This thesis also looks at the engine system trends and requirements. Their study has concluded that thermal stability is a problem today and trends in engine design are potentially toward a more severe environment for fuel. Thus, they emphasized the importance of having fuels available in the future with good thermal oxidative stability. That is important to my research because of the residue or deposit left on the turbine blades. The rest of this article is found in table 4. It says, “In view of the concern over fuel thermal stability problems and in the national interest as well, NASA should determine the realistically practical limits of aircraft emission control with full consideration of all fuel property and cost objectives, energy conservation, engine durability, consumer costs for transportation and inflationary pressure.”

CHAPTER 4

THE PROPOSED METHODOLGY

There will be two motors of equal size, but not of equal horsepower or torque output. One of the motors will be the gas turbine that is connect to an electric generator and the other motor will be a diesel engine connected also to an electric generator. The next step is to run both motors while recording the horsepower generated, torque output, brake horsepower, traction horsepower, maximum speed, continuous tractive effort, starting tractive effort, dynamic braking effort, weight, length, fuel burnt per hour, number of axles that are powered. The experiment will also record the bore and stroke, RPM (Maximum/Minimum), main generator used and engine temperatures. These recording will be of the diesel-electric motor setup. The gas-turbine electric motor will be somewhat different since it will not have a bore and stroke, but much of the same data will be recorded. The gas turbine will have the turbine motor that is connected by way of drive shaft to a generator. In front of the turbine motor is the air intake that draws air in from the roof and at the end of this motor is the exhaust that is sent to the rear of the locomotive through a large duct. It also will have a fuel heating and filtering, coolant water tank, starting fuel pump, control cabinet, traction motors and traction generator. The results would be that the turbine has more horsepower for the same space and weight of the diesel motor. However, the turbine would burn a lot of fuel and if the turbine was just sitting still, there would be fuel burned at high rates while the diesel can idle down with burning little fuel amounts.

Chapter 4.1

Data Collected

After the recorded parameters of the models have been collected and notes have been compared of the positives along with the negatives, changes will be made to improve the gas turbine. Those changes will include changing the type of materials the blades are made of, the design of the blades so they are 3D printed to include channel made with in the blades to extract some of the gases. Other changes will also include looking at ways to shut down the gas turbine motor faster, start it up faster, adding an exhaust silencer and harvesting the exhaust gases to be reused to help in improving the efficiency of this motor.

Chapter 4.2

Data Analyzing

The project will also include looking at the software needed to preform calculations. One of the software used to do calculations will be the Microsoft Excel Spread Sheet. These calculations will be used to check for correct horsepower ratings, traction effort, torque output and so on.

Once the improvements have been made to the new gas turbine, test will be run again. Data will be collected to recorded all of the parameters and check to see how much the gas turbine motor has improved in various situations. These situations will include shut downs, startups and idling. The project will also be looking to see how the locomotive preforms running while pulling freight at various speeds.

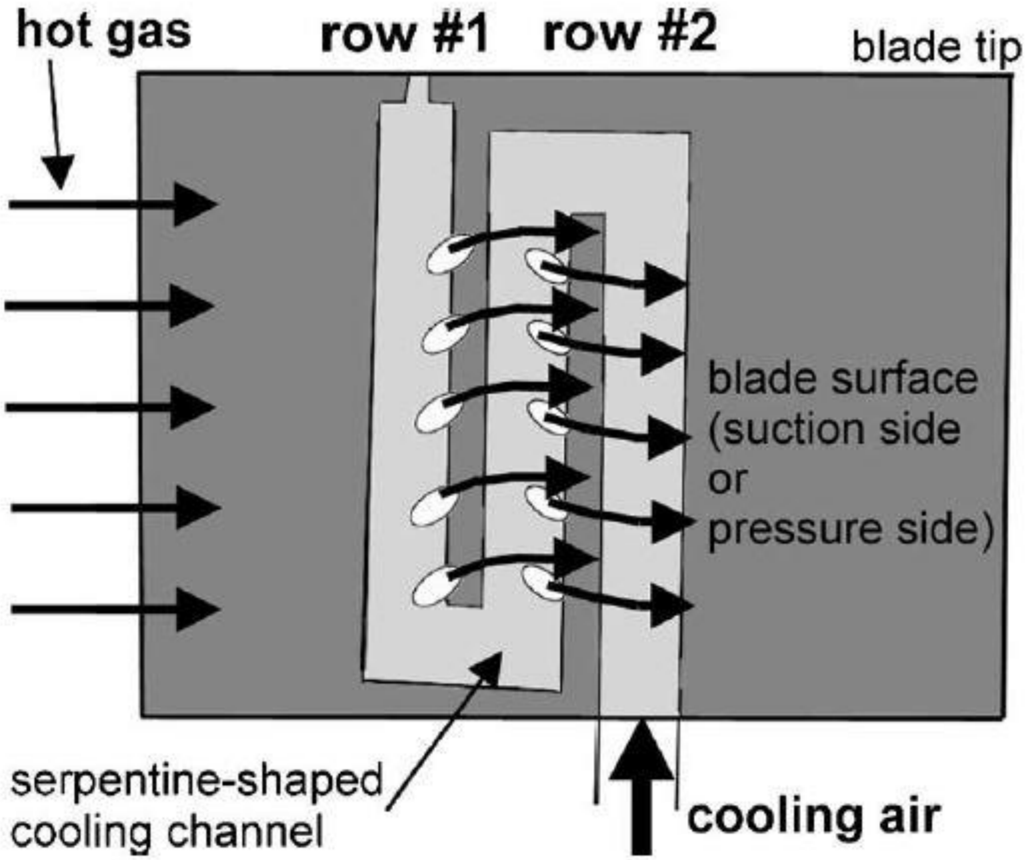

Figure 7. Application of the DJFC to a cooled GT blade (schematic drawing) [8]

CHAPTER 5

ACTUAL EXPERIMENT

I used a computer simulator design for aircrafts, file description Aircraft Engine Design System Analysis, type is application, file version is 6.0.0.4, the product name is AEDsys Aircraft Engine Design System and the product version 6.00.0004. The copyright is 2019 by jackdmattingly@gmail.com, the size is 3.30 MB and date modified 4/22/2020 10:19 p.m. The information needed to down load the software can be found in a textbook titled Aircraft Engine Design, Third Edition by Jack D. Mattingly, William H. Heiser, David T. Pratt, Keith M. Boyer and Brenda A. Haven and was Published Online:2 Aug 2018https://doi.org/10.2514/4.105173. The computer program AEDsys is founded on the creation tools in Chapters 2 through 7 of the AIAA Education Series. The reader can either use the book to get the software or go to Aerospace Research Central Website and click on link to down load a zip file. This file will contain AEDsys main, AFprop and other piece of the software that are needed to run the simulator. These piece plug into the AEDsys main that operate various sections of the Aircraft Engine. The simulator come preloaded with information, meaning data needed to generate results for the horsepower, Total Temperature Lvg Combustor (Tt4), thermal efficiency and so on. This is all preset numbers and setting base on the type of aircraft you select. It is referred to as reference data or numbers for the different parts of the gas turbine engines.

That data or reference data is used to run the simulator to generate the outputs. When you open up the AEDsys main, it is titled links to others programs, those programs are Inlet, EQL, Compressor, Combustion, Turbine, Main Burner, Nozzle, and

Afterburner. There is also another set of programs titled Atmosphere, Calculator, Gas Tables, AFprop, and Paint. When you go to open up any one of those given programs being say Turbine, the inputs for the Turbine are preloaded with numbers to the variables. Once the user or users select calculate, it will generate an output with the given inputs.

To help with generating the output and the different link to other programs is a PDF file on how to operate the simulator and other parts of the simulator. The computer program was generated to make it easier for engineers and student to do tasks or functions with lot of calculations over and over along detailed studies essential in aircraft engine conceptual design[9]. The software instructions have fourteen (14) constraint types, eight (8) contour plots, thirteen (16) mission types, seven (7) aircraft drag models, seven (7) engine thrust models, and seven (7) engine fuel consumption (TSFC) models. This software instructions can perform the following analyses:

a. Constraint analysis.

b. Contours of aircraft/engine performance.

c. Mission analysis.

d. Engine performance analysis.

Data windows with input data fields or windows with information store in them show the user being engineer or student what input data is needed to perform each set of calculations[9].

Plotting or the sequence of event of results is formed into each analysis using the Olectra Chart 6.0 software package[9]. Plots or plan of actions can be individual built or design to individual specifications and printed. Screens can be saved/printed by first pressing the Alt and PrtSc buttons at the same time (this captures a bit map of the current window onto the clip board); start the Paint program and paste the image from the clip board onto the blank screen; and then save/print the image, this information all comes from a PDF files titled AEDsys Program User Guide[9]. Using this information can help an engineer or student to design any type within the selection provide of an aircraft. Each data window or windows is preloaded with information of the specs of various aircrafts base upon user or users' selections. You can change them to satisfy you desire within the constraint limits.

I used this software program for the turbine engine. The goal was to achieve a better motor or engine because I am not using this motor or engine for flight, but rather it would be used to run a railroad locomotive. Most of the aircraft design converts the fuel to thrust power where my motor will convert it to a shaft to turn wheels on a railroad locomotive. This is why I am only interest in using this simulator for the turbine motor part and not the flight path and so on of flying. Now that I have explain the use for this simulator and my goals in using it, I moved into running the simulator and seeing the results. The numbers for the trial run come preset. The data or information has already been downloaded into the various windows by the people that create the software. In the original trial run, the total temperature was 3200 degrees of Rankine (2740.33°F) for the reference and when tested the total temperature was 3047 degrees of Rankine (2587.33°F). The reference horse power was 9346, but when tested the result was 7677 horse power along with the reference thermal efficiency was 12.91% and the test resulted in 13.09% thermal efficiency.

Table 4. Turbine Engine Results, Trial Run 1

AEDsys (Ver. 6.00) Turboshaft Date:6/5/2020 4:54:40 PM

using Modified Specific Heat (MSH) Model

Engine File: User Input--Date:6/5/2020_Time:4:51:35 PM

Input Constants

Pidmax = 0.9600	Pi b = 0.9500	Eta b = 0.9990	Pi n = 0.9700
cp c = 0.2400	cp t = 0.2950	Gam c = 1.4000	Gam t = 1.3000
Eta c = 0.8522	Eta tH = 0.9042	Eta tL = 0.9050	
Eta mL = 0.9950	Eta mH = 0.9950	Eta PL = 1.0000	Eta PH = 1.0000
PTO L = 0.0KW	PTO H = 0.0KW	hPR = 18400	
Bleed = 1.00%	Cool 1 = 5.00%	Cool 2 = 5.00%	
Control Limits:	Tt4 = 3200.0	Pi c = 20.00	

** Thrust Scale Factor = 1.0000

Parameter	Reference**	Test**
Mach Number @ 0	0.5000	0.0100
Temperature @ 0	518.67	518.67 R
Pressure @ 0	14.6960	14.6960 psia
Altitude @ 0	0	0 ft
Total Temp @ 4	3200.00	3047.70 R
Pi r (Pt0/P0)	1.1862	1.0001
Tau r (Tt0/T0)	1.0500	1.0000
Pi d (Pt2/Pt0)	0.9600	0.9600
Pi c (Pt3/Pt2)	20.0000	20.0003
Tau c (Tt3/Tt2)	2.5884	2.5884
Tau m1 (Tt41/Tt4)	0.9669	0.9669
Pi tH (Pt45/Pt4)	0.2693	0.2693
Tau tH (Tt44/Tt41)	0.7638	0.7638
Tau m2 (Tt45/Tt44)	0.9747	0.9747
Pi tL (Pt5/Pt45)	0.6119	0.6119
Tau tL (Tt5/Tt45)	0.9030	0.9030
Control Limit		PIC Max
LP Spool RPM (% of Reference Pt)	100.00	97.59
HP Spool RPM (% of Reference Pt)	100.00	97.59
Pt9/P9	1.8324	1.8324
P0/P9	0.5298	0.6284
Mach Number @ 9	1.0000	1.0000
Mass Flow Rate @ 0	100.00	86.39 lbm/s
Corrected Mass Flow @ 0	86.38	86.38 lbm/s
Flow Area @ 0	2.343	101.203 ft^2
Flow Area* @ 0	1.749	1.749 ft^2
Flow Area @ 9	1.220	1.219 ft^2
MB - Fuel/Air Ratio (f)	0.03124	0.02930
Overall Fuel/Air Ratio (fo)	0.02780	0.02608
Cshaft	0.5307	0.5046
Specific Power (P/m0)	93.46	88.87 hp/(lbm/s)
Power Spec Fuel Consumption (Sp)	1.0711	1.0564 (lbm/hr)/hp
Power (P)	9346	7677 hp
Fuel Flow Rate	10009	8110 lbm/hr
Thermal Efficiency (%)	12.91	13.09

The numbers for the various variables are preset by the software in the picture above.

The reference data in the picture above are preloaded by the software which is provided by the creator of the software. The reference data is used for the input of the different variables and the test is the results base on known information on various type of aircraft and users' selections of various aircrafts. As the reader can see from the results, the thermal efficiency is higher than the reference data. The efficiency is unacceptable for the amount of heat being generated. The efficiency is unacceptable because to compete with other type of engines, or at least railroad locomotives, it needs to be higher. Now moving onto some other big differences between the reference and the test was the fuel flow rate and specific power. The trial run was using Cargo/Passenger Turboprop low drag that is selected from the Aircraft Drag Model. To get the results, I open the Engine Model and selected Engine Cycle Deck (Chapter 4-7), once you do that, out popped another window that has all the Engine Reference Data. Within that window is various boxes, tabs and selections that can be selected. One of the tabs is titled Reference Engine Design which has a box labeled Design Limits: Total Temperature Lvg Combustor (Tt4) along with a few other boxes labeled Design Variables: Compressor Pressure Ratio (Pt3/Pt2) and Turbine Overall Temperature Ratio (Tt5/Tt4). At the top of the Reference Engine Design is various heading and one is titled Engine Cycle. From that heading, I opened it and selected Turboshaft. In able to make the change permanent, you must check the box titled Change Design and Data. This in turn will change the display of the Reference Engine Design along with the variables being displayed to reflex the type of parts or variables for a turboshaft. The second tab of the Reference Engine Design was Fuel/Gas Prop, Comp. Efficiencies which in the first trial run has low efficiencies setting. This is also the reasoning for the low thermal efficiencies results.

With this knowledge learned from the first trial run, I made changes to the Total Temperature Lvg Combustor (Tt4) and the Turbine Overall Temperature Ratio (Tt5/Tt4) along with making changings in the second tab of the Reference Engine Design being the efficiencies settings. These changes were made to represent better insulating materials and better design of the fins or blades used in the compressor along with the turbine. The Total Temperature Lvg Combustor (Tt4) was change to 2560 degrees of Rankine (2100.33°F) for the reference resulting in the test showing 2438.20 degrees of Rankine (1978.53°F). The reference horse power for the new changes was 12802 and the results for the test was 9787 horse power. The changes of the efficiencies settings not only resulted in better horse power, but better thermal efficiency percent. That thermal efficiency percent for the reference was 29.03 percent and the test resulted in 27.34 percent. The reference numbers are numbers I chose to use in the Total Temperature Lvg Combustor (Tt4) by observing the output from the first trial run and seeing that the Fuel/Gas Prop, Comp. Efficiencies setting were low. I changed them to the highest efficiencies that were allowed. To adjust the setting, the user must click on the Level of Technology button and then out pops a window with different section of the turbine engine and efficiency settings. It looks like this provide in a picture below.

Table 5. Turbine Efficiency Setting

Component	Figure of Merit	Type	1945-65 1	1965-85 2	1985-05 3	2005-25 4	2025-45 5	Current Value
Diffuser	$\pi_{d\,max}$ P_{t2}/P_{t1}	A - M<1 nacelle	0.90	0.95	0.98	0.995	0.998	0.96
		B - M<1 airframe	0.88	0.93	0.96	0.98	0.985	
		C - M>1 airframe	0.85	0.90	0.94	0.96	0.97	
Compressor	e_{cL}		0.80	0.84	0.88	0.90	0.91	0.89
	e_{cH}		0.80	0.84	0.88	0.90	0.91	0.9
Burner	π_b		0.90	0.92	0.94	0.95	0.96	0.95
	η_b		0.88	0.94	0.99	0.999	0.999	0.999
Turbine	e_{tH}	Uncooled	0.80	0.85	0.89	0.90	0.91	0.89
		Cooled		0.83	0.87	0.89	0.90	
	e_{tL}	Uncooled	0.80	0.85	0.89	0.90	0.91	0.9
		Cooled		0.83	0.87	0.89	0.90	
Nozzle	π_n P_{t9}/P_{t7}	D - Fixed Conv	0.95	0.97	0.98	0.995	0.997	0.97
		E - Varible Conv	0.93	0.96	0.97	0.98	0.99	
		F - Variable C-D	0.90	0.93	0.95	0.97	0.98	
Mech Shaft	η_{mL}	Shaft Only	0.95	0.97	0.99	0.995	0.996	0.995
		With Power Takeoff	0.90	0.92	0.95	0.97	0.98	
	η_{mH}	Shaft Only	0.95	0.97	0.99	0.995	0.996	0.995
		With Power Takeoff	0.90	0.92	0.95	0.97	0.98	

Done

Double click radio button to select

Note: Use of stealth reduces the total pressure ratios of the diffuser and nozzle from the values listed above.

The reference data and test results for trial run 2 have been provided below for the reader to see the horse power, Total Temperature at 4 and Thermal Efficiencies along with other data inputs/outputs of the turbine engine.

Table 6. Turbine Engine Results, Trial Run 2

```
AEDsys (Ver. 6.00)              Turboshaft              Date:5/28/2020 9:33:23 PM
                   using Modified Specific Heat (MSH) Model
Engine File: User Input--Date:5/28/2020_Time:9:32:33 PM

  Input Constants
  Pidmax = 0.9600   Pi b   = 0.9500   Eta b  = 0.9990   Pi n   = 0.9700
  cp c   = 0.2400   cp t   = 0.2950   Gam c  = 1.4000   Gam t  = 1.3000
  Eta c  = 0.8522   Eta tH = 0.9084   Eta tL = 0.9096
  Eta mL = 0.9950   Eta mH = 0.9950   Eta PL = 1.0000   Eta PH = 1.0000
  PTO L  =    0.0KW PTO H  =    0.0KW hPR    =  18400
  Bleed  =  1.00%   Cool 1 =   5.00%  Cool 2 =   5.00%
  Control Limits:   Tt4    = 4000.0   Pi c   =  20.00
  ** Thrust Scale Factor   = 1.0000

  Parameter                          Reference**          Test**
  Mach Number @ 0                      0.5000           0.0100
  Temperature @ 0                      518.67           518.67 R
  Pressure    @ 0                     14.6960          14.6960 psia
  Altitude    @ 0                           0                0 ft
  Total Temp  @ 4                     2560.00          2438.20 R
  Pi r    (Pt0/P0)                     1.1862           1.1862
  Tau r   (Tt0/T0)                     1.0500           1.0500
  Pi d    (Pt2/Pt0)                    0.9600           0.9600
  Pi c    (Pt3/Pt2)                   20.0000          20.0000
  Tau c   (Tt3/Tt2)                    2.5884           2.5884
  Tau m1  (Tt41/Tt4)                   0.9712           0.9712
  Pi tH   (Pt45/Pt4)                   0.1795           0.1795
  Tau tH  (Tt44/Tt41)                  0.7027           0.7027
  Tau m2  (Tt45/Tt44)                  0.9829           0.9829
  Pi tL   (Pt5/Pt45)                   0.3844           0.3844
  Tau tL  (Tt5/Tt45)                   0.8199           0.8199
  Control Limit                                        PIC Max
  LP Spool RPM (% of Reference Pt)   100.00             94.12
  HP Spool RPM (% of Reference Pt)   100.00             97.59
  Pt9/P9                               1.4479           1.4479
  P0/P9                                1.0000           1.0000
  Mach Number @ 9                      0.7710           0.6592
  Mass Flow Rate @ 0                   100.00           100.00 lbm/s
  Corrected Mass Flow @ 0               86.38            86.38 lbm/s
  Flow Area       @ 0                   2.343          101.205 ft^2
  Flow Area*      @ 0                   1.749            1.749 ft^2
  Flow Area       @ 9                   2.497            2.509 ft^2
  MB - Fuel/Air Ratio (f)             0.01903          0.01788
  Overall Fuel/Air Ratio (fo)         0.01694          0.01591
  Cshaft                               0.7269           0.6432
  Specific Power  (P/m0)               128.02           128.02 hp/(lbm/s)
  Power Spec Fuel Consumption (Sp)     0.4764           0.4764 (lbm/hr)/hp
  Power (P)                             12802            12802 hp
  Fuel Flow Rate                         6098             5729 lbm/hr
  Thermal Efficiency     (%)            29.03            27.34
```

The reference data and test data of the new changes is definitely better than the first trial run. However, I still feel that the efficiency is still low and need more improvements. For a railroad locomotive, it would need to be around 85 percent to compete with current engine designs that power the locomotives which pull or push railcars.

CHAPTER 6

CONCLUSION

In the first trial run, the results for the tested horse power was 7,677 hp with the reference horse power being 9346 hp. The total temperature at 4 which is the burner exit, nozzle vanes entry, modeled coolant mixer 1 entry and high-pressure turbine entry for π_{tH}definition according to the reference station of Figure 8,

98 AIRCRAFT ENGINE DESIGN

B)

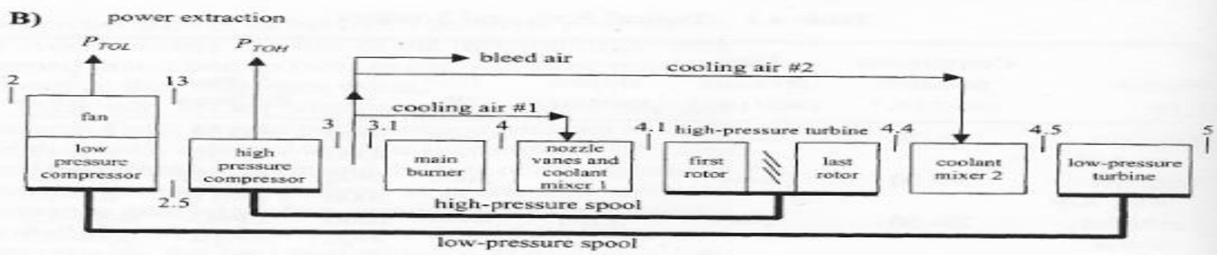

Fig. 4.1b Reference stations—bleed and turbine cooling airflows.

Recommended Practice (ARP) 755A (Ref. 3) and will be used throughout this textbook, and include:

Station	Location
0	Far upstream or freestream
1	Inlet or diffuser entry
2	Inlet or diffuser exit, fan entry
13	Fan exit
2.5	Low-pressure compressor exit High-pressure compressor entry
3	High-pressure compressor exit
3.1	Burner entry
4	Burner exit Nozzle vanes entry Modeled coolant mixer 1 entry High-pressure turbine entry for π_{tH} definition
4.1	Nozzle vanes exit Coolant mixer 1 exit High-pressure turbine entry for τ_{tH} definition
4.4	High-pressure turbine exit Modeled coolant mixer entry
4.5	Coolant mixer 2 exit Low-pressure turbine entry
5	Low-pressure turbine exit
6	Core stream mixer entry
16	Fan bypass stream mixer entry
6A	Mixer exit Afterburner entry
7	Afterburner exit Exhaust nozzle entry
8	Exhaust nozzle throat
9	Exhaust nozzle exit

Figure 8. Bleed & turbine cooling airflows diagram, key [9]

is 3,200 degrees of Rankine (2740.33°F) for the reference input, but when tested is 3047 degrees of Rankine (2587.33°F) and the reference thermal efficiency is 12.91 percent, but when tested, it is 13.09 percent. For a railroad locomotive, this motor or engine would not even be considered. The horse power is high enough, but lacks the efficiency. The information on different types of fuels and mixtures was described in detail for a few reasons. The first reason is the types of fuels play a great role in how long the blades of a compressor and turbine last. The second reason is that different fuels have different amount of BTU when burned. These play a major role in the running quality of the turbine motor and the efficiency of the engine. Compared to the fuels used nearly 60 years ago, the newer fuels burn better with more BTUs and do less damage to the wear on the moving part of the turbine engine. This is important because I change the efficiency sets in the second trial run to represent better fuels, materials used in building the turbine motor and with better insulations materials that will either hold in or seal off losses of heat. In the second trial run, the simulator for total temperature at 4 was set to 2560 degrees of Rankine (2100.33°F) for the reference which yielded 2438.20 degrees of Rankine (1978.53°F) for the test. The temperature is lower to represent better insulation and better materials which cut down on the lost of heat. The power generated for the reference is 12,802 hp and the test resulted in 9787 hp. This would be far more than any single engine generates of today. Even the thermal efficiency for the reference is better being 29.03 percent which resulted in 27.34 percent when tested. This is better, but it would need to come up to around 85 percent to compete with the current diesel-electric locomotives running the rails of today. More testing would need to be done along with more studying to understand the principles to generate a gas turbine with better efficiency. To understand this better as far as the principles of a gas turbine engines, let look at the past gas turbine engines compared with the new aircraft gas turbine engines. The railroad locomotives have gas turbine engines that use a 16-stage compressor with a two-stage turbine and it run on Bunker C fuel or diesel fuel. Airline companies have a gas turbine engine that use a 14-stage compressor with a 3-stage turbine or more which run on jet fuel. The GTEL 8500 which is the railroad locomotive being describe above which stand for gas-turbine electric locomotive of 8,500 horsepower. This locomotive used a cheap fuel at the time that would become very expensive and blades that didn’t have the nickel base superalloy coating on them much less the new designs of blades. These blades being used in the aircraft gas turbine engine are better because the new design allowed for better cooling, were lightweight along with better way to dissipate moisture. By dissipating the moisture, they are more resistant to corrosion. Another problem with the railroad locomotive gas turbine engines is that the railroads sometimes used diesel fuel to fire them and this cause corrosion of the blades. That would result in failure of the engine running and required maintenance. The aircraft gas turbine engine used a jet fuel which has been refined to use in gas turbine engines and doesn’t eat away the blades like the diesel fuel does. If you took the aircraft gas turbine engine that is made of better metals, better design blades using the nickel base coating along moisture control and light weight while burning jet fuel, your performance would improve big time.

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APPENDIX A

GAS TABLES

EQL: Equilibrium Combustion of Ideal Gases

Exit Help Units

. REACTANTS . | . FROZEN PROCESSES . | . EQUILIBRIUM PROCESSES . | . CYCLES .

Select a process for fixed or frozen composition of reactants:

- (s,p) - isentropic compression or expansion to assigned pressure p2
- (s,v) - isentropic compression or expansion to assigned specific volume v2
- (s,T) - isentropic compression or expansion to assigned temperature T2

Enter the end-state value p2 = 145.03 psia AIR ONLY? OK

PROPERTY		STATE 1	STATE 2	UNITS
Pressure	p =	14.695	145.03	psia
Temperature	T =	536.40	997.69	°R
Specific Volume	v =	14.175	2.6715	ft³/lbm
Engineering Gas Constant	R =	7.18650E-02	7.18650E-02	BTU/lbm-°R
Mean Molecular Weight	MW =	27.633	27.633	lbm/lbmol
Enthalpy	h =	-110.81	11.958	BTU/lbm
Internal Energy	u =	-149.36	-59.741	BTU/lbm
Entropy	s =	1.7289	1.7289	BTU/lbm-°R
Constant-p Specific Heat	Cp =	0.25737	0.27706	BTU/lbm-R
Constant-v Specific Heat	Cv =	0.18551	0.20519	BTU/lbm-°R
Specific Heat Ratio	Cp/Cv =	1.3874	1.3502	-
MOL NUMBERS				

PROPERTY			STATE 1	STATE 2	UNITS
MOL NUMBERS					
	O2	:	6.880E-03	6.880E-03	lbmol/lbm x
	N2	:	2.587E-02	2.587E-02	lbmol/lbm x
	CH4	:	3.440E-03	3.440E-03	lbmol/lbm x
MOL FRACTIONS					
	O2	:	0.190	0.190	lbmol/lbmol x
	N2	:	0.715	0.715	lbmol/lbmol x
	CH4	:	9.506E-02	9.506E-02	lbmol/lbmol x
MASS FRACTIONS					
	O2	:	0.220	0.220	lbm/lbm x
	N2	:	0.725	0.725	lbm/lbm x

CH4	:	5.519E-02	5.519E-02	lbm/lbm x
EMISSION INDEX				
O2	:	3.989E+03	3.989E+03	lbm/klbm fuel
N2	:	1.313E+04	1.313E+04	lbm/klbm fuel
CH4	:	1.000E+03	1.000E+03	lbm/klbm fuel

EQL: Equilibrium Combustion of Ideal Gases

Exit Help Units

. REACTANTS . | . FROZEN PROCESSES . | . EQUILIBRIUM PROCESSES . | . CYCL

Select a chemical equilibrium combustion process:

- (h,p) Adiabatic flame temperature at constant enthalpy and assigned pressure
- (T,p) Product gas composition at assigned temperature and pressure
- (u,v) Adiabatic flame temperature and pressure at constant internal energy and density
- (T,v) Product gas composition at assigned temperature and constant density
- (s,p) POST-COMBUSTION isentropic expansion or compression to assigned pressure
- (s,v) POST-COMBUSTION isentropic expansion or compression to assigned density
- "C-J" Mach number and speed of a Chapman-Jouguet (self-propagating) detonation

TRACE = 1.e- 15 OK

PROPERTY		STATE 1	STATE 2	UNITS
Pressure	p =	14.695	14.695	psia
Temperature	T =	536.40	4006.7	°R
Specific Volume	v =	14.175	106.67	ft³/lbm
Engineering Gas Constant	R =	7.18650E-02	7.24017E-02	BTU/lbm-°R
Mean Molecular Weight	MW =	27.633	27.428	lbm/lbmol
Enthalpy	h =	-110.81	-110.81	BTU/lbm
Internal Energy	u =	-149.36	-400.90	BTU/lbm
Entropy	s =	1.7289	2.3580	BTU/lbm-°R
Constant-p Specific Heat	Cp =	0.25737	0.36069	BTU/lbm-R
Constant-v Specific Heat	Cv =	0.18551	0.28829	BTU/lbm-°R
Specific Heat Ratio	Cp/Cv =	1.3874	1.2511	-
Complete Combustion Net/Lower Heating Value LHV =			21499.	BTU/lbm fuel

PROPERTY		STATE 1	STATE 2	UNITS
Equilibrium Combustion Enthalpy of Reaction hRP =			20295.	BTU/lbm fuel
MOL NUMBERS	> TRACE = 1.e-15			
H	:		1.425E-05	lbmol/lbm x
HO2	:		3.223E-08	lbmol/lbm x
H2	:		1.327E-04	lbmol/lbm x
H2O	:		6.688E-03	lbmol/lbm x
H2O2	:		1.708E-09	lbmol/lbm x
O	:		7.794E-06	lbmol/lbm x
OH	:		1.043E-04	lbmol/lbm x
O2	:	6.880E-03	1.671E-04	lbmol/lbm x
HCO	:		2.812E-11	lbmol/lbm x

PROPERTY			STATE 1	STATE 2	UNITS
	N2O	:		9.389E-08	lbmol/lbmol x
	NO	:		1.977E-03	lbmol/lbmol x
	NO2	:		3.315E-07	lbmol/lbmol x
	CH4	:	9.506E-02		lbmol/lbmol x
	CH2O	:		2.007E-11	lbmol/lbmol x
MASS FRACTIONS	> TRACE = 1.e-15				
	H	:		1.437E-05	lbm/lbm x
	HO2	:		1.064E-06	lbm/lbm x
	H2	:		2.676E-04	lbm/lbm x
	H2O	:		0.120	lbm/lbm x
	H2O2	:		5.809E-08	lbm/lbm x

PROPERTY			STATE 1	STATE 2	UNITS
	CO	:		3.265E-04	lbmol/lbm x
	CO2	:		3.113E-03	lbmol/lbm x
	N2	:	2.587E-02	2.583E-02	lbmol/lbm x
	N	:		5.170E-10	lbmol/lbm x
	N2O	:		3.423E-09	lbmol/lbm x
	NO	:		7.208E-05	lbmol/lbm x
	NO2	:		1.209E-08	lbmol/lbm x
	CH4	:	3.440E-03		lbmol/lbm x
	CH2O	:		7.318E-13	lbmol/lbm x
MOL FRACTIONS	> TRACE = 1.e-15				
	H	:		3.910E-04	lbmol/lbmol x

	O	:		1.247E-04	lbm/lbm x
	OH	:		1.774E-03	lbm/lbm x
	O2	:	0.220	5.348E-03	lbm/lbm x
	HCO	:		8.160E-10	lbm/lbm x
	CO	:		9.146E-03	lbm/lbm x
	CO2	:		0.137	lbm/lbm x
	N2	:	0.725	0.724	lbm/lbm x
	N	:		7.242E-09	lbm/lbm x
	N2O	:		1.507E-07	lbm/lbm x
	NO	:		2.163E-03	lbm/lbm x
	NO2	:		5.560E-07	lbm/lbm x
	CH4	:	5.519E-02		lbm/lbm x

	CH2O	:		2.197E-11	lbm/lbm x
EMISSION INDEX	> TRACE = 1.e-15				
	AR	:		7.239E-15	lbm/klbm fuel
	H	:		0.260	lbm/klbm fuel
	HO2	:		1.928E-02	lbm/klbm fuel
	H2	:		4.85	lbm/klbm fuel
	H2O	:		2.183E+03	lbm/klbm fuel
	H2O2	:		1.053E-03	lbm/klbm fuel
	O	:		2.26	lbm/klbm fuel
	OH	:		32.2	lbm/klbm fuel
	O2	:	3.989E+03	96.9	lbm/klbm fuel
	HCO	:		1.479E-05	lbm/klbm fuel
	CO	:		166.	lbm/klbm fuel
	CO2	:		2.483E+03	lbm/klbm fuel
	N2	:	1.313E+04	1.311E+04	lbm/klbm fuel
	N	:		1.312E-04	lbm/klbm fuel
	N2O	:		2.730E-03	lbm/klbm fuel
	NO	:		39.2	lbm/klbm fuel
	NO2	:		1.007E-02	lbm/klbm fuel
	CH4	:	1.000E+03	2.885E-13	lbm/klbm fuel
	C6H6	:		1.415E-14	lbm/klbm fuel
	C6H6(L)	:		1.415E-14	lbm/klbm fuel
	C7H8	:		1.670E-14	lbm/klbm fuel
	C8H16	:		2.033E-14	lbm/klbm fuel
	C8H18	:		2.070E-14	lbm/klbm fuel
	C8H18(L)	:		2.070E-14	lbm/klbm fuel
	C12H23	:		3.032E-14	lbm/klbm fuel
	CH3OH	:		5.806E-15	lbm/klbm fuel
	C2H5OH	:		8.348E-15	lbm/klbm fuel
	C3H8O	:		1.089E-14	lbm/klbm fuel
	CH2	:		1.251E-13	lbm/klbm fuel
	CH2O	:		3.981E-07	lbm/klbm fuel
	C2H2	:		4.718E-15	lbm/klbm fuel
	C2H4	:		5.083E-15	lbm/klbm fuel
	C2H6	:		5.449E-15	lbm/klbm fuel
	C3H8	:		7.990E-15	lbm/klbm fuel
	C12H26	:		3.087E-14	lbm/klbm fuel

