J58 (JT11D-20) Preliminary Design and Analysis

Christian J. Lagares,[[1]](#footnote-1) Edwin R. Aponte[[2]](#footnote-2) and Joel Quijano [[3]](#footnote-3)

*Department of Mechanical Engineering, University of Puerto Rico at Mayaguez*

**As part of the INME 4707 course offered at the Department of Mechanical Engineering, University of Puerto Rico at Mayaguez, we are required to model and analyze the thermal performance of a J58 Turbojet engine.**

1. **Nomenclature**

*T0* = ambient temperature

*T1* = inlet temperature

*T2*= compressor inlet temperature

*TD* = fourth stage compressor temperature

*T3* = burner inlet temperature

T4 = turbine inlet temperature

T5 = turbine exit temperature

*T6* = afterburner flame-holder temperature

*T8* = nozzle temperature

NEGT = Nominal Exhaust Gas Temperature

*z* = altitude

*M* = Mach Number

= Thrust

*QLHV* = Fuel Lower Heating Value

1. **Introduction**

This project is composed of an analysis of a turbojet engine and its components using the equations derived in class and parameters found in literature. The results obtained were compared to experimental values found in literature. The turbojet engine is the basic jet engine [1]. These engines are used extensively in military aircraft due to their supersonic flight capability. They were also used in commercial flight in airplanes such as the BAC Concorde. Turbojet engines are composed of an inlet, a compressor, a combustion chamber, a turbine, and a nozzle. The inlet reduces the velocity of the air mass before entering the engine. The air then enters the compressor, where its pressure is increased. A turbojet engine may have a single compressor or two compressors in series, a low pressure compressor (LPC) and a high pressure compressor (HPC). Then the air enters the combustion chamber where it is mixed with fuel and ignited. This causes the temperature of the mixture to increase. Next, the hot mixture enters the turbine where work is extracted from the fluid to power the compressor and the pressure of air is reduced. As with the compressor, the turbine might be a single one or it may be high pressure turbine (HPT) and a low pressure turbine (LPT) connected in series. The air-fuel mixture finally exits through the nozzle, where it is accelerated and thrust is generated. Some turbojets, specifically those used in military aircraft, may have an afterburner between the turbine and the nozzle that further increases the temperature and velocity of the air mixture. It is used to improve characteristics such as thrust at takeoff, climb, and the combat performance [ref?]. All the engine components play a part in the net thrust achievable by the engine and the efficiency of the engine.

## Problem Statement

To gain a better understanding of turbojet engines it is important to analyze the engine characteristics over a range of condition to fully grasp the capabilities of the engine. To that end, an analytical model will be developed that describes the impact of changes in component characterization on the overall performance of a turbojet engine. This will be done for a range of conditions to survey the design space.

## Background Information

The engine chosen to be analyzed for this project is the Pratt and Whittney J-58JT11D20 jet engine, commonly referred to as just the J58. This is a single spool (one compressor, one turbine) engine with an afterburner, developed from 1958 and produced from 1964 [Smithsonian ref]. It was used as the engine for the various “Blackbird” variants, the A12; YF-12; and SR-71, which were a series of stealth reconnaissance military aircraft used by the CIA and later by NASA as a research aircraft. This engine is famous for being the first with Mach 3 capabilities and broke a number of speed and altitude records [ref?].



Figure 1: Standard J11D-20 Station Nomenclature [1]

Table 1: Maximum Operating Temperatures [1] [2]

|  |  |  |
| --- | --- | --- |
| COMPONENT/STAGE | TEMP (ºF) | TEMP (ºC) |
| Inlet T1 | 800+ | 426+ |
| COMPRESSOR Inlet T2 | 800+ | 426+ |
| COMPRESSOR 4th Stage TD | 1050 | 565.56 |
| COMBUSTOR Inlet T3 | 1300 | 704.44 |
| TURBINE Inlet T4 | 2000 | 1093.33 |
| TURBINE Exit T5 | 1450 | 787.78 |
| AB T6 | 3200 | 1760 |
| Exhaust NOZZLE T8 | 1500 | 815.15 |

The JT11D-20 variant of the P&W J58 engine has several components that merit some explanation. For instance, Figure 1 depicts a Bypass Air and Secondary Air Flow; the engine behaved as a traditional afterburning turbojet from subsonic to Mach 2.2, but transitioned to a turboramjet at Mach 2.2 . Above Mach 2.2, 6 valves bypass air from the fourth compressor stage (Station D) to the afterburner thereby combining a turbojet with a compressor assisted ramjet. However, this report will limit the analysis to conditions below Mach 2.2 in order to consider the turbojet nature of the JT11D-20. The secondary airflow depicted in Figure 1 allows “descent at low airflow, low power, without unstarting the inlet.“ [3] (It is also shared with the cowl shock trap bleed as per [3].)

