# AE 5326 - Air-Breathing Propulsion
# Final Design Project

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# Chapter 1

# Design Challenge

**Design an engine cycle for a supersonic transport aircraft to meet the following specifications:**

- Mission: Dallas/Fort Worth to Seoul, South Korea (11,000 km)
- Transonic cruise over land
  - $M_0 = 0.9$
  - Alt = 40,000 ft
  - Range = 3000 km
- Supersonic cruise over water
  - $M_0 = 2.2$
  - Alt = 60,000 ft
  - Range = 8000 km

### 1.0.1 Design Requirements

- Assume JDM Level 4 technology for component efficiencies, twin-spool engine.
- Size engine to provide sea level static thrust (uninstalled) = 32,000 lbf without afterburner, 38,000 lbf with afterburner.
- Candidate engine cycles:
  - Afterburning turbojet
  - Mixed-flow afterburning turbofan
  - Variable cycle engine - unmixed turbofan with duct burning and afterburning
- Calculate maximum thust available and weight of fuel consumed for the transonic and supersonic cruise segments of the mission.
- Desirable design goals (in general, compromise is required between conflicting goals):

1. Minimize cruse **total** fuel consumption (lbm, kg)
2. Maximize cruise thrust (lbf, kN)
3. Minimize engine diameter (assume $M_2 = 0.5$)

#### 1.0.2 Report Requirements

Report must be typed.

- Discussion of methods, assumptions, calculation procedure, results.
- Graphical presentation of parametric study results to justify engine cycle design selection.
- Final cycle design parameters: ($\pi_c$, $\pi_f$, $\alpha$, $T_{t4}$, $T_{t7}$, $T_{t17}$), thrust available (lbf, kN) and total fuel consumption (lbm, kg) for both transonic and supersonic cruise, engine diameter (ft, m)
- Summary tabulation of final engine cycle parameters and performance.

## 1.1 Part 2: Off-Design Performance

Calculate and plot the Max Thrust available vs. Mach number and altitude for $0 < M_0 < 2.0$, $0 <$ Alt $<$ 60,000 ft (afterburner on, afterburner off).

## 1.2 Part 3: Acceleration Transient

Calculate the time required to accelerate the engine from 60% RPM to 100% RPM. Plot the time variation of fuel flow rate, air flow rate, RPM, $T_{t4}$, and thrust. Assume the compressors and turbines have polar moments of inertia of 10 slug-ft$^2$ each and the shafts 2 slug-ft$^2$.

# Chapter 2

# Engine Design

## 2.1 Cycle Selection

To get an idea of which design would perform best at the design points, a series of simulations were accomplished using NPSS. A short literature review was conducted and initial guesses for design variables were set to simplify the cycle selection process. The results and conclusions are outlined below.

Assumptions

1. Design point was taken to be takeoff conditions at sea level for a standard day.
2. Turbine inlet temperature, afterburner exit temperature, and exit temperature from duct burner are set for design point calculations.
3. Takeoff thrust is maintained for approximately 5 minutes (for fuel burn calculations).

The values of the temperatures set above were determined by referencing Technology Level 4 from Mattingly [2].

### 2.1.1 Afterburning Turbojet

To determine the performance of the engine with variations in compressor pressure ratio ($\pi_c$), 6 simulation were accomplished using NPSS. The simulations consisted of analyses of the turbojet performance with, and with out the afterburner at the three points of interest (i.e., take-off, subsonic cruise, and supersonic cruise). Figures 2.1 - 2.3 depict the variation in specific thrust and specific fuel consumption with variations in compressor pressure ratio at the design point (takeoff conditions). A value for the compressor pressure ratio was assumed ($\pi_c = 8$).

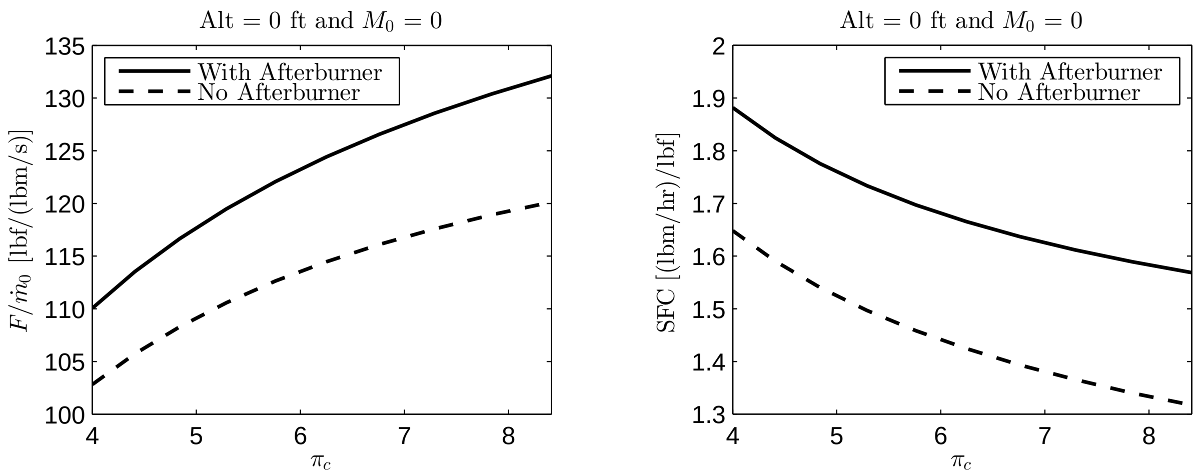


**Figure 2.1.** Design point - Alt = 0 ft, $M_0 = 0$.

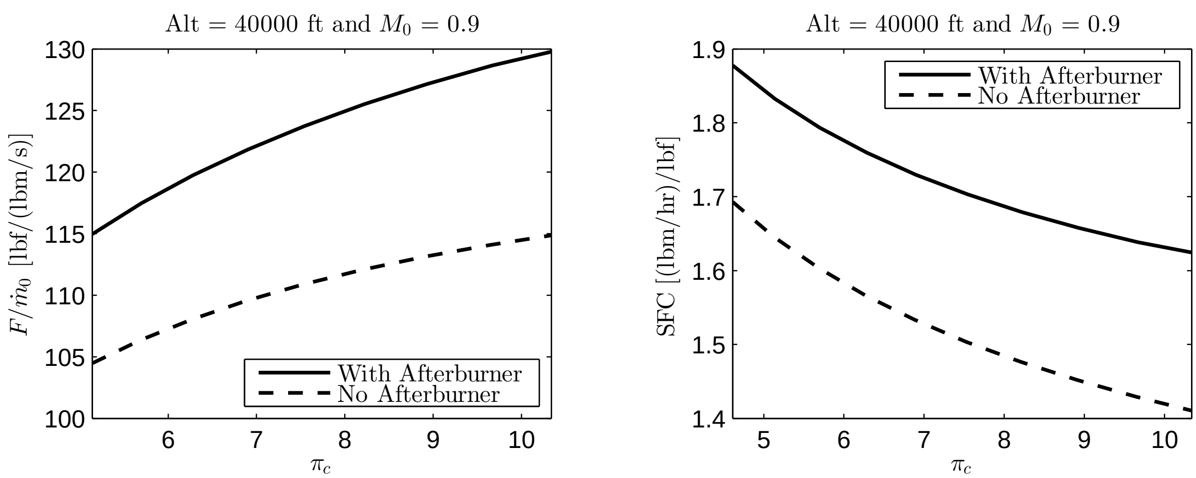


**Figure 2.2.** Off design point 1 - Alt = 40,000 ft, $M_0 = 0.9$.

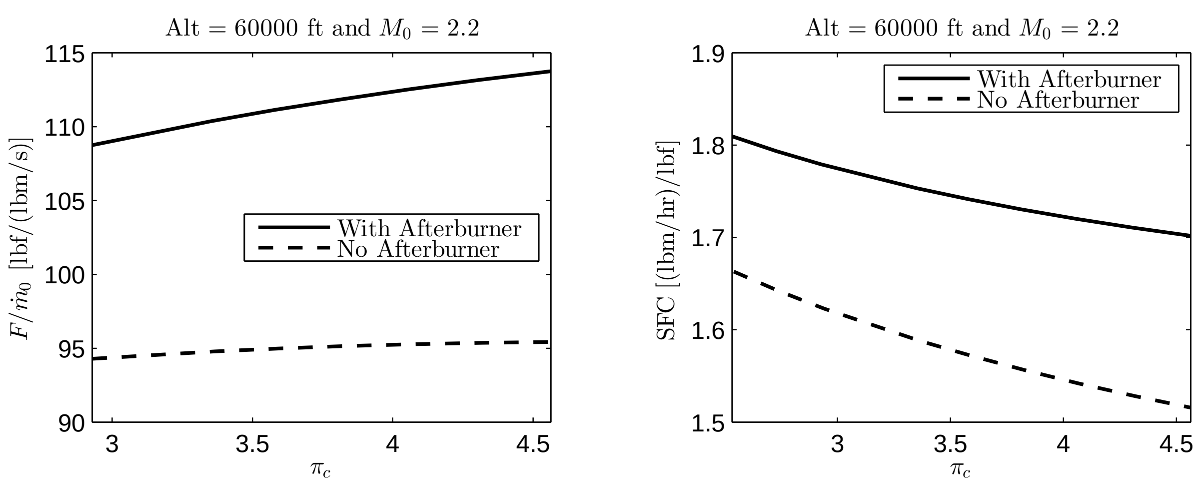


**Figure 2.3.** Off design point 2- Alt = 60,000 ft, $M_0 = 2.2$.

Choosing a single compressor pressure ratio at which to evaluate the performance of the engine at design and the two off design point yields the following data:

```
=============================================
=====    RUNNING DESIGN POINT - AB ON   =====
=============================================

F020 A = 1138.72
F090 A = 793.092
pi_c = 8
Engine Wair = 290.242 lbm/s
Burner Wfuel = 11.6082 lbm/s
Afterburner Wfuel = 5.09863 lbm/s
SFC = 1.58274 lbm/(hr*lbf)
Gross Thrust = 38000.3 lbf
Net Thrust = 38000.3 lbf
Specific Thrust = 130.926 lbf/(lbm/s)

===============================================
====   RUNNING OFF DESIGN POINT 1 - AB ON  ====
===============================================

F020 A = 1138.72
F090 A = 1179.9
pi_c = 9.74361
Engine Wair = 110.866 lbm/s
Burner Wfuel = 4.5448 lbm/s
Afterburner Wfuel = 1.94693 lbm/s
SFC = 1.63836 lbm/(hr*lbf)
Gross Thrust = 17267.9 lbf
Net Thrust = 14264.4 lbf
Specific Thrust = 128.664 lbf/(lbm/s)

==============================================
====   RUNNING OFF DESIGN POINT 2 - AB ON ====
==============================================

F020 A = 1138.72
F090 A = 2299.86
pi_c = 4.46109
Engine Wair = 122.458 lbm/s
Burner Wfuel = 4.43974 lbm/s
Afterburner Wfuel = 2.14425 lbm/s
SFC = 1.70231 lbm/(hr*lbf)
Gross Thrust = 22033.2 lbf
Net Thrust = 13923.6 lbf
Specific Thrust = 113.701 lbf/(lbm/s)

==============================================
=====    RUNNING DESIGN POINT - AB OFF   =====
==============================================

F020 A = 1138.72
F090 A = 642.717
pi_c = 8
Engine Wair = 268.198 lbm/s
```

```
Burner Wfuel = 11.8535 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 1.33352 lbm/(hr*lbf)
Gross Thrust = 32000 lbf
Net Thrust = 32000 lbf
Specific Thrust = 119.315 lbf/(lbm/s)

================================================
====   RUNNING OFF DESIGN POINT 1 - AB OFF  ====
================================================

F020 A = 1138.72
F090 A = 893.474
pi_c = 8.81001
Engine Wair = 95.6231 lbm/s
Burner Wfuel = 3.95807 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 1.39924 lbm/(hr*lbf)
Gross Thrust = 12773.9 lbf
Net Thrust = 10183.4 lbf
Specific Thrust = 106.495 lbf/(lbm/s)

===============================================
====   RUNNING OFF DESIGN POINT 2 - AB OFF ====
===============================================

F020 A = 1138.72
F090 A = 1734.33
pi_c = 4.14327
Engine Wair = 108.532 lbm/s
Burner Wfuel = 3.97661 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 1.48906 lbm/(hr*lbf)
Gross Thrust = 16801.3 lbf
Net Thrust = 9613.98 lbf
Specific Thrust = 88.5821 lbf/(lbm/s)
```

Making an assumption that takeoff thrust is maintained for approximately 5 minutes, and assuming a standard atmosphere, the total fuel consumption for a turbojet engine that utilizes afterburners on takeoff and during acceleration only was determined to be:

$$\boxed{\text{Total Fuel Consumption} \approx 98750 \text{ lbm}}$$

The calculations were accomplished using a MATLAB code that is included in the appendix. Fuel burns for the various possibilities are plotted below in Figure 2.4.

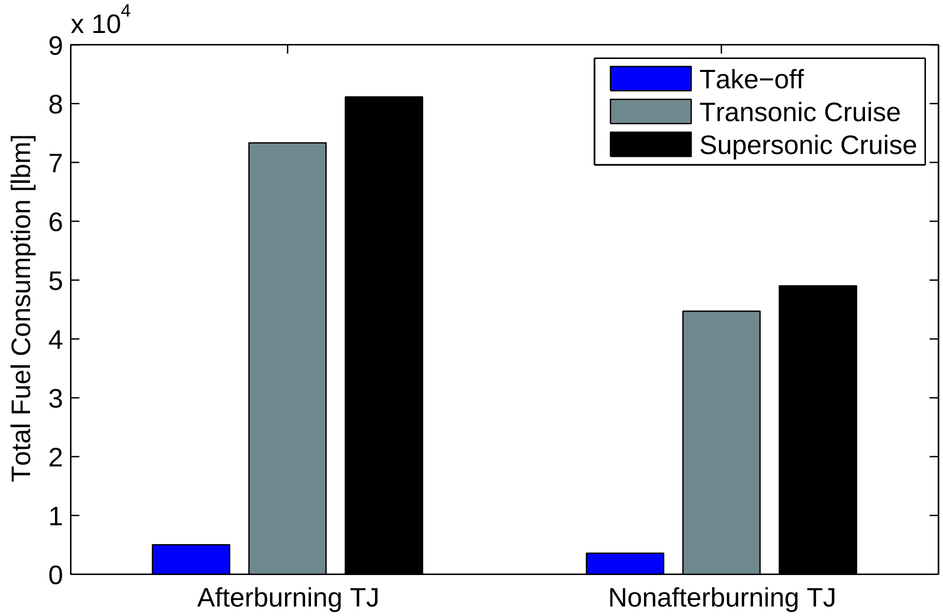


**Figure 2.4.** Fuel consumption for turbojet with and without afterburner.

### 2.1.2 Mixed-flow Turbofan

Design variable assumptions:

- BPR ($\alpha$) = 2.5
- Fan PR ($\pi_f$) = 3
- CPR ($\pi_c$) = 15

The values above were chosen based on example problems and values for which the NPSS solver converged adequately. Another assumption is made that the afterburner is only used during takeoff and acceleration. Four simulations were run: takeoff with afterburner, takeoff without afterburner, 40,000 ft with $M_0 = 0.9$, and 60,000 ft with $M_0 = 2.2$.