EQL: Equilibrium Combustion of Ideal Gases

Exit Help Units

. REACTANTS . | . FROZEN PROCESSES . | . EQUILIBRIUM PROCESSES . | . CYCLES

Select an internal-combustion ideal gas power cycle:

- (•) Brayton cycle (Turbojet, Ramjet, SCramjet)
- ( ) Diesel cycle (Compression-ignition diesel engine)
- ( ) Otto cycle (Spark-ignited gasoline engine)

Enter the pressure-rise ratio, PR = p2/p1 = 10.0 ☐ FROZEN 3-4? TRACE = 1.E-15

Compression Efficiency (1-2) = 100. % Expansion Efficiency (3-4) = 100. % OK

PROPERTY		STATE 1	STATE 2	STATE 3	STATE 4	UNITS
Pressure	p =	14.695	146.95	146.95	14.695	psia
Temperature	T =	536.40	1024.9	4543.8	3057.4	°R
Specific Volume	v =	13.577	2.5942	12.143	80.824	ft³/lbm
Engineering Gas Constant	R =	6.88324E-02	6.88324E-02	7.26742E-02	7.18898E-02	BTU/lbm-°R
Mean Molecular Weight	MW =	28.851	28.851	27.326	27.624	lbm/lbmol
Enthalpy	h =	-6.94569E-02	119.76	119.76	-510.96	BTU/lbm
Internal Energy	u =	-36.991	49.210	-210.46	-730.75	BTU/lbm
Entropy	s =	1.6442	1.6442	2.2450	2.2450	BTU/lbm-°R
Constant-p Specific Heat	Cp =	0.24150	0.25100	0.36550	0.34739	BTU/lbm-R
Constant-v Specific Heat	Cv =	0.17267	0.18217	0.29283	0.27550	BTU/lbm-°R
Specific Heat Ratio	Cp/Cv =	1.3986	1.3779	1.2482	1.2609	-
Brayton Cycle Fuel Efficiency	=	0.34960				

MOL NUMBERS > TRACE = 1.e-15						
H	:			2.266E-05	8.087E-08	lbmol/lbm x
HO2	:			1.545E-07	4.570E-10	lbmol/lbm x
H2	:			1.814E-04	8.632E-06	lbmol/lbm x
H2O	:			6.599E-03	6.870E-03	lbmol/lbm x
H2O2	:			1.263E-08	6.216E-11	lbmol/lbm x
O	:			1.452E-05	2.483E-08	lbmol/lbm x
OH	:			1.767E-04	3.295E-06	lbmol/lbm x
O2	:	7.282E-03	7.282E-03	2.197E-04	8.941E-06	lbmol/lbm x
HCO	:			4.193E-10	2.492E-14	lbmol/lbm x
CO	:			4.969E-04	1.454E-05	lbmol/lbm x
CO2	:			2.943E-03	3.425E-03	lbmol/lbm x
N2	:	2.738E-02	2.738E-02	2.579E-02	2.587E-02	lbmol/lbm x

	N	:			3.531E-09	1.647E-13	lbmol/lbm x
	N2O	:			2.202E-08	1.813E-10	lbmol/lbm x
	NO	:			1.470E-04	3.656E-06	lbmol/lbm x
	NO2	:			6.194E-08	3.732E-10	lbmol/lbm x
	CH2O	:			1.442E-11	2.535E-15	lbmol/lbm x
MOL FRACTIONS	> TRACE = 1.e-15						
	H	:			6.191E-04	2.234E-06	lbmol/lbmol x
	HO2	:			4.221E-06	1.263E-08	lbmol/lbmol x
	H2	:			4.956E-03	2.384E-04	lbmol/lbmol x
	H2O	:			0.180	0.190	lbmol/lbmol x
	H2O2	:			3.451E-07	1.717E-09	lbmol/lbmol x
	O	:			3.967E-04	6.860E-07	lbmol/lbmol x

	OH	:			4.828E-03	9.101E-05	lbmol/lbmol x
	O2	:	0.210	0.210	6.003E-03	2.470E-04	lbmol/lbmol x
	HCO	:			1.146E-08	6.884E-13	lbmol/lbmol x
	CO	:			1.358E-02	4.016E-04	lbmol/lbmol x
	CO2	:			8.042E-02	9.462E-02	lbmol/lbmol x
	N2	:	0.790	0.790	0.705	0.715	lbmol/lbmol x
	N	:			9.648E-08	4.549E-12	lbmol/lbmol x
	N2O	:			6.018E-07	5.007E-09	lbmol/lbmol x
	NO	:			4.018E-03	1.010E-04	lbmol/lbmol x
	NO2	:			1.692E-06	1.031E-08	lbmol/lbmol x
	CH4	:			2.552E-15		lbmol/lbmol x
	CH2	:			1.839E-15		lbmol/lbmol x
	CH2O	:			3.939E-10	7.002E-14	lbmol/lbmol x

MASS FRACTIONS	> TRACE = 1.e-15						
	H	:			2.284E-05	8.151E-08	lbm/lbm x
	HO2	:			5.098E-06	1.509E-08	lbm/lbm x
	H2	:			3.656E-04	1.740E-05	lbm/lbm x
	H2O	:			0.119	0.124	lbm/lbm x
	H2O2	:			4.296E-07	2.114E-09	lbm/lbm x
	O	:			2.322E-04	3.973E-07	lbm/lbm x
	OH	:			3.005E-03	5.603E-05	lbm/lbm x
	O2	:	0.233	0.233	7.029E-03	2.861E-04	lbm/lbm x
	HCO	:			1.217E-08	7.232E-13	lbm/lbm x
	CO	:			1.392E-02	4.073E-04	lbm/lbm x
	CO2	:			0.130	0.151	lbm/lbm x

	N2	:	0.767	0.767	0.723	0.725	lbm/lbm x
	N	:			4.945E-08	2.306E-12	lbm/lbm x
	N2O	:			9.693E-07	7.978E-09	lbm/lbm x
	NO	:			4.412E-03	1.097E-04	lbm/lbm x
	NO2	:			2.849E-06	1.717E-08	lbm/lbm x
	CH4	:			1.498E-15		lbm/lbm x
	CH2O	:			4.329E-10	7.611E-14	lbm/lbm x
EMISSION INDEX	> TRACE = 1.e-15						
	AR	:			7.239E-15	7.239E-15	lbm/klbm fuel
	H	:			0.414	1.477E-03	lbm/klbm fuel
	HO2	:			9.238E-02	2.733E-04	lbm/klbm fuel
	H2	:			6.62	0.315	lbm/klbm fuel
	H2O	:			2.154E+03	2.243E+03	lbm/klbm fuel
	H2O2	:			7.785E-03	3.831E-05	lbm/klbm fuel
	O	:			4.21	7.199E-03	lbm/klbm fuel
	OH	:			54.4	1.02	lbm/klbm fuel
	O2	:	4.222E+03	4.222E+03	127.	5.18	lbm/klbm fuel
	HCO	:			2.205E-04	1.310E-08	lbm/klbm fuel
	CO	:			252.	7.38	lbm/klbm fuel
	CO2	:			2.347E+03	2.732E+03	lbm/klbm fuel
	N2	:	1.390E+04	1.390E+04	1.309E+04	1.313E+04	lbm/klbm fuel
	N	:			8.961E-04	4.179E-08	lbm/klbm fuel
	N2O	:			1.756E-02	1.446E-04	lbm/klbm fuel
	NO	:			79.9	1.99	lbm/klbm fuel
	NO2	:			5.163E-02	3.111E-04	lbm/klbm fuel
	CH4	:			2.715E-11	2.907E-15	lbm/klbm fuel
	C6H6	:			1.415E-14	1.415E-14	lbm/klbm fuel
	C6H6(L)	:			1.415E-14	1.415E-14	lbm/klbm fuel
	C7H8	:			1.670E-14	1.670E-14	lbm/klbm fuel
	C8H16	:			2.033E-14	2.033E-14	lbm/klbm fuel
	C8H18	:			2.070E-14	2.070E-14	lbm/klbm fuel
	C8H18(L)	:			2.070E-14	2.070E-14	lbm/klbm fuel
	C12H23	:			3.032E-14	3.032E-14	lbm/klbm fuel
	CH3OH	:			5.806E-15	5.806E-15	lbm/klbm fuel
	C2H5OH	:			8.348E-15	8.348E-15	lbm/klbm fuel
	C3H8O	:			1.089E-14	1.089E-14	lbm/klbm fuel
	CH2	:			1.710E-11	2.542E-15	lbm/klbm fuel
	CH2O	:			7.844E-06	1.379E-09	lbm/klbm fuel

C2H2	:	8.535E-15	4.718E-15	lbm/klbm fuel
C2H4	:	5.083E-15	5.083E-15	lbm/klbm fuel
C2H6	:	5.449E-15	5.449E-15	lbm/klbm fuel
C3H8	:	7.990E-15	7.990E-15	lbm/klbm fuel
C12H26	:	3.087E-14	3.087E-14	lbm/klbm fuel

ATMOS - U.S. Standard Atmosphere, 1976

File Help Temperature Units

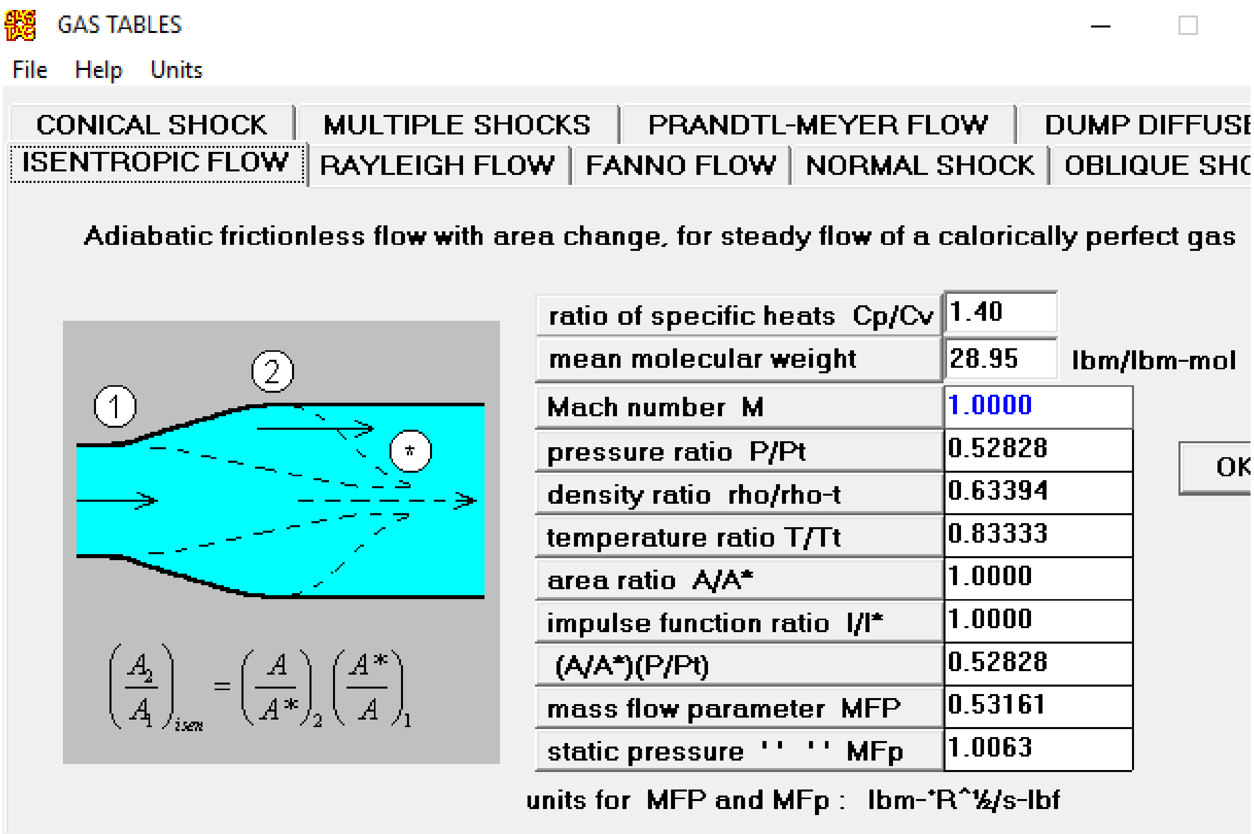
Variation of properties with altitude in a STANDARD atmosphere, with Cp/Cv = 1.4

enter altitude h = 0.0000 kft

OK

pressure P	14.695	lbf/in²
temperature T	518.67	°R
density rho	7.64669E-02	lbm/ft³
speed of sound a	1116.5	ft/s
absolute viscosity μ	3.73672E-07	lbf-s/ft²
kinematic viscosity nu	1.57225E-04	ft²/s
thermal conductivity k	3.90392E-06	BTU/s-ft-°R

P/Pstd	1.0000
T/Tstd	1.0000
rho/rho-std	1.0000
a/a-std	1.0000
μ/μ-std	1.0000
nu/nu-std	1.0000
k/k-std	1.0000


GAS TABLES
File Help Units
CONICAL SHOCK
MULTIPLE SHOCKS
PRANDTL-MEYER FLOW
DUMP DIFFUSE
ISENTROPIC FLOW
RAYLEIGH FLOW
FANNO FLOW
NORMAL SHOCK
OBLIQUE SHO
Adiabatic frictionless flow with area change, for steady flow of a calorically perfect gas
ratio of specific heats Cp/Cv 1.40
mean molecular weight 28.95 lbm/lbm-mol
Mach number M 1.0000
pressure ratio P/Pt 0.52828
density ratio rho/rho-t 0.63394
temperature ratio T/Tt 0.83333
area ratio A/A* 1.0000
impulse function ratio I/I* 1.0000
(A/A*)(P/Pt) 0.52828
mass flow parameter MFP 0.53161
static pressure ' ' ' ' MFp 1.0063
units for MFP and MFp : lbm-*R^½/s-lbf
OK
1
2
*
$\left(\frac{A_2}{A_1}\right)_{isen} = \left(\frac{A}{A^*}\right)_2 \left(\frac{A^*}{A}\right)_1$

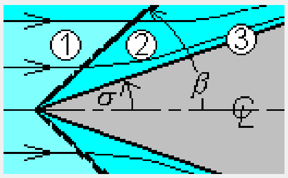
GAS TABLES

File Help Units

ISENTROPIC FLOW | RAYLEIGH FLOW | FANNO FLOW | NORMAL SHOCK | OBLIQUE SHOCK

CONICAL SHOCK | MULTIPLE SHOCKS | PRANDTL-MEYER FLOW | DUMP DIFFUSER

Freestream (1) , post-shock (2) and cone surface (3) Mach numbers and property ratios for weak oblique shock waves over a cone , for steady flow of a calorically perfect gas



ratio of specific heats Cp/Cv	1.40	
freestream Mach number M1	10.00	
cone half-angle sigma	5.00	deg
shock wave angle beta	7.73	deg

OK

WEAK SHOCK

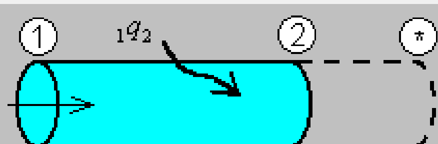
POST-SHOCK (2)

Mach number M2	9.0040
temperature ratio T2/T1	1.2199
pressure ratio P2/P1	1.9462
density ratio rho2/rho1	1.5954
total pressure ratio Pt2/Pt1	0.97063

CONE SURFACE (3)

Mach number M3	8.7725
temperature ratio T3/T1	1.2812
pressure ratio P3/P1	2.3104
density ratio rho3/rho1	1.8033
total pressure ratio Pt3/Pt1	0.97063

Constant-area frictionless flow with heat addition or removal, for steady flow of a calorically perfect gas



$$_1q_2 = \frac{T_{t2} - T_{t1}}{C_p}$$

$$\frac{T_{t2}}{T_{t1}} = \left(\frac{T_t}{T_{t*}}\right)_2 \left(\frac{T_{t*}}{T_t}\right)_1$$

OK

ratio of specific heats Cp/Cv	1.40
Mach number M	1.0000
total temperature ratio Tt/Tt*	1.0000
static temperature ratio T/T*	1.0000
static pressure ratio P/P*	1.0000
total pressure ratio Pt/Pt*	1.0000
velocity ratio V/V*	1.0000

Multiple weak oblique shocks of equal turning angle, for steady flow of a calorically perfect gas

specific heat ratio Cp/Cv	1.36	temperature rise ratio T2/To	7.000
freestream Mach number Mo	10.00	pressure rise ratio P2/Po	209.1
number of shocks N < 30	3	area contraction ratio Ao/A2	24.39

OK

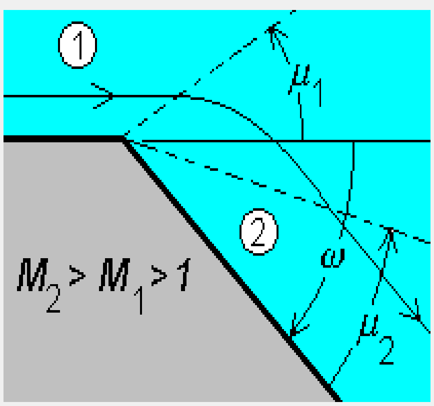
Each shock turns the flow through an angle 14.24 deg

	M	T/To	P/Po	Ao/A	Pt/Pto	(S-So)/Cp
1	5.7094	2.7666	11.815	4.0557	0.25284	0.36397
2	4.0611	4.7874	60.564	11.241	0.16328	0.47972
3	3.0861	7.0000	209.14	24.394	0.13423	0.53159

Isentropically turning a supersonic flow through an angle omega ,
for steady flow of a calorically perfect gas.

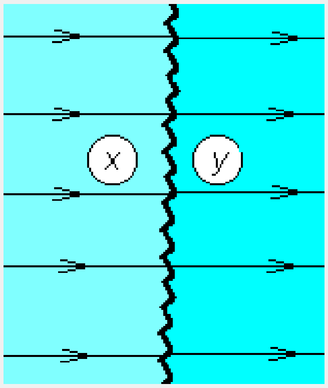
ratio of specific heats Cp/Cv	1.40
upstream Mach number M1	2.00

OK



turning angle omega (deg)	39.405
downstream Mach number M2	4.0000
temperature ratio T2/T1	0.42857
pressure ratio P2/P1	5.15325E-02
density ratio rho2/rho1	0.12024
area ratio A2/ A1	6.3519
upstream Mach angle mu1 (deg)	30.000
downstream Mach angle mu2 (deg)	14.478

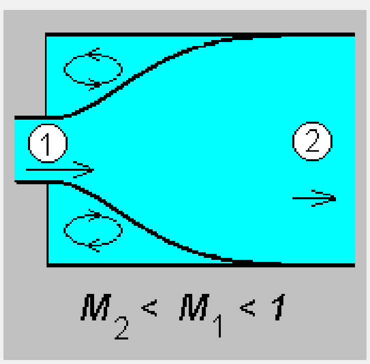
Pre- and post-shock Mach number and property ratios for normal shock waves, for steady flow of a calorically perfect gas.



OK

ratio of specific heats Cp/Cv	1.40
upstream Mach # Mx	1.0000
downstream Mach # My	1.0000
static pressure ratio Py/Px	1.0000
velocity Vx/Vy , rho-y/rho-x	1.0000
total temperature ratio Ty/Tx	1.0000
Ax*/Ay* , Pty/Ptx	1.0000
total-to-static pressure ratio Pty/Px	1.8929

Subsonic flow through a "sudden expansion," for steady flow of a calorically perfect gas

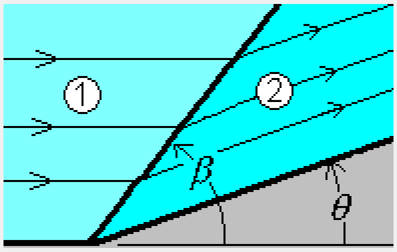


OK

ratio of specific heats Cp/Cv	1.40
upstream Mach number M1	0.5000
downstream Mach number M2	0.11998
area ratio A2/A1	4.0000

pressure recovery coefficient CP = (P2 - P1)/q1	0.37723
isentropic press. rec. coeff. {(P2 - P1)/q1}isen	1.0083
diffuser efficiency/effectiveness CP/CPisen	0.37414
total pressure loss coefficient (Pt1 - Pt2)/q1	0.62524
total pressure ratio Pt2/Pt1	0.90776

Pre- and post-shock Mach numbers and property ratios for planar oblique shock wa
for steady flow of a calorically perfect gas



WEAK SHOCK

ratio of specific heats Cp/Cv	1.40
upstream Mach number M1	1.50
turning angle theta (deg)	8.1853
wave angle beta (deg)	52.906
downstream Mach # M2	1.2000
temperature ratio T2/T1	1.1258
pressure ratio P2/P1	1.5035
density ratio rho2/rho1	1.3355
total pressure ratio Pt2/Pt1	0.99313

AFprop

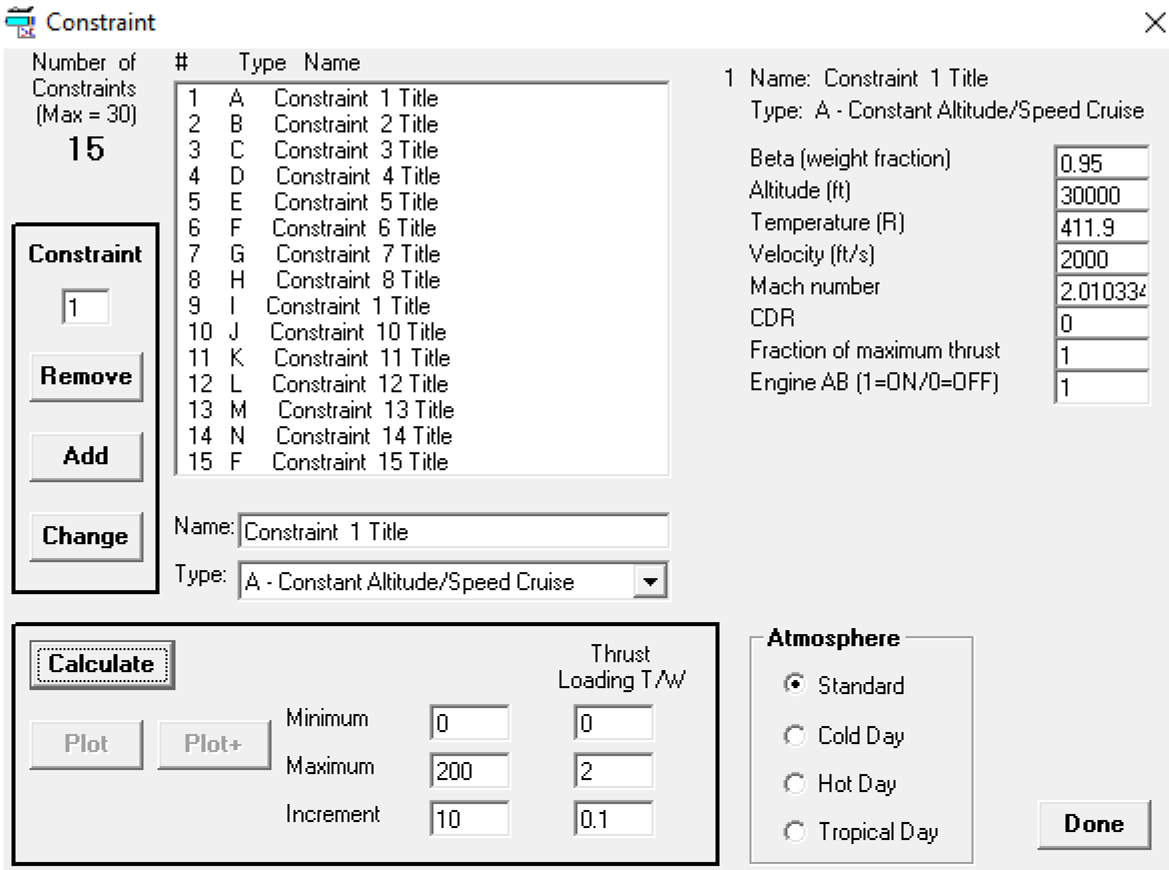
Air and $(CH_2)_n$ Properties
at Low Pressure

Version 2.0 April 3, 2005

Unit System
BE SI

Quit

Fuel/Air Ratio (f)	0.03	
Temperature (T)	2000.000	R
Enthalpy (h)	522.5640	Btu/lbm
Reduced Pressure (Pr)	211.3013	
Speed of Sound (a)	2119.651	ft/s
Ratio of Specific Heats (γ)	1.30760	
Gas Constant (R)	0.06861	Btu/lbm-R
Specific Heat (Cp)	0.29166	Btu/lbm-R
ϕ	1.94571	Btu/lbm-R


Constraint
Number of Constraints (Max = 30)
15
Constraint
1
Remove
Add
Change
Type Name
1 A Constraint 1 Title
2 B Constraint 2 Title
3 C Constraint 3 Title
4 D Constraint 4 Title
5 E Constraint 5 Title
6 F Constraint 6 Title
7 G Constraint 7 Title
8 H Constraint 8 Title
9 I Constraint 1 Title
10 J Constraint 10 Title
11 K Constraint 11 Title
12 L Constraint 12 Title
13 M Constraint 13 Title
14 N Constraint 14 Title
15 F Constraint 15 Title
Name: Constraint 1 Title
Type: A - Constant Altitude/Speed Cruise
1 Name: Constraint 1 Title
Type: A - Constant Altitude/Speed Cruise
Beta (weight fraction) 0.95
Altitude (ft) 30000
Temperature (R) 411.9
Velocity (ft/s) 2000
Mach number 2.010334
CDR 0
Fraction of maximum thrust 1
Engine AB (1=ON/0=OFF) 1
Calculate
Plot
Plot+
Thrust Loading T/W
Minimum 0 0
Maximum 200 2
Increment 10 0.1
Atmosphere
Standard
Cold Day
Hot Day
Tropical Day
Done

APPENDIX B

TRIAL RUN 1

CARGO/PASSENGER TURBOPROP (LOW DRAW) TURBOSHAFT

Engine Reference Data

Engine File | Engine Cycle | Gas Model | Component Interfaces | Scale Thrust

Engine File: User Input--Date:6/5/2020_Time:4:42:36 PM

Reference Engine Design | Fuel/Gas Prop, Comp. Efficiencies | Controls, Install Model, # of Engines

Engine Test | Done | Change Design and Data | Check Design | Parametric Carpet Plot | Plot of Temperature and Pressure

Reference Engine Design

Cycle: Turboshaft
Gas Model: Modified Specific Heat (MSH)

Flight Condition:
- Mach Number: 0.5
- Altitude: 0 feet
- Temperature: 518.67 R
- Pressure: 14.696 Psia

Design Limits: Total Temperature Lvg Combustor (Tt4): 3200 R

Design Variables:
- Compressor Pressure Ratio (Pt3/Pt2): 20.000
- Turbine Overall Temperature Ratio (Tt5/Tt4): 0.65

Size
- Mass Flow Rate: 100 lbm/s

Thrust Scale Factor: 1.0000

Uninstalled Engine Performance at Reference Point

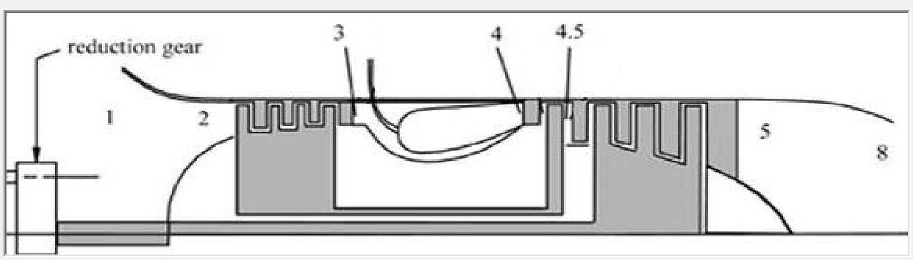
Power **9346 hp**
Power Specific Fuel Consumption **1.0711 lbm/(hr-hp)**

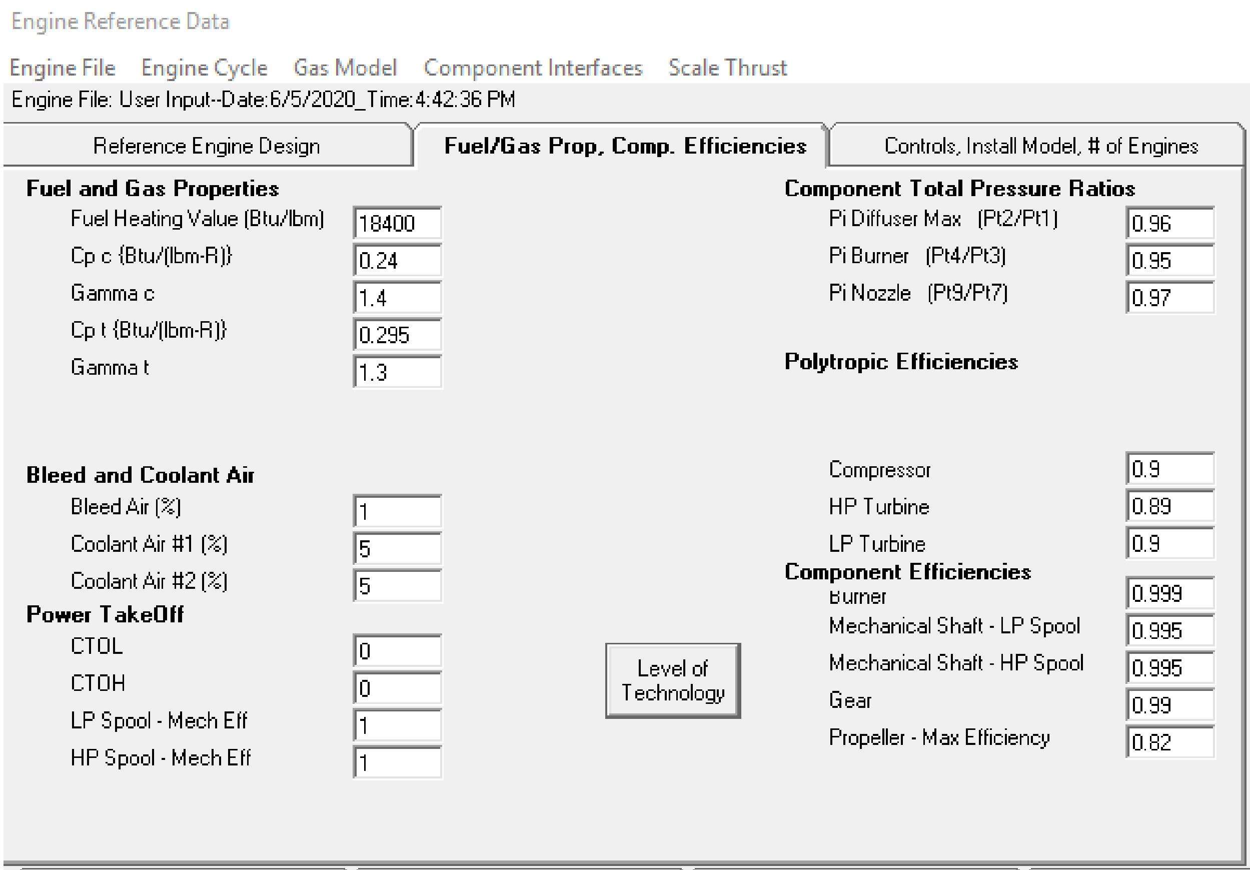
Thermal Efficiency (%) 12.91

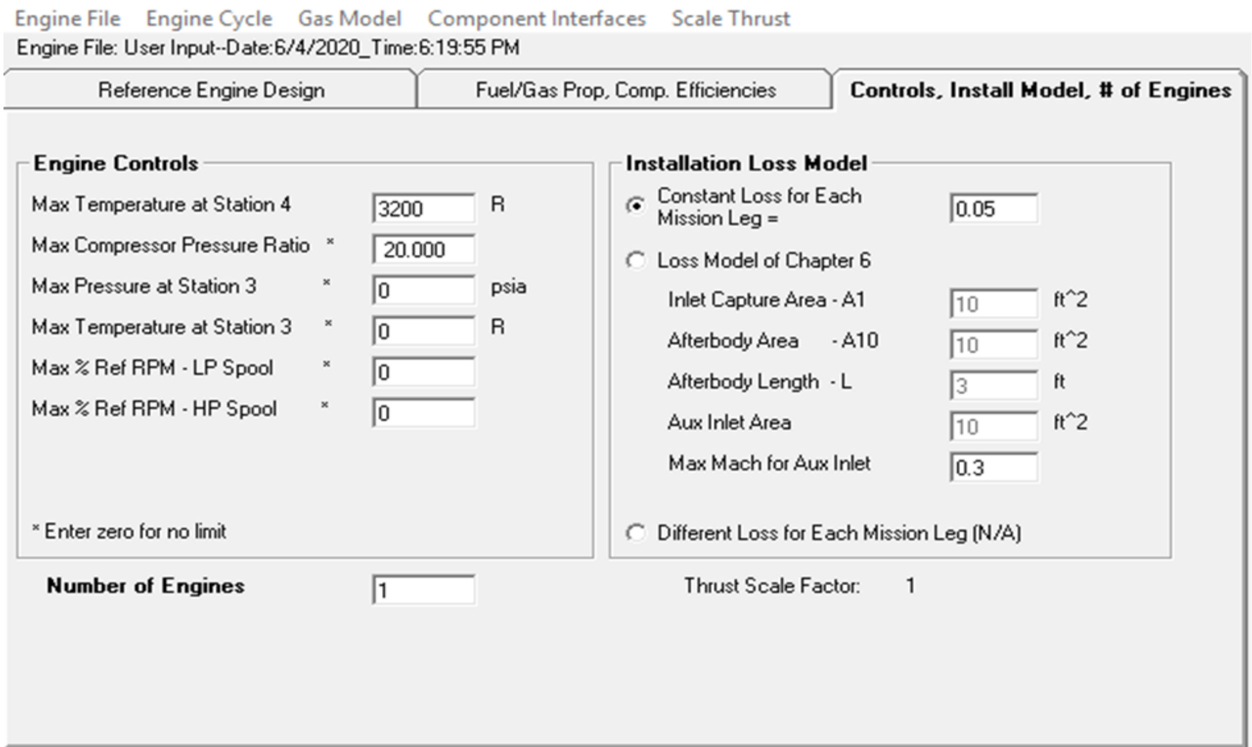
Turbomachinery Efficiency (%):
- Compressor: 85.22
- HP Turbine: 90.42
- LP Turbine: 90.50