The JT11D-20 was designed for a wide range of operational requirements which included sub- and supersonic flight conditions and a wide range of altitudes. This versatility requires the designed to be evaluated at several conditions which are listed in Table 3. The engine must be capable of performing Buddy Missions, Recon Missions, Long Range Flight Deployments plus the typical Takeoff/Landing conditions. Additionally, the aircraft usually performed high altitude, high Mach flights, but these will not be evaluated due to the Turbo-Ramjet limitation after Mach 2.2. The majority of the flight conditions closely resemble an actual flight condition possibly experienced by an SR-71.

Table 2: Engine Specs

|  |  |  |
| --- | --- | --- |
| SPECIFICATION | VALUE RANGE [EN] | VALUE RANGE [SI] |
| **Altitude** [4] | **25K-90K ft** | **7.62 – 27.43 km** |
| **Speed** [5] | **Mach 0.75 – 3.2** | |
| **Dry TSFC @ Max Thrust** [6] | **0.8 lb/lbf hr** | **81.6 kg/kN hr** |
| **Wet TSFC @ Max Thrust** [6] | **1.9 lb/lbf hr** | **164 kg/kN hr** |
| **Fuel** [7] | **JP-7** | |
| **Fuel Storage** [8] | **80,285 lb** | **36,416 kg** |
| **Fuel Lower Heating Value** [9] | **5.48 kWh/lb** | **43,682 kJ/kg** |
| **Thrust** [7] | **32,500 lbf** | **144,567 N** |
| **Air Volume Flow @ Cruise** [10] | **100K ft3/s** | **2831.68 m3/s** |
| **Compression Ratio < Mach 2.2** [8] | **8.8:1** | |
| **Compressor** [11] | **8-Stage Axial** | |
| **Turbine** [11] | **2-Stage** | |
| **Weight** [11] | **6,500 lb** | **2,948 kg** |
| **Air Mass Flow** [8] | **326-450 lb/s** | **147 – 204 kg/s** |
| **Dry Fuel Mass Flow @ Max** | **5.55 lb/s** | **2.52 kg/s** |
| **Wet Fuel Mass Flow @ Max** | **17.94 lb/s** | **8.14 kg/s** |
| **Dry Fuel to Air Ratio** | **0.012-0.017** | |
| **Wet Fuel to Air Ratio** | **0.0398-0.055** | |

# Methodology: Model Description

Modelling a JT11D-20 requires a non-linear approach; in other terms, the engine requires the coupled equations be solved simultaneously front-to-back and back-to-front in order to better approximate the engine’s actual functioning. For instance, the nominal EGT (T8) is provided by [2] as a function of compressor inlet temperature; therefore, this parameter is fixed once T2 is determined. The inlet design is also a major factor affecting the overall model. Given the supersonic nature of the SR-71 plane, the inlet was designed to minimize the losses incurred by shock waves. The recovery factor is then nonlinear and less than one for a typical flight.

### Ambient

Atmospheric condition will be modelled using [12] based on [13] and [14] with an offset temperature approximating typical aircraft temperatures.

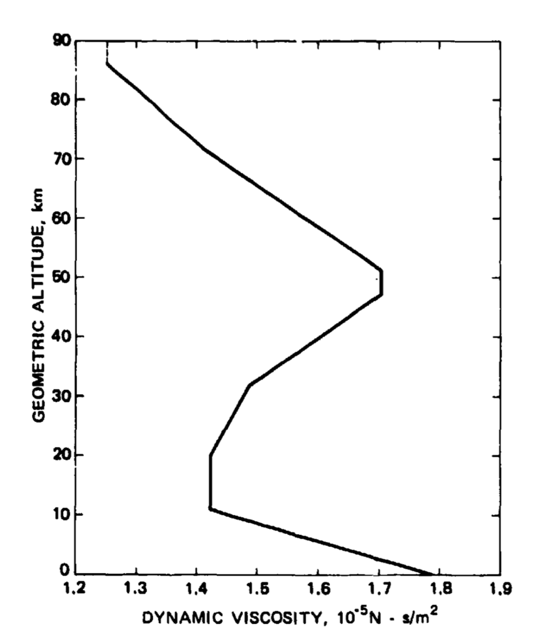


Figure 2: Standard Atmosphere Dynamic Viscosity [14]