Abbreviated results from NPSS are shown below:

```
==============================================
=====    RUNNING DESIGN POINT - AB ON   =====
==============================================

F020 A = 1340.13
F090 A = 1110.37
pi_c = 15
Engine Wair = 341.58 lbm/s
Burner Wfuel = 3.59595 lbm/s
Afterburner Wfuel = 16.1839 lbm/s
SFC = 1.87388 lbm/(hr*lbf)
Gross Thrust = 38000 lbf
Net Thrust = 38000 lbf
Specific Thrust = 111.248 lbf/(lbm/s)
```

```
=============================================
=====    RUNNING DESIGN POINT - AB OFF   =====
=============================================

F020 A = 2061.89
F090 A = 921.326
pi_c = 15
Engine Wair = 525.546 lbm/s
Burner Wfuel = 5.53263 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 0.622414 lbm/(hr*lbf)
Gross Thrust = 32000.3 lbf
Net Thrust = 32000.3 lbf
Specific Thrust = 60.8898 lbf/(lbm/s)

===============================================
====   RUNNING OFF DESIGN POINT 1 - AB OFF  ====
===============================================

F020 A = 2061.89
F090 A = 921.362
pi_c = 19.4923
Engine Wair = 195.526 lbm/s
Burner Wfuel = 2.31119 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 0.889698 lbm/(hr*lbf)
Gross Thrust = 14648.9 lbf
Net Thrust = 9351.82 lbf
Specific Thrust = 47.829 lbf/(lbm/s)

===============================================
====   RUNNING OFF DESIGN POINT 2 - AB OFF  ====
===============================================

F020 A = 2061.89
F090 A = 921.315
pi_c = 7.27851
Engine Wair = 225.284 lbm/s
Burner Wfuel = 1.84292 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 1.60985 lbm/(hr*lbf)
Gross Thrust = 19040.2 lbf
Net Thrust = 4121.19 lbf
Specific Thrust = 18.2933 lbf/(lbm/s)
```

If the aircraft is using afterburners on takeoff, then the total fuel consumption per engine is

$$\boxed{\text{Total Fuel Consumption with Afterburner on takeoff} = 54760 \text{ lbm}}$$

or, with no afterburner on takeoff

$$\boxed{\text{Total Fuel Consumption no Afterburner on takeoff} = 50490 \text{ lbm}}$$

### 2.1.3 Variable Cycle Engine

Design variable assumptions:

- BPR ($\alpha$) = 2.5
- Fan PR ($\pi_f$) = 3
- CPR ($\pi_c$) = 15

For purposes of simplicity, it is assumed that the duct burner and afterburner are only used for takeoff and acceleration purposes.

```
=============================================================
=====    RUNNING DESIGN POINT - AB ON & Duct Burner ON  =====
=============================================================

F020 A = 1458.18
F090 A = 354.916
pi_c = 15
Engine Wair = 371.668 lbm/s
Burner Wfuel = 3.9127 lbm/s
Afterburner Wfuel = 3.08226 lbm/s
Duct Burner Wfuel = 10.1306 lbm/s
SFC = 1.33042 lbm/(hr*lbf)
Gross Thrust = 38000 lbf
Net Thrust = 38000 lbf
Specific Thrust = 102.242 lbf/(lbm/s)

================================================================
=====    RUNNING DESIGN POINT - AB OFF & Duct Burner OFF   =====
================================================================

F020 A = 2179.35
F090 A = 406.731
pi_c = 15
Engine Wair = 555.485 lbm/s
Burner Wfuel = 5.84774 lbm/s
Afterburner Wfuel = 0 lbm/s
Duct Burner Wfuel = 0 lbm/s
SFC = 0.657875 lbm/(hr*lbf)
Gross Thrust = 31999.8 lbf
Net Thrust = 31999.8 lbf
Specific Thrust = 57.6069 lbf/(lbm/s)

==================================================================
====   RUNNING OFF DESIGN POINT 1 - AB OFF & Duct Burner OFF  ====
==================================================================

F020 A = 2179.35
F090 A = 406.731
pi_c = 19.0317
Engine Wair = 203.451 lbm/s
Burner Wfuel = 2.38471 lbm/s
Afterburner Wfuel = 0 lbm/s
Duct Burner Wfuel = 0 lbm/s
SFC = 0.990869 lbm/(hr*lbf)
```

```
Gross Thrust = 14175.8 lbf
Net Thrust = 8664.08 lbf
Specific Thrust = 42.5856 lbf/(lbm/s)

==================================================================
====   RUNNING OFF DESIGN POINT 2 - AB OFF & Duct Burner OFF  ====
==================================================================

F020 A = 2179.35
F090 A = 406.733
pi_c = 7.55735
Engine Wair = 233.746 lbm/s
Burner Wfuel = 2.00606 lbm/s
Afterburner Wfuel = 0 lbm/s
Duct Burner Wfuel = 0 lbm/s
SFC = 1.92022 lbm/(hr*lbf)
Gross Thrust = 19240.3 lbf
Net Thrust = 3760.93 lbf
Specific Thrust = 16.0898 lbf/(lbm/s)
```

If the aircraft is using afterburners and the duct burner on takeoff, then the total fuel consumption per engine is

$$\boxed{\text{Total Fuel Consumption with Afterburner on takeoff} = 56811 \text{ lbm}}$$

or, with no afterburner on takeoff

$$\boxed{\text{Total Fuel Consumption no Afterburner on takeoff} = 53427 \text{ lbm}}$$

### 2.1.4 Results Summary and Cycle Decision

The numerical results from the simulations can be seen in Tables 2.1 and 2.2 and a plot of the total fuel burn per engine is provided in Figure 2.5.

**Table 2.1.** Summary of Results.

| | | Afterburning Turbojet | | | Mixed-flow Turbofan | | | Variable Cycle Turbofan | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Parameter | Units | 0 ft. | 40,000 ft. | 60,000 ft. | 0 ft. | 40,000 ft. | 60,000 ft. | 0 ft. | 40,000 ft. | 60,000 ft. |
| SFC | [lbm/(hr·lbf)] | 1.5827 | 1.3992 | 1.4891 | 1.8739 | 0.8897 | 1.6099 | 1.3304 | 0.9909 | 1.9202 |
| $F/\dot{m}_0$ | [lbf/(lbm/s)] | 130.926 | 106.495 | 88.582 | 111.248 | 47.829 | 18.293 | 102.242 | 42.586 | 16.090 |
| Net Thrust | [lbf] | 38,000 | 10,183 | 9,613 | 38,000 | 9,351 | 4,121 | 38,000 | 8,664 | 3,760 |
| Total Fuel Flow Rate ($\dot{m}_f$) | [lbm/s] | 16.707 | 3.958 | 3.977 | 19.780 | 2.311 | 1.843 | 17.126 | 2.385 | 2.006 |

**Table 2.2.** Comparison of fuel burns for the various engines in lbm.

| | With Afterburner on Takeoff | No Afterburner on Takeoff |
|---|---|---|
| Afterburning Turbojet | 98,750 | 97,300 |
| Mixed-flow Turbofan | 54,760 | 50,490 |
| Variable Cycle Turbofan | 56,810 | 53,430 |

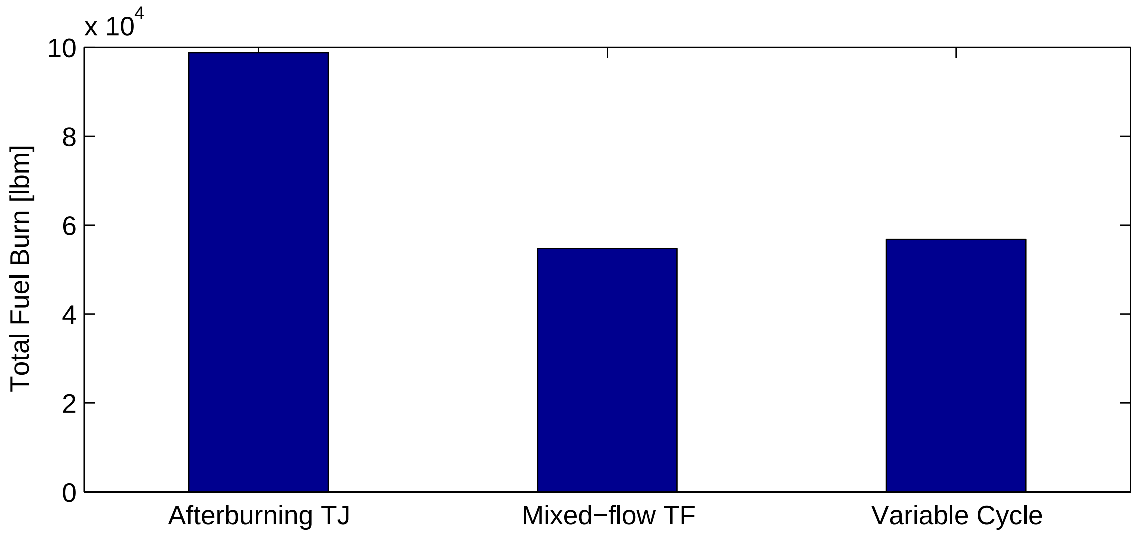


**Figure 2.5.** Fuel burn comparison.

The total fuel burn of the afterburning turbojet is much greater than the total fuel burns of the other cycles. However, at the supersonic cruise speed, the afterburning turbojet provides over double the net thrust of the other two engines (see Table 2.1). The design goals of this project are to minimize cruise total fuel consumption, maximize thrust, and minimize engine diameter. The turbojet has a reduced engine diameter compared to the other two engines because of the absence of the fan. Also, the thrust of the turbojet at the off design points is higher than the other cycles.

In addition to design constraints, the limitations and capabilities of the simulation software must also be taken into consideration during the cycle selection process. The software that is being used to design the cycle, NPSS, is flexible and robust. However, with this added flexibility comes additional responsibilities for the user. Although the code is very flexible for many different types of systems, it is very sensitive to inputs. Because of the sensitivity of the solver to inputs, achieving solver convergence for all cases of a parametric analysis is extremely difficult.

To aid in the cycle selection process, NPSS models were created for each cycle. Solver convergence became a serious issue for the parametric analysis of the variable cycle engine and the mixed-flow turbofan. To obtain single-point convergence (no variation of parameters), a trial-and-error approach was used to determine the input parameters for which the solver converged. This trial-and-error approach took approximately 5 hours per model.

Considering the dual-spool, afterburning turbojet, due to the simplicity of the model (relative to the other two cycles), the NPSS solver is less sensitive to user inputs. Considering manufacture of each of the engines, the turbojet is the most simple, and straightforward. Operationally, the pilots flying a turbojet powered aircraft would have fewer possible configurations compared to the variable cycle engines.

**Therefore, for reasons of simplicity and consistent solver convergence along with design constraints met, the afterburning turbojet was selected as the engine for the given mission.**

## 2.2 Afterburning Turbojet Parametric Cycle Analysis

To determine the optimum values for the design variables, a parametric cycle analysis was accomplished using NPSS.

Variables:

- CD nozzle throat area ($A_{th}$)
- Turbine inlet temperature ($T_{t4}$)
- Compressor pressure ratio ($\pi_c$)

### 2.2.1 Variation of converging-diverging nozzle throat area

The throat area of the converging-diverging nozzle at design point operation ($A_{th,\text{des}}$) is determined by the NPSS solver. To determine the optimal throat area for the off design operation, the nozzle throat area was varied as follows:

- 40,000 ft $\rightarrow 0.8\ A_{th,\text{des}} \leq A_{th} \leq 0.9\ A_{th,\text{des}}$
- 60,000 ft $\rightarrow 0.7\ A_{th,\text{des}} \leq A_{th} \leq A_{th,\text{des}}$

Examining Figures 2.6 and 2.7, a CD nozzle throat area of approximately $0.9A_{th,\text{des}}$ is chosen because it provides a low specific fuel consumption while maintaining sufficient net thrust for all design points. In addition, the NPSS solver converges sufficiently for the chosen throat area.

**Table 2.3.** Chosen throat area for off design points.

| | Throat Area ($A_{th}$) |
|---|---|
| 40,000 ft & $M_0 = 0.9$ | $0.9A_{th,\text{des}}$ |
| 60,000 ft & $M_0 = 2.2$ | $0.9A_{th,\text{des}}$ |