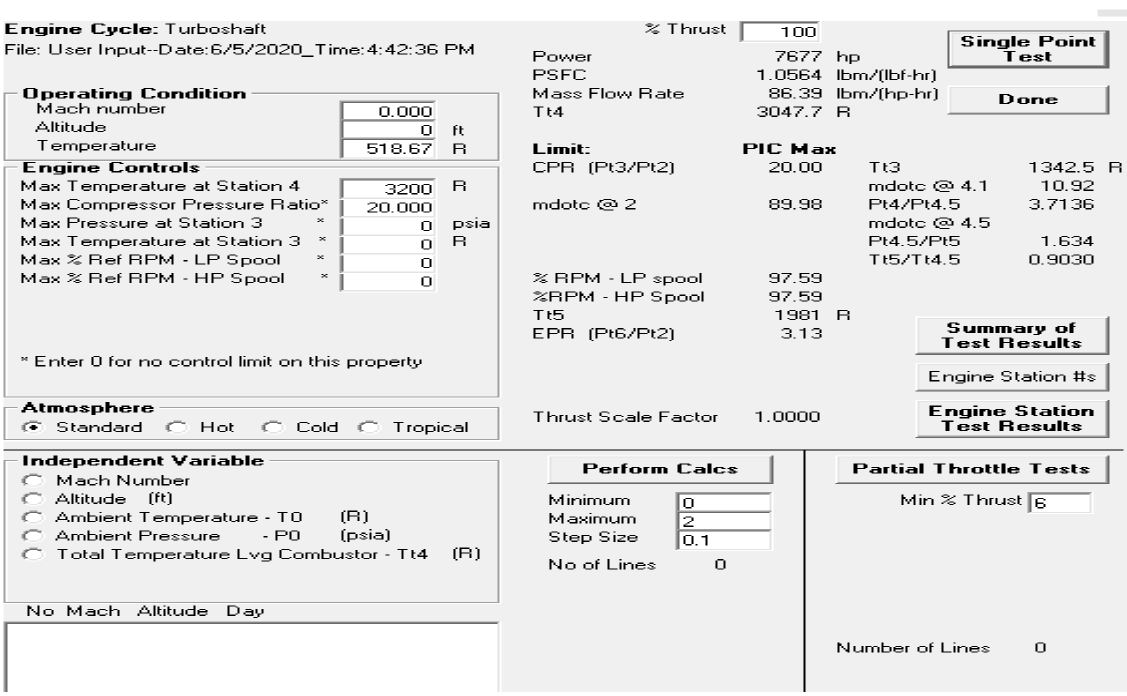
Station:	2	3	4	4.5	5	8
Tt (R)	544.60	1409.63	3200.00	2284.77	2063.22	2063.22
Pt (psia)	16.74	334.71	317.97	85.62	52.40	50.83
Mach			1.00	1.00		1.00

Turbojet - Single Spool | Turbojet - Dual Spool | Turbojet with Afterburner | Turbofan - Separate Exhausts
Turbofan - Mixed Exhaust | Turbofan with Afterburner | Turboprop | **Turboshaft**




Engine Reference Data
Engine File
Engine Cycle
Gas Model
Component Interfaces
Scale Thrust
Engine File: User Input--Date:6/5/2020_Time:4:42:36 PM
Reference Engine Design
Fuel/Gas Prop, Comp. Efficiencies
Controls, Install Model, # of Engines
Fuel and Gas Properties
Fuel Heating Value (Btu/lbm) 18400
Cp c {Btu/(lbm-R)} 0.24
Gamma c 1.4
Cp t {Btu/(lbm-R)} 0.295
Gamma t 1.3
Bleed and Coolant Air
Bleed Air (%) 1
Coolant Air #1 (%) 5
Coolant Air #2 (%) 5
Power TakeOff
CTOL 0
CTOH 0
LP Spool - Mech Eff 1
HP Spool - Mech Eff 1
Level of Technology
Component Total Pressure Ratios
Pi Diffuser Max (Pt2/Pt1) 0.96
Pi Burner (Pt4/Pt3) 0.95
Pi Nozzle (Pt9/Pt7) 0.97
Polytropic Efficiencies
Compressor 0.9
HP Turbine 0.89
LP Turbine 0.9
Component Efficiencies
Burner 0.999
Mechanical Shaft - LP Spool 0.995
Mechanical Shaft - HP Spool 0.995
Gear 0.99
Propeller - Max Efficiency 0.82

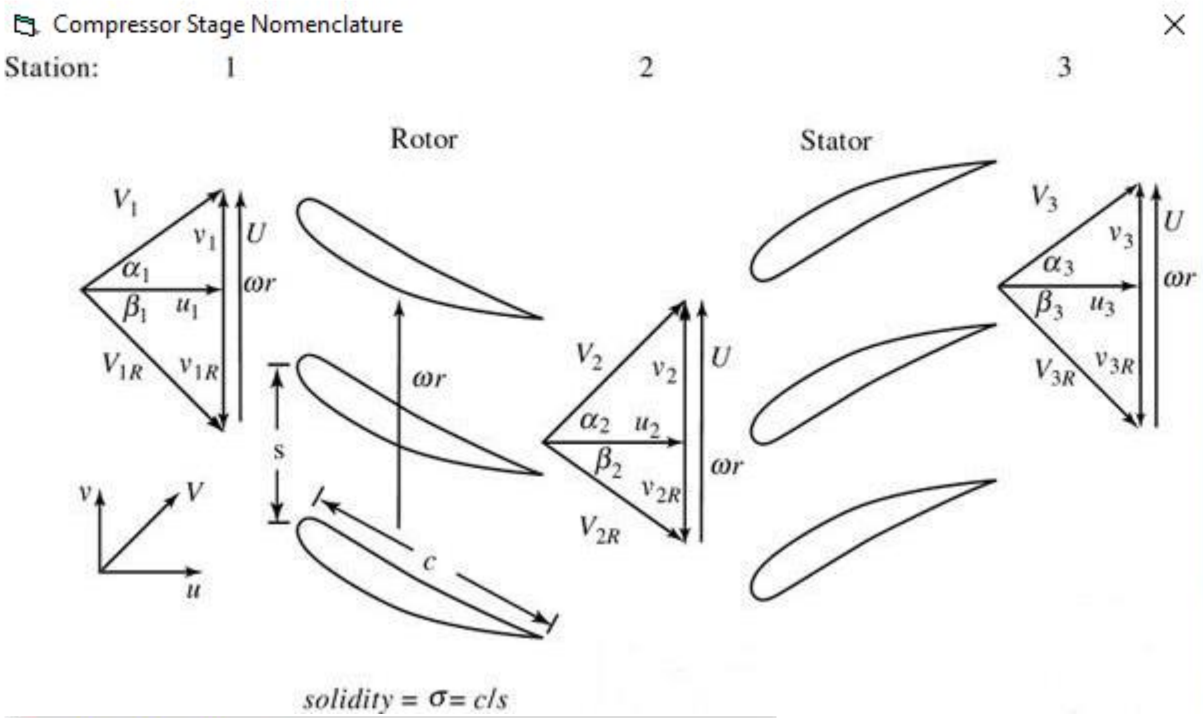

Engine File Engine Cycle Gas Model Component Interfaces Scale Thrust
Engine File: User Input--Date:6/4/2020_Time:6:19:55 PM
Reference Engine Design
Fuel/Gas Prop, Comp. Efficiencies
Controls, Install Model, # of Engines
Engine Controls
Max Temperature at Station 4 3200 R
Max Compressor Pressure Ratio * 20.000
Max Pressure at Station 3 * 0 psia
Max Temperature at Station 3 * 0 R
Max % Ref RPM - LP Spool * 0
Max % Ref RPM - HP Spool * 0
* Enter zero for no limit
Installation Loss Model
Constant Loss for Each Mission Leg = 0.05
Loss Model of Chapter 6
Inlet Capture Area - A1 10 ft^2
Afterbody Area - A10 10 ft^2
Afterbody Length - L 3 ft
Aux Inlet Area 10 ft^2
Max Mach for Aux Inlet 0.3
Different Loss for Each Mission Leg (N/A)
Number of Engines 1
Thrust Scale Factor: 1

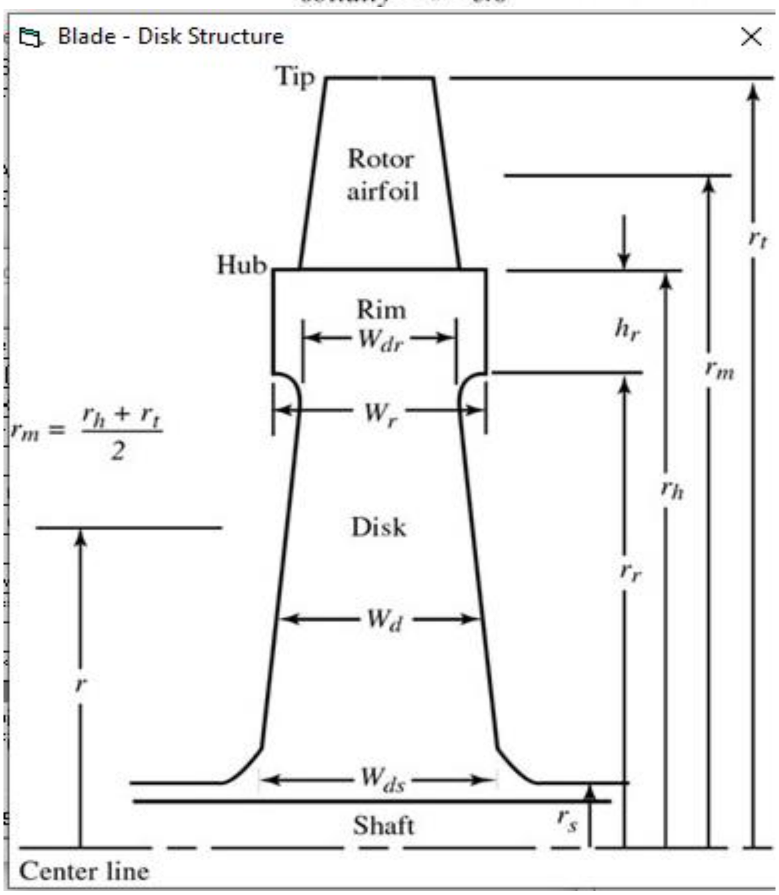

Engine Cycle: Turboshaft
File: User Input--Date:6/5/2020_Time:4:42:36 PM
% Thrust 100
Single Point Test
Done
Power 7677 hp
PSFC 1.0564 lbm/(lbf-hr)
Mass Flow Rate 86.39 lbm/(hp-hr)
Tt4 3047.7 R
Operating Condition
Mach number 0.000
Altitude 0 ft
Temperature 518.67 R
Engine Controls
Max Temperature at Station 4 3200 R
Max Compressor Pressure Ratio* 20.000
Max Pressure at Station 3 * 0 psia
Max Temperature at Station 3 * 0 R
Max % Ref RPM - LP Spool * 0
Max % Ref RPM - HP Spool * 0
* Enter 0 for no control limit on this property
Limit: PIC Max
CPR (Pt3/Pt2) 20.00
mdotc @ 2 89.98
Tt3 1342.5 R
mdotc @ 4.1 10.92
Pt4/Pt4.5 3.7136
mdotc @ 4.5
Pt4.5/Pt5 1.634
Tt5/Tt4.5 0.9030
% RPM - LP spool 97.59
%RPM - HP Spool 97.59
Tt5 1981 R
EPR (Pt6/Pt2) 3.13
Summary of Test Results
Engine Station #s
Engine Station Test Results
Atmosphere
Standard Hot Cold Tropical
Thrust Scale Factor 1.0000
Independent Variable
Mach Number
Altitude (ft)
Ambient Temperature - T0 (R)
Ambient Pressure - P0 (psia)
Total Temperature Lvg Combustor - Tt4 (R)
No Mach Altitude Day
Perform Calcs
Minimum 0
Maximum 2
Step Size 0.1
No of Lines 0
Partial Throttle Tests
Min % Thrust 6
Number of Lines 0

APPENDIX B.1
TRIAL RUN 1 RESULTS

CARGO/PASSENGER TURBOPROP (LOW DRAG)
TURBOSHAFT

```
AEDsys (Ver. 6.00)                Turboshaft                Date:6/5/2020 4:54:40 PM
                     using Modified Specific Heat (MSH) Model
Engine File: User Input--Date:6/5/2020_Time:4:51:35 PM

  Input Constants
  Pidmax = 0.9600   Pi b   = 0.9500   Eta b  = 0.9990   Pi n   = 0.9700
  cp c   = 0.2400   cp t   = 0.2950   Gam c  = 1.4000   Gam t  = 1.3000
  Eta c  = 0.8522   Eta tH = 0.9042   Eta tL = 0.9050
  Eta mL = 0.9950   Eta mH = 0.9950   Eta PL = 1.0000   Eta PH = 1.0000
  PTO L  =    0.0KW PTO H  =    0.0KW hPR    =  18400
  Bleed  =   1.00%  Cool 1 =   5.00%  Cool 2 =   5.00%
  Control Limits:   Tt4    = 3200.0   Pi c   =  20.00
  ** Thrust Scale Factor   = 1.0000

  Parameter                           Reference**          Test**
  Mach Number @ 0                       0.5000            0.0100
  Temperature @ 0                       518.67            518.67 R
  Pressure    @ 0                      14.6960           14.6960 psia
  Altitude    @ 0                            0                 0 ft
  Total Temp  @ 4                      3200.00           3047.70 R
  Pi r    (Pt0/P0)                      1.1862            1.0001
  Tau r   (Tt0/T0)                      1.0500            1.0000
  Pi d    (Pt2/Pt0)                     0.9600            0.9600
  Pi c    (Pt3/Pt2)                    20.0000           20.0003
  Tau c   (Tt3/Tt2)                     2.5884            2.5884
  Tau m1  (Tt41/Tt4)                    0.9669            0.9669
  Pi tH   (Pt45/Pt4)                    0.2693            0.2693
  Tau tH  (Tt44/Tt41)                   0.7638            0.7638
  Tau m2  (Tt45/Tt44)                   0.9747            0.9747
  Pi tL   (Pt5/Pt45)                    0.6119            0.6119
  Tau tL  (Tt5/Tt45)                    0.9030            0.9030
  Control Limit                                          PIC Max
  LP Spool RPM (% of Reference Pt)    100.00              97.59
  HP Spool RPM (% of Reference Pt)    100.00              97.59
  Pt9/P9                                1.8324            1.8324
  P0/P9                                 0.5298            0.6284
  Mach Number @ 9                       1.0000            1.0000
  Mass Flow Rate @ 0                    100.00             86.39 lbm/s
  Corrected Mass Flow @ 0                86.38             86.38 lbm/s
  Flow Area      @ 0                     2.343           101.203 ft^2
  Flow Area*     @ 0                     1.749             1.749 ft^2
  Flow Area      @ 9                     1.220             1.219 ft^2
  MB - Fuel/Air Ratio (f)              0.03124           0.02930
  Overall Fuel/Air Ratio (fo)          0.02780           0.02608
  Cshaft                                0.5307            0.5046
  Specific Power  (P/m0)                 93.46             88.87 hp/(lbm/s)
  Power Spec Fuel Consumption (Sp)    1.0711            1.0564 (lbm/hr)/hp
  Power (P)                               9346              7677 hp
  Fuel Flow Rate                         10009              8110 lbm/hr
  Thermal Efficiency    (%)              12.91             13.09
```


Compressor Stage Nomenclature
Station: 1 2 3
Rotor
Stator
V_1 v_1 U α_1 ωr β_1 u_1 V_{1R} v_{1R}
ωr
s
c
V_2 v_2 U α_2 u_2 β_2 ωr v_{2R} V_{2R}
V_3 v_3 U α_3 ωr β_3 u_3 V_{3R} v_{3R}
v V u
solidity = σ = c/s


Blade - Disk Structure
Tip
Rotor airfoil
Hub
Rim
W_{dr}
W_r
$r_m = \frac{r_h + r_t}{2}$
Disk
W_d
W_{ds}
Shaft
r_s
Center line
r
h_r
r_r
r_h
r_m
r_t

Initial/Stage Data

Number of Stages (20 max)	4	
Mass Flow Rate	150	lbm/s
Rotor Angular Velocity	900	rad/s
Inlet Total Pressure	14.696	psia
Inlet Total Temperature	518.7	R
Alpha 1	40	deg
Mach 1	0.5	
Diffusion Factor	0.5	
Solidity	1	
Rotor chord/height ratio	0.5	
Stator chord/height ratio	0.5	
Polytropic Efficiency	0.9	
Approx. Stator Loss Coeff.	0.03	
Ratio of Specific Heats	1.4	
Gas Constant	53.34	ft-lbf/lbm-R
Cp	0.2399	Btu/lbm-R

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 4/20/2020    Time - 11:01:05 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 1  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.1002  Pt3/Pt1(i) = 1.3508  DTt =051.96 R    AN^2=5.099E+10
  Hub   R = 0.0100  Dr = 0.1962  Ds = 0.5421  Phis = 0.0300  Eff = 0.8956
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.1006  r m = 13.459 in
  Tip   R = 0.7083  Dr = 0.3761  Ds = 0.4663  M1R  = 1.0634  U m = 1009.5 fps
  Flow  Area 1 = 0764.55  Area 2 = 0690.31  Area 3 = 0615.65 in^2
  Rotor  - # of Blades = 21  Chord = 4.301 in
  Stator - # of Blades = 23  Chord = 3.861 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      ------------------------------------------------------------------
  Tt     R | 518.7 518.7 518.7 544.7 544.7 570.7 570.7 570.7 570.7 570.7 570.7
  T      R | 481.1 494.0 498.5 494.0 520.0 481.6 520.0 534.9 537.0 546.0 549.8
  Pt  psia | 14.70 14.70 14.70 17.44 16.99 20.00 20.00 20.00 19.85 19.85 19.85
  P   psia | 11.29 12.39 12.79 12.39 14.44 11.05 14.44 15.94 16.05 17.00 17.43
  M        | 0.625 0.500 0.450 0.716 0.487 0.961 0.698 0.579 0.560 0.476 0.435
  Vel ft/s | 672.4 544.7 492.8 780.3 544.7 1034.2 780.3 655.8 636.0 544.7 500.1
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 527.2 350.1 262.1 659.3 350.1 946.3 659.3 505.9 479.9 350.1 275.6
 alpha deg | 51.64 40.00 32.13             66.20 57.67 50.48 48.99 40.00 33.44
 beta  deg |                   57.67 40.00
 radius in | 08.94 13.46 17.98 13.46 13.46 09.38 13.46 17.54 09.82 13.46 17.10
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 4/20/2020    Time - 11:03:14 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 2  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0911  Pt3/Pt1(i) = 1.3159  DTt =051.96 R    AN^2=4.145E+10
  Hub   R = 0.1364  Dr = 0.3929  Ds = 0.5320  Phis = 0.0300  Eff = 0.8960
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0978  r m = 13.459 in
  Tip   R = 0.6802  Dr = 0.3907  Ds = 0.4730  M1R  = 0.9482  U m = 1009.5 fps
  Flow  Area 1 = 0615.65  Area 2 = 0561.17  Area 3 = 0505.68 in^2
  Rotor  - # of Blades = 25  Chord = 3.479 in
  Stator - # of Blades = 28  Chord = 3.154 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt      R | 570.7 570.7 570.7 596.6 596.6 622.6 622.6 622.6 622.6 622.6 622.6
  T       R | 537.0 546.0 549.8 546.0 571.9 544.4 571.9 584.8 591.3 597.9 601.3
  Pt   psia | 19.85 19.85 19.85 23.20 22.66 26.30 26.30 26.30 26.12 26.12 26.12
  P    psia | 16.05 17.00 17.43 17.00 19.54 16.44 19.54 21.13 21.80 22.67 23.12
  M         | 0.560 0.476 0.435 0.681 0.465 0.848 0.666 0.568 0.515 0.454 0.421
  Vel  ft/s | 636.0 544.7 500.1 780.3 544.7 969.4 780.3 673.7 613.8 544.7 506.2
  u    ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v    ft/s | 479.9 350.1 275.6 659.3 350.1 875.0 659.3 528.9 450.1 350.1 286.5
 alpha deg  | 48.99 40.00 33.44             64.50 57.67 51.73 47.17 40.00 34.47
 beta  deg  |                   57.67 40.00
 radius in  | 09.82 13.46 17.10 13.46 13.46 10.14 13.46 16.78 10.47 13.46 16.45
```

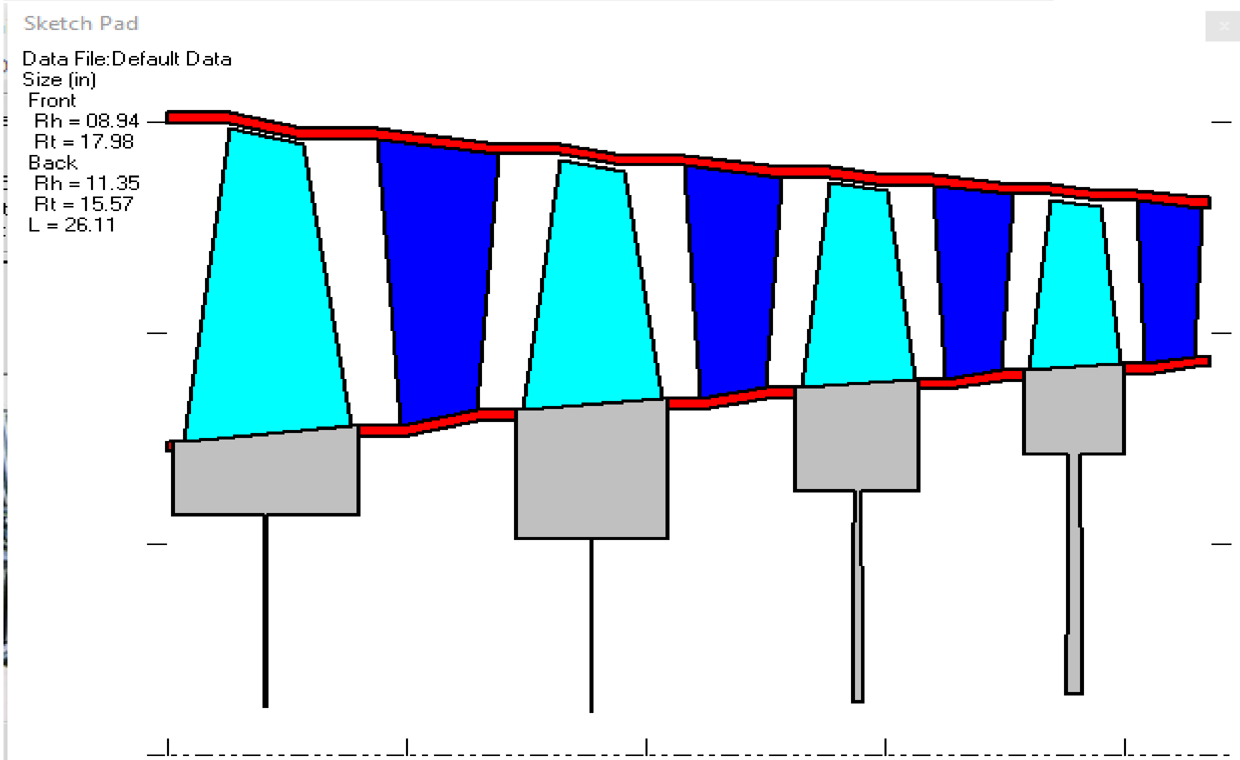
```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 4/20/2020    Time - 11:04:08 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 3  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0835  Pt3/Pt1(i) = 1.2872  DTt =051.96 R    AN^2=3.431E+10
  Hub   R = 0.2190  Dr = 0.4805  Ds = 0.5251  Phis = 0.0300  Eff = 0.8964
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0955  r m = 13.459 in
  Tip   R = 0.6566  Dr = 0.4040  Ds = 0.4780  M1R  = 0.8611  U m = 1009.5 fps
  Flow  Area 1 = 0505.68  Area 2 = 0464.57  Area 3 = 0422.26 in^2
  Rotor  - # of Blades = 30  Chord = 2.868 in
  Stator - # of Blades = 33  Chord = 2.622 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
 Tt      R | 622.6 622.6 622.6 648.6 648.6 674.6 674.6 674.6 674.6 674.6 674.6
 T       R | 591.3 597.9 601.3 597.9 623.9 603.0 623.9 635.1 644.7 649.9 652.8
 Pt   psia | 26.12 26.12 26.12 30.14 29.50 33.85 33.85 33.85 33.63 33.63 33.63
 P    psia | 21.80 22.67 23.12 22.67 25.75 22.85 25.75 27.41 28.70 29.51 29.98
 M         | 0.515 0.454 0.421 0.651 0.445 0.771 0.637 0.557 0.481 0.436 0.408
 Vel  ft/s | 613.8 544.7 506.2 780.3 544.7 927.5 780.3 688.4 599.1 544.7 511.2
 u    ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
 v    ft/s | 450.1 350.1 286.5 659.3 350.1 828.4 659.3 547.6 429.9 350.1 295.4
alpha deg  | 47.17 40.00 34.47             63.26 57.67 52.69 45.85 40.00 35.29
beta  deg  |                   57.67 40.00
radius in  | 10.47 13.46 16.45 13.46 13.46 10.71 13.46 16.21 10.96 13.46 15.96
```

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 4/20/2020    Time - 11:04:44 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 4  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0770  Pt3/Pt1(i) = 1.2633  DTt =051.96 R    AN^2=2.884E+10
  Hub   R = 0.2760  Dr = 0.5182  Ds = 0.5202  Phis = 0.0300  Eff = 0.8966
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0936  r m = 13.459 in
  Tip   R = 0.6368  Dr = 0.4157  Ds = 0.4818  M1R  = 0.7931  U m = 1009.5 fps
  Flow  Area 1 = 0422.26  Area 2 = 0390.51  Area 3 = 0357.56 in^2
  Rotor  - # of Blades = 36  Chord = 2.403 in
  Stator - # of Blades = 39  Chord = 2.211 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
 Tt      R | 674.6 674.6 674.6 700.6 700.6 726.5 726.5 726.5 726.5 726.5 726.5
 T       R | 644.7 649.9 652.8 649.9 675.9 659.3 675.9 685.7 697.7 701.8 704.4
 Pt   psia | 33.63 33.63 33.63 38.38 37.63 42.74 42.74 42.74 42.48 42.48 42.48
 P    psia | 28.70 29.51 29.98 29.51 33.18 30.43 33.18 34.90 36.86 37.64 38.12
 M         | 0.481 0.436 0.408 0.624 0.427 0.714 0.612 0.546 0.455 0.419 0.396
 Vel  ft/s | 599.1 544.7 511.2 780.3 544.7 898.6 780.3 700.6 588.8 544.7 515.5
 u    ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
 v    ft/s | 429.9 350.1 295.4 659.3 350.1 795.8 659.3 562.8 415.4 350.1 302.6
alpha deg  | 45.85 40.00 35.29             62.33 57.67 53.44 44.87 40.00 35.95
beta  deg  |                   57.67 40.00
radius in  | 10.96 13.46 15.96 13.46 13.46 11.15 13.46 15.77 11.35 13.46 15.57
```

Stage Sketch Data

Stage	1	2	3	4
Tt1R (R)	544.7	596.6	648.6	700.6
Wr/cx	1.1	1.1	1.1	1.1
hr/Wr	0.5	1.0	1.0	1.0
sigma b/r	0.1	0.1	0.1	0.1
sp str rim *	4.0	4.0	4.0	4.0
sp str disc *	4.0	4.0	4.0	4.0
Wdr/Wr	0.007	-0.064	0.058	0.111
DSF **	0.229	0.185	0.275	0.357
hr (in)	2.314	3.825	3.09	2.501
WS ***	513.4	461.7	562.6	641.7

Wr = width of rim, hr = height of rim, cx = axial chord of rotor blade at hub, Wdr = width of disk at rim
*Specific Strength (ksi-ft^3/slug) ** DSF = Disk Shape Factor *** WS = Wheel Speed at rim (ft/s)



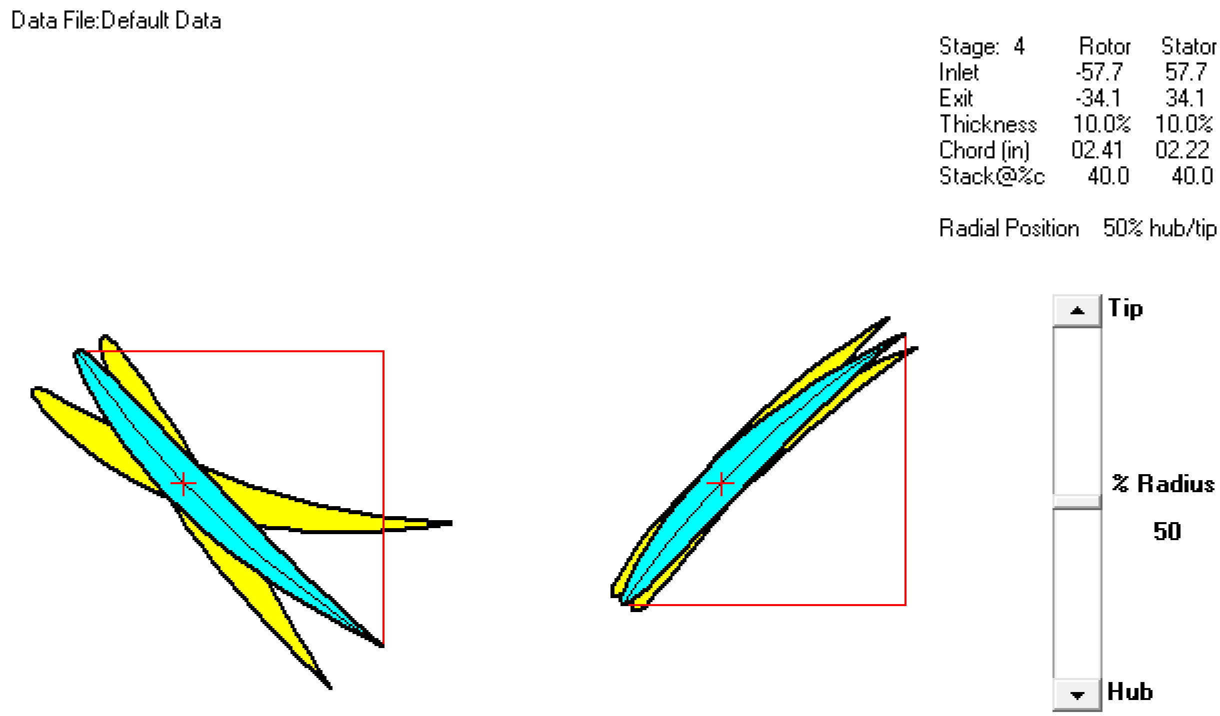
Results

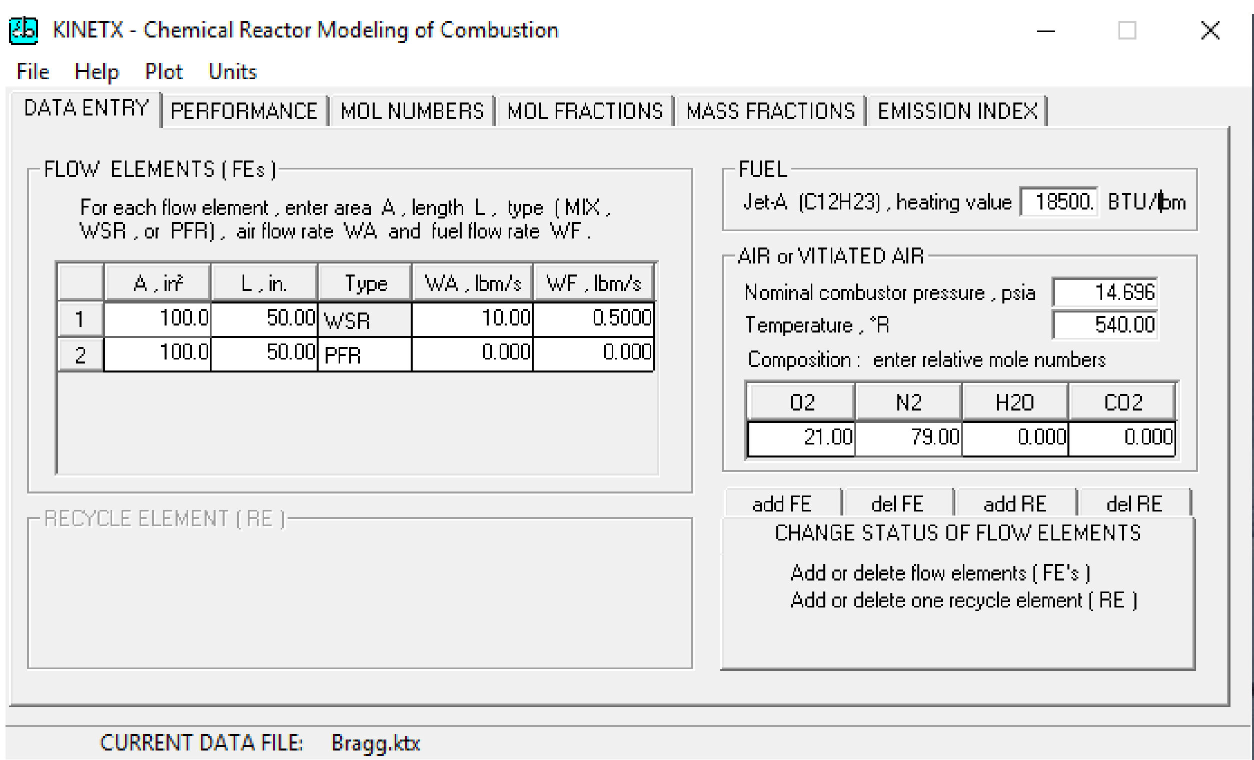
```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 4/20/2020     Time - 11:10:23 PM
Data File:Default Data
```

Stage	#	Axial Position (in)	Inner Radius (in)	Axial Position (in)	Outer Radius (in)
1	0	00.000	08.939	00.000	17.980
1	1	00.378	08.939	01.559	17.980
1	2	04.585	09.378	03.404	17.541
1	3	05.837	09.378	05.269	17.541
1	4	07.719	09.820	08.287	17.099
2	1	08.911	09.820	09.845	17.099
2	2	12.388	10.142	11.455	16.777
2	3	13.356	10.142	12.960	16.777
2	4	14.987	10.470	15.383	16.449
3	1	15.900	10.470	16.600	16.449
3	2	18.709	10.713	18.010	16.206
3	3	19.475	10.713	19.185	16.206
3	4	20.883	10.963	21.172	15.956
4	1	21.604	10.963	22.121	15.956
4	2	23.878	11.151	23.361	15.768
4	3	24.496	11.151	24.277	15.768
4	4	25.716	11.345	25.934	15.573
4	5	27.159	11.345	27.159	15.573

Blade Description

Stage Number (0 = IGV) (5=EGV)	4
Rotor Blade Thickness (%)	10
Stator Blade Thickness (%)	10
Rotor Stack @ % of Chord	40
Stator Stack @ % of Chord	40
Number of Blades per Row	1
Radial Location in % of hub/tip	50


Data File:Default Data
Stage: 4 Rotor Stator
Inlet -57.7 57.7
Exit -34.1 34.1
Thickness 10.0% 10.0%
Chord (in) 02.41 02.22
Stack@%c 40.0 40.0
Radial Position 50% hub/tip
Tip
% Radius
50
Hub


KINETX - Chemical Reactor Modeling of Combustion
File Help Plot Units
DATA ENTRY
PERFORMANCE
MOL NUMBERS
MOL FRACTIONS
MASS FRACTIONS
EMISSION INDEX
FLOW ELEMENTS (FEs)
For each flow element , enter area A , length L , type (MIX , WSR , or PFR) , air flow rate WA and fuel flow rate WF .
A , in² L , in. Type WA , lbm/s WF , lbm/s
1 100.0 50.00 WSR 10.00 0.5000
2 100.0 50.00 PFR 0.000 0.000
RECYCLE ELEMENT (RE)
FUEL
Jet-A (C12H23) , heating value 18500. BTU/lbm
AIR or VITIATED AIR
Nominal combustor pressure , psia 14.696
Temperature , °R 540.00
Composition : enter relative mole numbers
O2 N2 H2O CO2
21.00 79.00 0.000 0.000
add FE
del FE
add RE
del RE
CHANGE STATUS OF FLOW ELEMENTS
Add or delete flow elements (FE's)
Add or delete one recycle element (RE)
CURRENT DATA FILE: Bragg.ktx

KINETX - Chemical Reactor Modeling of Combustion

File Help Plot Units

DATA ENTRY | PERFORMANCE | MOL NUMBERS | MOL FRACTIONS | MASS FRACTIONS | EMISSION INDEX

Flow element # :	1	2	EQL	1@Rfmax	1@Blowout
Flow element type :	WSR	PFR	EQL	(WSR)	(WSR)
Equivalence ratio	0.7288	0.7288	0.7288	0.7288	0.7288
Residence time , s	3.5401E-03	3.2742E-03	0.000	6.2416E-04	6.3126E-04
Air loading , l / l-BO	0.1418	0.000	0.000	0.9793	1.000
Area , in²	100.0	100.0	0.000	100.0	100.0
Length , in.	50.00	50.00	0.000	7.238	7.088
Volume , in^3	5000.	5000.	0.000	723.8	708.8
Space velocity , ft/s	1177.	1307.	0.000	966.3	935.7
Flow rate , lbm/s	10.50	10.50	10.50	10.50	10.50
Enthalpy , BTU/lbm	-36.34	-36.34	-36.34	-36.34	-36.34
Combustion efficiency	0.8569	0.9758	1.000	0.6743	0.6480
Temperature , °R	3058.	3407.	3477.	2521.	2444.