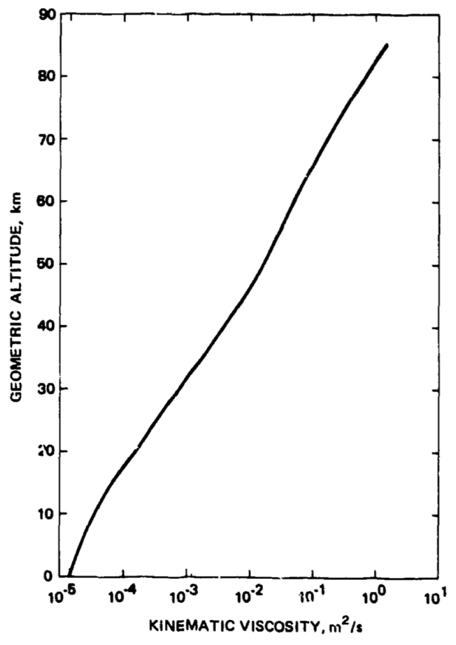


Figure 3: Standard Atmosphere Kinematic Viscosity [14]

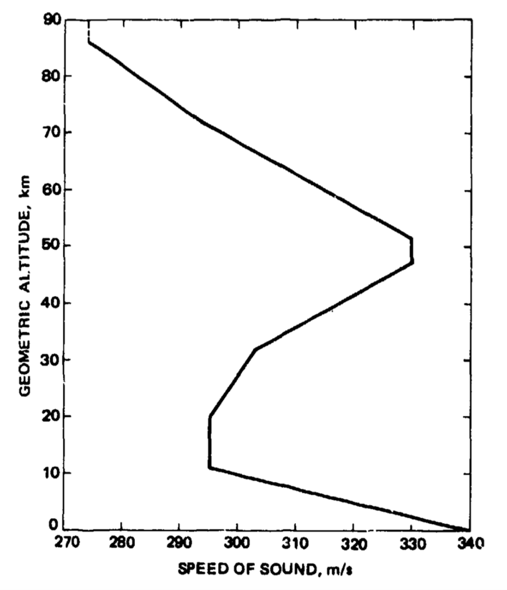


Figure 4: Standard Atmosphere Speed of Sound [14]

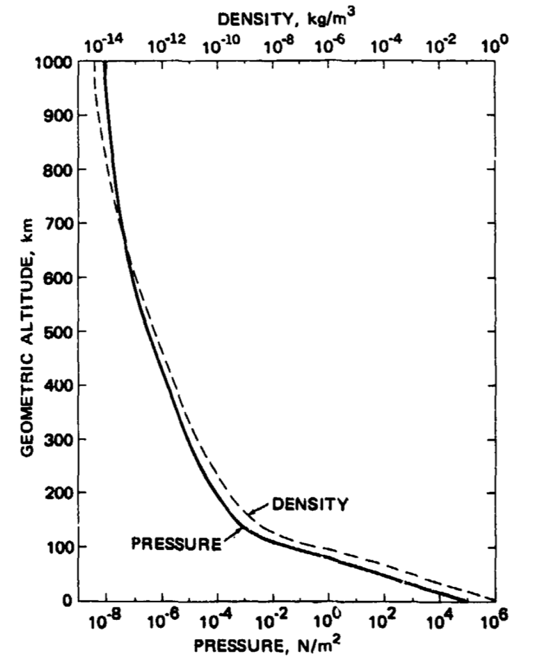


Figure 5: Standard Atmosphere Pressure [14]

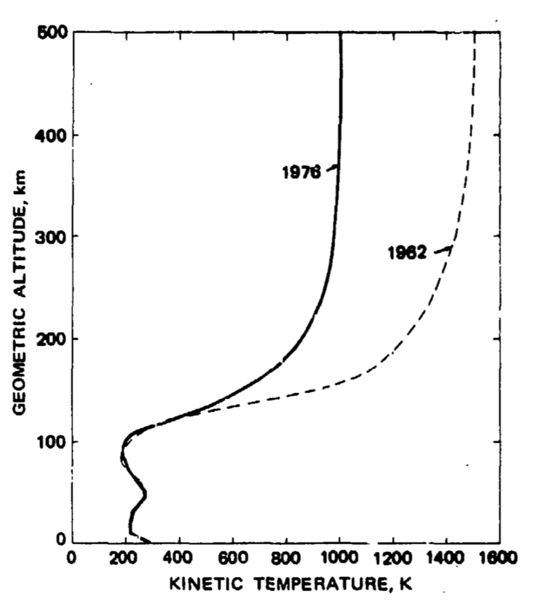


Figure 6: Standard Atmosphere Kinetic Temperature [14]