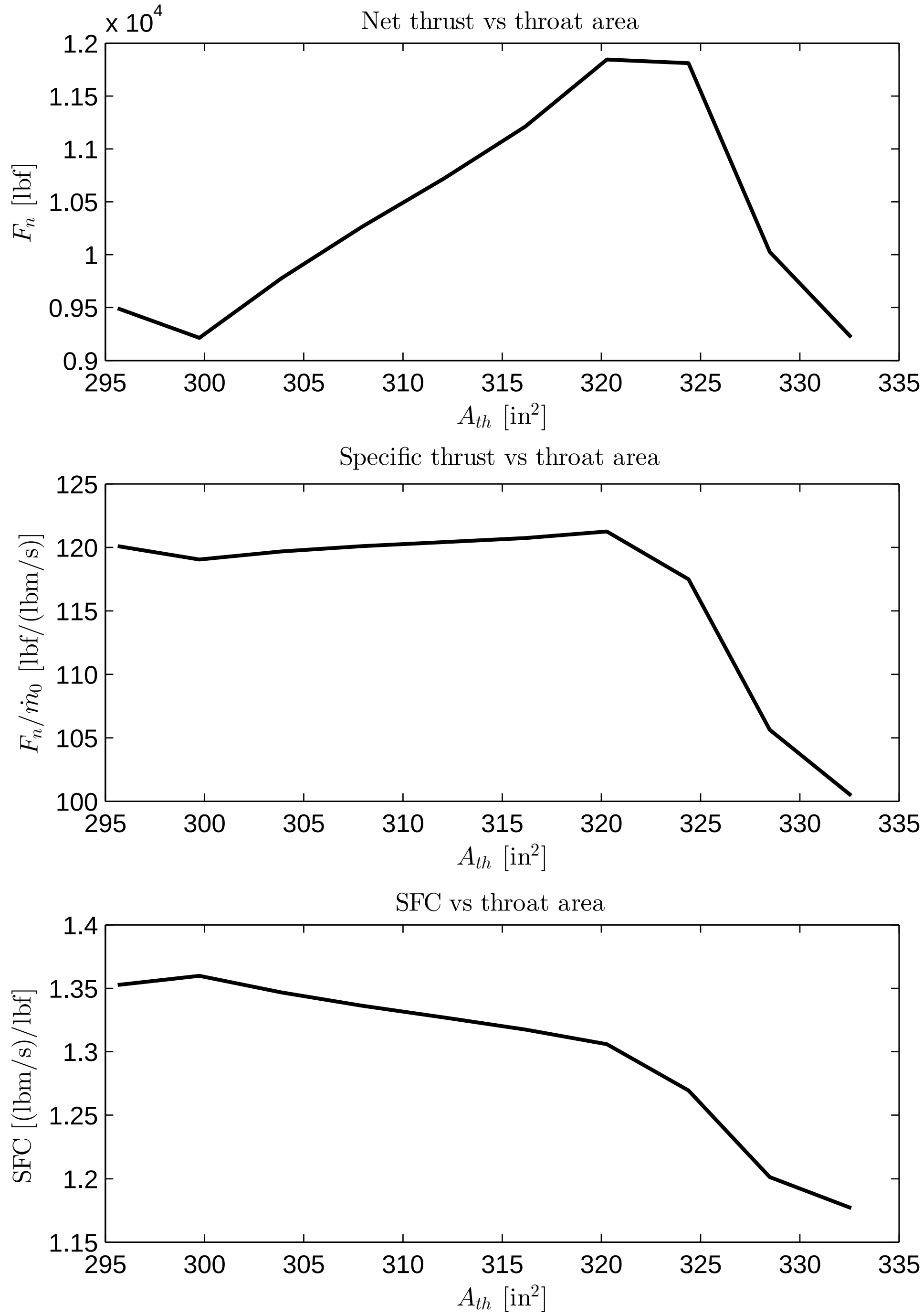


**Figure 2.6.** Engine performance vs nozzle throat area at 40,000 ft.

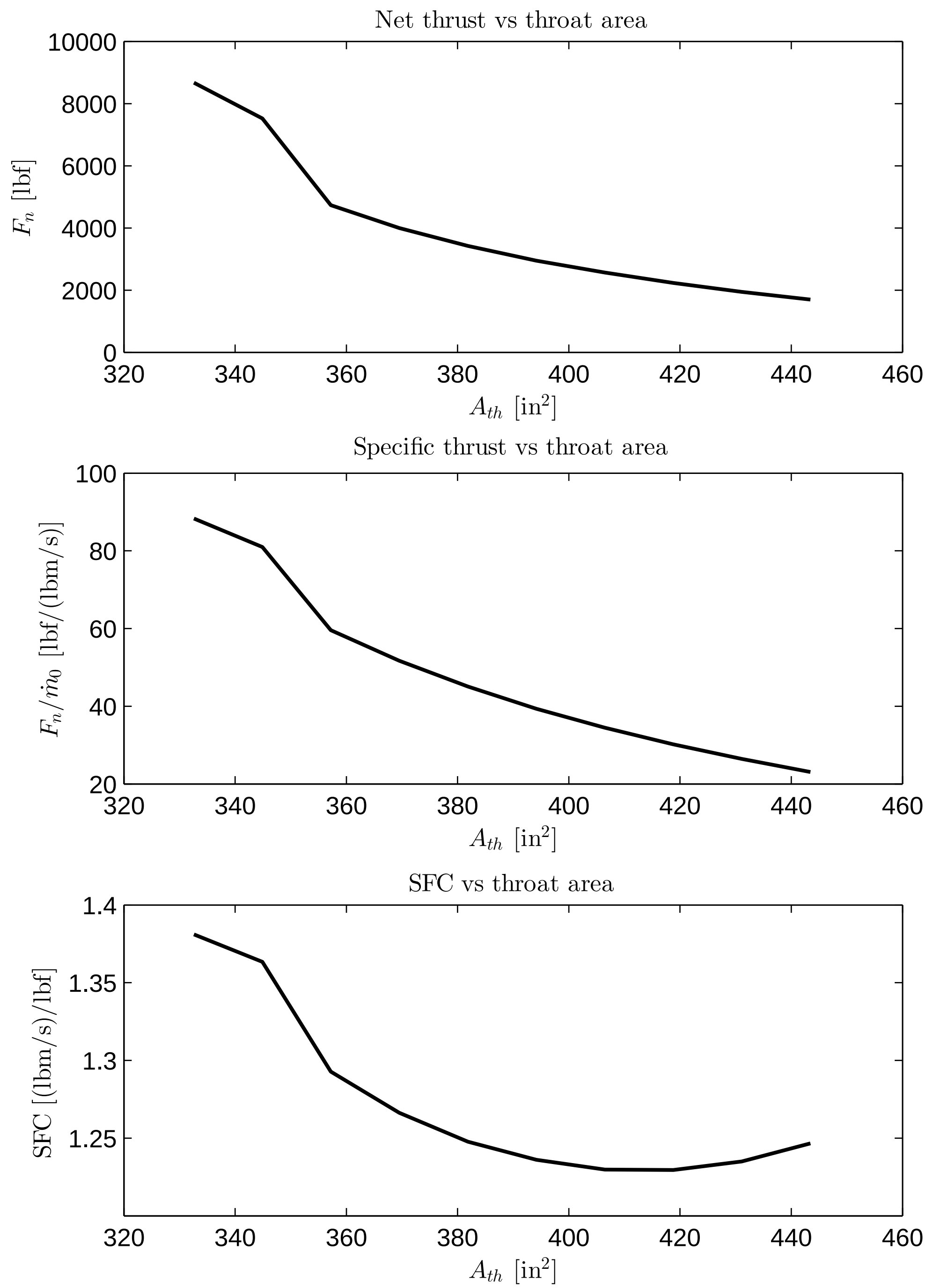


**Figure 2.7.** Engine performance vs nozzle throat area at 60,000 ft.

### 2.2.2 Variation of turbine inlet temperature

To select the optimum design point turbine inlet temperature ($T_{t4}$), the design and off design performance of the afterburning turbojet cycle was calculated for a range of $T_{t4}$ from 3000-3500 °R.

To determine the approximate best value for the design turbine inlet temperature, Figures 2.8 – 2.11 are examined. For each variable, 10 points are plotted. Originally, 100 points were plotted, but due to solver convergence issues, the number of points was reduced. This way, the trends can still be discerned without the issue of solver convergence.

Figures 2.10 and 2.11 depict the variation in off-design engine performance with changes in design point turbine inlet temperature. The plots are depicted in this way so that the effect of the chosen design point value on the off-design operation can be determined.

Examining Figure 2.10, the majority of the range of design point $T_{t4}$ values don't affect the specific thrust too greatly. However, the net thrust peaks around a design point $T_{t4} \approx 3150$ °R. However, the fuel flow rate also peaks around the same design point turbine inlet temperature.

Examining Figure 2.11, the plots spike down from a maximum performance values at $T_{t4} = 3000$ °R. If this rapid decrease in performance with increase in turbine inlet temperature were to be studied in more depth, the first step would be to edit the NPSS code so that the solver converged for an increased number of points, thereby providing increased resolution of the region of interest. Because this trend cannot be fully explained within the time constraints of this project, the range of $T_{t4}$ values to be considered will be reduced to 3100 °R$\leq T_{t4} \leq$ 3500 °R.

Balancing all of the requirements, a design point $T_{t4}$ value of 3300 °R is chosen.