KINETX - Chemical Reactor Modeling of Combustion

File Help Plot Units

DATA ENTRY | PERFORMANCE | MOL NUMBERS | MOL FRACTIONS | MASS FRACTIONS | EMISSION INDEX

UNITS: lbmols i / lbm mixture

FE # :	1	2	EQL	1@Rfmax	1@Blowout
FE type :	WSR	PFR	EQL	(WSR)	(WSR)
C12H23	1.432E-06	1.861E-20	1.000E-20	3.409E-05	4.196E-05
C2H2	1.887E-04	2.050E-05	1.000E-20	2.076E-04	1.951E-04
C2H3	5.619E-06	3.566E-10	1.000E-20	2.070E-05	1.977E-05
C2H4	6.330E-06	9.609E-11	1.000E-20	5.555E-05	6.043E-05
CH2O	1.275E-06	3.779E-08	4.952E-16	2.007E-05	2.378E-05
CH3	4.783E-07	3.811E-08	1.000E-20	3.603E-06	3.989E-06
CH4	2.121E-14	2.485E-14	1.000E-20	1.194E-14	1.112E-14
CO	1.046E-04	7.469E-05	1.074E-05	2.355E-04	2.673E-04
CO2	2.889E-03	3.300E-03	3.405E-03	2.166E-03	2.052E-03
HCO	1.145E-06	2.486E-08	1.096E-12	1.301E-05	1.414E-05
H	1.762E-05	6.076E-06	2.881E-07	1.125E-05	1.027E-05

H2	2.850E-05	1.740E-05	2.401E-06	1.817E-05	1.640E-05
H2O	2.951E-03	3.187E-03	3.254E-03	2.375E-03	2.283E-03
HO2	1.952E-05	4.561E-07	1.266E-08	1.754E-04	1.856E-04
N	1.295E-09	2.589E-09	9.716E-12	7.799E-11	4.094E-11
NO	4.063E-07	1.129E-06	1.134E-04	3.235E-09	1.654E-09
NO2	9.490E-09	1.036E-08	1.032E-07	1.242E-10	6.808E-11
N2	2.608E-02	2.608E-02	2.602E-02	2.608E-02	2.608E-02
O	4.845E-05	2.389E-05	3.062E-06	2.493E-05	2.127E-05
OH	9.276E-05	8.996E-05	3.412E-05	2.552E-05	2.051E-05
O2	2.424E-03	1.944E-03	1.820E-03	3.243E-03	3.380E-03

KINETX - Chemical Reactor Modeling of Combustion

File Help Plot Units

DATA ENTRY | PERFORMANCE | MOL NUMBERS | MOL FRACTIONS | MASS FRACTIONS | EMISSION INDEX

UNITS: lbmols i / lbmol mixture

FE # :	1	2	EQL	1@Rfmax	1@Blowout
FE type :	WSR	PFR	EQL	(WSR)	(WSR)
C12H23	4.108E-05	5.357E-19	2.885E-19	9.823E-04	1.210E-03
C2H2	5.413E-03	5.901E-04	2.885E-19	5.982E-03	5.628E-03
C2H3	1.612E-04	1.026E-08	2.885E-19	5.965E-04	5.703E-04
C2H4	1.816E-04	2.766E-09	2.885E-19	1.600E-03	1.743E-03
CH2O	3.657E-05	1.088E-06	1.428E-14	5.783E-04	6.858E-04
CH3	1.372E-05	1.097E-06	2.885E-19	1.038E-04	1.150E-04
CH4	6.083E-13	7.152E-13	2.885E-19	3.440E-13	3.206E-13
CO	3.001E-03	2.150E-03	3.099E-04	6.785E-03	7.708E-03
CO2	8.289E-02	9.497E-02	9.822E-02	6.242E-02	5.918E-02
HCO	3.285E-05	7.155E-07	3.161E-11	3.748E-04	4.078E-04
H	5.056E-04	1.749E-04	8.311E-06	3.241E-04	2.962E-04

H2	8.176E-04	5.008E-04	6.925E-05	5.235E-04	4.730E-04
H2O	8.465E-02	9.173E-02	9.386E-02	6.843E-02	6.586E-02
HO2	5.599E-04	1.313E-05	3.653E-07	5.055E-03	5.352E-03
N	3.716E-08	7.452E-08	2.803E-10	2.247E-09	1.181E-09
NO	1.166E-05	3.250E-05	3.271E-03	9.319E-08	4.771E-08
NO2	2.722E-07	2.981E-07	2.976E-06	3.580E-09	1.964E-09
N2	0.748	0.751	0.751	0.751	0.752
O	1.390E-03	6.877E-04	8.834E-05	7.182E-04	6.135E-04
OH	2.661E-03	2.589E-03	9.844E-04	7.353E-04	5.914E-04
O2	6.953E-02	5.595E-02	5.251E-02	9.345E-02	9.746E-02

KINETX - Chemical Reactor Modeling of Combustion

File Help Plot Units

DATA ENTRY | PERFORMANCE | MOL NUMBERS | MOL FRACTIONS | MASS FRACTIONS | EMISSION INDEX

UNITS: lbm i / lbm mixture

FE # :	1	2	EQL	1@Rfmax	1@Blowout
FE type :	WSR	PFR	EQL	(WSR)	(WSR)
C12H23	2.396E-04	3.114E-18	1.673E-18	5.705E-03	7.021E-03
C2H2	4.913E-03	5.338E-04	2.604E-19	5.406E-03	5.081E-03
C2H3	1.520E-04	9.645E-09	2.705E-19	5.600E-04	5.348E-04
C2H4	1.776E-04	2.696E-09	2.805E-19	1.558E-03	1.695E-03
CH2O	3.828E-05	1.135E-06	1.487E-14	6.027E-04	7.140E-04
CH3	7.191E-06	5.730E-07	1.504E-19	5.417E-05	5.997E-05
CH4	3.402E-13	3.986E-13	1.604E-19	1.916E-13	1.783E-13
CO	2.930E-03	2.092E-03	3.009E-04	6.596E-03	7.486E-03
CO2	0.127	0.145	0.150	9.534E-02	9.031E-02
HCO	3.323E-05	7.214E-07	3.180E-11	3.775E-04	4.103E-04
H	1.776E-05	6.125E-06	2.904E-07	1.134E-05	1.035E-05
H2	5.746E-05	3.508E-05	4.839E-06	3.663E-05	3.306E-05
H2O	5.316E-02	5.741E-02	5.861E-02	4.279E-02	4.114E-02
HO2	6.443E-04	1.505E-05	4.180E-07	5.791E-03	6.125E-03
N	1.814E-08	3.626E-08	1.361E-10	1.092E-09	5.734E-10
NO	1.219E-05	3.388E-05	3.402E-03	9.706E-08	4.964E-08
NO2	4.366E-07	4.765E-07	4.746E-06	5.716E-09	3.132E-09
N2	0.731	0.731	0.729	0.731	0.731
O	7.752E-04	3.823E-04	4.899E-05	3.988E-04	3.403E-04
OH	1.578E-03	1.530E-03	5.804E-04	4.341E-04	3.488E-04
O2	7.755E-02	6.220E-02	5.824E-02	0.104	0.108

KINETX - Chemical Reactor Modeling of Combustion

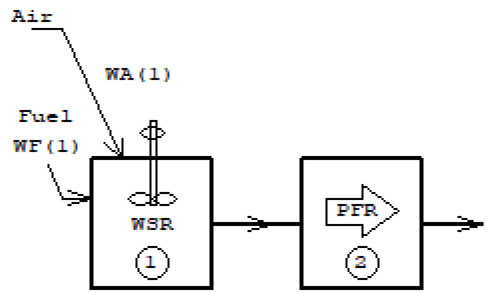
File Help Plot Units

DATA ENTRY | PERFORMANCE | MOL NUMBERS | MOL FRACTIONS | MASS FRACTIONS | EMISSION INDEX

UNITS: lbm i / 1000 lbm fuel

FE # :	1	2	EQL	1@Rfmax	1@Blowout
FE type :	WSR	PFR	EQL	(WSR)	(WSR)
C12H23	5.03	6.540E-14	3.514E-14	120.	147.
C2H2	103.	11.2	5.468E-15	114.	107.
C2H3	3.19	2.026E-04	5.680E-15	11.8	11.2
C2H4	3.73	5.661E-05	5.891E-15	32.7	35.6
CH2O	0.804	2.383E-02	3.122E-10	12.7	15.0
CH3	0.151	1.203E-02	3.157E-15	1.14	1.26
CH4	7.145E-09	8.371E-09	3.369E-15	4.023E-09	3.745E-09
CO	61.5	43.9	6.32	139.	157.
CO2	2.670E+03	3.050E+03	3.147E+03	2.002E+03	1.896E+03
HCO	0.698	1.515E-02	6.678E-07	7.93	8.62
H	0.373	0.129	6.098E-03	0.238	0.217
H2	1.21	0.737	0.102	0.769	0.694
H2O	1.116E+03	1.206E+03	1.231E+03	899.	864.
HO2	13.5	0.316	8.778E-03	122.	129.
N	3.810E-04	7.616E-04	2.858E-06	2.294E-05	1.204E-05
NO	0.256	0.711	71.4	2.038E-03	1.043E-03
NO2	9.168E-03	1.001E-02	9.966E-02	1.200E-04	6.578E-05
N2	1.534E+04	1.534E+04	1.531E+04	1.534E+04	1.534E+04
O	16.3	8.03	1.03	8.38	7.15
OH	33.1	32.1	12.2	9.12	7.32
O2	1.629E+03	1.306E+03	1.223E+03	2.180E+03	2.271E+03

Layout of Reactor Network (Schematic - NOT TO SCALE)



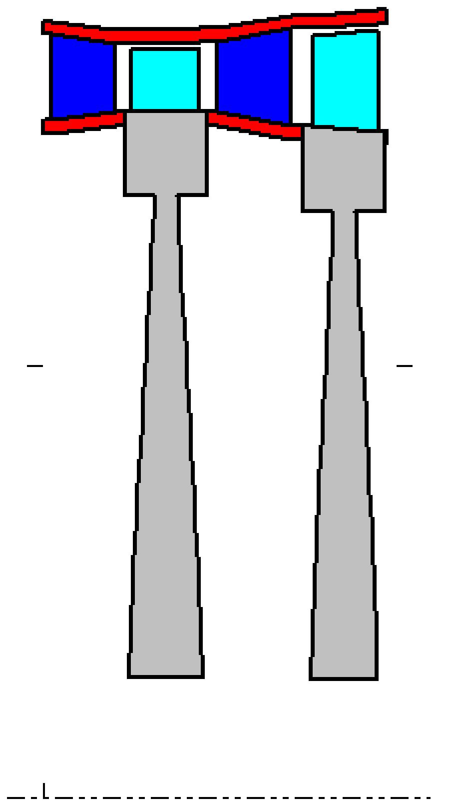
Initial Data

Number of Stages (10 max)	2	
Mass Flow Rate	100	lbm/s
Rotor Angular Velocity	1200	rad/s
Inlet Total Pressure	300	psia
Inlet Total Temperature	3200	R
Alpha 1 for First Stage	0	deg
Mach 1 for First Stage	0.3	
Ratio of Specific Heats	1.3	
Gas Constant	53.4	ft-lbf/lbm-R
Cp	0.2974	Btu/lbm-R
Mean Radius	10	inches
Mean Rotor Velocity	1000	ft/sec

Sketch Pad

Data File: Default Data
Size (in)
Front
Rh = 9.41
Rt = 10.59
Back
Rh = 9.25
rt = 10.75

L = 5.01 in



Replot

Flow Path Dimensions

Center Line

Done

Tic spacing = 6.0 in

Turbine Cross Section

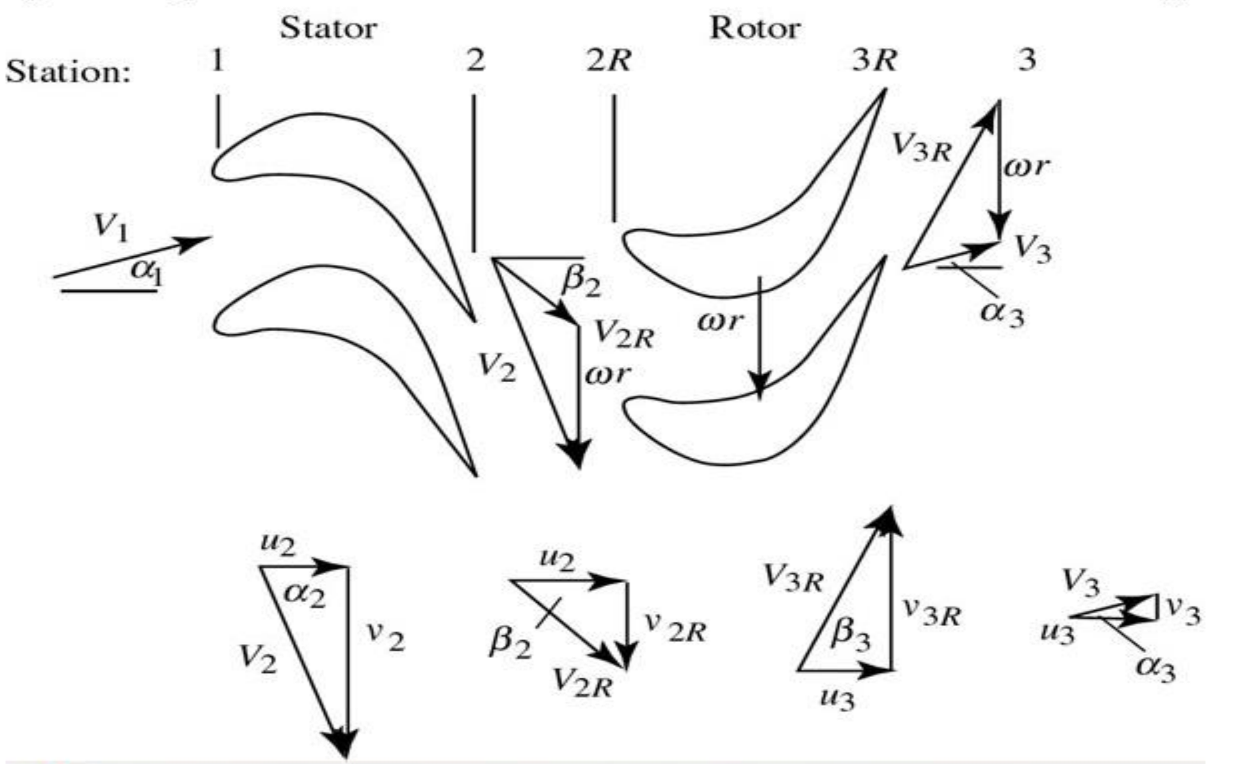
Stage Data

	1	2
u3/u2	1.0	1.0
Mach @ 2	1.05	0.65
Alpha @ 3	0.0	0.0
Tt3 (R)	2925.0	2775.0
Stator Z	1.0	1.0
Rotor Z	1.0	1.0
Stator c/h	1.0	1.0
Rotor c/h	1.0	0.7
Stator phi	0.02	0.02
Poly Eff	0.9	0.9

Results

```
TURBN V6.00 - Data File: Default Data
Stage #01     Date - 4/21/2020     Time - 5:10:11 PM
 Corr Flow =   12.17 lbm/s  M1   = 0.3000  Tt1 = 3200.0 R   Pt1 = 300.00 psia
 Mass Flow = 100.00 lbm/s  M2   = 1.0500  Tt3 = 2925.0 R   AL1 =   0.00
 u3/u2 = 1.0000 phis= 0.020 et  = 0.900  Um  =  1000 ft/s rm  = 10.00 in
 Stator: Z = 1.0000   c/h = 1.0000   Rotor: Z = 1.0000   c/h = 1.0000
 Gamma = 1.3000 Gas Const = 53.40ft-lbf/lbm-R  w =  1200 rad/s  AL3 =   0.00
 Omega = 0.2049        Cp = 0.2974 Btu/lbm-R

RESULT: Tt3/Tt1 = 0.9141  Pt3/Pt1 = 0.6488  DTt = 275.00 R  AN^2=7.846E+09
  Reaction  Hub =-0.1285  Mean    =-0.0237  Tip = 0.0671    Eff = 90.44%
  Flow    Area 1 =  74.77  Area 2  =  59.75  Area 3 =  61.31  in^2
  Coeff.  Load = 2.0474  Flow = 1.6031  Vel Rat = 0.4942  RPM  = 11,459
  Nozzle - # of Vanes  = 35   c/s = 0.596
  Rotor  - # of Blades = 123   c/s = 1.886  M3Rt = 0.7726

   Station     1h     1m     1t     2h     2m     2t    2Rm    3Rm     3h     3m     3t
Prop:     -------------------------------------------------------------------
 Tt      R |  3200   3200   3200   3200   3200   3200   2992   2992   2925   2925   2925
 T       R |  3157   3157   3157   2717   2746   2771   2746   2752   2752   2752   2752
 Pt   psia | 300.0  300.0  300.0  297.1  297.1  297.1  222.1  214.8  194.6  194.6  194.6
 P    psia | 283.1  283.1  283.1  146.2  153.1  159.2  153.1  149.5  149.5  149.5  149.5
 M         | 0.300  0.300  0.300  1.089  1.050  1.016  0.773  0.762  0.647  0.647  0.647
 Vel ft/s  |   797    797    797   2682   2600   2528   1915   1889   1603   1603   1603
 u    ft/s |   797    797    797   1603   1603   1603   1603   1603   1603   1603   1603
 v    ft/s |     0      0      0   2150   2047   1954   1047   1000      0      0      0
 alpha deg|   0.00   0.00   0.00  53.29  51.94  50.64                 0.00   0.00   0.00
 beta  deg|                                           33.16  31.96
 radius in|   9.41  10.00  10.59   9.52  10.00  10.48  10.00  10.00   9.51  10.00  10.49
```

Turbine Stage Nomenclature



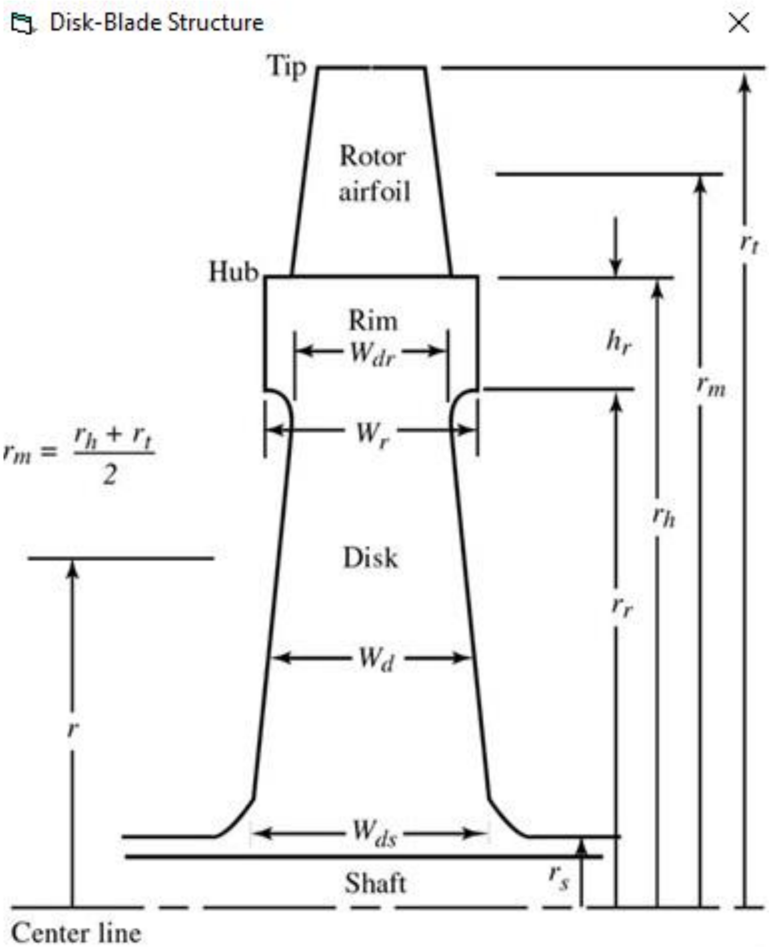
Results

```
TURBN V6.00 - Data File: Default Data
Stage #02    Date - 4/21/2020    Time - 5:11:44 PM
 Corr Flow =  17.93 lbm/s  M1  = 0.6465  Tt1 = 2925.0 R   Pt1 = 194.64 psia
 Mass Flow = 100.00 lbm/s  M2  = 0.6500  Tt3 = 2775.0 R   AL1 =  0.00
 u3/u2 = 1.0000 phis= 0.020 et  = 0.900  Um  =  1000 ft/s rm  = 10.00 in
 Stator: Z = 1.0000   c/h = 1.0000   Rotor: Z = 1.0000   c/h = 0.7000
 Gamma = 1.3000 Gas Const = 53.40ft-lbf/lbm-R  w =  1200 rad/s  AL3 =  0.00
 Omega = 0.2143        Cp = 0.2974 Btu/lbm-R

RESULT: Tt3/Tt1 = 0.9487  Pt3/Pt1 = 0.7761  DTt = 150.00 R  AN^2=1.119E+10
  Reaction  Hub = 0.3574  Mean    = 0.4416  Tip = 0.5103    Eff = 90.26%
  Flow   Area 1 =  61.31  Area 2  =  85.21  Area 3 =  94.35  in^2
  Coeff.  Load = 1.1168  Flow = 1.1613  Vel Rat = 0.6691  RPM  = 11,459
  Nozzle - # of Vanes  = 85   c/s = 1.577
  Rotor  - # of Blades = 76   c/s = 1.210  M3Rt = 0.6463

   Station    1h    1m    1t    2h    2m    2t   2Rm   3Rm    3h    3m    3t
Prop:    -------------------------------------------------------------------
 Tt     R |  2925  2925  2925  2925  2925  2925  2842  2842  2775  2775  2775
 T      R |  2752  2752  2752  2738  2751  2761  2751  2684  2684  2684  2684
 Pt  psia | 194.6 194.6 194.6 193.7 193.7 193.7 171.1 167.6 151.1 151.1 151.1
 P   psia | 149.5 149.5 149.5 145.5 148.4 150.9 148.4 130.8 130.8 130.8 130.8
 M        | 0.647 0.647 0.647 0.675 0.650 0.629 0.471 0.626 0.474 0.474 0.474
 Vel ft/s |  1603  1603  1603  1668  1611  1563  1167  1533  1161  1161  1161
 u   ft/s |  1603  1603  1603  1161  1161  1161  1161  1161  1161  1161  1161
 v   ft/s |     0     0     0  1198  1117  1046   117  1000     0     0     0
 alpha deg|  0.00  0.00  0.00 45.89 43.88 42.01              0.00  0.00  0.00
 beta  deg|                                      5.74 40.73
 radius in|  9.51 10.00 10.49  9.32 10.00 10.68 10.00 10.00  9.25 10.00 10.75
```

Stage Sketch Data

Stage	1	2
Tt2R (R)	2992.2	2842.2
Wr/cx	1.2	1.2
hr/Wr	1.0	1.0
sigma b/r	0.2	0.2
sp str rim *	4.0	4.0
sp str disk *	2.0	2.0
Wdr/Wr	0.281	0.273
DSF **	1.214	1.148
hr (in)	1.16	1.15
WS ***	836.2	813.2

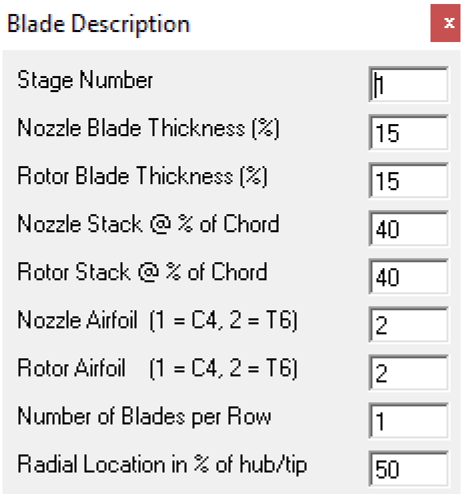
cx = rotor blade axial chord at hub
* Specific Strength (ksi-ft^3/slug) ** Disk Shape Factor *** Wheel Speed at rim (ft/s)

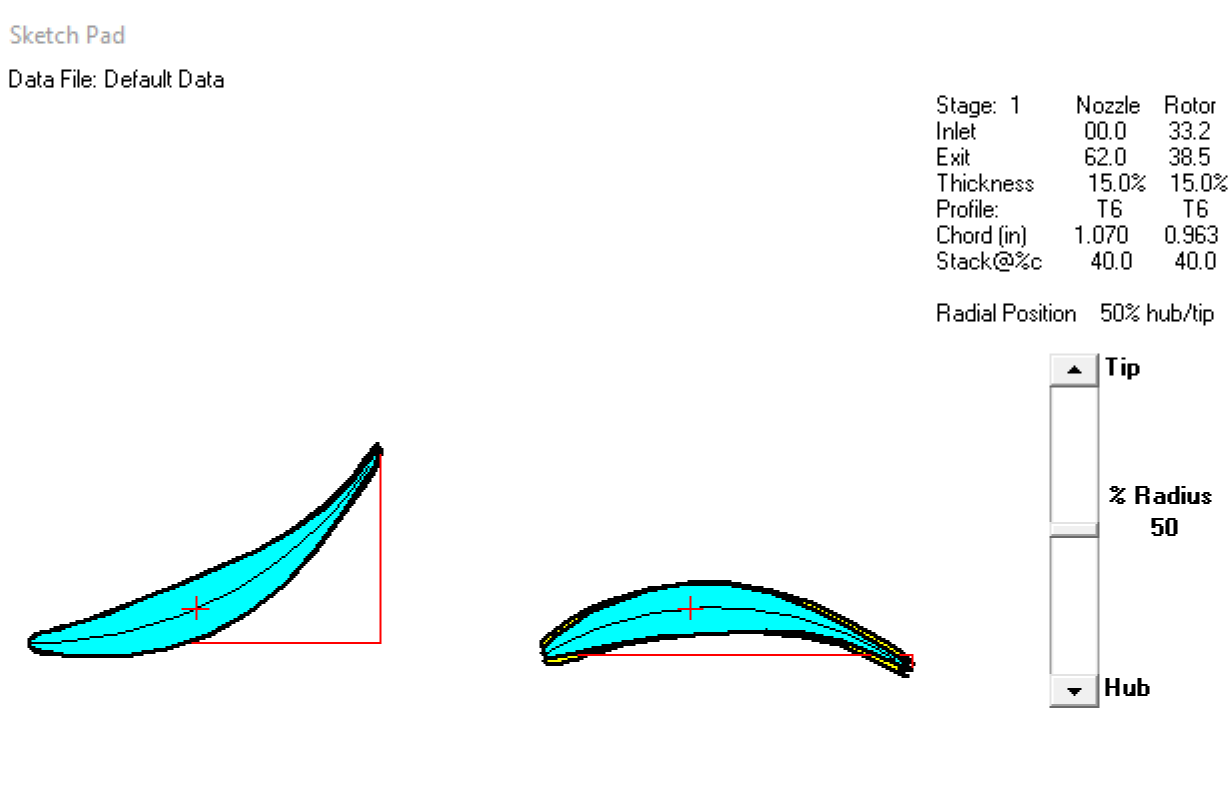


Results

```
TURBN V5.11  ---  Date - 4/21/2020    Time - 5:15:09 PM
Data File: Default Data
```

Stage	#	Axial Position (in)	Inner Radius (in)	Axial Position (in)	Outer Radius (in)
1	0	00.000	09.405	00.000	10.595
1	1	00.123	09.405	00.115	10.595
1	2	01.031	09.525	01.039	10.476
1	3	01.270	09.525	01.272	10.476
1	4	02.233	09.512	02.231	10.488
2	1	02.483	09.512	02.474	10.488
2	2	03.535	09.322	03.544	10.678
2	3	03.812	09.322	03.839	10.678
2	4	04.773	09.249	04.747	10.751
2	5	04.894	09.249	04.894	10.751


Blade Description
Stage Number 1
Nozzle Blade Thickness (%) 15
Rotor Blade Thickness (%) 15
Nozzle Stack @ % of Chord 40
Rotor Stack @ % of Chord 40
Nozzle Airfoil (1 = C4, 2 = T6) 2
Rotor Airfoil (1 = C4, 2 = T6) 2
Number of Blades per Row 1
Radial Location in % of hub/tip 50


Sketch Pad
Data File: Default Data
Stage: 1 Nozzle Rotor
Inlet 00.0 33.2
Exit 62.0 38.5
Thickness 15.0% 15.0%
Profile: T6 T6
Chord (in) 1.070 0.963
Stack@%c 40.0 40.0
Radial Position 50% hub/tip
Tip
% Radius
50
Hub

MAINBRN - Design of Annular Main Burner

File Help Plot Units

1) DATA ENTRY | 2) AIR PARTITIONING | 3) DIFFUSER | 4) PRIMARY ZONE | 5) SECONDARY ZONE | 6) DILUTION ZONE

Station 3.1

HPC exit / MB diffuser entrance

Total pressure , psia	585.11
Total temperature , ° R	1660.0
AIR mass flow , lbm/s	104.24
Mach number	0.29780
HPC mean radius *, in.	9.0000
HPC outer radius , in.	9.2472
HPC inner radius , in.	8.7528
HPC radial height , in.	0.49444
Static pressure , psia	550.19
Static temperature, ° R	1631.1
Velocity , ft/s	589.53
Area , ft²	0.19417

** fixed by design of HPC*

Station 3.2

MB diffuser exit / MB entrance

Total pressure , psia **	579.26
Total temperature , ° R	1660.0
FUEL mass flow , lbm/s	2.7017
Mach number **	5.00000E-02
Mean radius , in.	8.5000
Outer radius , in.	9.9961
Inner radius , in.	7.0039
Radial height , in.	2.9923
Static pressure , psia	578.25
Static temperature, ° R	1659.2
Velocity , ft/s	99.829
Area , ft²	1.1098

*** principal design variables*

Station 4

MB exit / HPT nozzle entrance

Total pressure , psia	555.86
Total temperature , ° R	3138.8
Equivalence ratio	0.37832
Mach number	0.20000
HPT mean radius * , in.	7.0000
HPT outer radius , in.	7.7055
HPT inner radius , in.	6.2945
HPT radial height , in.	1.4110
Static pressure , psia	541.64
Static temperature, ° R	3120.1
Velocity , ft/s	525.86
Area , ft²	0.43096

** fixed by design of HPT*

CURRENT DATA FILE: AAF Final Engine.mbn

MAINBRN - Design of Annular Main Burner

File Help Plot Units

1) DATA ENTRY | 2) AIR PARTITIONING | 3) DIFFUSER | 4) PRIMARY ZONE | 5) SECONDARY ZONE | 6) DILUTION ZONE

DESIGN INPUTS

Wall cooling method : ○ Film ● Transpiration/effusion

PZ reaction progress variable: epsPZ in Eq.9.105	0.81130
PZ equivalence ratio: phiPZ in Eqs.9.105-106	0.80000
Max. material temperature : Tm in Eqs.9.49-50, °R	2110.0

RESULTS

Gas temperature: Tg in Eq.9.105, °R 3849.