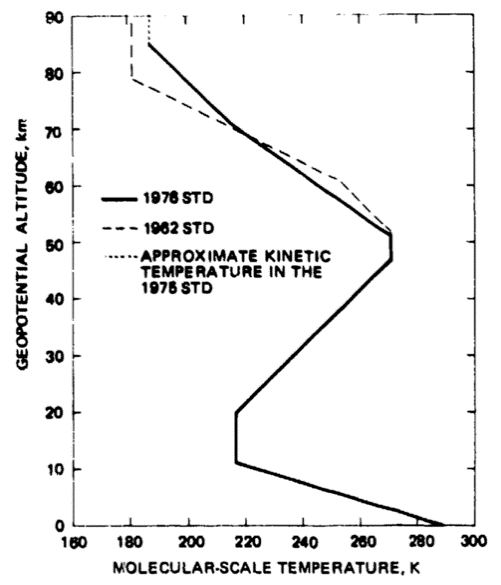


Figure 7: Standard Atmosphere Molecular-Scale Temperature [14]

### Inlet

The inlet’s recovery factor will be modelled after the more conservative curve in Figure 2.

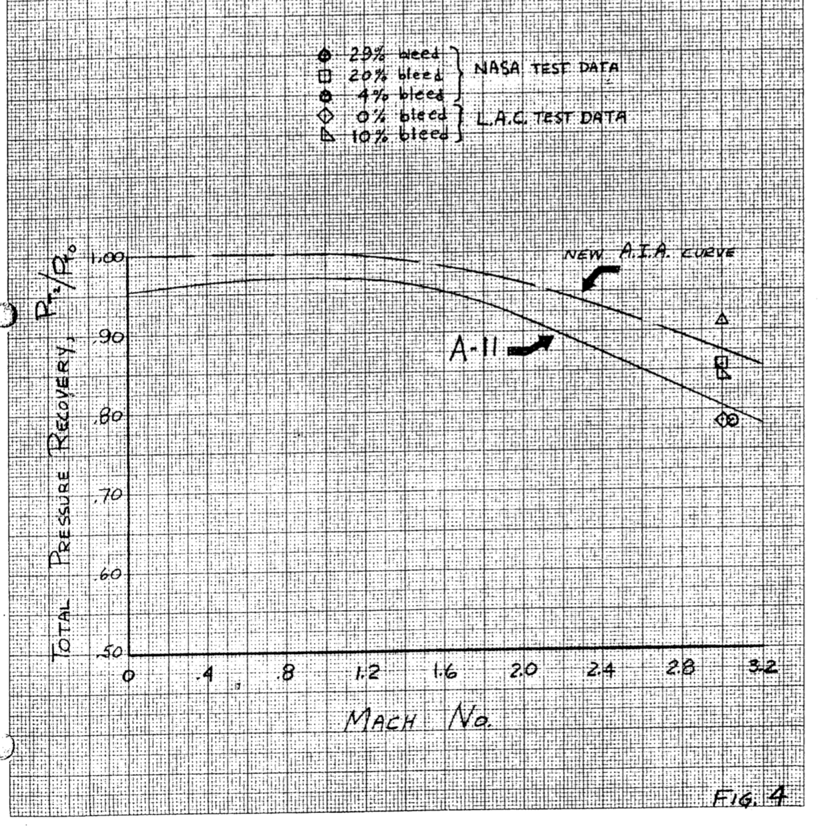


Figure 8: Expected Inlet Performance [15]

The air density will be modelled using Equation (1). The speed of sound inside the inlet is then determined as shown in Equation (2). From this change in density and the total pressure recovery, the inlet temperature (T1 or T2 for typical operations) can be determined as seen in Equation (3).

(1)

(2)

(3)

### Nominal EGT

The EGT is given by Figure 3 extracted from [2].



Figure 9: Indicated EGT vs Compressor Inlet Temperature [2]

### Compressor

As per [11], the compression ratio is typically 8.8 and will be assumed constant throughout the model.