$$\boxed{T_{t4,\text{des}} = 3300\ °\text{R}}$$

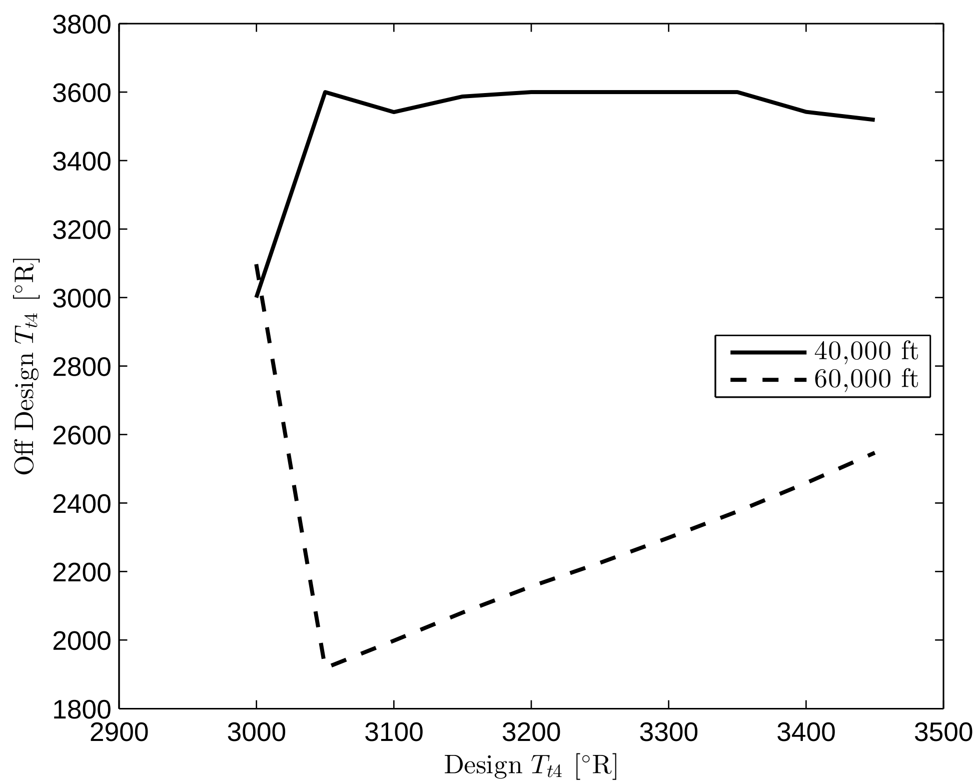


**Figure 2.8.** Effect of variation of design $T_{t4}$ on off design $T_{t4}$.

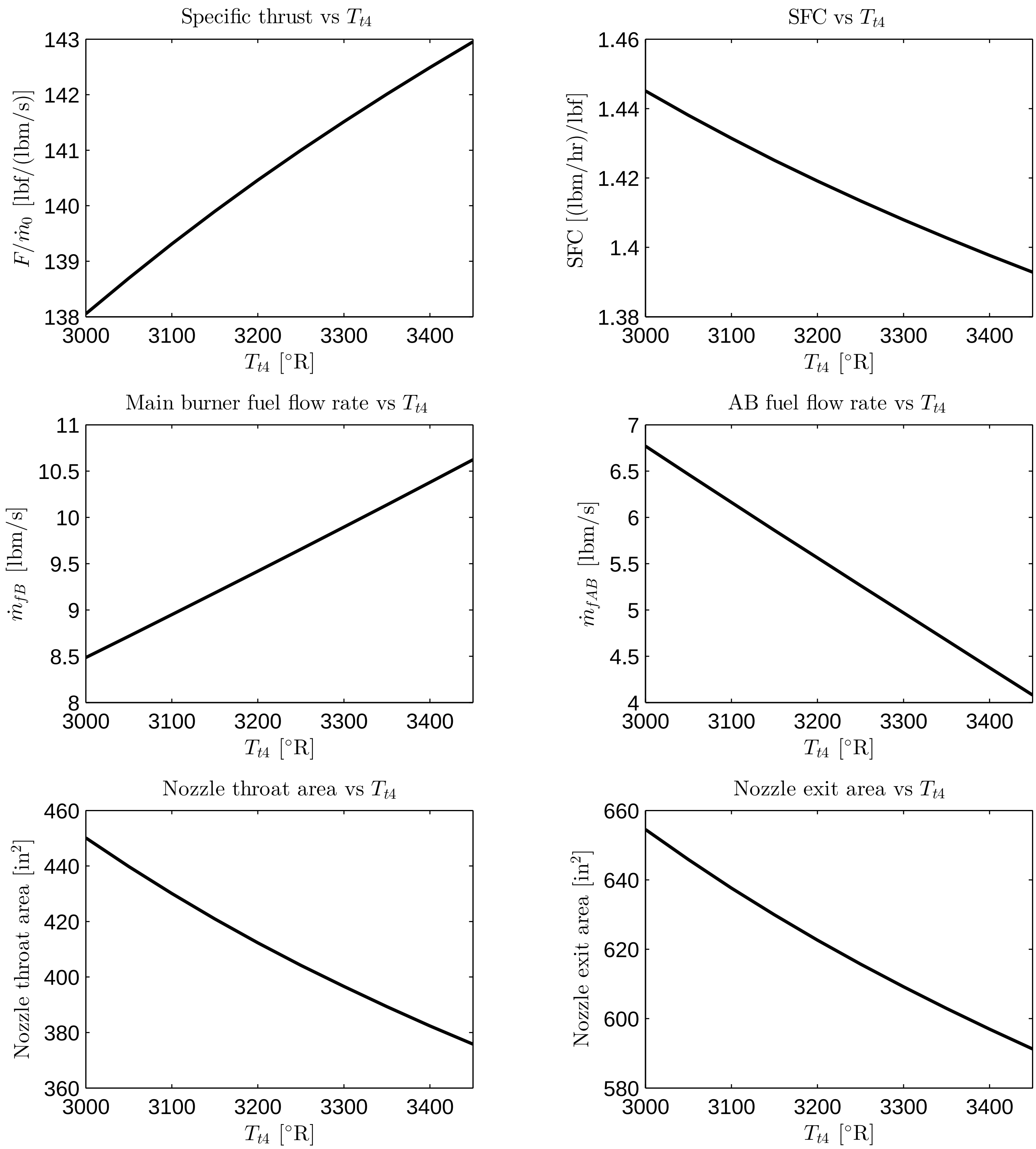


**Figure 2.9.** Variation of design $T_{t4}$ at design point.

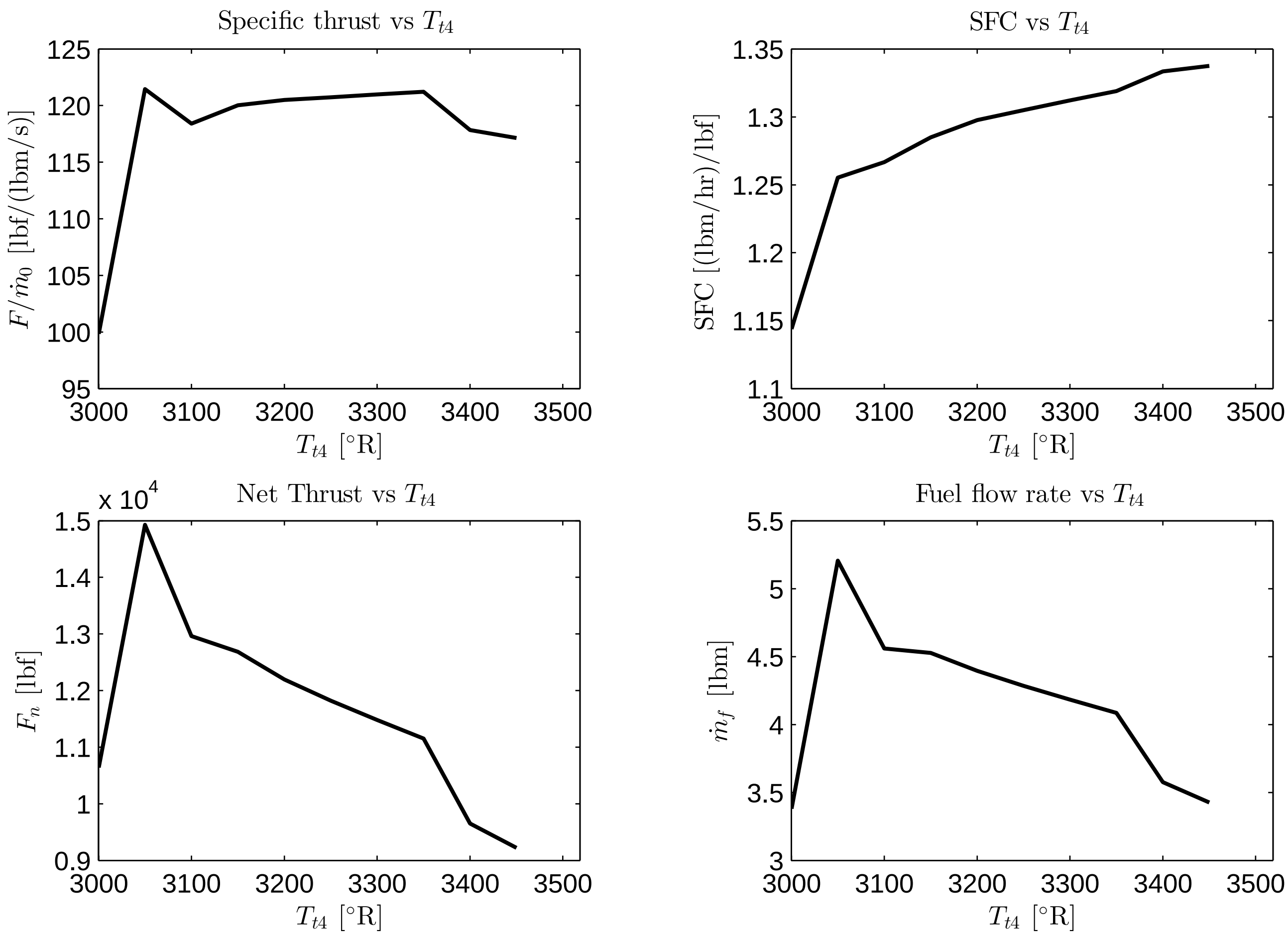


**Figure 2.10.** Effect of variation of design $T_{t4}$ on off design operation at 40,000 ft.

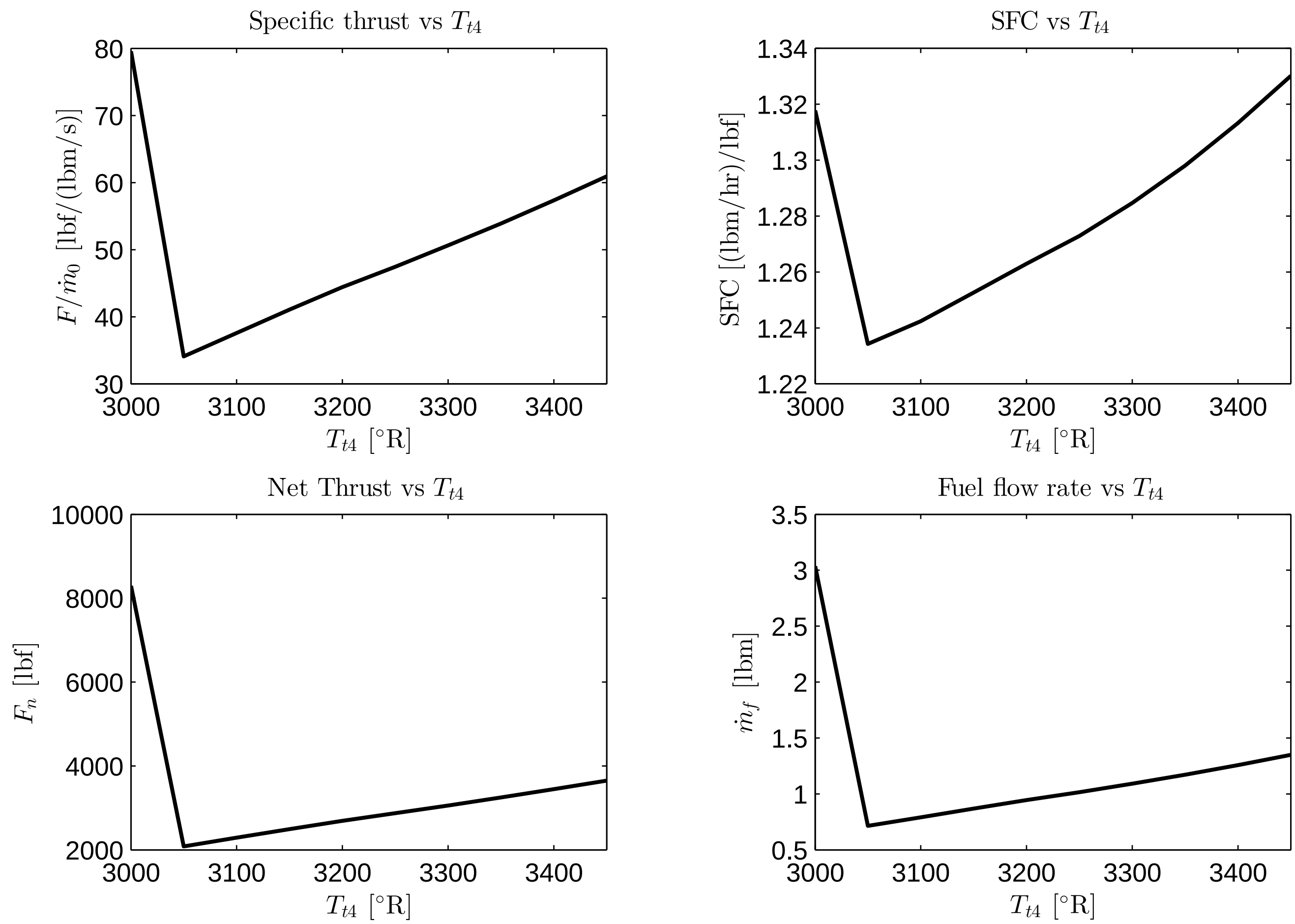


**Figure 2.11.** Effect of variation of design $T_{t4}$ on off design operation at 60,000 ft.

### 2.2.3 Variation of compressor pressure ratio

To select the optimum compressor pressure ratio (CPR), the design and off-design performance of the afterburning turbojet cycle was calculated for a range of $\pi_c$ from 9 to 23. Plots of the resulting data are provided below.

To determine the approximate best value for the design compressor pressure ratio, Figures 2.12 − 2.15 are examined. Balancing the requirements of high thrust, low fuel consumption and solver convergence, a compressor pressure ratio of 15 is chosen.

$$\boxed{\pi_c = 15}$$

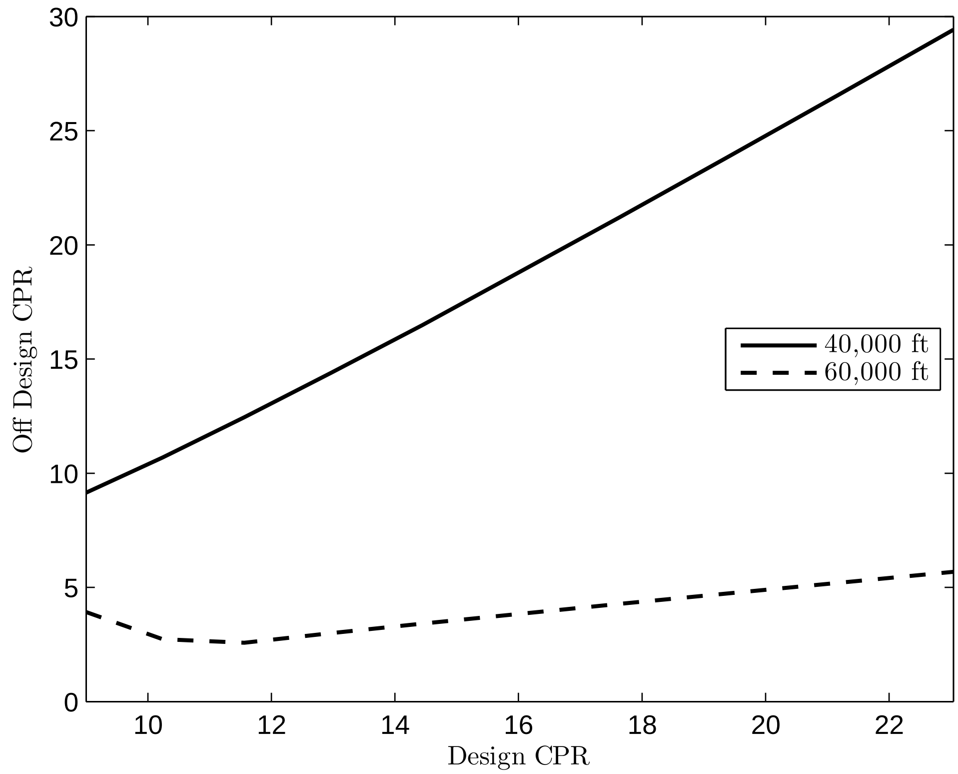


**Figure 2.12.** Effect of variation of design CPR on off design CPRs.

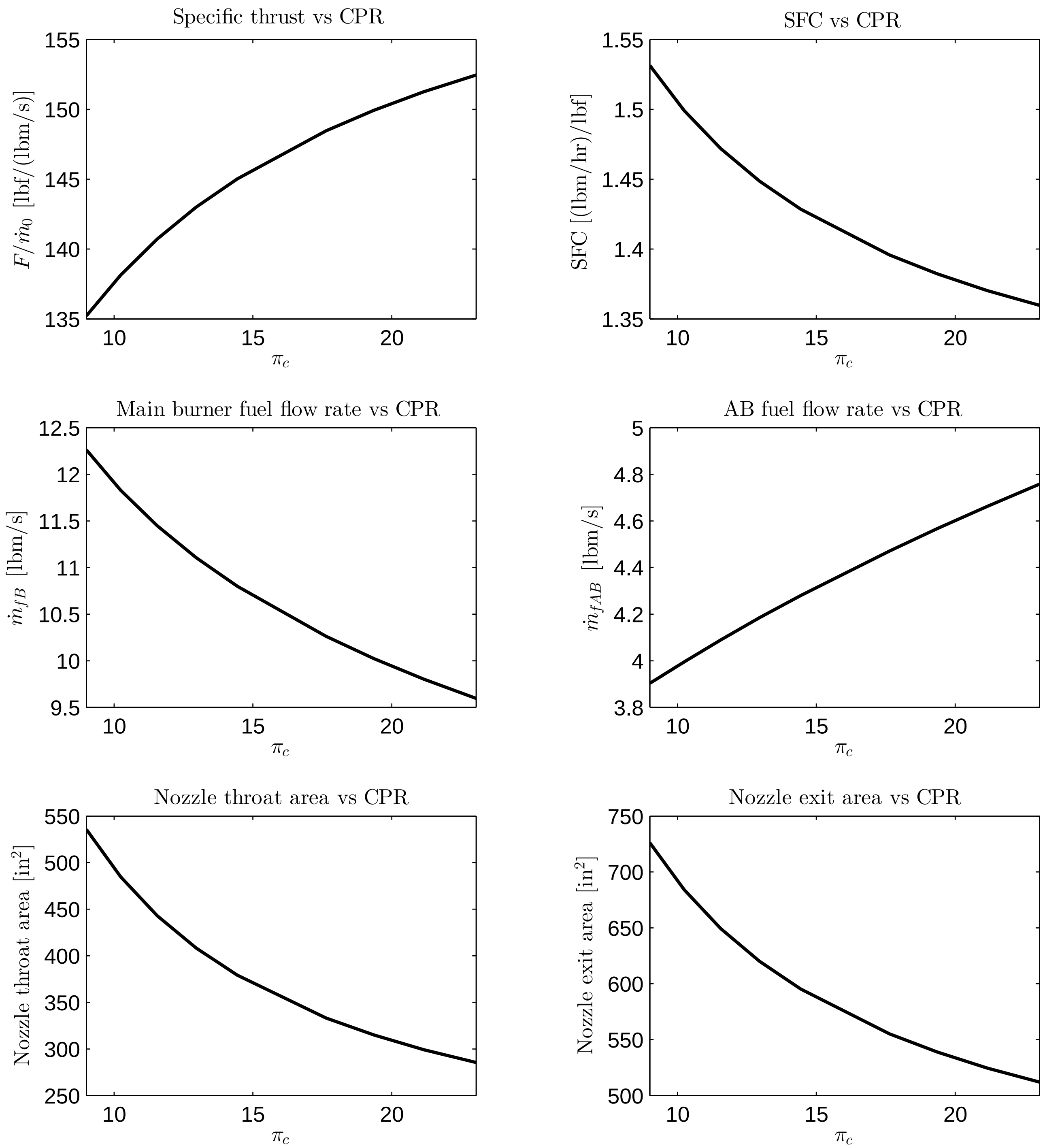


**Figure 2.13.** Variation of design CPR at design point.

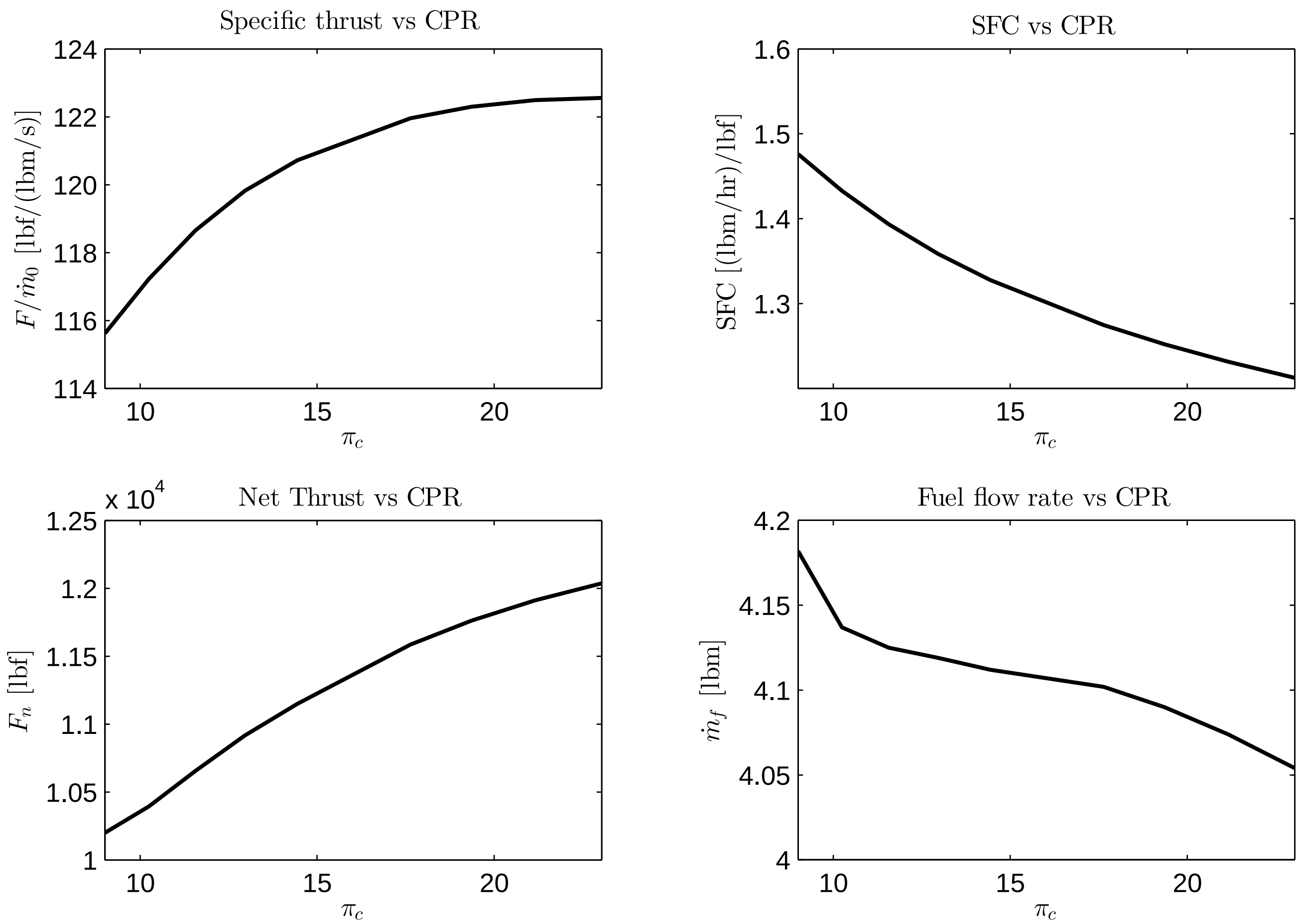


**Figure 2.14.** Effect of variation of design CPR on off design operation at 40,000 ft.

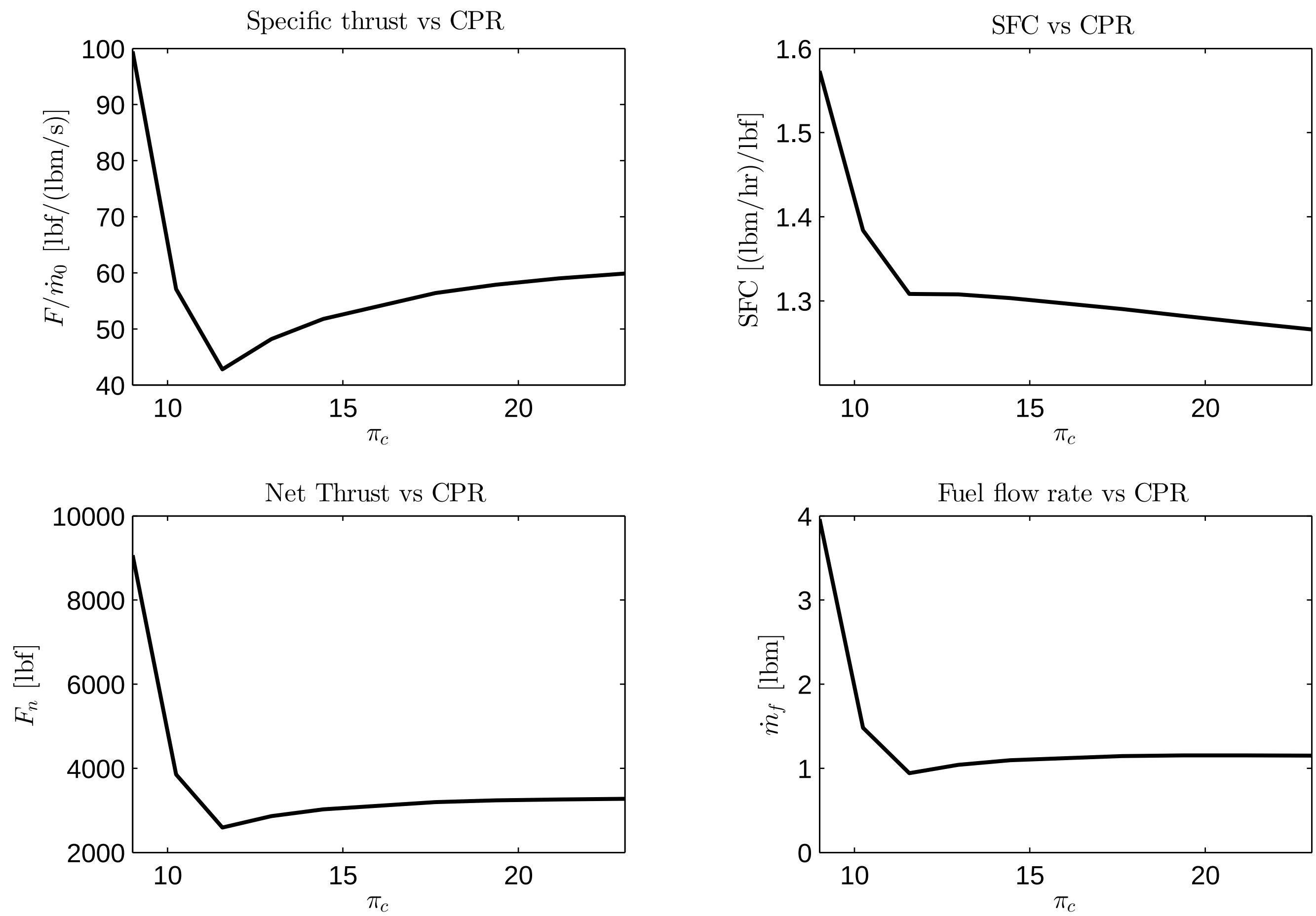


**Figure 2.15.** Effect of variation of design CPR on off design operation at 60,000 ft.

### 2.2.4 Engine diameter

Assuming a Mach number at the compressor face of $M_2 = 0.5$, the area of the compressor face can be determined. NPSS carries out this operation automatically. For all of the previously chosen design parameters, the resulting compressor face area is 1070.8 in$^2$ and engine diameter is 36.9 in.