Cooling effectiveness : Eqs. (9.94-50) 0.7944

	lbm/s	fraction
Primary air flow : m-dot PZ	49.295	0.47290
Cooling air flow : m-dot c	16.113	0.15457
Secondary air flow : m-dot SZ	15.626	0.14990
Dilution air flow : m-dot DZ	23.206	0.22262
Total air flow : m-dot 3.1	104.24	1.0000

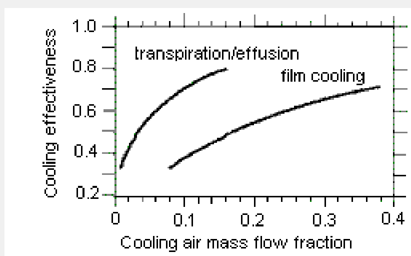


Fig. 9.18
p. 424

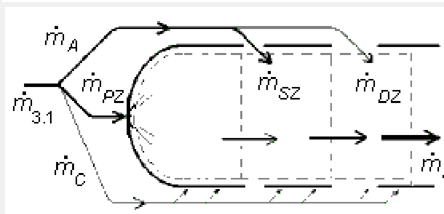
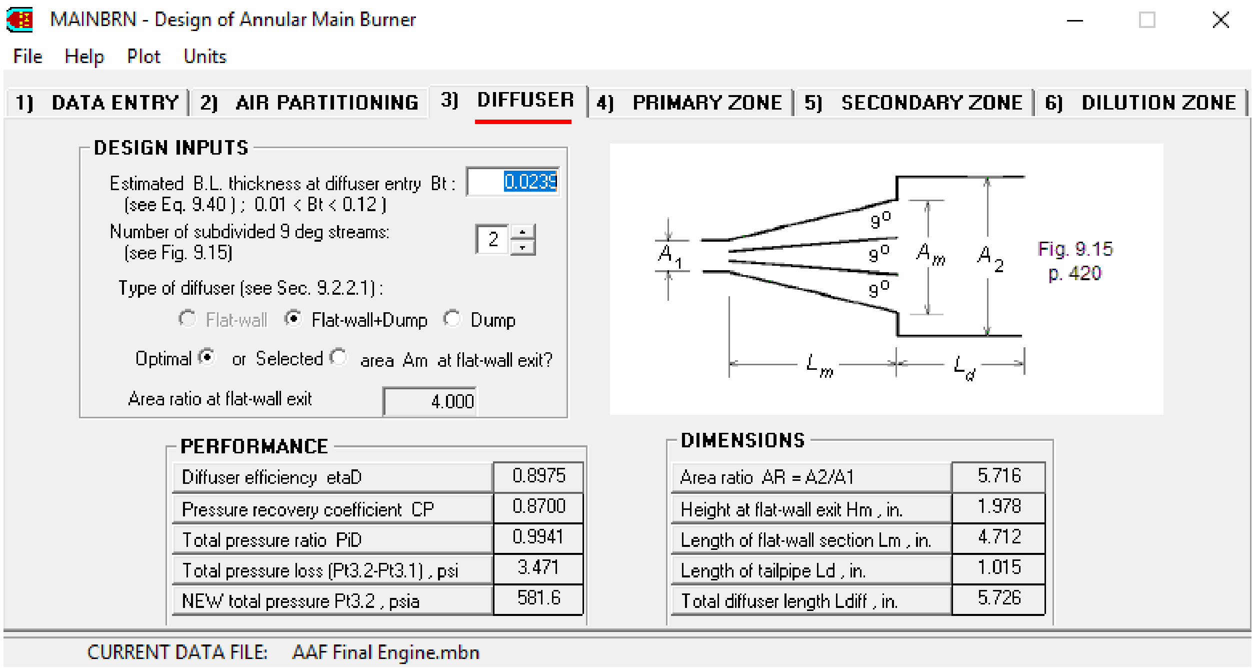
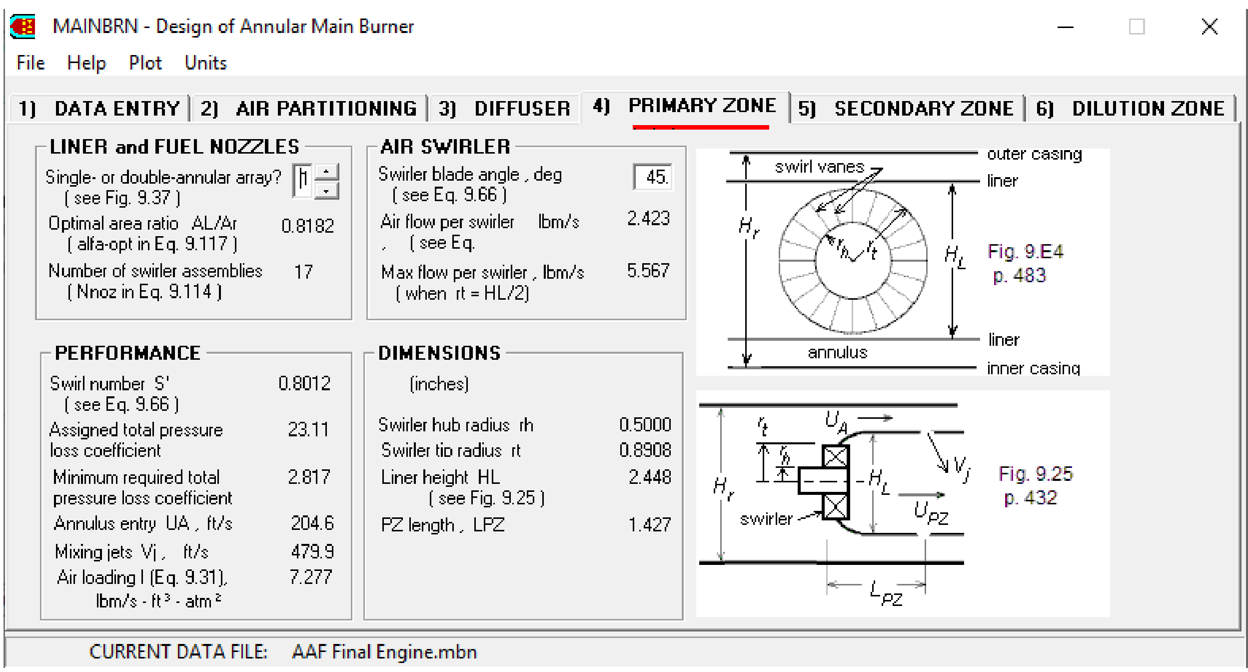


Fig. 9.33
p. 449

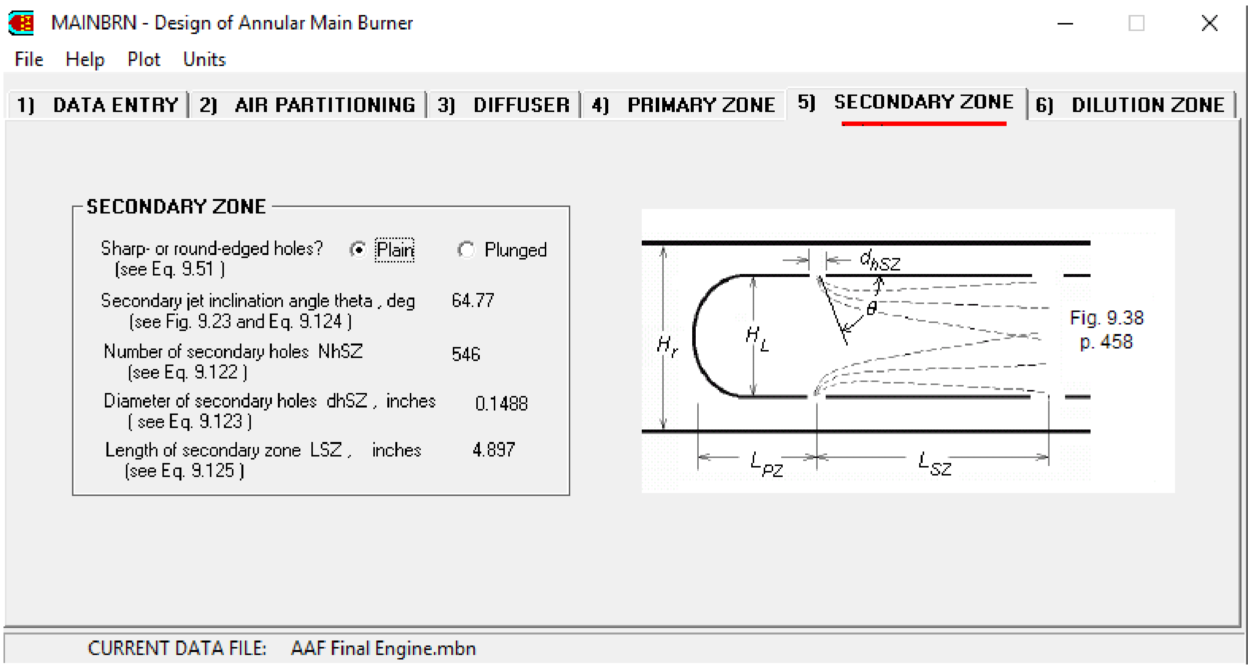
CURRENT DATA FILE: AAF Final Engine.mbn

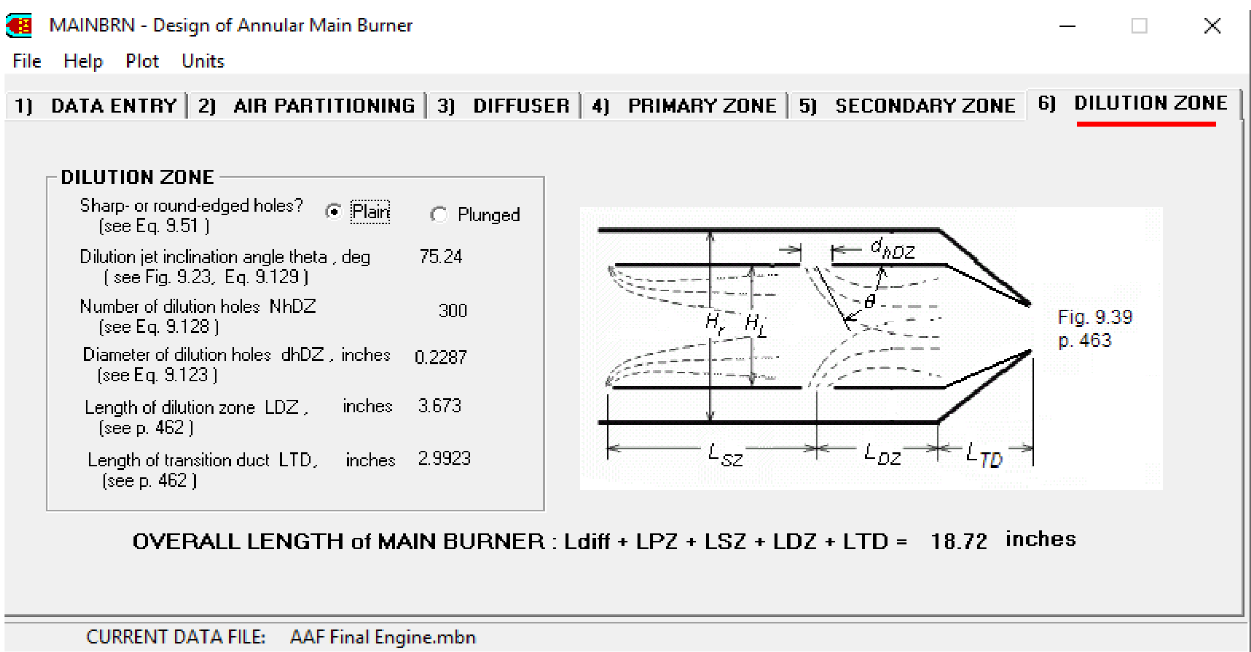


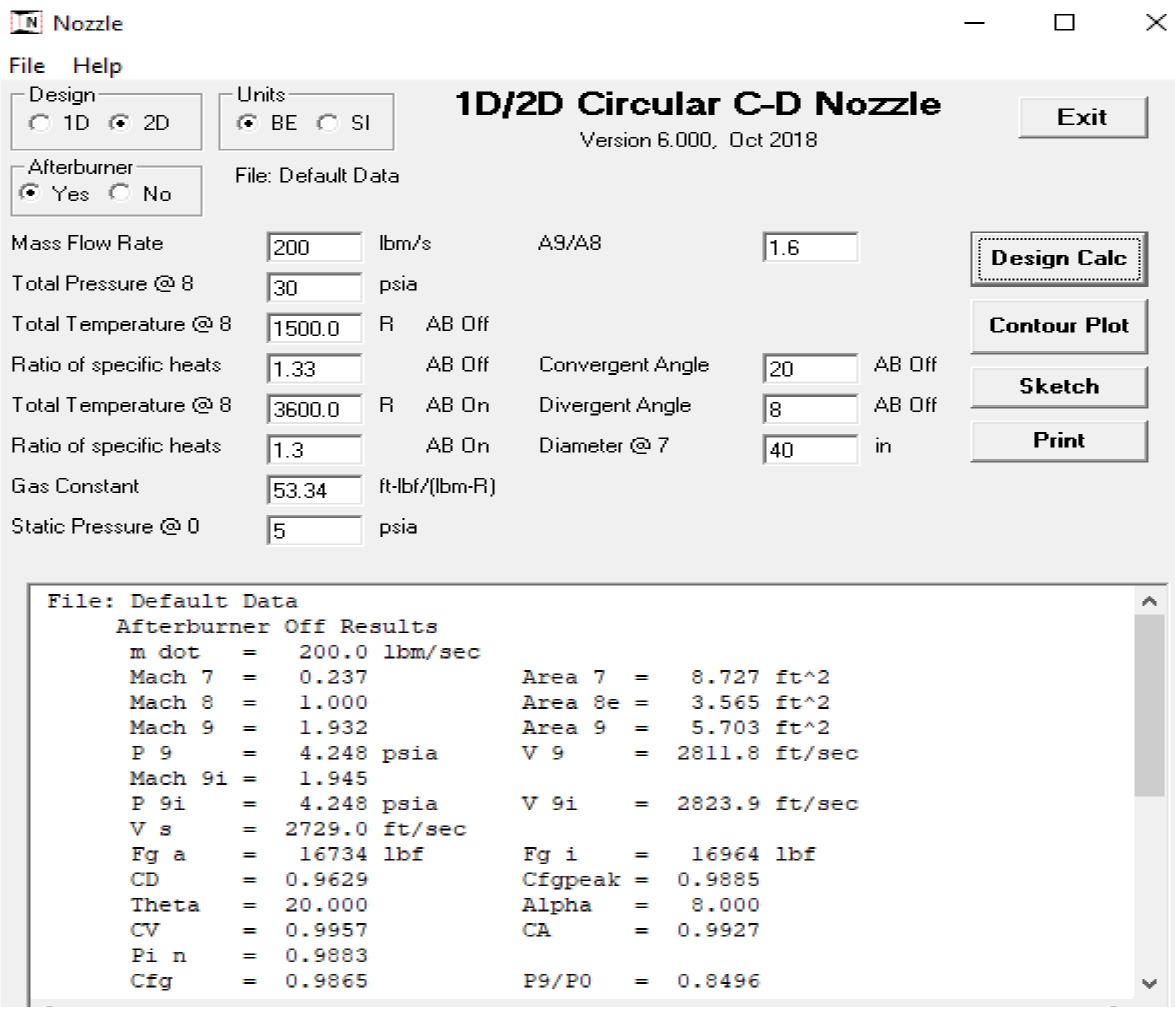
MAINBRN - Design of Annular Main Burner
File Help Plot Units
1) DATA ENTRY
2) AIR PARTITIONING
3) DIFFUSER
4) PRIMARY ZONE
5) SECONDARY ZONE
6) DILUTION ZONE
DESIGN INPUTS
Estimated B.L. thickness at diffuser entry Bt : 0.0239
(see Eq. 9.40) ; 0.01 < Bt < 0.12)
Number of subdivided 9 deg streams: 2
(see Fig. 9.15)
Type of diffuser (see Sec. 9.2.2.1) :
Flat-wall Flat-wall+Dump Dump
Optimal or Selected area Am at flat-wall exit?
Area ratio at flat-wall exit 4.000
Fig. 9.15
p. 420
PERFORMANCE
Diffuser efficiency etaD 0.8975
Pressure recovery coefficient CP 0.8700
Total pressure ratio PiD 0.9941
Total pressure loss (Pt3.2-Pt3.1) , psi 3.471
NEW total pressure Pt3.2 , psia 581.6
DIMENSIONS
Area ratio AR = A2/A1 5.716
Height at flat-wall exit Hm , in. 1.978
Length of flat-wall section Lm , in. 4.712
Length of tailpipe Ld , in. 1.015
Total diffuser length Ldiff , in. 5.726
CURRENT DATA FILE: AAF Final Engine.mbn



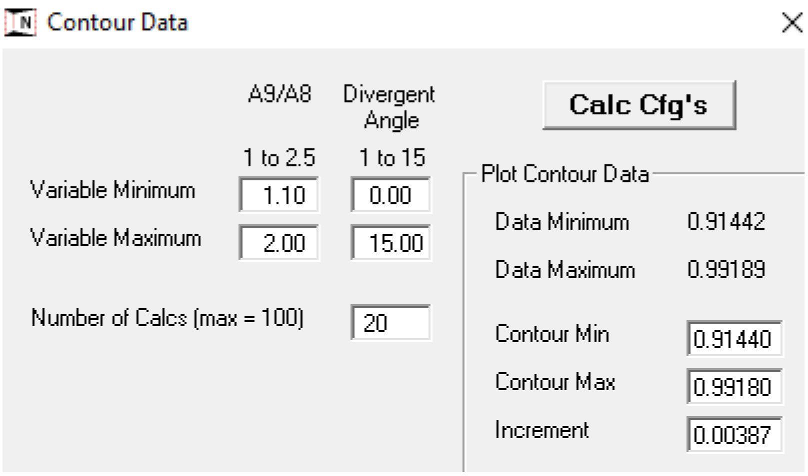
MAINBRN - Design of Annular Main Burner
File Help Plot Units
1) DATA ENTRY
2) AIR PARTITIONING
3) DIFFUSER
4) PRIMARY ZONE
5) SECONDARY ZONE
6) DILUTION ZONE
LINER and FUEL NOZZLES
Single- or double-annular array? 1
(see Fig. 9.37)
Optimal area ratio AL/Ar 0.8182
(alfa-opt in Eq. 9.117)
Number of swirler assemblies 17
(Nnoz in Eq. 9.114)
AIR SWIRLER
Swirler blade angle , deg 45.
(see Eq. 9.66)
Air flow per swirler lbm/s 2.423
(see Eq.
Max flow per swirler , lbm/s 5.567
(when rt = HL/2)
swirl vanes
outer casing
liner
Fig. 9.E4
p. 483
liner
annulus
inner casing
PERFORMANCE
Swirl number S' 0.8012
(see Eq. 9.66)
Assigned total pressure loss coefficient 23.11
Minimum required total pressure loss coefficient 2.817
Annulus entry UA , ft/s 204.6
Mixing jets Vj , ft/s 479.9
Air loading I (Eq. 9.31), lbm/s - ft³ - atm² 7.277
DIMENSIONS
(inches)
Swirler hub radius rh 0.5000
Swirler tip radius rt 0.8908
Liner height HL 2.448
(see Fig. 9.25)
PZ length , LPZ 1.427
swirler
Fig. 9.25
p. 432
CURRENT DATA FILE: AAF Final Engine.mbn


MAINBRN - Design of Annular Main Burner
File Help Plot Units
1) DATA ENTRY
2) AIR PARTITIONING
3) DIFFUSER
4) PRIMARY ZONE
5) SECONDARY ZONE
6) DILUTION ZONE
SECONDARY ZONE
Sharp- or round-edged holes? (see Eq. 9.51)
Plain
Plunged
Secondary jet inclination angle theta, deg (see Fig. 9.23 and Eq. 9.124) 64.77
Number of secondary holes NhSZ (see Eq. 9.122) 546
Diameter of secondary holes dhSZ, inches (see Eq. 9.123) 0.1488
Length of secondary zone LSZ, inches (see Eq. 9.125) 4.897
d_{hSZ}
θ
H_r
H_L
L_{PZ}
L_{SZ}
Fig. 9.38
p. 458
CURRENT DATA FILE: AAF Final Engine.mbn

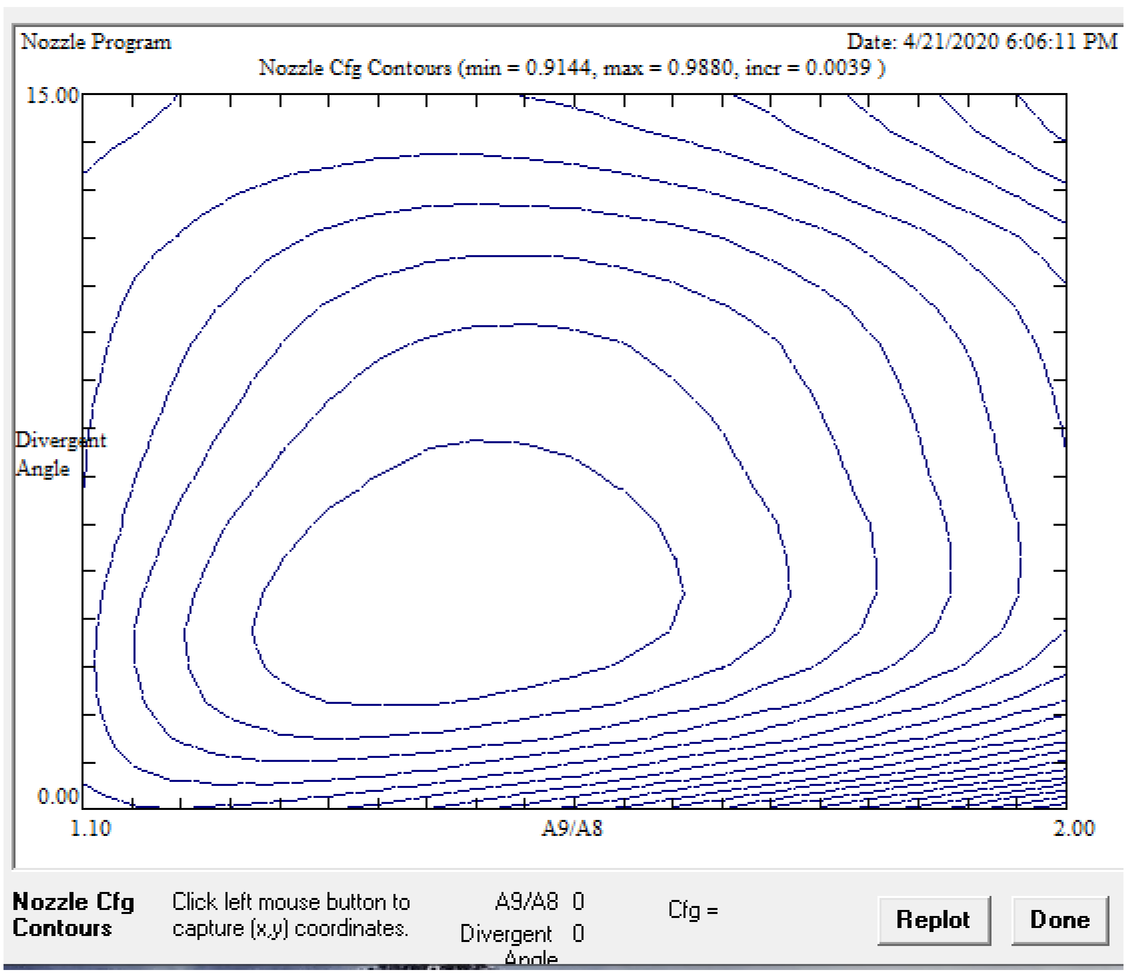

MAINBRN - Design of Annular Main Burner
File Help Plot Units
1) DATA ENTRY
2) AIR PARTITIONING
3) DIFFUSER
4) PRIMARY ZONE
5) SECONDARY ZONE
6) DILUTION ZONE
DILUTION ZONE
Sharp- or round-edged holes? (see Eq. 9.51)
Plain
Plunged
Dilution jet inclination angle theta, deg (see Fig. 9.23, Eq. 9.129) 75.24
Number of dilution holes NhDZ (see Eq. 9.128) 300
Diameter of dilution holes dhDZ, inches (see Eq. 9.123) 0.2287
Length of dilution zone LDZ, inches (see p. 462) 3.673
Length of transition duct LTD, inches (see p. 462) 2.9923
d_{hDZ}
θ
H_r
H_L
L_{SZ}
L_{DZ}
L_{TD}
Fig. 9.39
p. 463
OVERALL LENGTH of MAIN BURNER : Ldiff + LPZ + LSZ + LDZ + LTD = 18.72 inches
CURRENT DATA FILE: AAF Final Engine.mbn



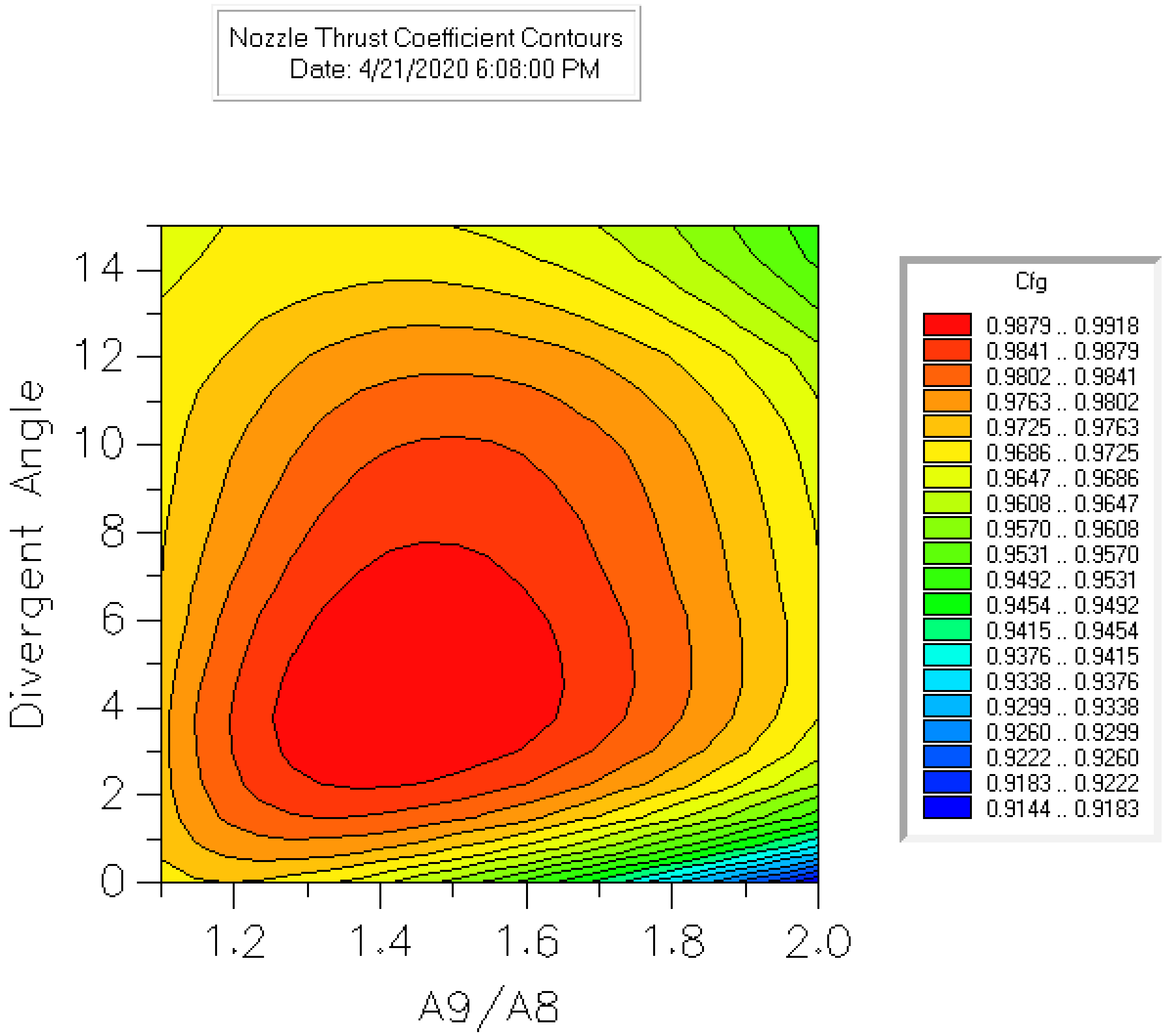

```
Afterburner On Results
 m dot    =   200.0 lbm/sec
 Mach 7   =   0.237           Area 7  =   8.727 ft^2
 Mach 8   =   1.000           Area 8e =   5.479 ft^2
 Mach 9   =   1.927           Area 9  =   8.766 ft^2
 P 9      =   4.341 psia      V 9     =  4376.7 ft/sec
 Mach 9i  =   1.936
 P 9i     =   4.341 psia      V 9i    =  4389.7 ft/sec
 V s      =  4258.3 ft/sec
 Fg a     =   26071 lbf       Fg i    =   26470 lbf
 CD       =  0.9784
 Theta    =  11.350           Alpha   =   9.936
 CV       =  0.9971           CA      =  0.9888
```

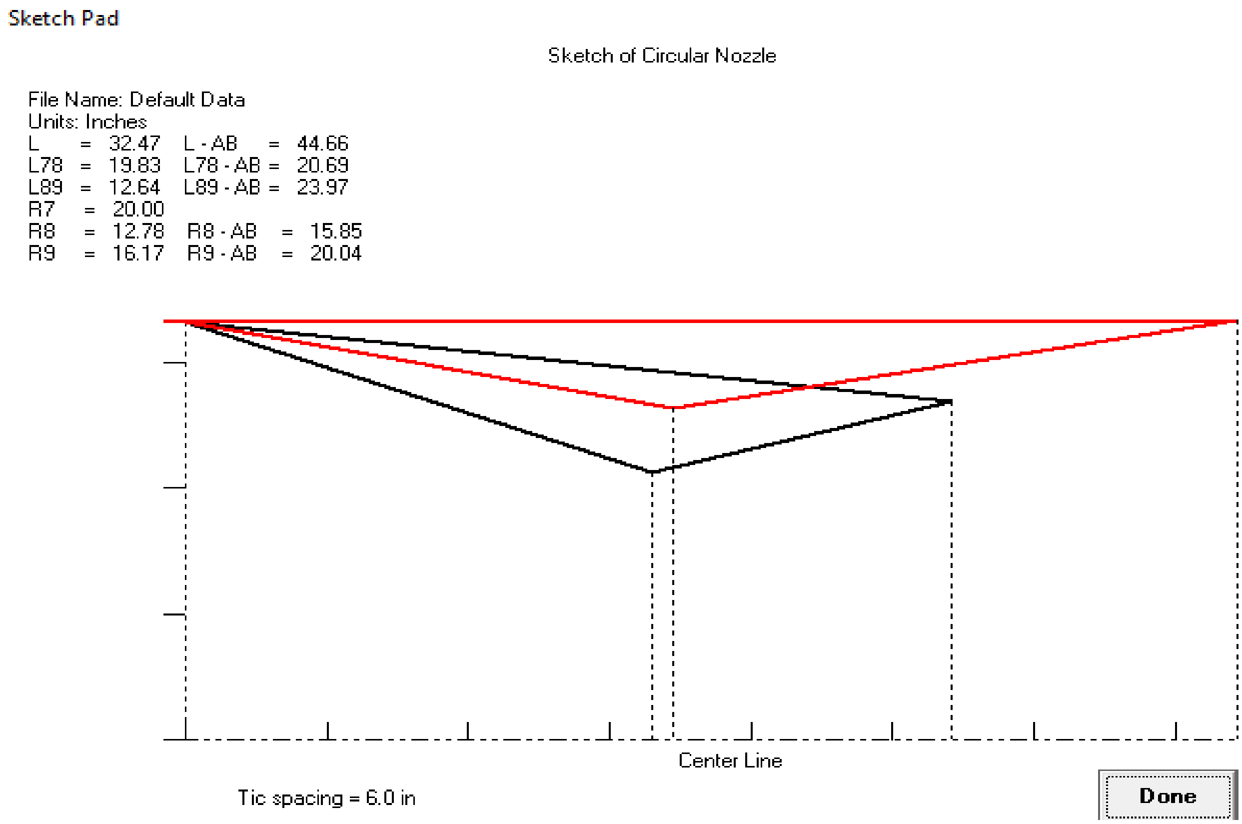

Contour Data
A9/A8
Divergent Angle
Calc Cfg's
1 to 2.5
1 to 15
Plot Contour Data
Variable Minimum
1.10
0.00
Variable Maximum
2.00
15.00
Data Minimum 0.91442
Data Maximum 0.99189
Number of Calcs (max = 100)
20
Contour Min 0.91440
Contour Max 0.99180
Increment 0.00387