### Burner

The JT11D-20’s burner is another source of complexity in the overall design. Albeit the main fuel consumed is JP-7, it is typically mixed with a nitrogen-based additive to promote the ignition of the stable JP-7 [8] [2]. The model assumes JP-7 to be the only fuel present; thereby treating the additive as a neglectable component per unit volume of fuel. Another major assumption presumes the turbine inlet temperature (T4) to remain constant at a maximum value.

The afterburner will be modeled as the burner, however the JP-7 additive assumption is relaxed as the fuel added to the AB is exclusively JP-7.

### Nozzle

The Nozzle’s Area is variable and is a major limiting factor in the numerical modelling still being researched.

### Model Validation

The model will be validated at standby with maximum afterburner where a 34000 lbf is expected at 1.9 pounds of JP-7 per hour per pound of thrust generated.

### JT11D-20 Conditions

Table 3: Flight Conditions

|  |  |  |  |
| --- | --- | --- | --- |
| Condition ID | Altitude [ft] | Mach | Afterburner |
| Takeoff [2] | 0 (@ Sea level) | 0.3542 | ON |
| Refueling/Buddy Mission [2] | 25000 | 0.75 | OFF |
| Climbing [2] | 30000 | 1.25 | ON |
| Concorde [16] | 60000 | 2.00 | ON |
| YF12A (03/18/65) [17] | 65000 | 2.2 | ON |
| A12 Max Altitude at Mach 2.2 [18] | 75000 | 2.2 | ON |
| Lake County Airport [18] | 9928 | 0.3545 | ON |
| Lowest Altitude at Mach 1.0 [18] | 15000 | 1.0 | ON |
| MA139-XAA[] | 40000 | 1.9 | ON |
| French Griffon II [] | 61000 | 2.1 | ON |
| Constant Climb[5] | 33000 | 0.9 | ON |
| Supersonic Transport flight [19] | 70000 | 2.5 | OFF |

### Implementation

The model’s implementation language is Matlab and the code is being maintained in GitHub for source control facilitation.

# Appendix

## Group Meetings

INME 4707 Team 1: Group Meeting|Minutes 

## Meeting date | time 04/02/18 | 10:30 | Meeting location Lucchetti

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| |  |  | | --- | --- | | Meeting called by | Christian Lagares | | Type of meeting | Work Division | | Facilitator | Christian Lagares | | Note taker | Christian Lagares | | Timekeeper | Edwin Aponte | | Edwin Aponte  Joel Quijano (Excused from meeting) |

# Agenda topics

## Time allotted | 15 | Agenda topic Source Control | Presenter Christian Lagares

Discuss the importance of Source Control for Code and Document Management and sharing.

Team agreed to a platform

|  |  |  |
| --- | --- | --- |
| Action items | Person responsible | Deadline |
| Create GitHub Account | Joel/Edwin | 04/03/2018 |

## Time allotted | 15 | Agenda topic Code Division | Presenter Christian Lagares

Created basic source tree

Allowed team members to choose desired code sections

|  |  |  |
| --- | --- | --- |
| Action items | Person responsible | Deadline |
| Vote on code section | All | ASAP |



## Model

The Codebase has been organized as follows:

* EngineModel
  + afterburner.m
  + burner.m
  + compressor.m
  + inlet.m
  + nozzle.m
  + shock\_trap.m
  + turbine.m
* PerfParameters
  + flight\_conditions.m
  + impulse.m
  + overall\_efficiency.m
  + propulsive\_efficiency.m
  + range.m
  + thermal\_efficiency.m
  + thrust.m
  + tsfc.m
* utils
  + atmos
    - atmos.m
    - densityalt.m
    - tropos.m
    - license.txt
  + EngineParameters
    - atm2comp.m
    - engine.m
    - recovery.m
  + FlightManualUtilities
    - knots.m
    - nominalEGT.m
* Main.m

## Group Meetings

## Biosketch

Christian Lagares is currently an undergraduate student at the Department of Mechanical Engineering at the University of Puerto Rico at Mayaguez and an Artificial Intelligence/Machine Learning Researcher at SIL Technologies, LLC. His main research interests include Supervised Learning Strategies for Advanced Signal Analysis, Real Time Systems for Simultaneous DAQ/Processing in low power portable devices and AI-Enabled Materials.

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1. Undergraduate Researcher, Bubble Dynamics Laboratory & SIL Technologies. [↑](#footnote-ref-1)
2. Undergraduate Student, Department of Mechanical Engineering, University of Puerto Rico at Mayaguez. [↑](#footnote-ref-2)
3. Undergraduate Student, Department of Mechanical Engineering, University of Puerto Rico at Mayaguez. [↑](#footnote-ref-3)