$$\boxed{A_2 = 1070.8 \text{ in}^2}$$

$$\boxed{\text{Engine Diameter} = 36.9 \text{ in} = 3.1 \text{ ft}}$$

## 2.3 Summary of Final Engine Design

**Table 2.4.** Variation in total temperature and total pressure through engine.

| | Total Temperature [°R] | | | Total Pressure [psia] | | |
|---|---|---|---|---|---|---|
| Station Number | Design Point | 40,000 ft | 60,000 ft | Design Point | 40,000 ft | 60,000 ft |
| F0 | 518.67 | 453.353 | 767.016 | 14.6959 | 4.60152 | 11.1326 |
| F020 | 518.67 | 453.353 | 767.012 | 14.6225 | 4.57851 | 11.0769 |
| F025 | 730.497 | 683.339 | 987.497 | 43.8674 | 16.8577 | 24.8456 |
| F030 | 1187.3 | 1047.43 | 1410.84 | 219.337 | 69.5179 | 79.9612 |
| F040 | 3300 | 2777.07 | 3117.49 | 208.37 | 66.042 | 75.9632 |
| F045 | 2953.9 | 2491.34 | 2778.36 | 117.823 | 38.5348 | 42.4055 |
| F050 | 2796.18 | 2312.07 | 2606.25 | 89.1949 | 26.8118 | 30.8297 |
| F070 | 3600 | 2329.11 | 2623.48 | 84.7352 | 25.4712 | 29.2882 |
| F090 | 3600 | 2329.11 | 2623.48 | 84.7352 | 25.4712 | 29.2882 |

**Table 2.5.** Summary of final design parameters.

| Parameter | Chosen Value |
|---|---|
| $\pi_c$ | 15 |
| $T_{t4}$ | 3300 °R |
| $T_{t7}$ | 3600 °R |
| Engine diameter | 3.1 ft |

**Table 2.6.** Performance data per engine.

| | Units | Design Point | 40,000 ft | 60,000 ft |
|---|---|---|---|---|
| Net Thrust Available | [lbf] | 38000 | 8739 | 8189 |
| Specific Fuel Consumption | [lbm/(hr·lbf)] | 1.3736 | 1.1213 | 1.3343 |
| Total Fuel Flow Rate | [lbm/s] | 14.500 | 2.7217 | 3.0351 |
| Fuel Consumption | [lbm] | 4350[a] | 30752 | 51439 |
| Engine Air Flow Rate | [lbm/s] | 272.94 | 94.955 | 102.56 |

The total fuel consumption is determined by summing the takeoff and off design fuel consumption values.

$$\boxed{\begin{aligned} \text{Total Fuel Consumption with Takeoff Fuel Burn} &= 86,541 \text{ lbm} \\ \text{Total Fuel Consumption for Cruise} &= 82,191 \text{ lbm} \end{aligned}}$$

The NPSS output for the designed engine is included below for reference.

[a]This value for fuel consumption is calculated assuming take-off power is maintained for 5 minutes.

```
=======================================
=====    RUNNING DESIGN POINT     =====
=======================================

Altitude = 0 ft
Mach Number = 0
Engine Air Flow = 272.939 lbm/s

F020 A = 1070.83
F080 A = 396.501
F090 A = 608.003

F020 M = 0.5
F080 M = 1
F090 M = 1.82267

F0  Tt = 518.67 R
F020 Tt = 518.67 R
F025 Tt = 730.497 R
F030 Tt = 1187.3 R
F040 Tt = 3300 R
F045 Tt = 2953.9 R
F050 Tt = 2796.18 R
F070 Tt = 3600 R
F090 Tt = 3600 R

F0  Pt  = 14.6959 psia
F0  Ps  = 14.6959 psia
F020 Pt = 14.6225 psia
F025 Pt = 43.8674 psia
F030 Pt = 219.337 psia
F040 Pt = 208.37 psia
F045 Pt = 117.823 psia
F050 Pt = 89.1949 psia
F070 Pt = 84.7352 psia
F080 Pt = 84.7352 psia
F090 Pt = 84.7352 psia
F090 Ps = 14.6959 psia

CompL PR = 3
CompH PR = 5
TurbH PR = 1.7685
TurbL PR = 1.32096
CompL eff = 0.9
CompH eff = 0.9
TurbH eff = 0.9
TurbL eff = 0.9
Comp pwr = -63381.6 hp
Turb pwr = 63381.1 hp

L Shaft RPM = 5000
H Shaft RPM = 10000
Burner Wfuel = 10.0567 lbm/s
Afterburner Wfuel = 4.44343 lbm/s
SFC = 1.37369 lbm/(hr*lbf)
Gross Thrust = 38000.1 lbf
Net Thrust = 38000.1 lbf
```

```
Solver converged (1 = yes, 0 = no) ? = 1
Iterations = 71
Constraints Active? = 0
Constraints Hit =

==============================================
=====    RUNNING OFF DESIGN - 40k ft     =====
==============================================

Altitude = 40000 ft
Mach Number = 0.9
Engine Air Flow = 94.9552 lbm/s

F020 A = 1070.83
F080 A = 356.849
F090 A = 698.573

F020 M = 0.527892
F080 M = 1
F090 M = 2.10838

F0  Tt = 453.353 R
F020 Tt = 453.353 R
F025 Tt = 683.339 R
F030 Tt = 1047.43 R
F040 Tt = 2777.07 R
F045 Tt = 2491.34 R
F050 Tt = 2312.07 R
F070 Tt = 2329.11 R
F090 Tt = 2329.11 R

F0  Pt  = 4.60152 psia
F0  Ps  = 2.71999 psia
F020 Pt = 4.57851 psia
F025 Pt = 16.8577 psia
F030 Pt = 69.5179 psia
F040 Pt = 66.042 psia
F045 Pt = 38.5348 psia
F050 Pt = 26.8118 psia
F070 Pt = 25.4712 psia
F080 Pt = 25.4712 psia
F090 Pt = 25.4712 psia
F090 Ps = 2.71998 psia

CompL PR = 3.68191
CompH PR = 4.12381
TurbH PR = 1.71383
TurbL PR = 1.43724
CompL eff = 0.888861
CompH eff = 0.913523
TurbH eff = 0.898512
TurbL eff = 0.904154
Comp pwr = -19413.5 hp
Turb pwr = 19413.5 hp

L Shaft RPM = 5200
H Shaft RPM = 9376.69
Burner Wfuel = 2.72171 lbm/s
Afterburner Wfuel = 0 lbm/s
```

```
SFC = 1.12126 lbm/(hr*lbf)
Gross Thrust = 11311 lbf
Net Thrust = 8738.52 lbf

Solver converged (1 = yes, 0 = no) ? = 1
Iterations = 52
Constraints Active? = 1
Constraints Hit =
        Constraint 'dep_NmechL_max' overrides Target 'dep_Fn'.

==============================================
=====    RUNNING OFF DESIGN - 60k ft     =====
==============================================

Altitude = 60000 ft
Mach Number = 2.2
Engine Air Flow = 102.563 lbm/s

F020 A = 1070.83
F080 A = 356.851
F090 A = 1391.46

F020 M = 0.273005
F080 M = 1
F090 M = 2.76867

F0  Tt = 767.016 R
F020 Tt = 767.012 R
F025 Tt = 987.497 R
F030 Tt = 1410.84 R
F040 Tt = 3117.49 R
F045 Tt = 2778.36 R
F050 Tt = 2606.25 R
F070 Tt = 2623.48 R
F090 Tt = 2623.48 R

F0  Pt  = 11.1326 psia
F0  Ps  = 1.04012 psia
F020 Pt = 11.0769 psia
F025 Pt = 24.8456 psia
F030 Pt = 79.9612 psia
F040 Pt = 75.9632 psia
F045 Pt = 42.4055 psia
F050 Pt = 30.8297 psia
F070 Pt = 29.2882 psia
F080 Pt = 29.2882 psia
F090 Pt = 29.2882 psia
F090 Ps = 1.04013 psia

CompL PR = 2.243
CompH PR = 3.21833
TurbH PR = 1.79135
TurbL PR = 1.37548
CompL eff = 0.881087
CompH eff = 0.864033
TurbH eff = 0.896308
TurbL eff = 0.897125
Comp pwr = -23500.3 hp
Turb pwr = 23500.1 hp
```

```
L Shaft RPM = 4767.36
H Shaft RPM = 11000
Burner Wfuel = 3.03512 lbm/s
Afterburner Wfuel = 0 lbm/s
SFC = 1.3343 lbm/(hr*lbf)
Gross Thrust = 14980.9 lbf
Net Thrust = 8188.9 lbf

Solver converged (1 = yes, 0 = no) ? = 1
Iterations = 79
Constraints Active? = 1
Constraints Hit =
        Constraint 'dep_NmechH_max' overrides Target 'dep_Fn'.
```

# Chapter 3

# Off-Design Performance

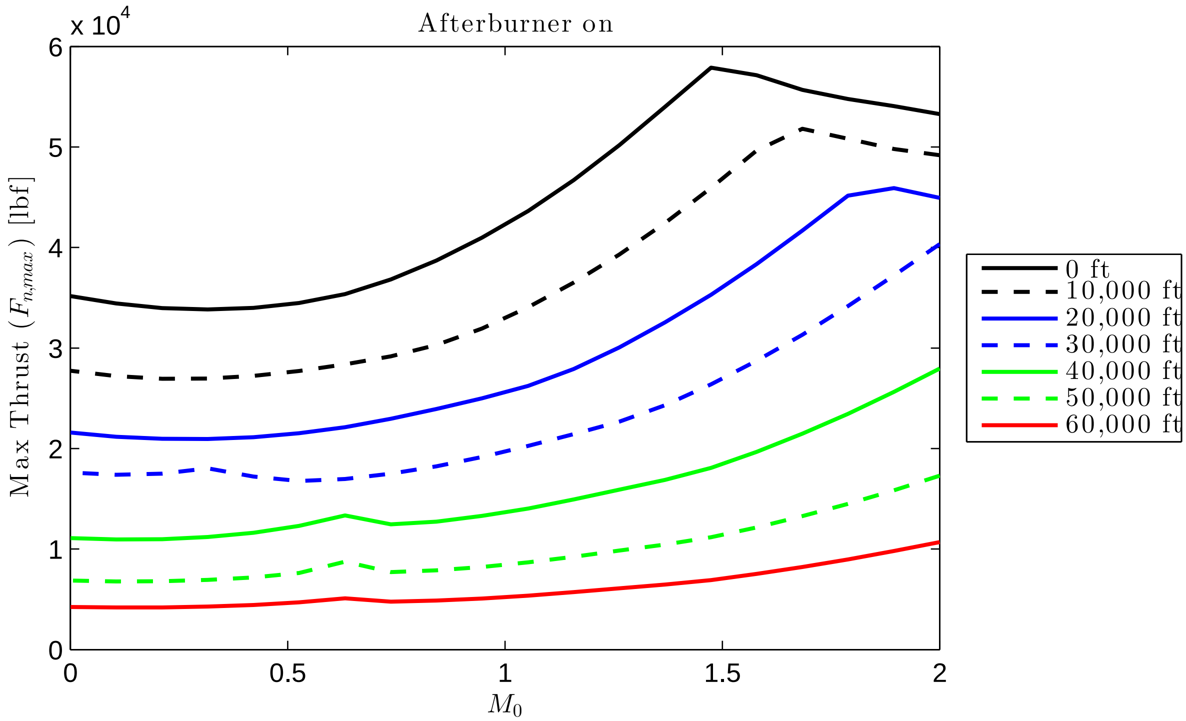


**Figure 3.1.** Max Thrust vs $M_0$ with afterburner on.

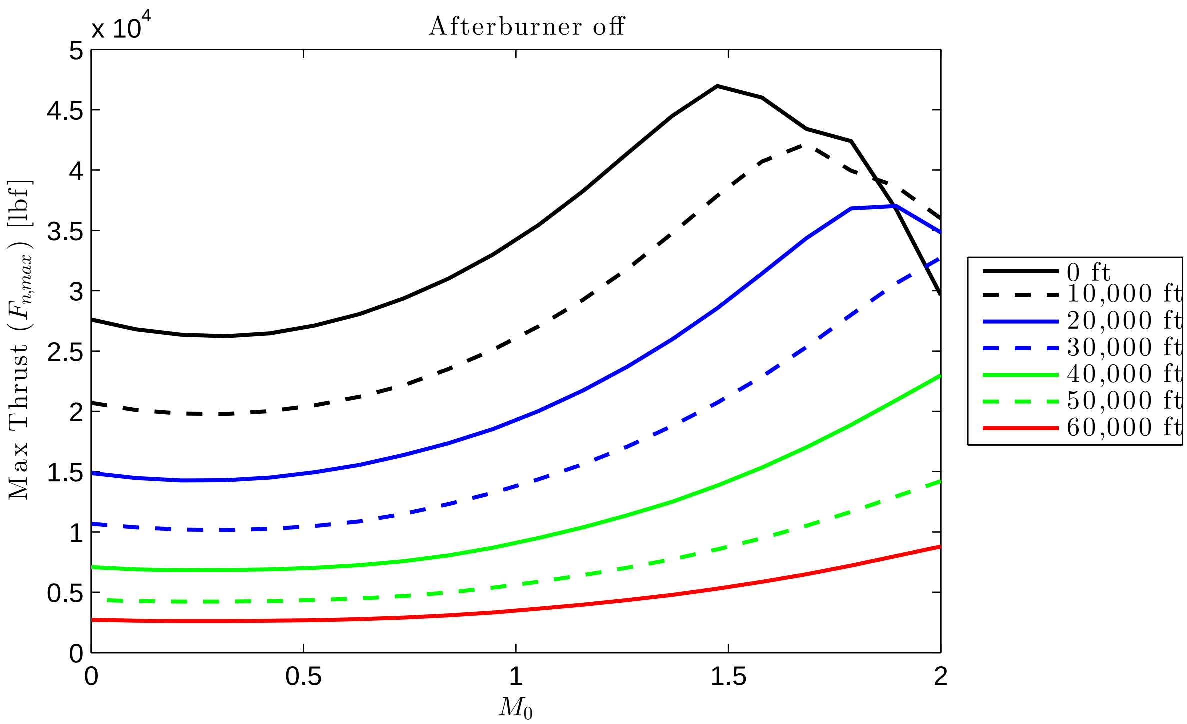


**Figure 3.2.** Max Thrust vs $M_0$ with afterburner off.

# Chapter 4

# Acceleration Transient

NPSS was used to calculate the transient response of the engine to a fuel flow rate increase. The problem statement requires calculation of the time required to accelerate the engine from 60% RPM to 100% RPM. To simulate a phase of flight in which this transient engine response is critical, the altitude and Mach number inputs to NPSS were set to 500 feet and $M_0 = 0.25$, respectively. These values were chosen because they represent realistic values for a situation in which the aircraft is on final approach to a runway. If the pilots must execute a missed approach, engine power is increased rapidly to provide the thrust necessary for climb out.

Assuming the max RPM is fixed at 5200 (set in NPSS), previously written NPSS code was modified for this transient simulation. Because the engine is dual spool, there are two RPMs to consider, the low pressure shaft and the high pressure shaft. For this simulation, the initial and final fuel flow rates were varied so that the increase in engine RPM was from approximately 60% of the max RPM to the actual max RPM of 5200. The variation in shaft RPM for both shafts can be seen in Figures 4.3 and 4.4.