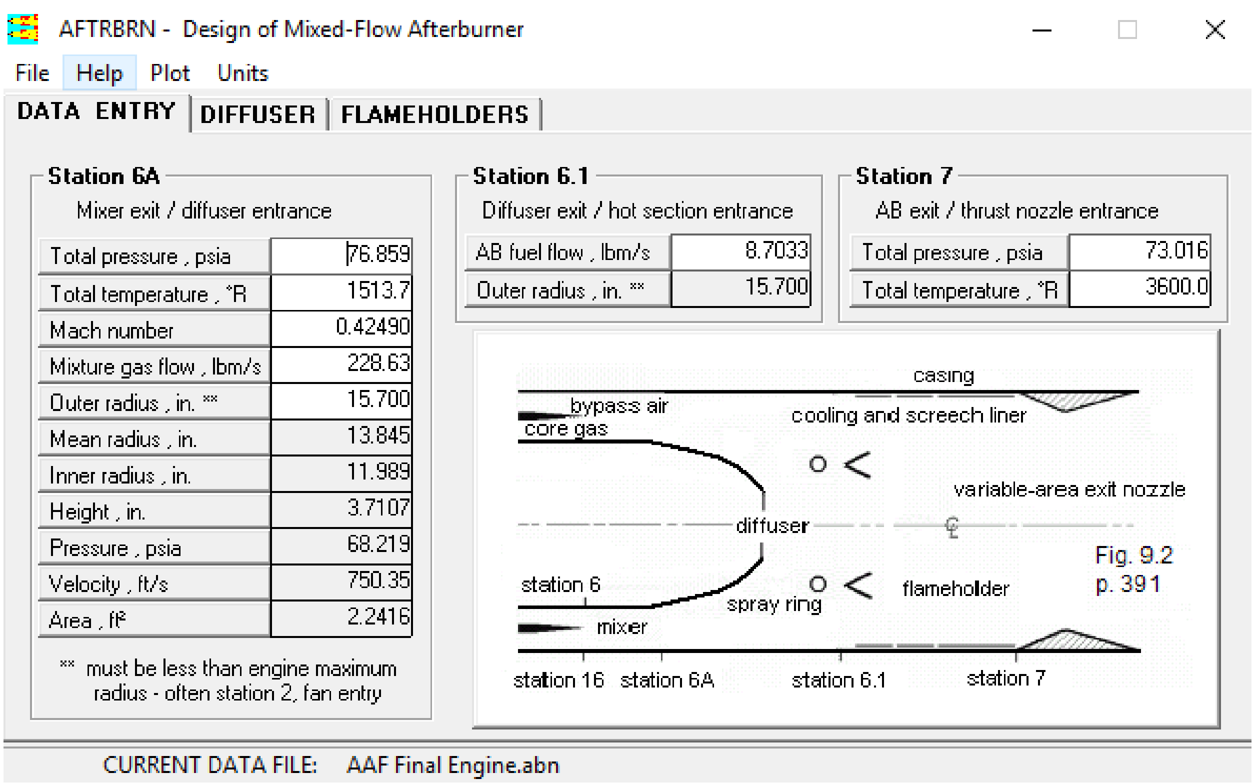
Plot

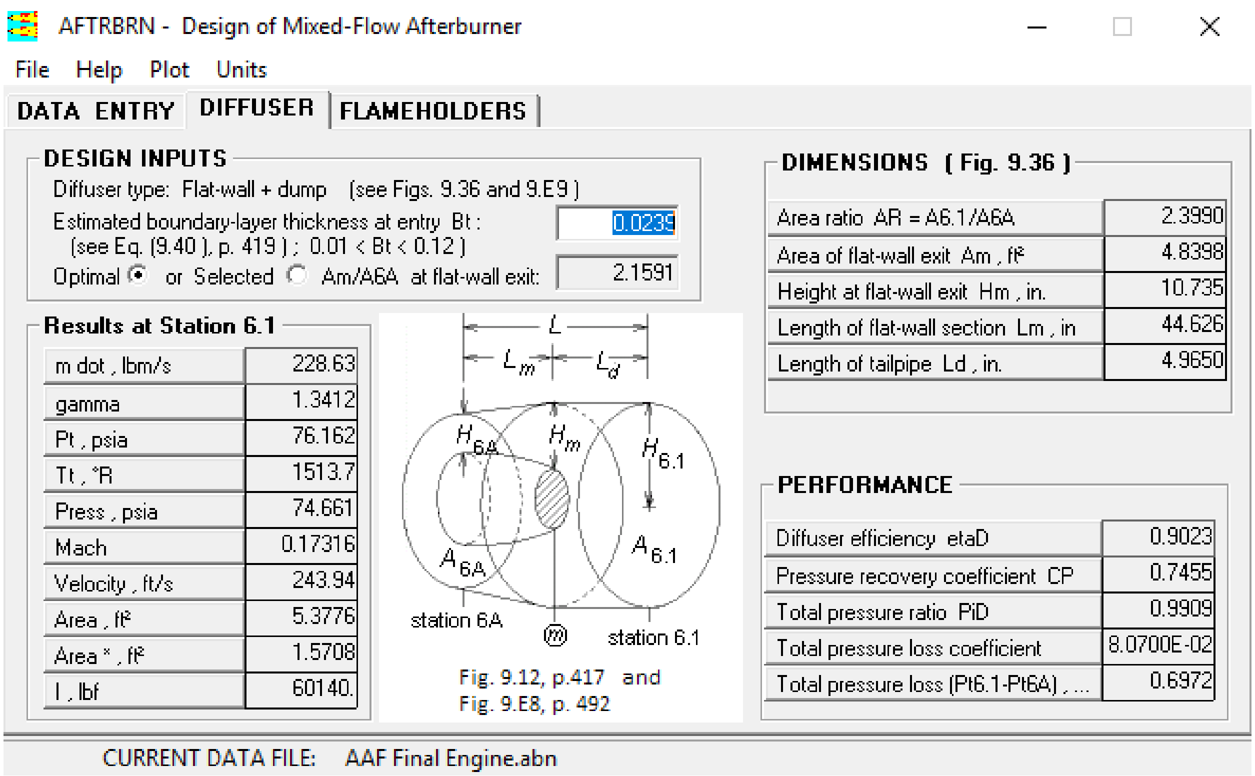

Nozzle Program
Date: 4/21/2020 6:06:11 PM
Nozzle Cfg Contours (min = 0.9144, max = 0.9880, incr = 0.0039)
15.00
Divergent Angle
0.00
1.10
A9/A8
2.00
Nozzle Cfg Contours
Click left mouse button to capture (x,y) coordinates.
A9/A8 0
Divergent Angle 0
Cfg =
Replot
Done

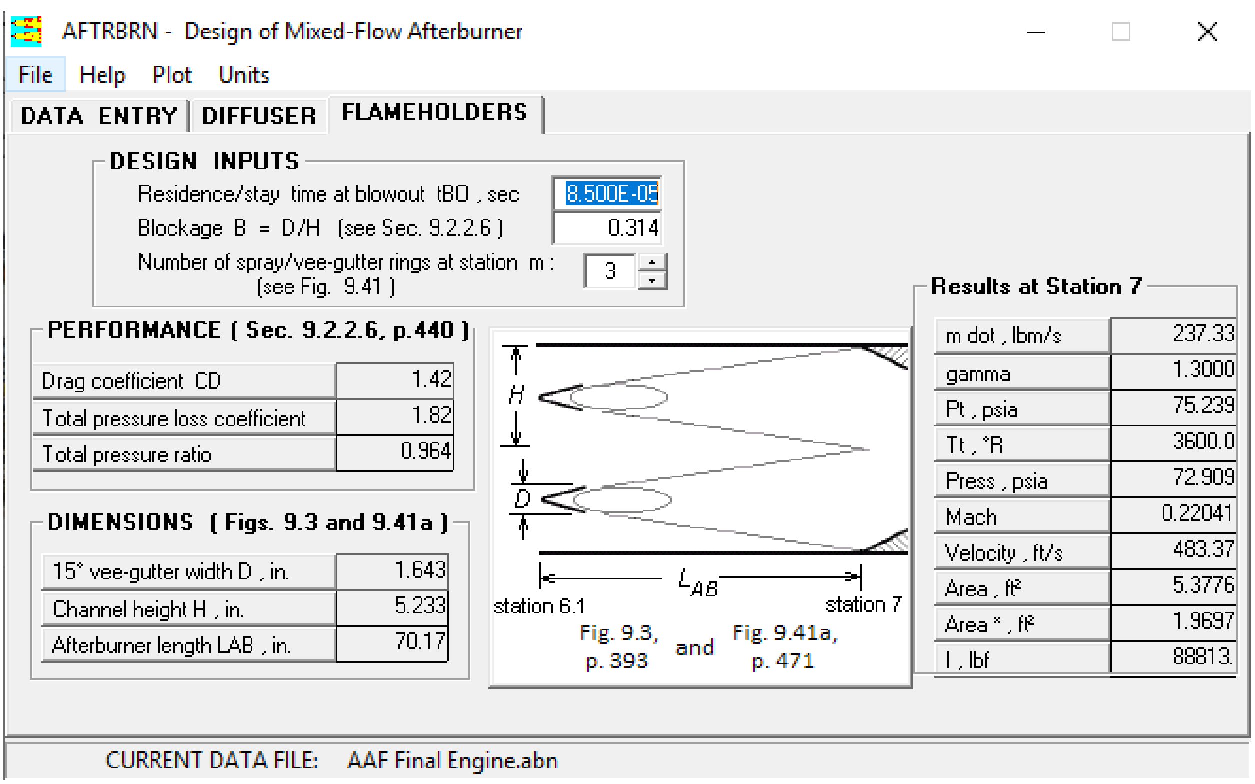
Contour Plot - Component One Chart




Sketch Pad
Sketch of Circular Nozzle
File Name: Default Data
Units: Inches
L = 32.47 L - AB = 44.66
L78 = 19.83 L78 - AB = 20.69
L89 = 12.64 L89 - AB = 23.97
R7 = 20.00
R8 = 12.78 R8 - AB = 15.85
R9 = 16.17 R9 - AB = 20.04
Center Line
Tic spacing = 6.0 in
Done

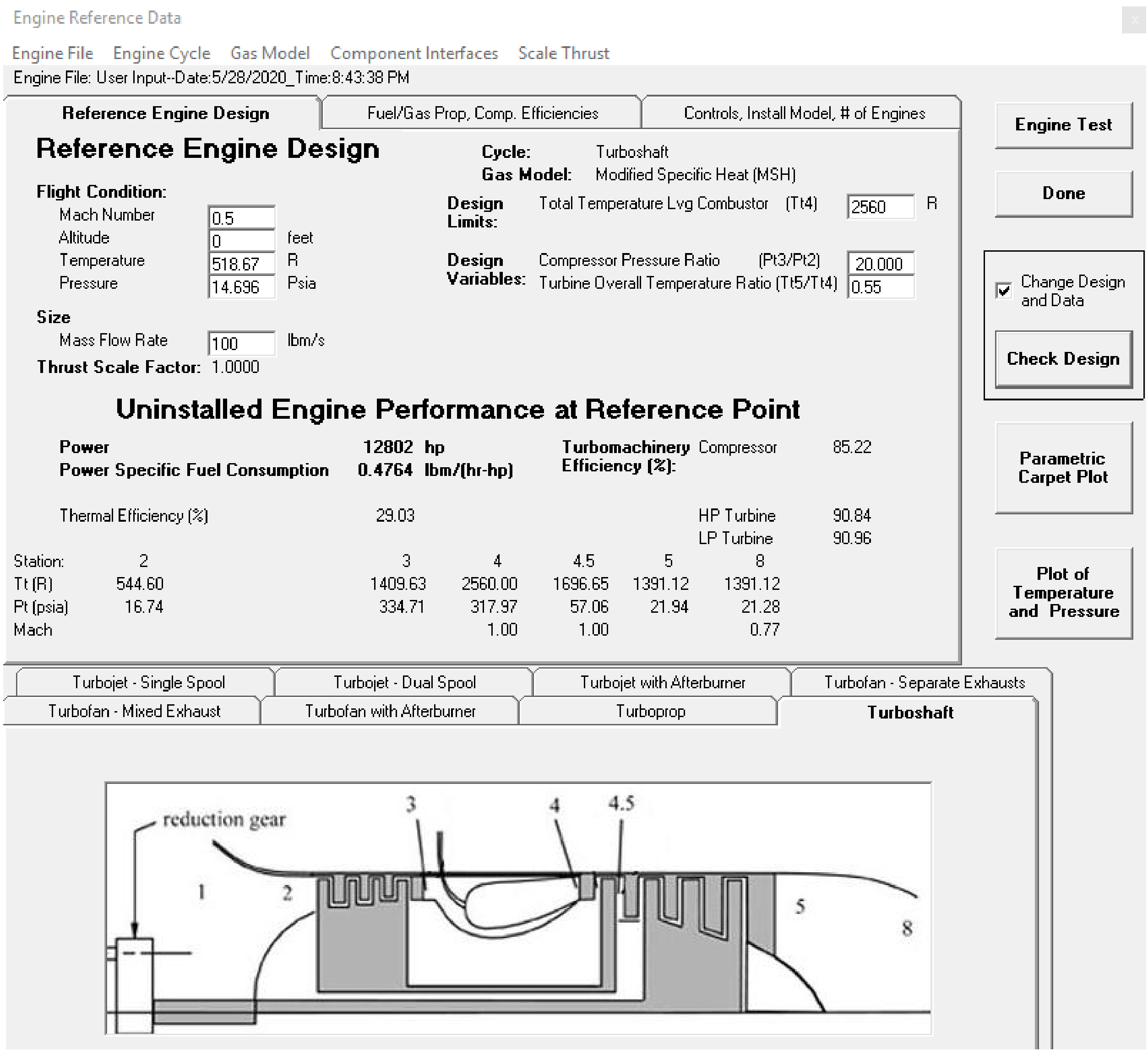

AFTRBRN - Design of Mixed-Flow Afterburner
File Help Plot Units
DATA ENTRY DIFFUSER FLAMEHOLDERS
Station 6A
Mixer exit / diffuser entrance
Total pressure , psia 76.859
Total temperature , °R 1513.7
Mach number 0.42490
Mixture gas flow , lbm/s 228.63
Outer radius , in. ** 15.700
Mean radius , in. 13.845
Inner radius , in. 11.989
Height , in. 3.7107
Pressure , psia 68.219
Velocity , ft/s 750.35
Area , ft² 2.2416
** must be less than engine maximum radius - often station 2, fan entry
Station 6.1
Diffuser exit / hot section entrance
AB fuel flow , lbm/s 8.7033
Outer radius , in. ** 15.700
Station 7
AB exit / thrust nozzle entrance
Total pressure , psia 73.016
Total temperature , °R 3600.0
casing
bypass air
core gas
cooling and screech liner
variable-area exit nozzle
diffuser
station 6
spray ring
flameholder
mixer
Fig. 9.2
p. 391
station 16
station 6A
station 6.1
station 7
CURRENT DATA FILE: AAF Final Engine.abn

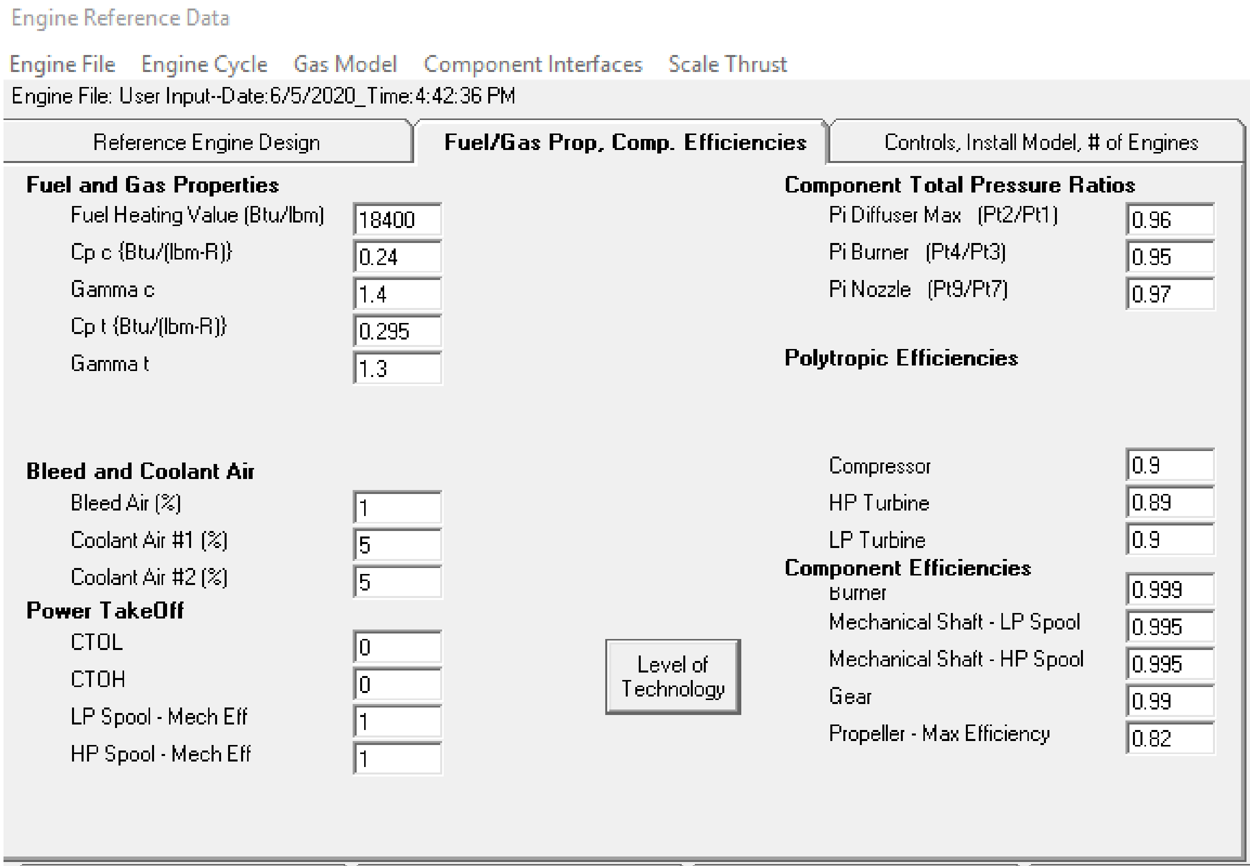

AFTRBRN - Design of Mixed-Flow Afterburner
File Help Plot Units
DATA ENTRY
DIFFUSER
FLAMEHOLDERS
DESIGN INPUTS
Diffuser type: Flat-wall + dump (see Figs. 9.36 and 9.E9)
Estimated boundary-layer thickness at entry Bt : 0.0239
(see Eq. (9.40), p. 419) ; 0.01 < Bt < 0.12)
Optimal or Selected Am/A6A at flat-wall exit: 2.1591
Results at Station 6.1
m dot , lbm/s 228.63
gamma 1.3412
Pt , psia 76.162
Tt , °R 1513.7
Press , psia 74.661
Mach 0.17316
Velocity , ft/s 243.94
Area , ft² 5.3776
Area * , ft² 1.5708
I , lbf 60140.
L
Lm
Ld
H6A
Hm
H6.1
A6A
A6.1
station 6A
station 6.1
m
Fig. 9.12, p.417 and
Fig. 9.E8, p. 492
DIMENSIONS (Fig. 9.36)
Area ratio AR = A6.1/A6A 2.3990
Area of flat-wall exit Am , ft² 4.8398
Height at flat-wall exit Hm , in. 10.735
Length of flat-wall section Lm , in 44.626
Length of tailpipe Ld , in. 4.9650
PERFORMANCE
Diffuser efficiency etaD 0.9023
Pressure recovery coefficient CP 0.7455
Total pressure ratio PiD 0.9909
Total pressure loss coefficient 8.0700E-02
Total pressure loss (Pt6.1-Pt6A) , ... 0.6972
CURRENT DATA FILE: AAF Final Engine.abn

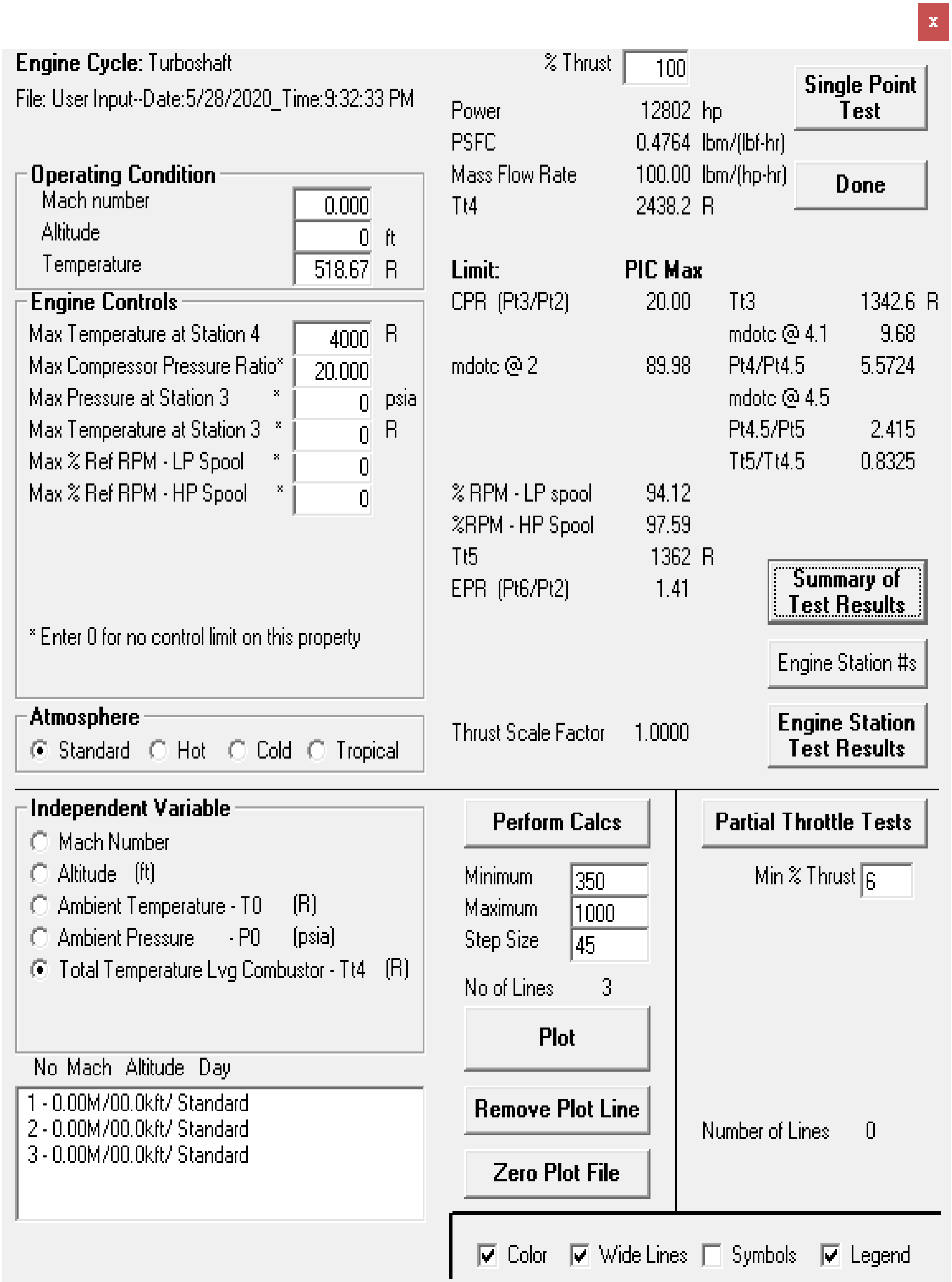

AFTRBRN - Design of Mixed-Flow Afterburner
File Help Plot Units
DATA ENTRY
DIFFUSER
FLAMEHOLDERS
DESIGN INPUTS
Residence/stay time at blowout tBO , sec 8.500E-05
Blockage B = D/H (see Sec. 9.2.2.6) 0.314
Number of spray/vee-gutter rings at station m : 3
(see Fig. 9.41)
PERFORMANCE (Sec. 9.2.2.6, p.440)
Drag coefficient CD 1.42
Total pressure loss coefficient 1.82
Total pressure ratio 0.964
DIMENSIONS (Figs. 9.3 and 9.41a)
15° vee-gutter width D , in. 1.643
Channel height H , in. 5.233
Afterburner length LAB , in. 70.17
H
D
LAB
station 6.1
station 7
Fig. 9.3, p. 393
and
Fig. 9.41a, p. 471
Results at Station 7
m dot , lbm/s 237.33
gamma 1.3000
Pt , psia 75.239
Tt , °R 3600.0
Press , psia 72.909
Mach 0.22041
Velocity , ft/s 483.37
Area , ft² 5.3776
Area * , ft² 1.9697
I , lbf 88813.
CURRENT DATA FILE: AAF Final Engine.abn

APPENDIX C
TRIAL RUN 2

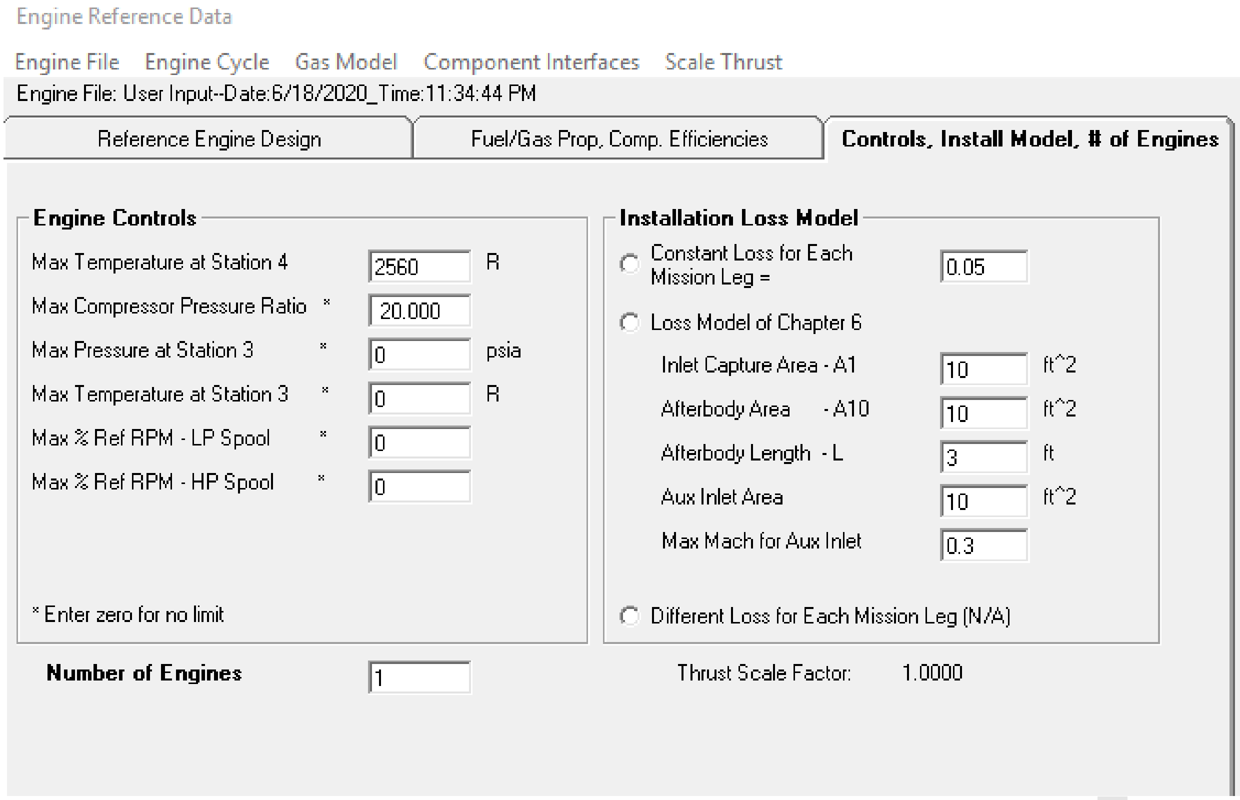
CARGO/PASSENGER TURBOPROP (LOW DRAG)
TURBOSHAFT

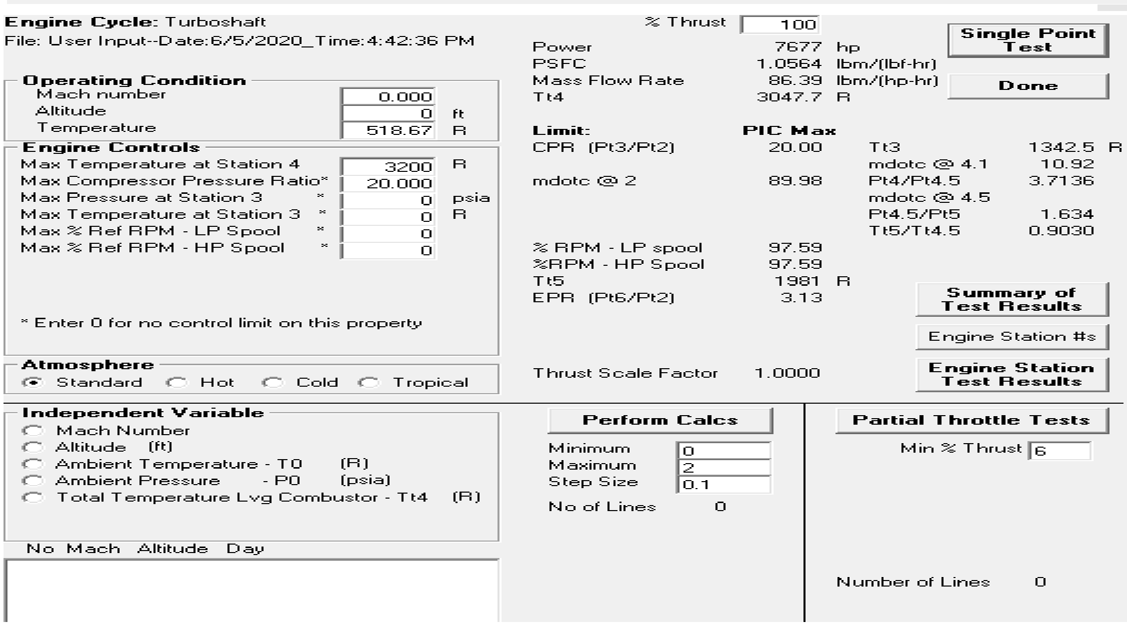



Engine Reference Data
Engine File
Engine Cycle
Gas Model
Component Interfaces
Scale Thrust
Engine File: User Input--Date:6/5/2020_Time:4:42:36 PM
Reference Engine Design
Fuel/Gas Prop, Comp. Efficiencies
Controls, Install Model, # of Engines
Fuel and Gas Properties
Fuel Heating Value (Btu/lbm) 18400
Cp c {Btu/(lbm-R)} 0.24
Gamma c 1.4
Cp t {Btu/(lbm-R)} 0.295
Gamma t 1.3
Bleed and Coolant Air
Bleed Air (%) 1
Coolant Air #1 (%) 5
Coolant Air #2 (%) 5
Power TakeOff
CTOL 0
CTOH 0
LP Spool - Mech Eff 1
HP Spool - Mech Eff 1
Level of Technology
Component Total Pressure Ratios
Pi Diffuser Max (Pt2/Pt1) 0.96
Pi Burner (Pt4/Pt3) 0.95
Pi Nozzle (Pt9/Pt7) 0.97
Polytropic Efficiencies
Compressor 0.9
HP Turbine 0.89
LP Turbine 0.9
Component Efficiencies
Burner 0.999
Mechanical Shaft - LP Spool 0.995
Mechanical Shaft - HP Spool 0.995
Gear 0.99
Propeller - Max Efficiency 0.82



Engine Cycle: Turboshaft
File: User Input--Date:5/28/2020_Time:9:32:33 PM
% Thrust 100
Single Point Test
Done
Power 12802 hp
PSFC 0.4764 lbm/(lbf-hr)
Mass Flow Rate 100.00 lbm/(hp-hr)
Tt4 2438.2 R
Operating Condition
Mach number 0.000
Altitude 0 ft
Temperature 518.67 R
Limit: PIC Max
CPR (Pt3/Pt2) 20.00
Tt3 1342.6 R
mdotc @ 4.1 9.68
mdotc @ 2 89.98
Pt4/Pt4.5 5.5724
mdotc @ 4.5
Pt4.5/Pt5 2.415
Tt5/Tt4.5 0.8325
% RPM - LP spool 94.12
%RPM - HP Spool 97.59
Tt5 1362 R
EPR (Pt6/Pt2) 1.41
Engine Controls
Max Temperature at Station 4 4000 R
Max Compressor Pressure Ratio* 20.000
Max Pressure at Station 3 * 0 psia
Max Temperature at Station 3 * 0 R
Max % Ref RPM - LP Spool * 0
Max % Ref RPM - HP Spool * 0
* Enter 0 for no control limit on this property
Summary of Test Results
Engine Station #s
Atmosphere
Standard Hot Cold Tropical
Thrust Scale Factor 1.0000
Engine Station Test Results
Independent Variable
Mach Number
Altitude (ft)
Ambient Temperature - T0 (R)
Ambient Pressure - P0 (psia)
Total Temperature Lvg Combustor - Tt4 (R)
Perform Calcs
Minimum 350
Maximum 1000
Step Size 45
No of Lines 3
Plot
Remove Plot Line
Zero Plot File
Partial Throttle Tests
Min % Thrust 6
Number of Lines 0
No Mach Altitude Day
1 - 0.00M/00.0kft/ Standard
2 - 0.00M/00.0kft/ Standard
3 - 0.00M/00.0kft/ Standard
Color Wide Lines Symbols Legend