Initially, the fuel flow rate was increased rapidly over a time duration of 0.1 seconds. This input resulted in the turbine inlet temperature ($T_{t4}$) peaking at approximately 4500 °R, well above the max turbine inlet temperature of 3600 °R from Mattingly's level 4 technology values. To mitigate this potentially disastrous scenario, the time duration of the unit step was increased to 0.5 seconds. This time duration results in turbine inlet temperatures that are within limitations (see Figure 4.5).

To determine the approximate value for the time required to accelerate the engine from 60% RPM to 100% RPM, Figure 4.3 is used because the low pressure shaft was chosen as a reference. Using Figure 4.3, the time is determined to be

$$\boxed{t \approx 3 \text{ seconds}}$$

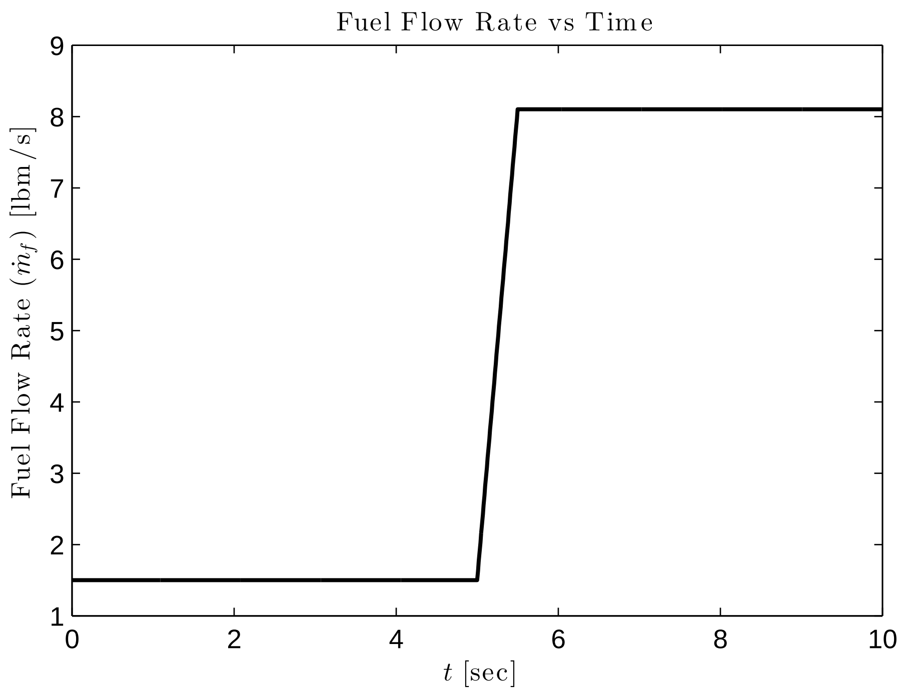


**Figure 4.1.** Fuel flow rate ($\dot{m}_f$) vs time.

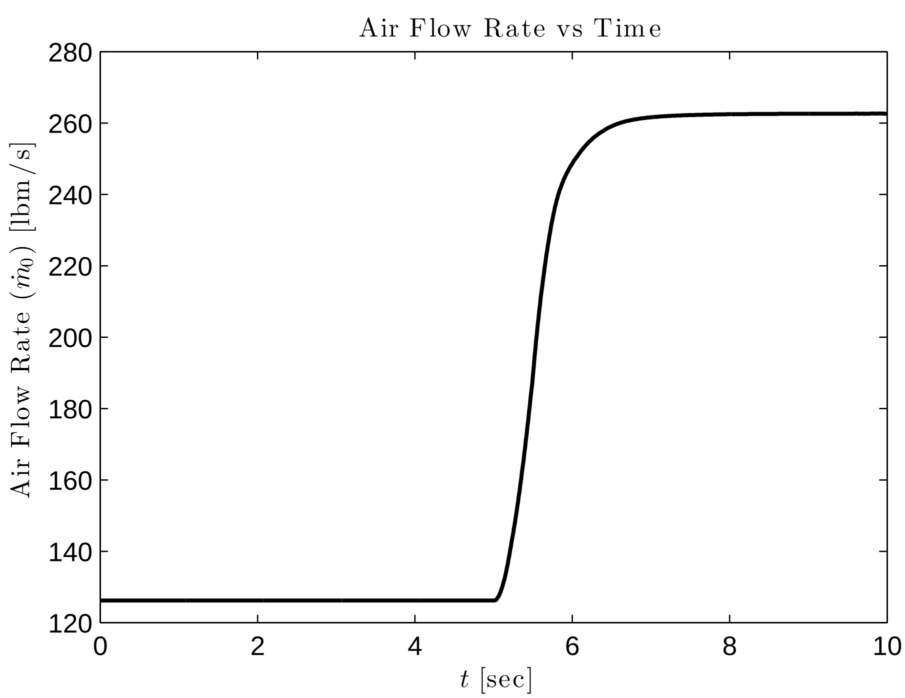


**Figure 4.2.** Air flow rate ($\dot{m}_0$) vs time.

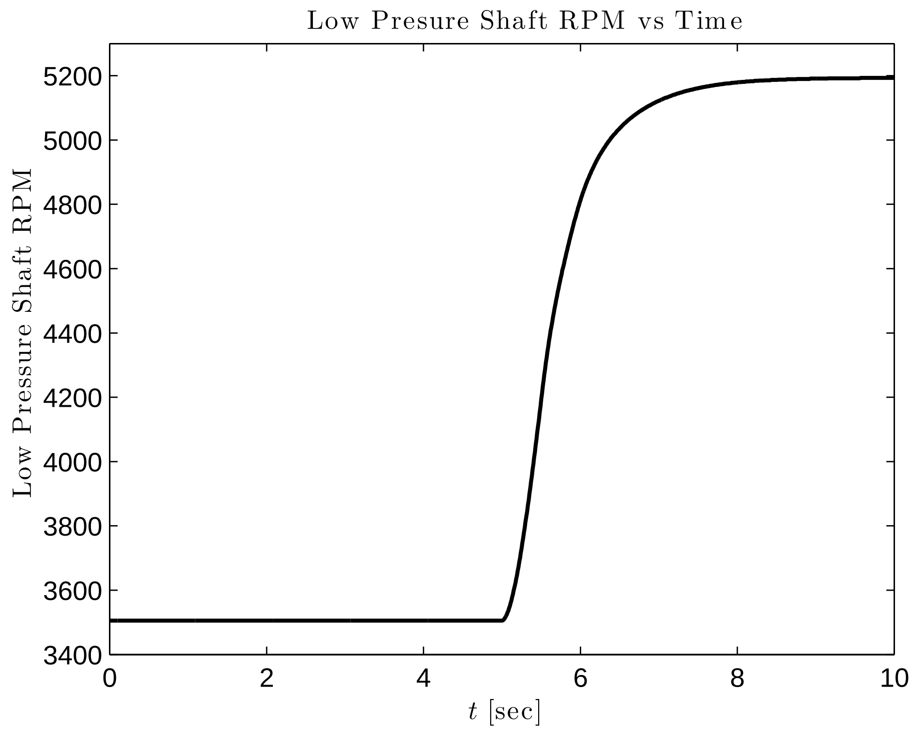


**Figure 4.3.** Low pressure shaft RPM vs time.

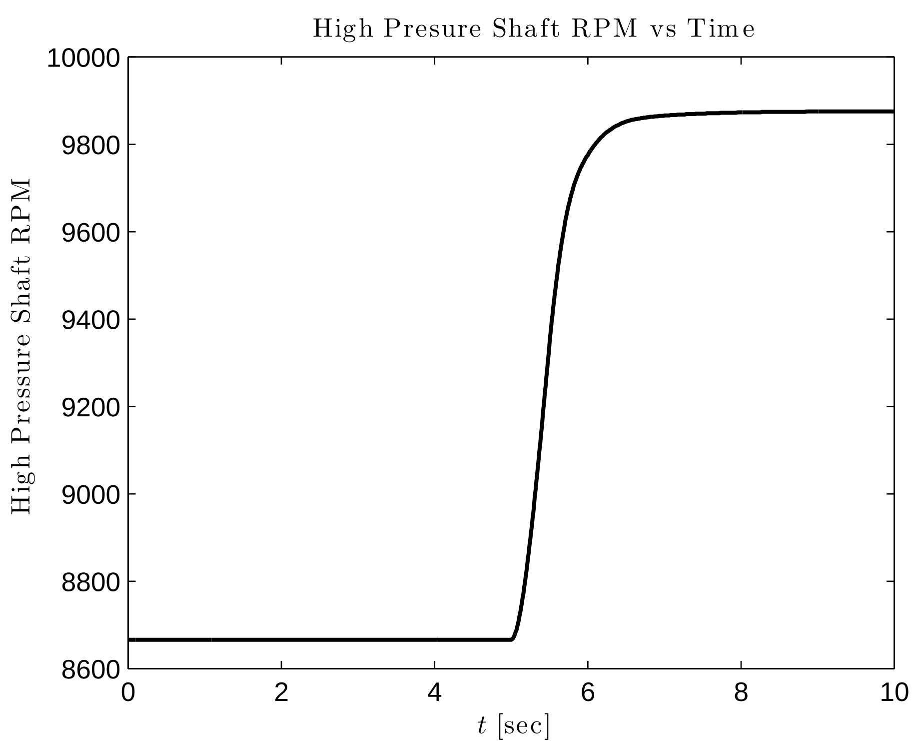


**Figure 4.4.** High pressure shaft RPM vs time.

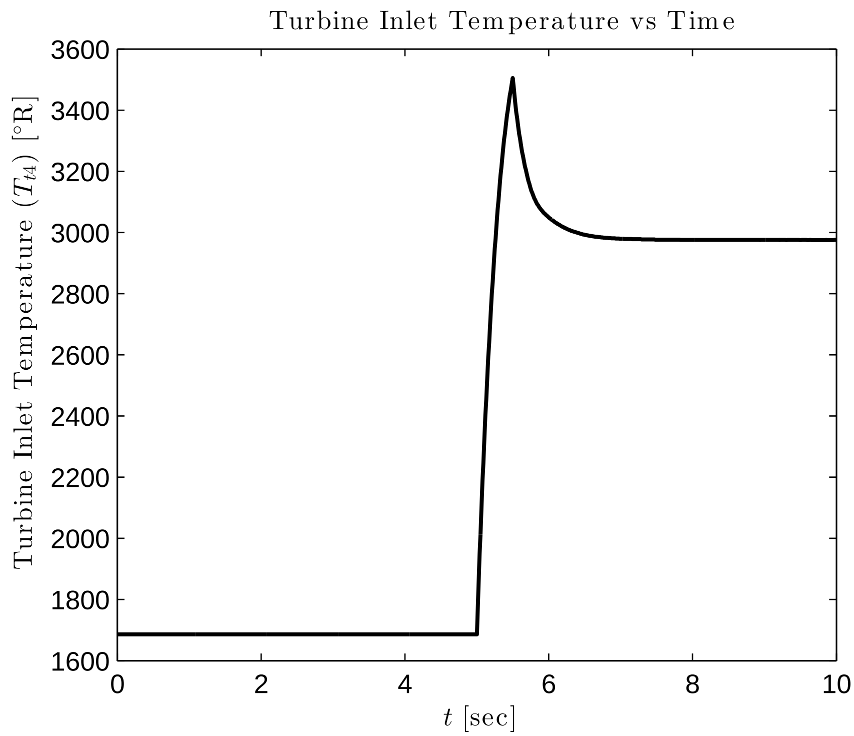


**Figure 4.5.** Turbine inlet temperature ($T_{t4}$) vs time.

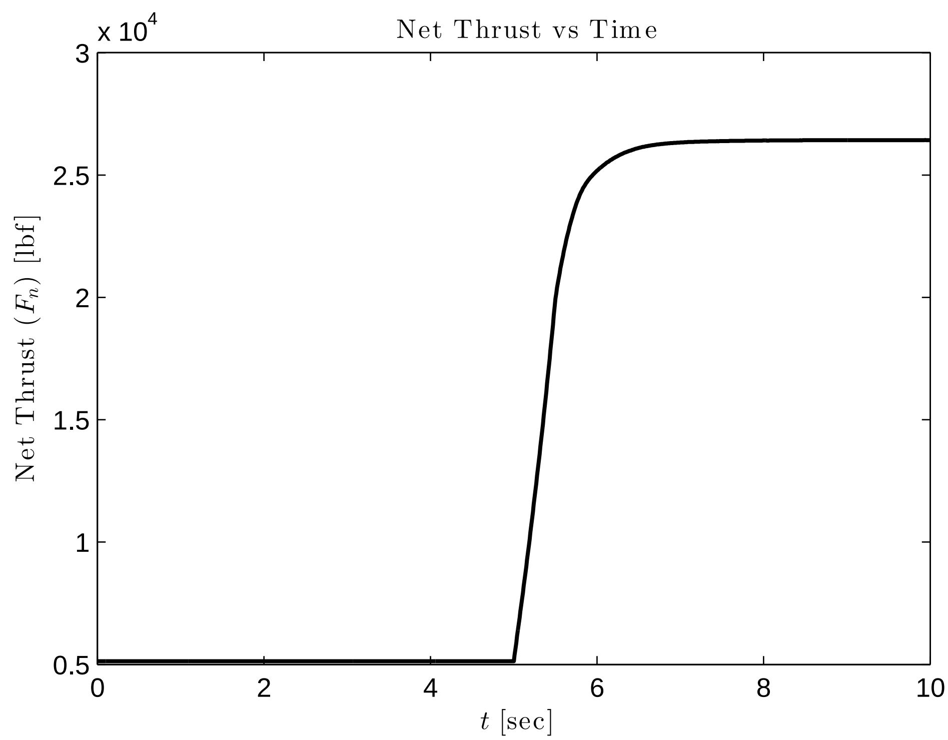


**Figure 4.6.** Net thrust ($F_n$) vs time.

# Bibliography

[1] Kurzke, Joachim, ”The Mission Defines the Cycle: Turbojet, Turbofan and Variable Cycle Engines for High Speed Propulsion”, RTO-EN-AVT-185, 2010.

[2] Mattingly, Jack D., *Elements of Propulsion: Gas Turbines and Rockets*, AIAA, Reston, Virginia, 2006.

[3] Whitlow, John B., C, *Comparison of Parametric Duct-Burning Turbofan and Non-Afterburning Turbojet Engines in a Mach 2.7 Transport*, NASA TM X-71679, March 1975.

# Appendix A

# Model Validation

To make sure that the NPSS models were functioning correctly, results from two NPSS models, the afterburning turbojet and the mixed-flow turbofan, were compared with results from Mattingly's PERF code. The results are outlined below.

## A.1 Afterburning Turbojet

Comparing the Thrust Specific Fuel Consumption and the Net Thrust between Mattingly's PERF and NPSS, the numbers are relatively close.