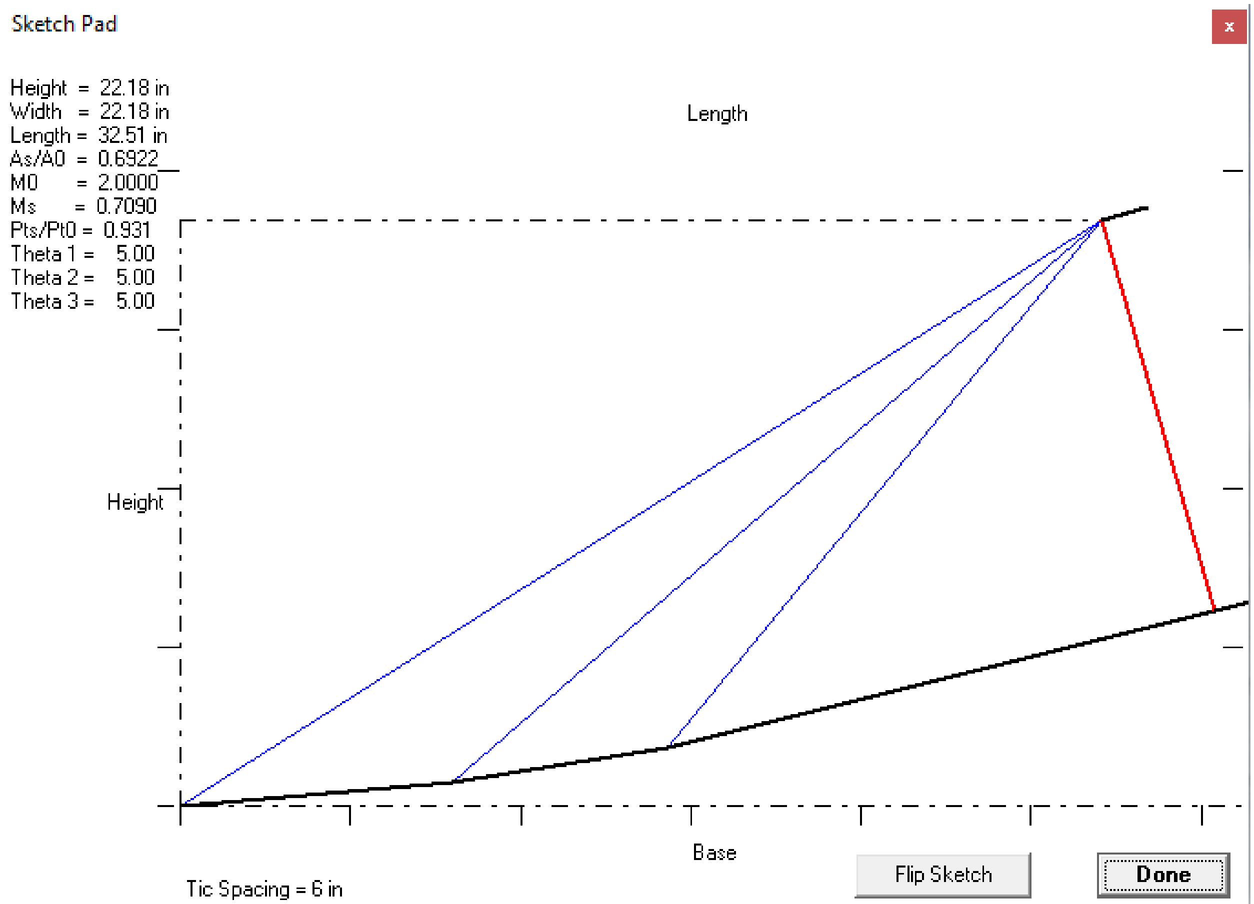

Engine Reference Data
Engine File
Engine Cycle
Gas Model
Component Interfaces
Scale Thrust
Engine File: User Input--Date:6/18/2020_Time:11:34:44 PM
Reference Engine Design
Fuel/Gas Prop, Comp. Efficiencies
Controls, Install Model, # of Engines
Engine Controls
Max Temperature at Station 4 2560 R
Max Compressor Pressure Ratio * 20.000
Max Pressure at Station 3 * 0 psia
Max Temperature at Station 3 * 0 R
Max % Ref RPM - LP Spool * 0
Max % Ref RPM - HP Spool * 0
* Enter zero for no limit
Installation Loss Model
Constant Loss for Each Mission Leg = 0.05
Loss Model of Chapter 6
Inlet Capture Area - A1 10 ft^2
Afterbody Area - A10 10 ft^2
Afterbody Length - L 3 ft
Aux Inlet Area 10 ft^2
Max Mach for Aux Inlet 0.3
Different Loss for Each Mission Leg (N/A)
Number of Engines 1
Thrust Scale Factor: 1.0000


Engine Cycle: Turboshaft
File: User Input--Date:6/5/2020_Time:4:42:36 PM
% Thrust 100
Single Point Test
Done
Power 7677 hp
PSFC 1.0564 lbm/(lbf-hr)
Mass Flow Rate 86.39 lbm/(hp-hr)
Tt4 3047.7 R
Operating Condition
Mach number 0.000
Altitude 0 ft
Temperature 518.67 R
Engine Controls
Max Temperature at Station 4 3200 R
Max Compressor Pressure Ratio* 20.000
Max Pressure at Station 3 * 0 psia
Max Temperature at Station 3 * 0 R
Max % Ref RPM - LP Spool * 0
Max % Ref RPM - HP Spool * 0
* Enter 0 for no control limit on this property
Limit: PIC Max
CPR (Pt3/Pt2) 20.00
mdotc @ 2 89.98
Tt3 1342.5 R
mdotc @ 4.1 10.92
Pt4/Pt4.5 3.7136
mdotc @ 4.5
Pt4.5/Pt5 1.634
Tt5/Tt4.5 0.9030
% RPM - LP spool 97.59
%RPM - HP Spool 97.59
Tt5 1981 R
EPR (Pt6/Pt2) 3.13
Summary of Test Results
Engine Station #s
Engine Station Test Results
Atmosphere
Standard Hot Cold Tropical
Thrust Scale Factor 1.0000
Independent Variable
Mach Number
Altitude (ft)
Ambient Temperature - T0 (R)
Ambient Pressure - P0 (psia)
Total Temperature Lvg Combustor - Tt4 (R)
Perform Calcs
Minimum 0
Maximum 2
Step Size 0.1
No of Lines 0
Partial Throttle Tests
Min % Thrust 6
Number of Lines 0
No Mach Altitude Day

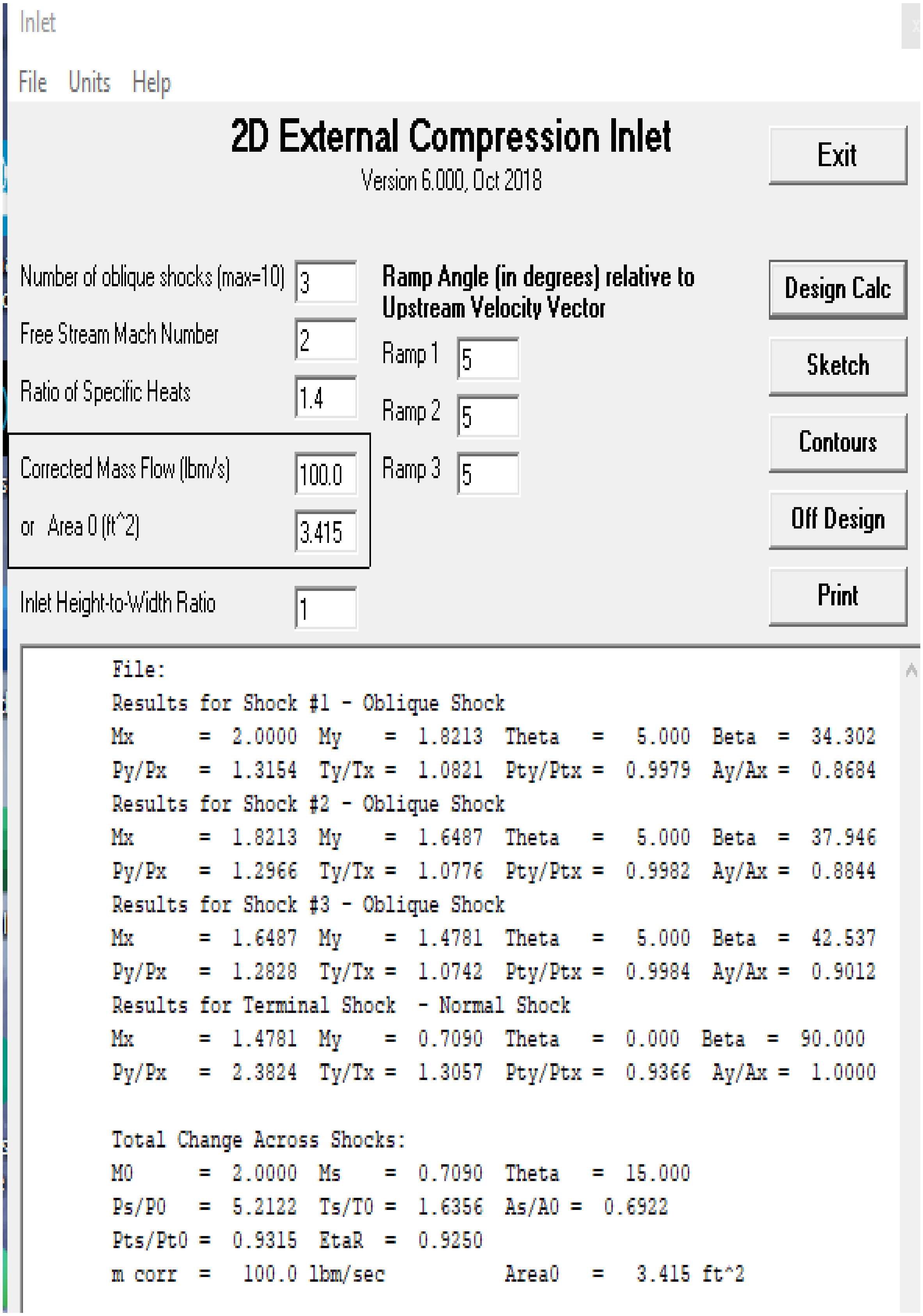
APPENDIX C.1
TRIAL RUN 1 RESULTS

CARGO/PASSENGER TURBOPROP (LOW DRAG)
TURBOSHAFT

```
AEDsys (Ver. 6.00)                 Turboshaft                  Date:5/28/2020 9:33:23 PM
                   using Modified Specific Heat (MSH) Model
Engine File: User Input--Date:5/28/2020_Time:9:32:33 PM

  Input Constants
  Pidmax = 0.9600   Pi b   = 0.9500   Eta b  = 0.9990   Pi n   = 0.9700
  cp c   = 0.2400   cp t   = 0.2950   Gam c  = 1.4000   Gam t  = 1.3000
  Eta c  = 0.8522   Eta tH = 0.9084   Eta tL = 0.9096
  Eta mL = 0.9950   Eta mH = 0.9950   Eta PL = 1.0000   Eta PH = 1.0000
  PTO L  =    0.0KW PTO H  =    0.0KW hPR    =  18400
  Bleed  =  1.00%  Cool 1 =   5.00%  Cool 2 =   5.00%
  Control Limits:   Tt4    = 4000.0   Pi c   =  20.00
  ** Thrust Scale Factor  = 1.0000

  Parameter                           Reference**           Test**
  Mach Number @ 0                       0.5000             0.0100
  Temperature @ 0                       518.67             518.67 R
  Pressure    @ 0                      14.6960            14.6960 psia
  Altitude    @ 0                          0                    0 ft
  Total Temp  @ 4                      2560.00            2438.20 R
  Pi r     (Pt0/P0)                     1.1862             1.1862
  Tau r    (Tt0/T0)                     1.0500             1.0500
  Pi d     (Pt2/Pt0)                    0.9600             0.9600
  Pi c     (Pt3/Pt2)                   20.0000            20.0000
  Tau c    (Tt3/Tt2)                    2.5884             2.5884
  Tau m1   (Tt41/Tt4)                   0.9712             0.9712
  Pi tH    (Pt45/Pt4)                   0.1795             0.1795
  Tau tH   (Tt44/Tt41)                  0.7027             0.7027
  Tau m2   (Tt45/Tt44)                  0.9829             0.9829
  Pi tL    (Pt5/Pt45)                   0.3844             0.3844
  Tau tL   (Tt5/Tt45)                   0.8199             0.8199
  Control Limit                                            PIC Max
  LP Spool RPM (% of Reference Pt)  100.00                  94.12
  HP Spool RPM (% of Reference Pt)  100.00                  97.59
  Pt9/P9                              1.4479               1.4479
  P0/P9                               1.0000               1.0000
  Mach Number @ 9                     0.7710               0.6592
  Mass Flow Rate @ 0                  100.00               100.00 lbm/s
  Corrected Mass Flow @ 0              86.38                86.38 lbm/s
  Flow Area      @ 0                   2.343              101.205 ft^2
  Flow Area*     @ 0                   1.749                1.749 ft^2
  Flow Area      @ 9                   2.497                2.509 ft^2
  MB - Fuel/Air Ratio (f)            0.01903              0.01788
  Overall Fuel/Air Ratio (fo)        0.01694              0.01591
  Cshaft                              0.7269               0.6432
  Specific Power  (P/m0)              128.02               128.02 hp/(lbm/s)
  Power Spec Fuel Consumption (Sp)    0.4764               0.4764 (lbm/hr)/hp
  Power (P)                            12802                12802 hp
  Fuel Flow Rate                        6098                 5729 lbm/hr
  Thermal Efficiency    (%)            29.03                27.34
```



Sketch Pad
Height = 22.18 in
Width = 22.18 in
Length = 32.51 in
As/A0 = 0.6922
M0 = 2.0000
Ms = 0.7090
Pts/Pt0 = 0.931
Theta 1 = 5.00
Theta 2 = 5.00
Theta 3 = 5.00
Length
Height
Base
Tic Spacing = 6 in
Flip Sketch
Done


Inlet
File Units Help
2D External Compression Inlet
Version 6.000, Oct 2018
Exit
Number of oblique shocks (max=10)
3
Free Stream Mach Number
2
Ratio of Specific Heats
1.4
Ramp Angle (in degrees) relative to Upstream Velocity Vector
Ramp 1
5
Ramp 2
5
Ramp 3
5
Corrected Mass Flow (lbm/s)
100.0
or Area 0 (ft^2)
3.415
Inlet Height-to-Width Ratio
1
Design Calc
Sketch
Contours
Off Design
Print
File:
Results for Shock #1 - Oblique Shock
Mx = 2.0000 My = 1.8213 Theta = 5.000 Beta = 34.302
Py/Px = 1.3154 Ty/Tx = 1.0821 Pty/Ptx = 0.9979 Ay/Ax = 0.8684
Results for Shock #2 - Oblique Shock
Mx = 1.8213 My = 1.6487 Theta = 5.000 Beta = 37.946
Py/Px = 1.2966 Ty/Tx = 1.0776 Pty/Ptx = 0.9982 Ay/Ax = 0.8844
Results for Shock #3 - Oblique Shock
Mx = 1.6487 My = 1.4781 Theta = 5.000 Beta = 42.537
Py/Px = 1.2828 Ty/Tx = 1.0742 Pty/Ptx = 0.9984 Ay/Ax = 0.9012
Results for Terminal Shock - Normal Shock
Mx = 1.4781 My = 0.7090 Theta = 0.000 Beta = 90.000
Py/Px = 2.3824 Ty/Tx = 1.3057 Pty/Ptx = 0.9366 Ay/Ax = 1.0000
Total Change Across Shocks:
M0 = 2.0000 Ms = 0.7090 Theta = 15.000
Ps/P0 = 5.2122 Ts/T0 = 1.6356 As/A0 = 0.6922
Pts/Pt0 = 0.9315 EtaR = 0.9250
m corr = 100.0 lbm/sec Area0 = 3.415 ft^2

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:04:52 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 1  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.1002  Pt3/Pt1(i) = 1.3508  DTt =051.96 R    AN^2=5.099E+1
  Hub   R = 0.0100  Dr = 0.1962  Ds = 0.5421  Phis = 0.0300  Eff = 0.8956
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.1006  r m = 13.459 in
  Tip   R = 0.7083  Dr = 0.3761  Ds = 0.4663  M1R  = 1.0634  U m = 1009.5 fps
  Flow  Area 1 = 0764.55  Area 2 = 0690.31  Area 3 = 0615.65 in^2
  Rotor  - # of Blades = 21  Chord = 4.301 in
  Stator - # of Blades = 23  Chord = 3.861 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -----------------------------------------------------------------
 Tt      R | 518.7 518.7 518.7 544.7 544.7 570.7 570.7 570.7 570.7 570.7 570.7
 T       R | 481.1 494.0 498.5 494.0 520.0 481.6 520.0 534.9 537.0 546.0 549.8
 Pt   psia | 14.70 14.70 14.70 17.44 16.99 20.00 20.00 20.00 19.85 19.85 19.85
 P    psia | 11.29 12.39 12.79 12.39 14.44 11.05 14.44 15.94 16.05 17.00 17.43
 M         | 0.625 0.500 0.450 0.716 0.487 0.961 0.698 0.579 0.560 0.476 0.435
 Vel  ft/s | 672.4 544.7 492.8 780.3 544.7 1034.2 780.3 655.8 636.0 544.7 500.1
 u    ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
 v    ft/s | 527.2 350.1 262.1 659.3 350.1 946.3 659.3 505.9 479.9 350.1 275.6
alpha deg  | 51.64 40.00 32.13             66.20 57.67 50.48 48.99 40.00 33.44
beta  deg  |                   57.67 40.00
radius in  | 08.94 13.46 17.98 13.46 13.46 09.38 13.46 17.54 09.82 13.46 17.10
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:06:24 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 2  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0911  Pt3/Pt1(i) = 1.3159  DTt =051.96 R    AN^2=4.145E+1
  Hub   R = 0.1364  Dr = 0.3929  Ds = 0.5320  Phis = 0.0300  Eff = 0.8960
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0978  r m = 13.459 in
  Tip   R = 0.6802  Dr = 0.3907  Ds = 0.4730  M1R  = 0.9482  U m = 1009.5 fps
  Flow  Area 1 = 0615.65  Area 2 = 0561.17  Area 3 = 0505.68 in^2
  Rotor  - # of Blades = 25  Chord = 3.479 in
  Stator - # of Blades = 28  Chord = 3.154 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -----------------------------------------------------------------
 Tt      R | 570.7 570.7 570.7 596.6 596.6 622.6 622.6 622.6 622.6 622.6 622.6
 T       R | 537.0 546.0 549.8 546.0 571.9 544.4 571.9 584.8 591.3 597.9 601.3
 Pt   psia | 19.85 19.85 19.85 23.20 22.66 26.30 26.30 26.30 26.12 26.12 26.12
 P    psia | 16.05 17.00 17.43 17.00 19.54 16.44 19.54 21.13 21.80 22.67 23.12
 M         | 0.560 0.476 0.435 0.681 0.465 0.848 0.666 0.568 0.515 0.454 0.421
 Vel  ft/s | 636.0 544.7 500.1 780.3 544.7 969.4 780.3 673.7 613.8 544.7 506.2
 u    ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
 v    ft/s | 479.9 350.1 275.6 659.3 350.1 875.0 659.3 528.9 450.1 350.1 286.5
alpha deg  | 48.99 40.00 33.44             64.50 57.67 51.73 47.17 40.00 34.47
beta  deg  |                   57.67 40.00
radius in  | 09.82 13.46 17.10 13.46 13.46 10.14 13.46 16.78 10.47 13.46 16.45
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:19:09 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 3  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0835  Pt3/Pt1(i) = 1.2872  DTt =051.96 R    AN^2=3.431E+10
  Hub   R = 0.2190  Dr = 0.4805  Ds = 0.5251  Phis = 0.0300  Eff = 0.8964
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0955  r m = 13.459 in
  Tip   R = 0.6566  Dr = 0.4040  Ds = 0.4780  M1R  = 0.8611  U m = 1009.5 fps
  Flow  Area 1 = 0505.68  Area 2 = 0464.57  Area 3 = 0422.26 in^2
  Rotor  - # of Blades = 30  Chord = 2.868 in
  Stator - # of Blades = 33  Chord = 2.622 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 622.6 622.6 622.6 648.6 648.6 674.6 674.6 674.6 674.6 674.6 674.6
  T      R | 591.3 597.9 601.3 597.9 623.9 603.0 623.9 635.1 644.7 649.9 652.8
  Pt  psia | 26.12 26.12 26.12 30.14 29.50 33.85 33.85 33.85 33.63 33.63 33.63
  P   psia | 21.80 22.67 23.12 22.67 25.75 22.85 25.75 27.41 28.70 29.51 29.98
  M        | 0.515 0.454 0.421 0.651 0.445 0.771 0.637 0.557 0.481 0.436 0.408
  Vel ft/s | 613.8 544.7 506.2 780.3 544.7 927.5 780.3 688.4 599.1 544.7 511.2
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 450.1 350.1 286.5 659.3 350.1 828.4 659.3 547.6 429.9 350.1 295.4
 alpha deg | 47.17 40.00 34.47             63.26 57.67 52.69 45.85 40.00 35.29
 beta  deg |                   57.67 40.00
 radius in | 10.47 13.46 16.45 13.46 13.46 10.71 13.46 16.21 10.96 13.46 15.96
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:20:11 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 4  u2/ul = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0770  Pt3/Pt1(i) = 1.2633  DTt =051.96 R    AN^2=2.884E+10
  Hub   R = 0.2760  Dr = 0.5182  Ds = 0.5202  Phis = 0.0300  Eff = 0.8966
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0936  r m = 13.459 in
  Tip   R = 0.6368  Dr = 0.4157  Ds = 0.4818  M1R  = 0.7931  U m = 1009.5 fps
  Flow  Area 1 = 0422.26  Area 2 = 0390.51  Area 3 = 0357.56 in^2
  Rotor  - # of Blades = 36  Chord = 2.403 in
  Stator - # of Blades = 39  Chord = 2.211 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 674.6 674.6 674.6 700.6 700.6 726.5 726.5 726.5 726.5 726.5 726.5
  T      R | 644.7 649.9 652.8 649.9 675.9 659.3 675.9 685.7 697.7 701.8 704.4
  Pt  psia | 33.63 33.63 33.63 38.38 37.63 42.74 42.74 42.74 42.48 42.48 42.48
  P   psia | 28.70 29.51 29.98 29.51 33.18 30.43 33.18 34.90 36.86 37.64 38.12
  M        | 0.481 0.436 0.408 0.624 0.427 0.714 0.612 0.546 0.455 0.419 0.396
  Vel ft/s | 599.1 544.7 511.2 780.3 544.7 898.6 780.3 700.6 588.8 544.7 515.5
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 429.9 350.1 295.4 659.3 350.1 795.8 659.3 562.8 415.4 350.1 302.6
 alpha deg | 45.85 40.00 35.29             62.33 57.67 53.44 44.87 40.00 35.95
 beta  deg |                   57.67 40.00
 radius in | 10.96 13.46 15.96 13.46 13.46 11.15 13.46 15.77 11.35 13.46 15.57
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:20:58 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 5  u2/ul = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0715  Pt3/Pt1(i) = 1.2431  DTt =051.96 R    AN^2=2.456E+10
  Hub   R = 0.3169  Dr = 0.5338  Ds = 0.5165  Phis = 0.0300  Eff = 0.8969
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0920  r m = 13.459 in
  Tip   R = 0.6202  Dr = 0.4258  Ds = 0.4847  M1R  = 0.7385  U m = 1009.5 fps
  Flow  Area 1 = 0357.56  Area 2 = 0332.56  Area 3 = 0306.41 in^2
  Rotor  - # of Blades = 42  Chord = 2.040 in
  Stator - # of Blades = 46  Chord = 1.889 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 726.5 726.5 726.5 752.5 752.5 778.5 778.5 778.5 778.5 778.5 778.5
  T      R | 697.7 701.8 704.4 701.8 727.8 714.4 727.8 736.5 750.4 753.8 756.1
  Pt  psia | 42.48 42.48 42.48 48.04 47.16 53.11 53.11 53.11 52.81 52.81 52.81
  P   psia | 36.86 37.64 38.12 37.64 41.96 39.31 41.96 43.73 46.43 47.17 47.67
  M        | 0.455 0.419 0.396 0.601 0.412 0.670 0.590 0.534 0.433 0.405 0.385
  Vel ft/s | 588.8 544.7 515.5 780.3 544.7 877.7 780.3 710.7 581.2 544.7 519.0
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 415.4 350.1 302.6 659.3 350.1 772.1 659.3 575.3 404.6 350.1 308.6
 alpha deg | 44.87 40.00 35.95             61.61 57.67 54.04 44.12 40.00 36.49
 beta  deg |                   57.67 40.00
 radius in | 11.35 13.46 15.57 13.46 13.46 11.49 13.46 15.43 11.65 13.46 15.27
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:22:22 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 6  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0667  Pt3/Pt1(i) = 1.2257  DTt =051.96 R    AN^2=2.115E+10
  Hub   R = 0.3473  Dr = 0.5394  Ds = 0.5138  Phis = 0.0300  Eff = 0.8971
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0906  r m = 13.459 in
  Tip   R = 0.6061  Dr = 0.4344  Ds = 0.4871  M1R  = 0.6937  U m = 1009.5 fps
  Flow  Area 1 = 0306.41  Area 2 = 0286.38  Area 3 = 0265.31 in^2
  Rotor  - # of Blades = 49  Chord = 1.752 in
  Stator - # of Blades = 53  Chord = 1.631 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 778.5 778.5 778.5 804.5 804.5 830.5 830.5 830.5 830.5 830.5 830.5
  T      R | 750.4 753.8 756.1 753.8 779.8 768.6 779.8 787.4 802.9 805.8 807.8
  Pt  psia | 52.81 52.81 52.81 59.23 58.23 65.08 65.08 65.08 64.72 64.72 64.72
  P   psia | 46.43 47.17 47.67 47.17 52.21 49.64 52.21 54.02 57.51 58.23 58.75
  M        | 0.433 0.405 0.385 0.580 0.398 0.634 0.570 0.523 0.414 0.391 0.375
  Vel ft/s | 581.2 544.7 519.0 780.3 544.7 861.9 780.3 719.1 575.5 544.7 522.0
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 404.6 350.1 308.6 659.3 350.1 754.2 659.3 585.6 396.3 350.1 313.6
 alpha deg | 44.12 40.00 36.49             61.05 57.67 54.53 43.52 40.00 36.93
 beta  deg |                   57.67 40.00
 radius in | 11.65 13.46 15.27 13.46 13.46 11.77 13.46 15.15 11.89 13.46 15.03
```


Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:22:22 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 6  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0667  Pt3/Pt1(i) = 1.2257  DTt =051.96 R    AN^2=2.115E+10
  Hub   R = 0.3473  Dr = 0.5394  Ds = 0.5138  Phis = 0.0300  Eff = 0.8971
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0906  r m = 13.459 in
  Tip   R = 0.6061  Dr = 0.4344  Ds = 0.4871  M1R  = 0.6937  U m = 1009.5 fps
  Flow  Area 1 = 0306.41  Area 2 = 0286.38  Area 3 = 0265.31 in^2
  Rotor  - # of Blades = 49  Chord = 1.752 in
  Stator - # of Blades = 53  Chord = 1.631 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 778.5 778.5 778.5 804.5 804.5 830.5 830.5 830.5 830.5 830.5 830.5
  T      R | 750.4 753.8 756.1 753.8 779.8 768.6 779.8 787.4 802.9 805.8 807.8
  Pt  psia | 52.81 52.81 52.81 59.23 58.23 65.08 65.08 65.08 64.72 64.72 64.72
  P   psia | 46.43 47.17 47.67 47.17 52.21 49.64 52.21 54.02 57.51 58.23 58.75
  M        | 0.433 0.405 0.385 0.580 0.398 0.634 0.570 0.523 0.414 0.391 0.375
  Vel ft/s | 581.2 544.7 519.0 780.3 544.7 861.9 780.3 719.1 575.5 544.7 522.0
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 404.6 350.1 308.6 659.3 350.1 754.2 659.3 585.6 396.3 350.1 313.6
 alpha deg | 44.12 40.00 36.49             61.05 57.67 54.53 43.52 40.00 36.93
 beta  deg |                   57.67 40.00
 radius in | 11.65 13.46 15.27 13.46 13.46 11.77 13.46 15.15 11.89 13.46 15.03
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:24:07 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 7  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0626  Pt3/Pt1(i) = 1.2107  DTt =051.96 R    AN^2=1.839E+10
  Hub   R = 0.3706  Dr = 0.5404  Ds = 0.5117  Phis = 0.0300  Eff = 0.8972
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0894  r m = 13.459 in
  Tip   R = 0.5942  Dr = 0.4418  Ds = 0.4889  M1R  = 0.6563  U m = 1009.5 fps
  Flow  Area 1 = 0265.31  Area 2 = 0249.03  Area 3 = 0231.81 in^2
  Rotor  - # of Blades = 57  Chord = 1.520 in
  Stator - # of Blades = 60  Chord = 1.421 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 830.5 830.5 830.5 856.4 856.4 882.4 882.4 882.4 882.4 882.4 882.4
  T      R | 802.9 805.8 807.8 805.8 831.7 822.3 831.7 838.5 855.3 857.7 859.5
  Pt  psia | 64.72 64.72 64.72 72.09 70.95 78.77 78.77 78.77 78.36 78.36 78.36
  P   psia | 57.51 58.23 58.75 58.23 64.04 61.53 64.04 65.89 70.24 70.95 71.47
  M        | 0.414 0.391 0.375 0.561 0.385 0.605 0.552 0.512 0.398 0.379 0.365
  Vel ft/s | 575.5 544.7 522.0 780.3 544.7 849.8 780.3 726.2 571.1 544.7 524.5
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 396.3 350.1 313.6 659.3 350.1 740.3 659.3 594.3 389.8 350.1 317.8
 alpha deg | 43.52 40.00 36.93             60.59 57.67 54.93 43.05 40.00 37.29
 beta  deg |                   57.67 40.00
 radius in | 11.89 13.46 15.03 13.46 13.46 11.99 13.46 14.93 12.09 13.46 14.83
```

Results

```
COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 5/28/2020    Time - 11:24:52 PM
Data File:Default Data
Corr Flow = 150.00 lbm/s  Mass Flow = 150.00 lbm/s  Rotor Speed = 0900 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.0000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 8  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1(i) = 1.0589  Pt3/Pt1(i) = 1.1975  DTt =051.96 R    AN^2=1.613E+10
  Hub   R = 0.3889  Dr = 0.5393  Ds = 0.5100  Phis = 0.0300  Eff = 0.8974
  Mean  R = 0.5000  Dr = 0.5000  Ds = 0.5000  Phir = 0.0884  r m = 13.459 in
  Tip   R = 0.5841  Dr = 0.4481  Ds = 0.4904  M1R  = 0.6245  U m = 1009.5 fps
  Flow  Area 1 = 0231.81  Area 2 = 0218.41  Area 3 = 0204.16 in^2
  Rotor  - # of Blades = 65  Chord = 1.331 in
  Stator - # of Blades = 69  Chord = 1.249 in
  Coefficients:  Stage Loading = 0.3063   Flow = 0.4134

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      -------------------------------------------------------------------
  Tt     R | 882.4 882.4 882.4 908.4 908.4 934.4 934.4 934.4 934.4 934.4 934.4
  T      R | 855.3 857.7 859.5 857.7 883.7 875.6 883.7 889.8 907.6 909.7 911.3
  Pt  psia | 78.36 78.36 78.36 86.74 85.44 94.30 94.30 94.30 93.83 93.83 93.83
  P   psia | 70.24 70.95 71.47 70.95 77.58 75.12 77.58 79.46 84.74 85.44 85.97
  M        | 0.398 0.379 0.365 0.544 0.374 0.579 0.535 0.501 0.384 0.368 0.356
  Vel ft/s | 571.1 544.7 524.5 780.3 544.7 840.2 780.3 732.2 567.5 544.7 526.7
  u   ft/s | 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3 417.3
  v   ft/s | 389.8 350.1 317.8 659.3 350.1 729.3 659.3 601.6 384.6 350.1 321.3
 alpha deg | 43.05 40.00 37.29             60.22 57.67 55.25 42.67 40.00 37.60
 beta  deg |                   57.67 40.00
 radius in | 12.09 13.46 14.83 13.46 13.46 12.17 13.46 14.75 12.25 13.46 14.67
```

Stage Sketch Data

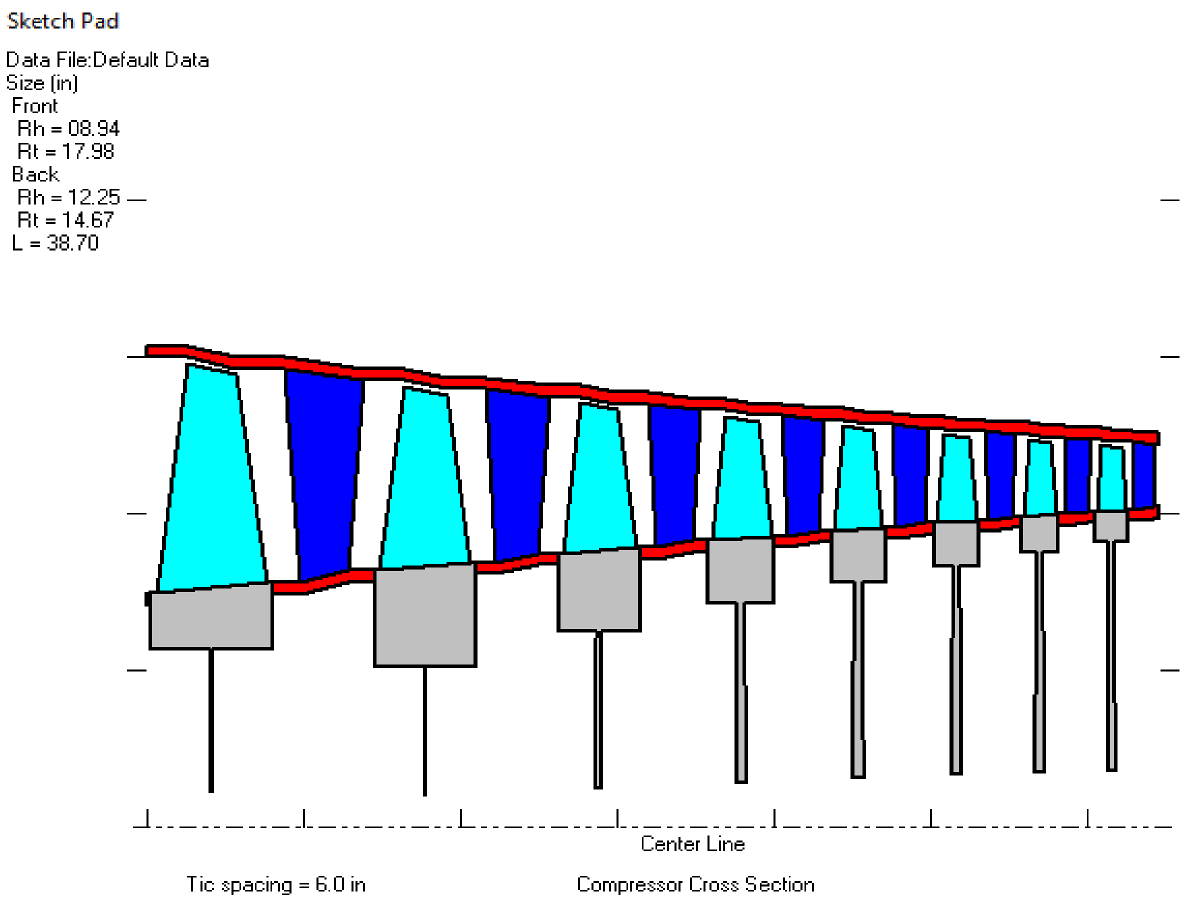
Stage	1	2	3	4	5	6
Tt1R (R)	544.7	596.6	648.6	700.6	752.5	804.5
hr/Wr	0.5	1.0	1.0	1.0	1.0	1.0
sigma b/r	0.1	0.1	0.1	0.1	0.1	0.1
sp str rim *	4.0	4.0	4.0	4.0	4.0	4.0
sp str disc *	4.0	4.0	4.0	4.0	4.0	4.0
Wdr/Wr	0.007	-0.064	0.058	0.111	0.134	0.143
DSF **	0.229	0.185	0.275	0.357	0.429	0.489
hr (in)	2.314	3.825	3.09	2.501	2.049	1.703
WS ***	513.4	461.7	562.6	641.7	702.8	750.3