PERF Results:

```
Parameter                        Reference**           Test**
Mach Number @ 0                    2.0000            2.0000
Temperature @ 0                    393.85            394.06 R
Pressure    @ 0                    3.4676            3.4676 psia
Altitude    @ 0                     35000             35000 ft
Total Temp  @ 4                   3200.00           3200.00 R
Total Temp  @ 7                   3600.00           3600.00 R
Pi r  / Tau r                7.8244/ 1.8000     7.8245/ 1.8000
Pi d                               0.9065            0.9065
Pi cL / Tau cL               3.0000/ 1.4229     2.9985/ 1.4227
Pi cH / Tau cH               4.6667/ 1.6307     4.6645/ 1.6305
Pi tH / Tau tH               0.3997/ 0.8283     0.3997/ 0.8283
Pi tL / Tau tL               0.6097/ 0.9023     0.6097/ 0.9023
Control Limit                                         Tt4max
LP Spool RPM (% of Reference Pt)  100.00            100.00
HP Spool RPM (% of Reference Pt)  100.00            100.00
Pt9/P9                            23.0088            1.8324
P0/P9                              1.0000            0.0805
Mach Number @ 9                    2.6608            1.0000
Mass Flow Rate @ 0                 200.00            199.81
Corr Mass Flow @ 0                 126.65            126.56 lb/sec
Flow Area      @ 0                  4.326             4.323 ft^2
Flow Area*     @ 0                  2.563             2.562 ft^2
Flow Area      @ 9                  7.442             2.133 ft^2
MB - Fuel/Air Ratio (f)           0.02766           0.02765
```

```
    AB - Fuel/Air Ratio (fAB)        0.02375            0.02375
    Overall Fuel/Air Ratio (fo)      0.05140            0.05140
    Specific Thrust  (F/m0)           110.54              86.44 lbf/(lbm/sec)
    Thrust Spec Fuel Consumption (S)  1.6741             2.1405 lbm/(hr-lbf)
    Thrust (F)                         22108              17271 lb
    Fuel Flow Rate                     37010              36969 lb/hr
    Propulsive Efficiency (%)          55.34             308.96
    Thermal Efficiency    (%)          52.81               7.40
    Overall Efficiency    (%)          29.23              22.86

  Test Results at Engine Stations (PERF Ver 4.2)    Date:4/22/2013 3:30:03 PM
   Filename: User_Input_Date:4/22/2013_Time:3:06:39 PM
   Percent Thrust = 100   Altitude = 35000 ft   Mach = 2   Standard Day

 Station   m dot  gamma     Pt      Tt        P        T      Mach Velocity
         (lbm/s)         (psia)     (R)    (psia)     (R)            (ft/s)
  0       199.81 1.4000  27.132  709.31   3.468  394.06  2.0000 1946.16
  1       199.81 1.4000  25.097  709.31  16.503  629.24  0.7977  980.82
  2       199.81 1.4000  24.595  709.31  20.742  675.61  0.4994  636.33
  2.5     199.81 1.4000  73.750 1009.11  65.474  975.37  0.4159  636.67
  3       199.81 1.4000 344.004 1645.35 319.924 1611.58  0.3237  636.92
 MB fuel  5.5246
  4       205.33 1.3000 337.124 3200.00 183.978 2782.61  1.0000 2401.75
  4.5     205.33 1.3000 134.748 2650.65  73.536 2304.91  1.0000 2185.89
  5       205.33 1.3000  82.157 2391.80  63.502 2253.78  0.6390 1381.11
 AB fuel  4.7448
  7       210.08 1.3000  80.514 3600.00  68.642 3469.88  0.5000 1386.40
  8       210.08 1.3000  80.514 3600.00  43.939 3130.43  1.0000 2633.67
  9       210.08 1.3000  78.904 3600.00  43.060 3130.43  1.0000 2633.67
```

NPSS Results:

```
Altitude = 35000 ft
Mach Number = 2
Engine Air Flow = 200 lbm/s

F0   Ts = 393.853 R
F0   Tt = 708.982 R
F020 Tt = 708.979 R
F025 Tt = 996.104 R
F030 Tt = 1559.75 R
F040 Tt = 3200 R
F045 Tt = 2743.54 R
F050 Tt = 2518.64 R
F070 Tt = 3599.99 R
F090 Tt = 3599.99 R

F0   Pt   = 27.0706 psia
F0   Ps   = 3.45777 psia
F020 Pt = 26.5292 psia
F025 Pt = 79.5877 psia
F030 Pt = 371.404 psia
F040 Pt = 363.976 psia
F045 Pt = 165.711 psia
F050 Pt = 108.532 psia
F070 Pt = 106.361 psia
F090 Pt = 106.361 psia
```

```
F090 Ps = 58.646 psia

CompL PR = 3
TurbL PR = 1.52685
CompL eff = 0.89
TurbL eff = 0.9
CompL pwr = -19887.1 hp
TurbL pwr = 19887.6 hp

Shaft L RPM = 5000
Shaft H RPM = 10000
Wfuel = 5.75984 lbm/s
ABWfuel = 4.46129 lbm/s
SFC = 2.06417 lbm/(hr*lbf)
Gross Thrust = 29926.4 lbf
Net Thrust = 17826.1 lbf
```

## A.2 Mixed-flow Afterburning Turbofan

PERF Results:

```
Parameter                        Reference**            Test**
Mach Number @ 0                      2.0000            2.0000
Temperature @ 0                      394.06            394.06 R
Pressure    @ 0                      3.4676            3.4676 psia
Altitude    @ 0                       35000             35000 ft
Total Temp  @ 4                     3200.00           3200.00 R
Total Temp  @ 7                     3600.00           3600.00 R
Pi r  / Tau r              7.8244/ 1.8000     7.8244/ 1.8000
Pi d                                 0.9204            0.9204
Pi f  / Tau f              2.0000/ 1.2492     2.0000/ 1.2492
Pi cL / Tau cL             4.0000/ 1.5529     4.0000/ 1.5529
Pi cH / Tau cH             5.0000/ 1.6668     5.0000/ 1.6668
Pi tH / Tau tH             0.3773/ 0.8168     0.3773/ 0.8168
Pi tL / Tau tL             0.2881/ 0.7722     0.2881/ 0.7722
Control Limit                                           Tt4max
LP Spool RPM (% of Reference Pt)  100.00            100.00
HP Spool RPM (% of Reference Pt)  100.00            100.00
Mach Number @ 6                      0.5000            0.5000
Mach Number @ 16                     0.4305            0.4305
Mach Number @ 6A                     0.4922            0.4922
Gamma       @ 6A                     1.3596            1.3596
cp          @ 6A                     0.2586            0.2586
Pt16/Pt6                             0.9684            0.9684
Pi M / Tau M               0.9401/ 0.6557     0.9401/ 0.6557
Alpha                                 2.000             2.000
Pt9/P9                              12.8840            1.8685
P0/P9                                1.0000            0.1450
Mach Number @ 9                      2.3147            1.0172
Mass Flow Rate @ 0                   200.00            200.00
Corr Mass Flow @ 0                   126.68            126.68 lb/sec
Flow Area      @ 0                    4.327             4.327 ft^2
Flow Area*     @ 0                    2.564             2.564 ft^2
Flow Area      @ 9                    9.131             3.765 ft^2
```

```
   MB - Fuel/Air Ratio (f)          0.02417            0.02417
   AB - Fuel/Air Ratio (fAB)        0.04147            0.04147
   Overall Fuel/Air Ratio (fo)      0.04952            0.04952
   Specific Thrust  (F/m0)            98.29              82.11 lbf/(lbm/sec)
   Thrust Spec Fuel Consumption (S)  1.8138             2.1711 lbm/(hr-lbf)
   Thrust (F)                         19658              16423 lb
   Fuel Flow Rate                     35656              35656 lb/hr
   Propulsive Efficiency (%)          58.40             277.27
   Thermal Efficiency    (%)          46.20               8.13
   Overall Efficiency    (%)          26.98              22.54

Station    m dot  gamma     Pt      Tt
          (lbm/s)          (psia)     (R)
 0        200.00 1.4000  27.132  709.31
 1        200.00 1.4000  25.097  709.31
 2        200.00 1.4000  24.972  709.31
 13       200.00 1.4000  49.944  886.09
bypass    133.33 1.4000  49.944  886.09
 2.5       66.67 1.4000  99.888 1101.46
 3         66.67 1.4000 499.439 1835.96
MB fuel   1.6112
 4         68.28 1.3000 474.467 3200.00
 4.5       68.28 1.3000 179.035 2613.61
 5         68.28 1.3000  51.574 2018.28
 6         68.28 1.3000  51.574 2018.28
 16       133.33 1.4000  49.944  886.09
 6A       201.61 1.3596  48.483 1323.44
AB fuel   8.2934
 7        209.90 1.3000  46.059 3600.00
 8        209.90 1.3000  46.059 3600.00
 9        209.90 1.3000  44.677 3600.00
```

NPSS Results:

```
Altitude = 35000 ft
Mach Number = 2
Engine Air Flow = 200 lbm/s

============  Primary Stream =============

F0   Tt = 708.982 R
F020 Tt = 708.979 R
F025 Tt = 708.979 R
F026 Tt = 878.84 R
F030 Tt = 1710.45 R
F040 Tt = 3200 R
F045 Tt = 2516.93 R
F060 Tt = 1762.65 R
F060A Tt = 1327.18 R
F070 Tt = 3599.99 R
F090 Tt = 3599.99 R

F0   Pt  = 27.0706 psia
F0   Ps  = 3.45777 psia
F020 Pt = 26.9353 psia
F025 Pt = 26.9353 psia
F026 Pt = 53.8706 psia
```

```
F030 Pt = 538.706 psia
F040 Pt = 511.771 psia
F045 Pt = 153.074 psia
F060 Pt = 27.2359 psia
F060A Pt = 44.8957 psia
F070 Pt = 42.6509 psia
F090 Pt = 42.6509 psia
F090 Ps = 23.5145 psia

pi_f = 4
pi_c = 20
============  Secondary Stream =============

F120 Tt = 708.979 R
F130 Tt = 1085.27 R
F160 Tt = 1085.27 R

F120 Pt = 26.9353 psia
F130 Pt = 107.741 psia
F160 Pt = 106.125 psia

Fan PR = 4
Fan eff = 0.89
CompL PR = 2
CompH PR = 10
TurbH PR = 3.34329
TurbL PR = 5.62031
CompL eff = 0.9
CompH eff = 0.9
TurbH eff = 0.9
TurbL eff = 0.9
CompL pwr = -3899.34 hp
TurbL pwr = 21360.2 hp

Shaft L RPM = 5000
Shaft H RPM = 10000
Bypass Ratio = 2
Wfuel = 1.75295 lbm/s
ABWfuel = 8.35623 lbm/s
SFC = 2.19019 lbm/(hr*lbf)
Gross Thrust = 28716.7 lbf
Net Thrust = 16616.4 lbf
```

# Appendix B

# MATLAB Code for Cycle Selection Data Analysis

```
%% Clearing workspace
clc,clear,close all

%% Inputs

% set(0,'DefaultTextInterpreter','LaTeX');

ImgPath = ['C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-',...
    'Breathing Propulsion\Final Design Project\Images\'];

% Isentropic index
gamma = 1.4;
R = 1716;                                           % ft*lb/(slug*R)

% Importing data from turbojet file
abtj_name = 'C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-Breathing ...
    Propulsion\Final Design Project\NPSS Code\Down-select\Afterburning ...
    Turbojet\AB_Turbojet_Results.dat';

mftf_name = 'C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-Breathing ...
    Propulsion\Final Design Project\NPSS Code\Down-select\Mixed-flow ...
    Turbofan\Mixed_Flow_Turbofan_Results.dat';

umftf_name = 'C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-Breathing ...
    Propulsion\Final Design Project\NPSS Code\Down-select\Variable Cycle ...
    Engine\Variable_Cycle_Results.dat';

% Importing data
abtjData = importdata(abtj_name);
mftfData = importdata(mftf_name);
umftfData = importdata(umftf_name);

% Conversion factor from kilometers to feet
conFact = 1/1.60934*5280;

% Creating structure in which to place the data
data = struct('M_0',[],'Alt',[],'Range',[],'t',[],'mdotF',[],'imported',...
```

```
    [],'Wb',[],'Wab',[],'a',[],'V',[],'fuelBurn',[]);


%% Afterburning turbojet

for n = 1:6

    data(n).imported = abtjData.data(n,:);
    data(n).Wb = data(n).imported(8);
    data(n).Wab = data(n).imported(9);
    data(n).mdotF = data(n).Wb + data(n).Wab;

    if n == 1 || n == 4
        data(n).M_0 = 0;
        data(n).Alt = 0;
        data(n).t = 5*60;                                   % sec
    elseif n == 2 || n == 5
        data(n).M_0 = 0.9;
        data(n).Alt = 40000;
        data(n).Range = 3000*conFact;
    else
        data(n).M_0 = 2.2;
        data(n).Alt = 60000;
        data(n).Range = 8000*conFact;
    end

end

% Determining speed of sound at altitude assuming standard day
data(2).a = sqrt(gamma*R*389.970);
data(3).a = data(2).a;
data(5).a = data(2).a;
data(6).a = data(2).a;

% Finding velocities in ft/s
t = [2 3 5 6];
for n = 1:numel(t)

    % Finding velocity for each design pt
    data(t(n)).V = data(t(n)).M_0*data(t(n)).a;

    % Finding time spent at each design pt
    data(t(n)).t = data(t(n)).Range/data(t(n)).V;

end

% Finding total fuel burn for each case

for n = 1:6
    data(n).fuelBurn = data(n).mdotF*data(n).t;
end

% Creating bar plot and comparing fuel burns (lbm)

Y = zeros(2,3);

for n = 1:6
    if n <=3
        Y(1,n) = data(n).fuelBurn;
```

```
    else
        Y(2,n-3) = data(n).fuelBurn;
    end
end

% Bar plot
figure('Position',[980 50 560 325])
h = bar(Y);

% Setting face colors
set(h(1),'facecolor','b')
set(h(2),'facecolor',[112/256 138/256 144/256])
set(h(3),'facecolor','k')

% Legend
lh = legend('Take-off','Transonic Cruise','Supersonic Cruise');

% Axis labels
ylabel('Total Fuel Consumption [lbm]')
set(gca,'XTickLabel',{'Afterburning TJ','Nonafterburning TJ'})

% % Saving plot
% set(gcf,'PaperPositionMode','auto')
% print(gcf, '-depsc', [ImgPath,'ABtj_total_fuel_cons.eps'])

% Calculating total fuel burn for an afterburning turbojet using
% afterburners at takeoff
tjFuelBurn = data(1).fuelBurn + data(5).fuelBurn + data(6).fuelBurn;
tjFuelBurn_noAB = data(4).fuelBurn + data(5).fuelBurn + data(6).fuelBurn;
fprintf('Total fuel burn for AB turbojet = %5.0f lbm per engine.\n\n',...
    tjFuelBurn)
fprintf('Total fuel burn for nonAB turbojet = %5.0f lbm per engine.\n\n',...
    tjFuelBurn_noAB)

%% Mixed-flow turbofan

nSets = 4;

for n = (numel(data)+1):(numel(data)+nSets)

    data(n).imported = mftfData.data(n-6,:);
    data(n).Wb = data(n).imported(8);
    data(n).Wab = data(n).imported(9);
    data(n).mdotF = data(n).Wb + data(n).Wab;

    if n <= 8
        data(n).M_0 = 0;
        data(n).Alt = 0;
        data(n).t = 5*60;                                % sec
    elseif n == 9
        data(n).M_0 = 0.9;
        data(n).Alt = 40000;
        data(n).Range = 3000*conFact;
        data(n).a = data(2).a;
    elseif n == 10
        data(n).M_0 = 2.2;
        data(n).Alt = 60000;
        data(n).Range = 8000*conFact;
        data(n).a = data(2).a;
```

```
    end

end

% Finding velocities in ft/s
t = [9 10];
for n = 1:numel(t)

    % Finding velocity for each design pt
    data(t(n)).V = data(t(n)).M_0*data(t(n)).a;

    % Finding time spent at each design pt
    data(t(n)).t = data(t(n)).Range/data(t(n)).V;

end

% Finding total fuel burn for each case
for n = 7:10
    data(n).fuelBurn = data(n).mdotF*data(n).t;
end

% Total fuel burn with AB on takeoff
tfFuelBurn = data(7).fuelBurn + data(9).fuelBurn + data(10).fuelBurn;
tfFuelBurn_noAB = data(8).fuelBurn + data(9).fuelBurn + data(10).fuelBurn;

fprintf('Total fuel burn for MF turbofan w/AB on t/o = %5.0f lbm per ...
    engine.\n\n',tfFuelBurn)
fprintf('Total fuel burn for MF turbofan no AB on t/o = %5.0f lbm per ...
    engine.\n\n',tfFuelBurn_noAB)

%% Variable cycle engine

nSets = 4;

for n = (numel(data)+1):(numel(data)+nSets)
    data(n).imported = umftfData.data(n-10,:);
    data(n).Wb = data(n).imported(8);
    data(n).Wab = data(n).imported(9);
    data(n).mdotF = data(n).Wb + data(n).Wab;

    if n <= 12
        data(n).M_0 = 0;
        data(n).Alt = 0;
        data(n).t = 5*60;                                   % sec
    elseif n == 13
        data(n).M_0 = 0.9;
        data(n).Alt = 40000;
        data(n).Range = 3000*conFact;
        data(n).a = data(2).a;
    elseif n == 14
        data(n).M_0 = 2.2;
        data(n).Alt = 60000;
        data(n).Range = 8000*conFact;
        data(n).a = data(2).a;
    end

end

% Finding velocities in ft/s
```

```
t = [13 14];
for n = 1:numel(t)

    % Finding velocity for each design pt
    data(t(n)).V = data(t(n)).M_0*data(t(n)).a;

    % Finding time spent at each design pt
    data(t(n)).t = data(t(n)).Range/data(t(n)).V;

end

% Finding total fuel burn for each case
for n = 11:14
    data(n).fuelBurn = data(n).mdotF*data(n).t;
end

% Total fuel burn with AB on takeoff
umtfFuelBurn = data(11).fuelBurn + data(13).fuelBurn + data(14).fuelBurn;
umtfFuelBurn_noAB = data(12).fuelBurn + data(13).fuelBurn + data(14).fuelBurn;

fprintf('Total fuel burn for UMF turbofan w/AB on t/o = %5.0f lbm per ... engine.\n\n',umtfFuelBurn)
fprintf('Total fuel burn for UMF turbofan no AB on t/o = %5.0f lbm per ... engine.\n\n',umtfFuelBurn_noAB)

%% Plotting fuel burns

figure('Position',[900 50 675 275])
y = [tjFuelBurn tfFuelBurn umtfFuelBurn];
h = bar(y,.4);

% Axis labels
set(gca,'XTickLabel',{'Afterburning TJ',...
    'Mixed-flow TF','Variable Cycle'})
ylabel('Total Fuel Burn [lbm]')

% % Saving plot
% set(gcf,'PaperPositionMode','auto')
% print(gcf, '-depsc', [ImgPath,'FuelBurnComparison.eps'])
```