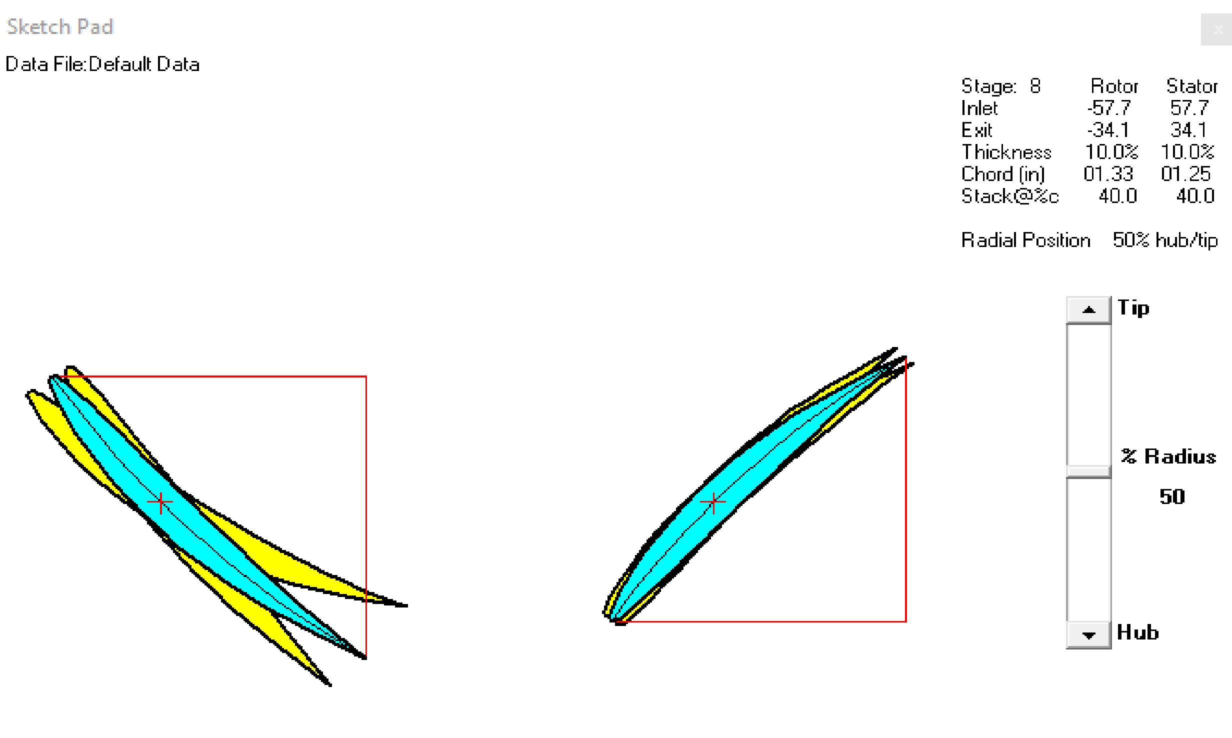
Wr = width of rim, hr = height of rim, cx = axial chord of rotor blade at hub, Wdr = width of disk
*Specific Strength (ksi-ft^3/slug) ** DSF = Disk Shape Factor *** WS = Wheel Speed at rim (f

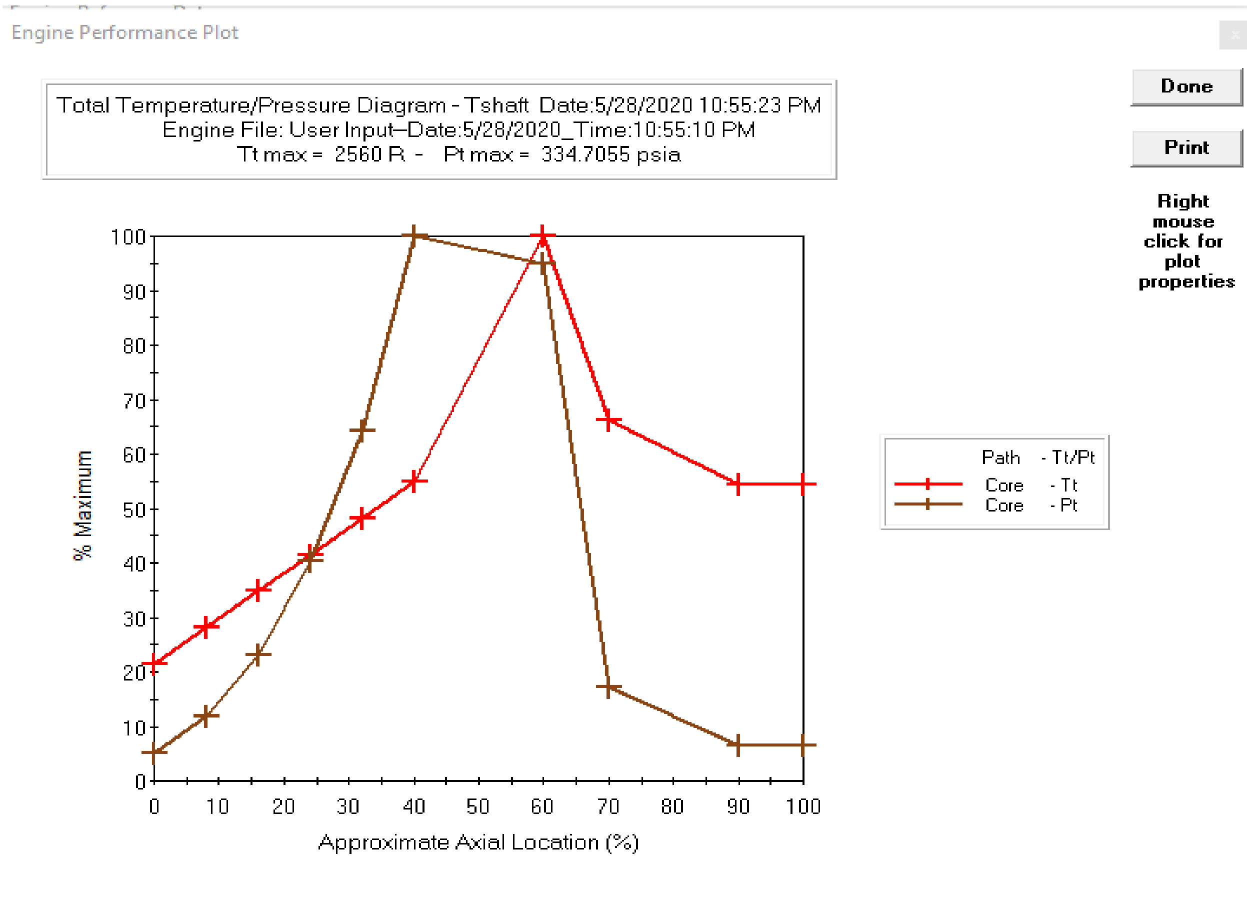
Stage Sketch Data

Stage	3	4	5	6	7	8
Tt1R (R)	648.6	700.6	752.5	804.5	856.4	908.4
hr/Wr	1.0	1.0	1.0	1.0	1.0	1.0
sigma b/r	0.1	0.1	0.1	0.1	0.1	0.1
sp str rim *	4.0	4.0	4.0	4.0	4.0	4.0
sp str disc *	4.0	4.0	4.0	4.0	4.0	4.0
Wdr/Wr	0.058	0.111	0.134	0.143	0.145	0.144
DSF **	0.275	0.357	0.429	0.489	0.539	0.58
hr (in)	3.09	2.501	2.049	1.703	1.435	1.226
WS ***	562.6	641.7	702.8	750.3	787.8	817.7

Wr = width of rim, hr = height of rim, cx = axial chord of rotor blade at hub, Wdr = width of disk at rim
*Specific Strength (ksi-ft^3/slug) ** DSF = Disk Shape Factor *** WS = Wheel Speed at rim (ft/s)

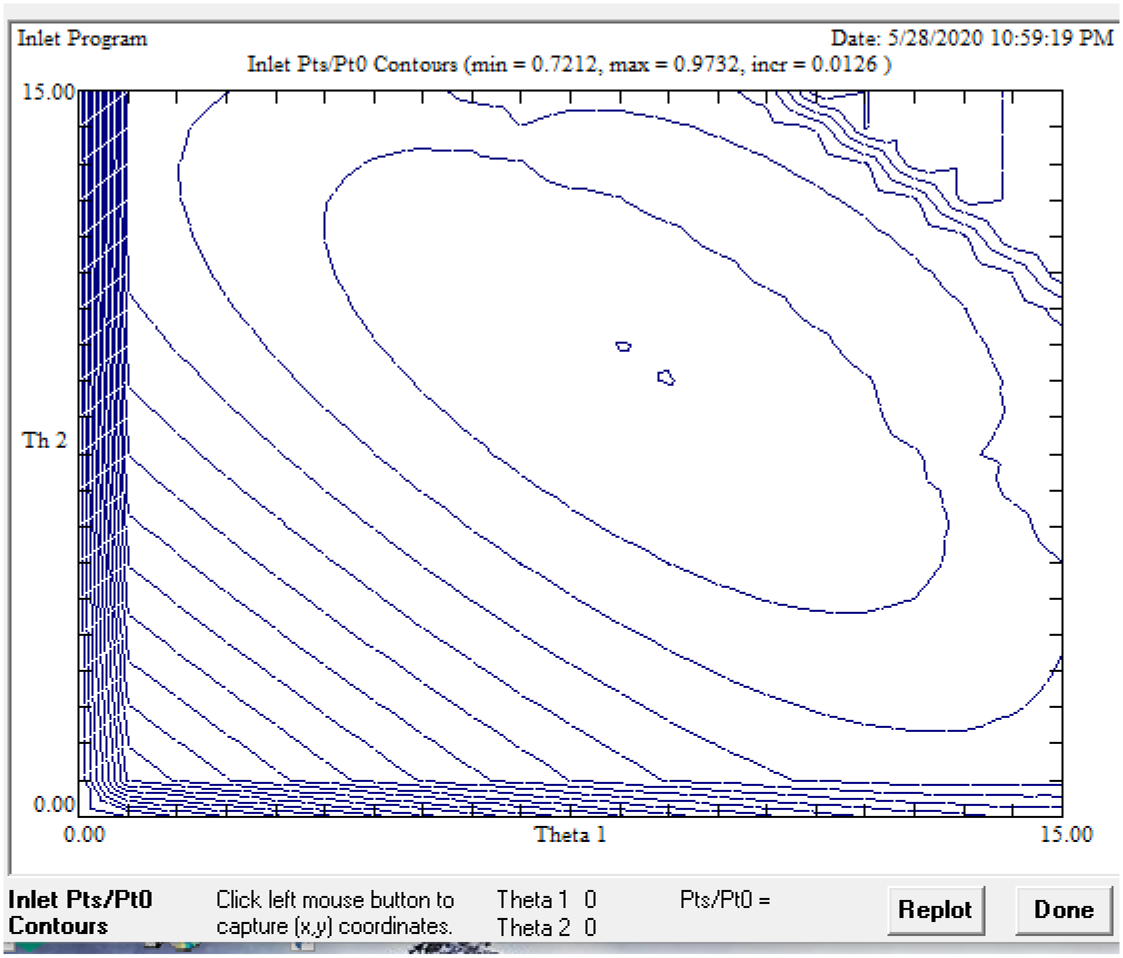

Sketch Pad
Data File:Default Data
Size (in)
Front
Rh = 08.94
Rt = 17.98
Back
Rh = 12.25
Rt = 14.67
L = 38.70
Center Line
Tic spacing = 6.0 in
Compressor Cross Section

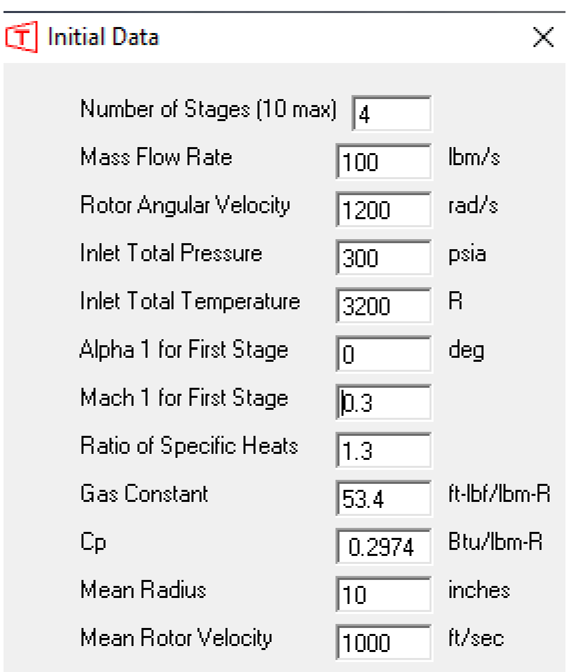

Sketch Pad
Data File:Default Data
Stage: 8 Rotor Stator
Inlet -57.7 57.7
Exit -34.1 34.1
Thickness 10.0% 10.0%
Chord (in) 01.33 01.25
Stack@%c 40.0 40.0
Radial Position 50% hub/tip
Tip
% Radius
50
Hub



Engine Performance Plot
Done
Print
Right mouse click for plot properties
Total Temperature/Pressure Diagram - Tshaft Date:5/28/2020 10:55:23 PM
Engine File: User Input--Date:5/28/2020_Time:10:55:10 PM
Tt max = 2560 R - Pt max = 334.7055 psia
% Maximum
Approximate Axial Location (%)
Path - Tt/Pt
Core - Tt
Core - Pt

Plot




Initial Data

Number of Stages (10 max)	4	
Mass Flow Rate	100	lbm/s
Rotor Angular Velocity	1200	rad/s
Inlet Total Pressure	300	psia
Inlet Total Temperature	3200	R
Alpha 1 for First Stage	0	deg
Mach 1 for First Stage	0.3	
Ratio of Specific Heats	1.3	
Gas Constant	53.4	ft-lbf/lbm-R
Cp	0.2974	Btu/lbm-R
Mean Radius	10	inches
Mean Rotor Velocity	1000	ft/sec

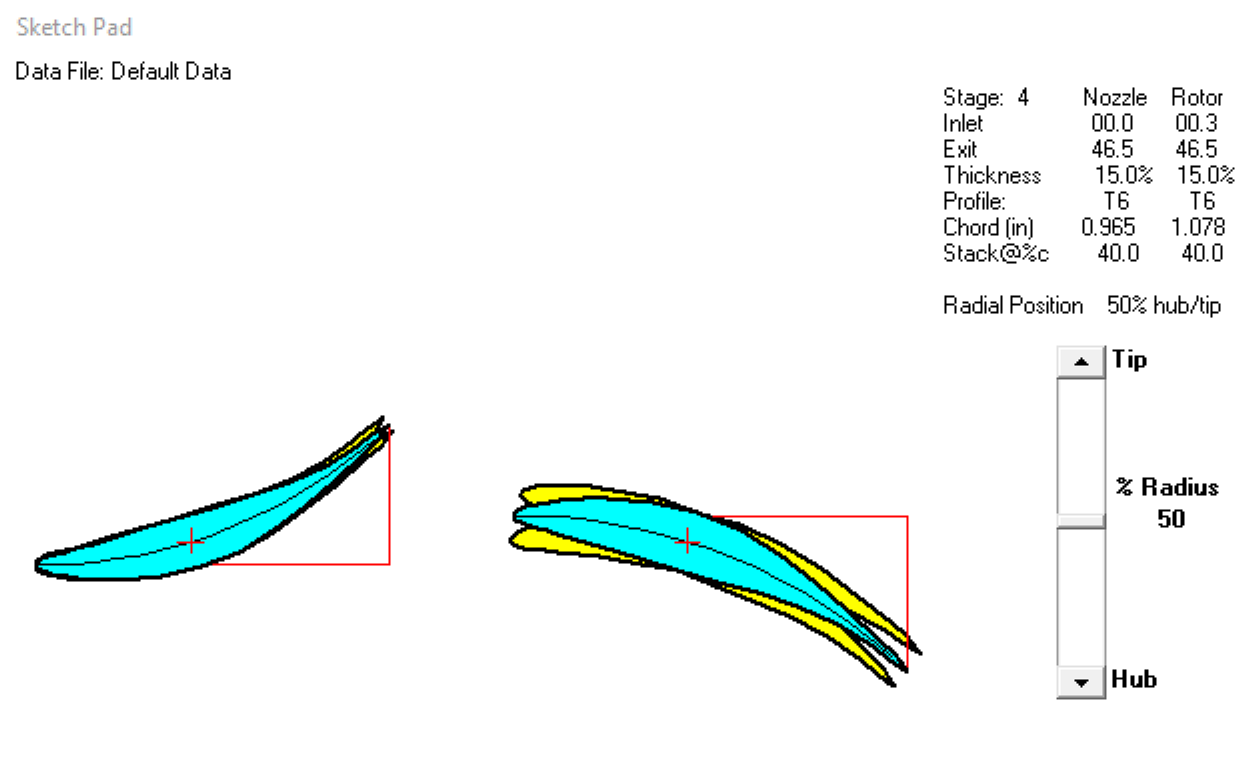
Stage Data

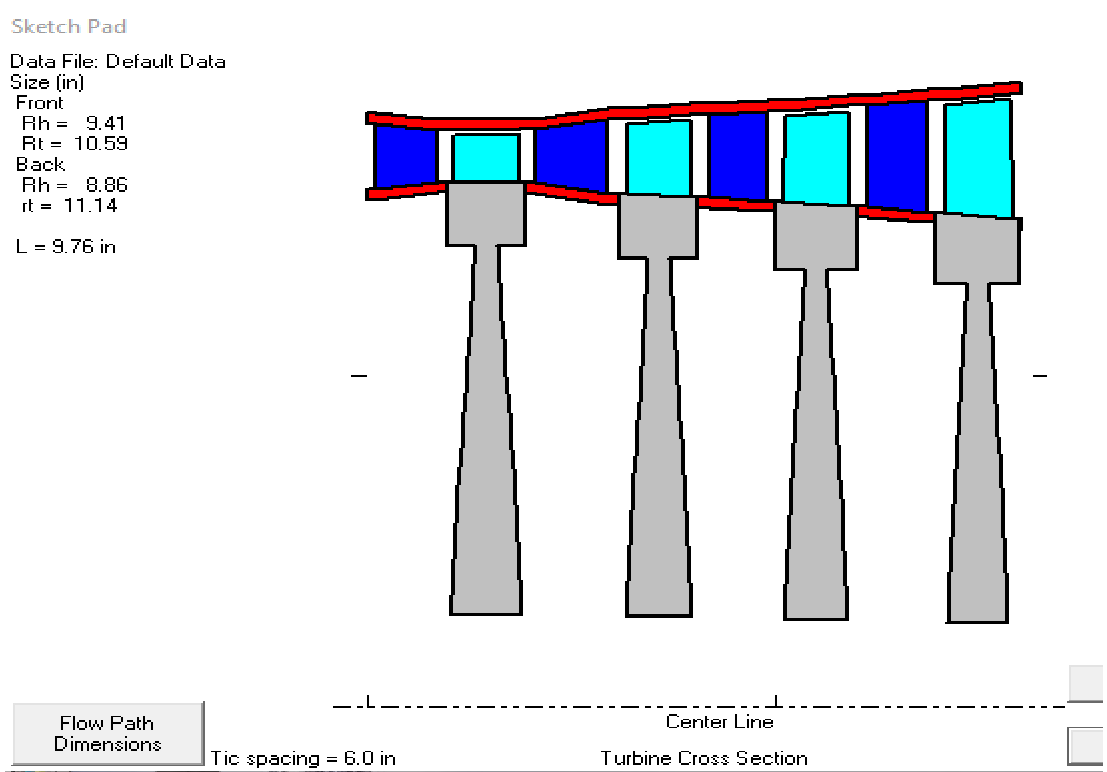
	1	2	3	4
u3/u2	1.0	1.0	1.0	1.0
Mach @ 2	1.05	0.65	0.65	0.65
Alpha @ 3	0.0	0.0	0.0	0.0
Tt3 (R)	2925.0	2775.0	2635.0	2500.0
Stator Z	1.0	1.0	1.0	1.0
Rotor Z	1.0	1.0	1.0	1.0
Stator c/h	1.0	1.0	0.6	0.5
Rotor c/h	1.0	0.7	0.6	0.5
Stator phi	0.02	0.02	0.02	0.02
Poly Eff	0.9	0.9	0.9	0.9

Stage Sketch Data

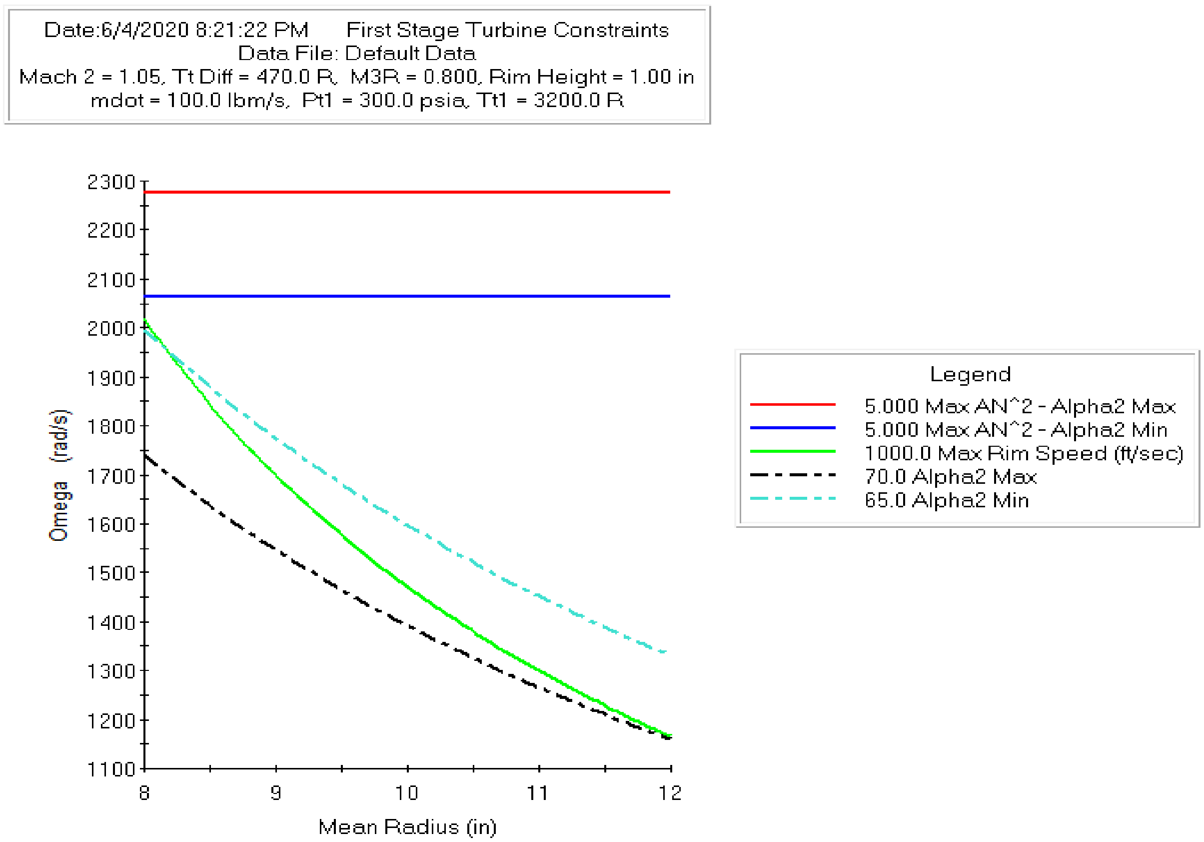
Stage	1	2	3	4
Tt2R (R)	2992.2	2842.2	2702.2	2567.2
Wr/cx	1.2	1.2	1.2	1.2
hr/Wr	1.0	1.0	1.0	1.0
sigma b/r	0.2	0.2	0.2	0.2
sp str rim *	4.0	4.0	4.0	4.0
sp str disk *	2.0	2.0	2.0	2.0
Wdr/Wr	0.281	0.273	0.27	0.264
DSF **	1.214	1.148	1.094	1.024
hr (in)	1.16	1.15	1.20	1.24
WS ***	836.2	813.2	793.7	768.1

cx = rotor blade axial chord at hub
* Specific Strength (ksi-ft^3/slug) ** Disk Shape Factor *** Wheel Speed at rim (ft/s)

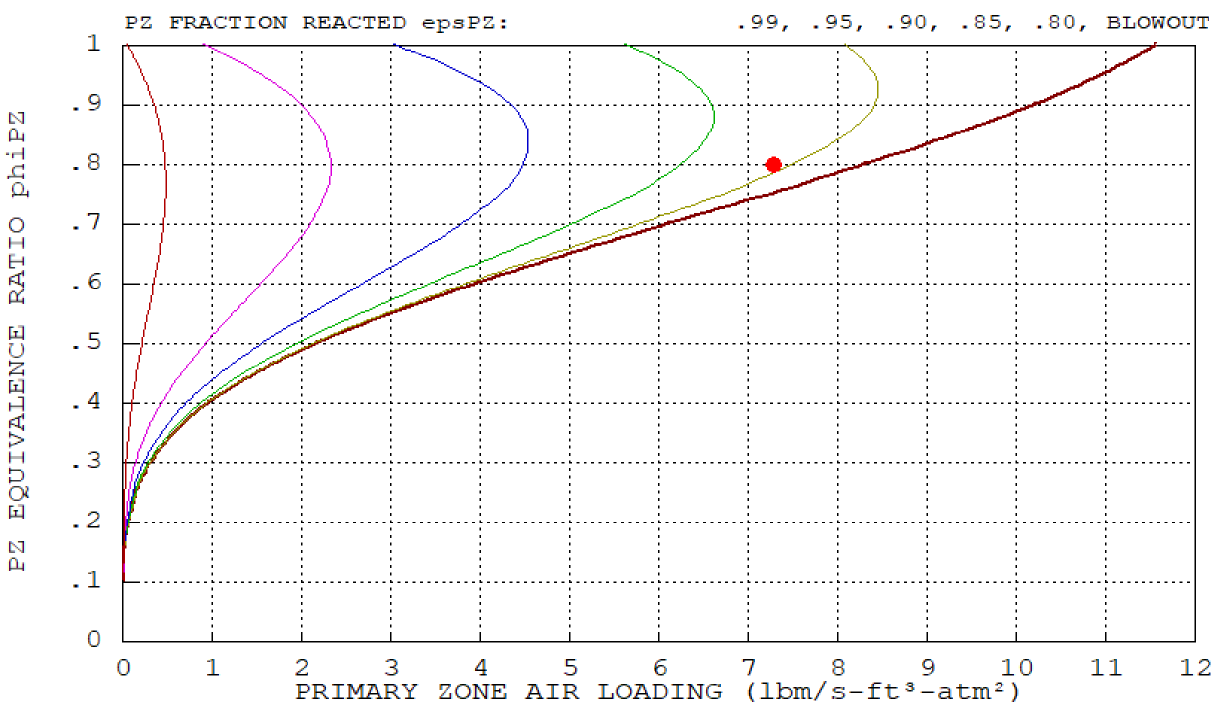

Sketch Pad
Data File: Default Data
Stage: 4 Nozzle Rotor
Inlet 00.0 00.3
Exit 46.5 46.5
Thickness 15.0% 15.0%
Profile: T6 T6
Chord (in) 0.965 1.078
Stack@%c 40.0 40.0
Radial Position 50% hub/tip
Tip
% Radius
50
Hub

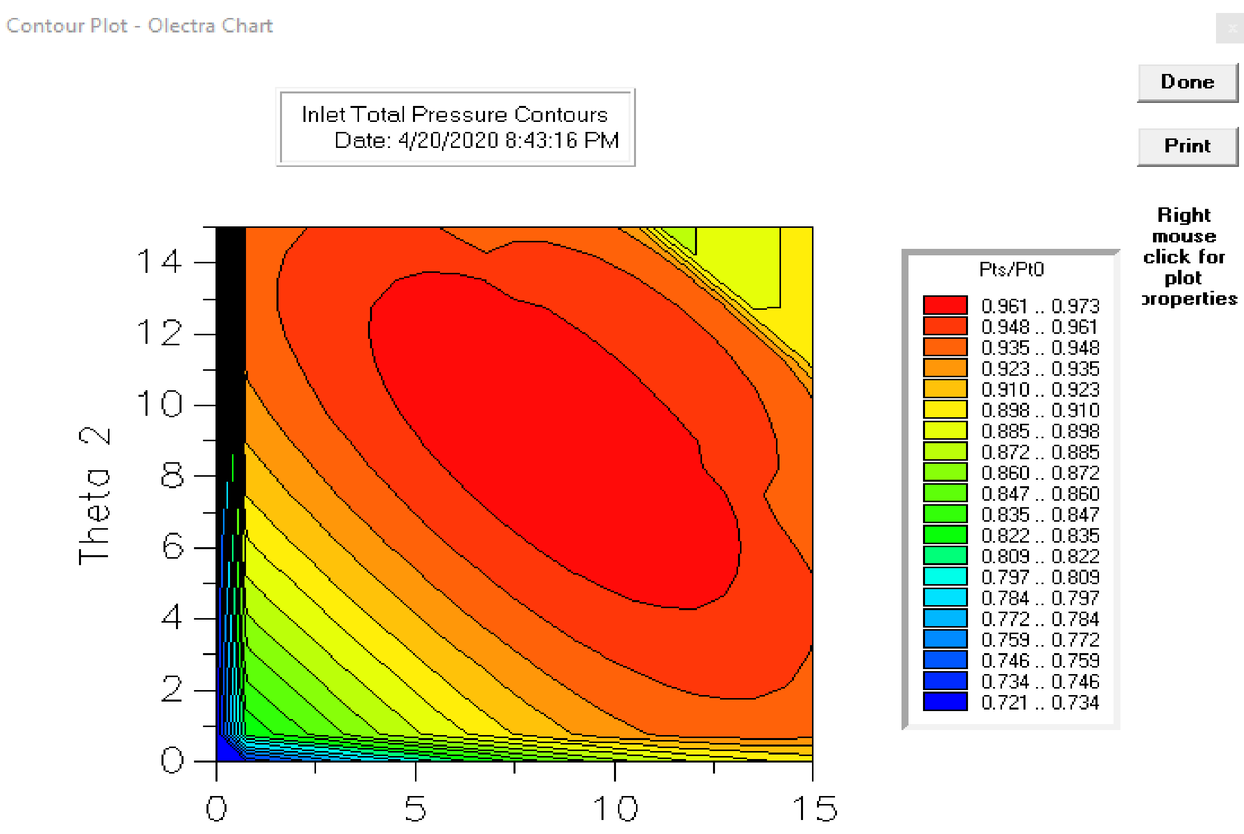

Sketch Pad
Data File: Default Data
Size (in)
Front
Rh = 9.41
Rt = 10.59
Back
Rh = 8.86
rt = 11.14
L = 9.76 in
Flow Path Dimensions
Tic spacing = 6.0 in
Center Line
Turbine Cross Section

Constraint Plot



PRIMARY ZONE STABILITY MAP, data file = AAF Final Engine.mbn




Contour Plot - Olectra Chart
Inlet Total Pressure Contours
Date: 4/20/2020 8:43:16 PM
Done
Print
Right mouse click for plot properties
Pts/Pt0
0.961 .. 0.973
0.948 .. 0.961
0.935 .. 0.948
0.923 .. 0.935
0.910 .. 0.923
0.898 .. 0.910
0.885 .. 0.898
0.872 .. 0.885
0.860 .. 0.872
0.847 .. 0.860
0.835 .. 0.847
0.822 .. 0.835
0.809 .. 0.822
0.797 .. 0.809
0.784 .. 0.797
0.772 .. 0.784
0.759 .. 0.772
0.746 .. 0.759
0.734 .. 0.746
0.721 .. 0.734
Theta 2
14
12
10
8
6
4
2
0
0
5
10
15

APPENDIX D
PERMISSION
FIGURE 1. AIR FLOW DIAGRAM OF THE 4,500-HORSEPOWER GAS TURBINE HORSEPOWER GAS TURBINE ENGINE OUT OF A LOCOMOTIVE. EXHAUST GASES EXPELLED THROUGH THE ROOF APERTURE AT VELOCITY OF 150 M.P.H., 850° F WITH VOLUME OF 150,000 CUBIC FEET

FIGURE 2. CUTAWAY SIDE VIEW OF THE 4,500-HORSEPOWER GAS TURBINE ELECTRIC LOCOMOTIVE SHOWS THE LAYOUT OF THE INTERIOR EQUIPMENT WHILE SHOWING THE EXTERIOR LAYOUT OF 7,200-GALLON FUEL FORMED STRUCTURAL BASE, CARBODY RESTED ON TWO SPAN BOLTERS CONTAINING TWO FOUR-WHEEL POWERED TRUCKS

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FIGURE 6. GAS TURBINE PROCESS FOR ENTROPY DIAGRAM

FIGURE 7. APPLICATION OF THE DJFC TO A COOLED GT BLADE (SCHEMATIC DRAWING)

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FIGURE 8. BLEED & TURBINE COOLING AIRFLOWS DIAGRAMS, KEY

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FIGURE 5. CONSTANT-VOLUME OXYGEN BOMB CALORIMETRY DIAGRAM

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FIGURE 4. GAS TURBINE DIAGRAM AND POWER SYSTEM

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Southern Illinois University Carbondale
Bachelor of Science, Engineering, May 2016

Thesis Paper Title:

Advancements of Gas Turbine Engines and Materials

Major Professor: Dr. Jarlen Don