# Appendix C

# MATLAB Code for Turbojet Parametric Cycle Analysis

```
%==========================================================================
%% Clearing workspace
%==========================================================================

clc,clear,close all

%==========================================================================
%% Setting defaults
%==========================================================================

set(0,'DefaultTextInterpreter','LaTeX');

CPRfile = 'C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-Breathing ...
    Propulsion\Final Design Project\NPSS Code\Parametric Analysis\AB ...
    Turbojet\CPR Hook\ABTJ_Results.dat';
T_t4file = 'C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-Breathing ...
    Propulsion\Final Design Project\NPSS Code\Parametric Analysis\AB ...
    Turbojet\T_t4 Hook\ABTJ_Results.dat';
Athfile = 'C:\Users\James\Desktop\School\Courses\UTA\AE 5326 - Air-Breathing ...
    Propulsion\Final Design Project\NPSS Code\Parametric Analysis\AB ...
    Turbojet\Nozzle Throat Area Hook\EngResults.txt';
% Path to images
ImgPath = ['C:\Users\James\Desktop\School\Courses\UTA\',...
    'AE 5326 - Air-Breathing Propulsion\Final Design Project\Images\'];

%==========================================================================
%% Importing text file
%==========================================================================

engDataCPR = importdata(CPRfile);
engDataT_t4 = importdata(T_t4file);
engDataAth = importdata(Athfile);

numericDataT_t4 = engDataT_t4.data;
numericDataAth = engDataAth.data;

nPointsCPR = 30;
```

```
nPointsT_t4 = 30;
nPointsAth = 21;

% Removing data that is unconverged from CPR hook
[CPRdata,engDataCPR_new,casesRemoved] = ...
    RemoveUnconvergedData(CPRfile,nPointsCPR);

engDataCPR = importdata(engDataCPR_new);
numericDataCPR= engDataCPR.data;
% Removing corresponding points
% numericDataCPR(numericDataCPR(:,1)==casesRemoved,:) = [];

% Manually removing 0 alt and 60,000 alt for unconverged 40,000 ft case
numericDataCPR(16,:) = [];
numericDataCPR(16,:) = [];
% Column numbers for data
cNcase = 1;
cNAlt = 2;
cNM = 3;
cNWair = 4;
cNF020A = 5;
cNF080A = 6;
cNF090A = 7;
cNpi_c = 8;
cNBWfuel = 9;
cNABWfuel = 10;
cNSFC = 11;
cNFn = 12;
cNFnqmdot = 13;
cNT_t4 = 14;

%==========================================================================
%% Separating data for CPR sweeps
%==========================================================================

% declaring structure for data
perfData = struct('Case',[],'Alt',[],'MN',[],'Wair',[],'F020A',[],...
    'F080A',[],'F090A',[],'pi_c',[],'BrnWfuel',[],'ABrnWfuel',[],...
    'SFC',[],'Fn',[],'Fnqmdot0',[],'T_t4',[]);

% Separating design point data
designPoint1CPR = numericDataCPR(numericDataCPR(:,cNAlt)==0,:);

perfData(1).Case = designPoint1CPR(:,cNcase);
perfData(1).Wair = designPoint1CPR(:,cNWair);
perfData(1).F020A = designPoint1CPR(:,cNF020A);
perfData(1).F080A = designPoint1CPR(:,cNF080A);
perfData(1).F090A = designPoint1CPR(:,cNF090A);
perfData(1).pi_c = designPoint1CPR(:,cNpi_c);
perfData(1).BrnWfuel = designPoint1CPR(:,cNBWfuel);
perfData(1).ABrnWfuel = designPoint1CPR(:,cNABWfuel);
perfData(1).SFC = designPoint1CPR(:,cNSFC);
perfData(1).Fn = designPoint1CPR(:,cNFn);
perfData(1).Fnqmdot0 = designPoint1CPR(:,cNFnqmdot);
perfData(1).T_t4 = designPoint1CPR(:,cNT_t4);

% Separating off design point data for 40k ft
designPoint2CPR = numericDataCPR(numericDataCPR(:,2)==40000,:);

```

```
perfData(2).Case = designPoint2CPR(:,cNcase);
perfData(2).Wair = designPoint2CPR(:,cNWair);
perfData(2).F020A = designPoint2CPR(:,cNF020A);
perfData(2).F080A = designPoint2CPR(:,cNF080A);
perfData(2).F090A = designPoint2CPR(:,cNF090A);
perfData(2).pi_c = designPoint2CPR(:,cNpi_c);
perfData(2).BrnWfuel = designPoint2CPR(:,cNBWfuel);
perfData(2).ABrnWfuel = designPoint2CPR(:,cNABWfuel);
perfData(2).SFC = designPoint2CPR(:,cNSFC);
perfData(2).Fn = designPoint2CPR(:,cNFn);
perfData(2).Fnqmdot0 = designPoint2CPR(:,cNFnqmdot);
perfData(2).T_t4 = designPoint2CPR(:,cNT_t4);

% Separating off design point data for 60k ft
designPoint3CPR = numericDataCPR(numericDataCPR(:,2)==60000,:);

perfData(3).Case = designPoint3CPR(:,cNcase);
perfData(3).Wair = designPoint3CPR(:,cNWair);
perfData(3).F020A = designPoint3CPR(:,cNF020A);
perfData(3).F080A = designPoint3CPR(:,cNF080A);
perfData(3).F090A = designPoint3CPR(:,cNF090A);
perfData(3).pi_c = designPoint3CPR(:,cNpi_c);
perfData(3).BrnWfuel = designPoint3CPR(:,cNBWfuel);
perfData(3).ABrnWfuel = designPoint3CPR(:,cNABWfuel);
perfData(3).SFC = designPoint3CPR(:,cNSFC);
perfData(3).Fn = designPoint3CPR(:,cNFn);
perfData(3).Fnqmdot0 = designPoint3CPR(:,cNFnqmdot);
perfData(3).T_t4 = designPoint3CPR(:,cNT_t4);

%==========================================================================
%% Separating data for T_t4 sweeps
%==========================================================================

%  Separating design point data
designPoint1T_t4 = numericDataT_t4(numericDataT_t4(:,2)==0,:);

perfData(4).Case = designPoint1T_t4(:,cNcase);
perfData(4).Wair = designPoint1T_t4(:,cNWair);
perfData(4).F020A = designPoint1T_t4(:,cNF020A);
perfData(4).F080A = designPoint1T_t4(:,cNF080A);
perfData(4).F090A = designPoint1T_t4(:,cNF090A);
perfData(4).pi_c = designPoint1T_t4(:,cNpi_c);
perfData(4).BrnWfuel = designPoint1T_t4(:,cNBWfuel);
perfData(4).ABrnWfuel = designPoint1T_t4(:,cNABWfuel);
perfData(4).SFC = designPoint1T_t4(:,cNSFC);
perfData(4).Fn = designPoint1T_t4(:,cNFn);
perfData(4).Fnqmdot0 = designPoint1T_t4(:,cNFnqmdot);
perfData(4).T_t4 = designPoint1T_t4(:,cNT_t4);

% Separating off design point data for 40k ft
designPoint2T_t4 = numericDataT_t4(numericDataT_t4(:,2)==40000,:);

perfData(5).Case = designPoint2T_t4(:,cNcase);
perfData(5).Wair = designPoint2T_t4(:,cNWair);
perfData(5).F020A = designPoint2T_t4(:,cNF020A);
perfData(5).F080A = designPoint2T_t4(:,cNF080A);
perfData(5).F090A = designPoint2T_t4(:,cNF090A);
perfData(5).pi_c = designPoint2T_t4(:,cNpi_c);
perfData(5).BrnWfuel = designPoint2T_t4(:,cNBWfuel);
```

```
perfData(5).ABrnWfuel = designPoint2T_t4(:,cNABWfuel);
perfData(5).SFC = designPoint2T_t4(:,cNSFC);
perfData(5).Fn = designPoint2T_t4(:,cNFn);
perfData(5).Fnqmdot0 = designPoint2T_t4(:,cNFnqmdot);
perfData(5).T_t4 = designPoint2T_t4(:,cNT_t4);

% Separating off design point data for 60k ft
designPoint3T_t4 = numericDataT_t4(numericDataT_t4(:,2)==60000,:);

perfData(6).Case = designPoint3T_t4(:,cNcase);
perfData(6).Wair = designPoint3T_t4(:,cNWair);
perfData(6).F020A = designPoint3T_t4(:,cNF020A);
perfData(6).F080A = designPoint3T_t4(:,cNF080A);
perfData(6).F090A = designPoint3T_t4(:,cNF090A);
perfData(6).pi_c = designPoint3T_t4(:,cNpi_c);
perfData(6).BrnWfuel = designPoint3T_t4(:,cNBWfuel);
perfData(6).ABrnWfuel = designPoint3T_t4(:,cNABWfuel);
perfData(6).SFC = designPoint3T_t4(:,cNSFC);
perfData(6).Fn = designPoint3T_t4(:,cNFn);
perfData(6).Fnqmdot0 = designPoint3T_t4(:,cNFnqmdot);
perfData(6).T_t4 = designPoint3T_t4(:,cNT_t4);

%==========================================================================
%% Separating throat area sweeps
%==========================================================================

%  Separating design point data
designPoint1Ath = numericDataAth(numericDataAth(:,2)==0,:);

perfData(7).Case = designPoint1Ath(:,cNcase);
perfData(7).Wair = designPoint1Ath(:,cNWair);
perfData(7).F020A = designPoint1Ath(:,cNF020A);
perfData(7).F080A = designPoint1Ath(:,cNF080A);
perfData(7).F090A = designPoint1Ath(:,cNF090A);
perfData(7).pi_c = designPoint1Ath(:,cNpi_c);
perfData(7).BrnWfuel = designPoint1Ath(:,cNBWfuel);
perfData(7).ABrnWfuel = designPoint1Ath(:,cNABWfuel);
perfData(7).SFC = designPoint1Ath(:,cNSFC);
perfData(7).Fn = designPoint1Ath(:,cNFn);
perfData(7).Fnqmdot0 = designPoint1Ath(:,cNFnqmdot);
perfData(7).T_t4 = designPoint1Ath(:,cNT_t4);

% Separating off design point data for 40k ft
designPoint2Ath = numericDataAth(numericDataAth(:,2)==40000,:);

perfData(8).Case = designPoint2Ath(:,cNcase);
perfData(8).Wair = designPoint2Ath(:,cNWair);
perfData(8).F020A = designPoint2Ath(:,cNF020A);
perfData(8).F080A = designPoint2Ath(:,cNF080A);
perfData(8).F090A = designPoint2Ath(:,cNF090A);
perfData(8).pi_c = designPoint2Ath(:,cNpi_c);
perfData(8).BrnWfuel = designPoint2Ath(:,cNBWfuel);
perfData(8).ABrnWfuel = designPoint2Ath(:,cNABWfuel);
perfData(8).SFC = designPoint2Ath(:,cNSFC);
perfData(8).Fn = designPoint2Ath(:,cNFn);
perfData(8).Fnqmdot0 = designPoint2Ath(:,cNFnqmdot);
perfData(8).T_t4 = designPoint2Ath(:,cNT_t4);

% Separating off design point data for 60k ft
```

```
designPoint3Ath = numericDataAth(numericDataAth(:,2)==60000,:);

perfData(9).Case = designPoint3Ath(:,cNcase);
perfData(9).Wair = designPoint3Ath(:,cNWair);
perfData(9).F020A = designPoint3Ath(:,cNF020A);
perfData(9).F080A = designPoint3Ath(:,cNF080A);
perfData(9).F090A = designPoint3Ath(:,cNF090A);
perfData(9).pi_c = designPoint3Ath(:,cNpi_c);
perfData(9).BrnWfuel = designPoint3Ath(:,cNBWfuel);
perfData(9).ABrnWfuel = designPoint3Ath(:,cNABWfuel);
perfData(9).SFC = designPoint3Ath(:,cNSFC);
perfData(9).Fn = designPoint3Ath(:,cNFn);
perfData(9).Fnqmdot0 = designPoint3Ath(:,cNFnqmdot);
perfData(9).T_t4 = designPoint3Ath(:,cNT_t4);

%==========================================================================
%% Plotting pi_c hook
%==========================================================================

% Plotting variation in pi_c for design and off design
f1 = plot(perfData(1).pi_c,perfData(2).pi_c,'-k',...
    perfData(1).pi_c,perfData(3).pi_c,'--k','LineWidth',1.5);
xlabel('Design CPR')
ylabel('Off Design CPR')
lh = legend('40,000 ft','60,000 ft');
set(lh,'Location','East')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'pi_cDesignVSoffDesign.eps'])

close(gcf)

%--------------------------------------------------------------------------
% Design point
%--------------------------------------------------------------------------

% Setting up figure
figure('Position',[795 60 790 800])

% Design point specific thrust
subplot(3,2,1)
plot(perfData(1).pi_c,perfData(1).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$F/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Design point specific fuel consumption
subplot(3,2,2)
plot(perfData(1).pi_c,perfData(1).SFC,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('SFC [(lbm/hr)/lbf]')
title('SFC vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Design point afterburner fuel flow rate required to attain T7_req
subplot(3,2,3)
```

```
plot(perfData(1).pi_c,perfData(1).BrnWfuel,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$\dot{m}_{fB}$ [lbm/s]')
title('Main burner fuel flow rate vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Design point afterburner fuel flow rate required to attain T7_req
subplot(3,2,4)
plot(perfData(1).pi_c,perfData(1).ABrnWfuel,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$\dot{m}_{fAB}$ [lbm/s]')
title('AB fuel flow rate vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Throat area vs pi_c
subplot(3,2,5)
plot(perfData(1).pi_c,perfData(1).F080A,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('Nozzle throat area [in$^2$]')
title('Nozzle throat area vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Exit area vs pi_c
subplot(3,2,6)
plot(perfData(1).pi_c,perfData(1).F090A,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('Nozzle exit area [in$^2$]')
title('Nozzle exit area vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'ABturbojet_pi_c1.eps'])

%-------------------------------------------------------------------------
% 40,000 ft
%-------------------------------------------------------------------------

% Setting up figure
figure('Position',[790 311 790 500])

% Specific thrust vs compressor pressure ratio off-design
subplot(2,2,1)
plot(perfData(1).pi_c,perfData(2).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$F/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% SFC vs pi_c
subplot(2,2,2)
plot(perfData(1).pi_c,perfData(2).SFC,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('SFC [(lbm/hr)/lbf]')
title('SFC vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Fn vs pi_c
subplot(2,2,3)
```

```
plot(perfData(1).pi_c,perfData(2).Fn,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$F_n$ [lbf]')
title('Net Thrust vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Fuel flow rate vs pi_c
subplot(2,2,4)
plot(perfData(1).pi_c,perfData(2).BrnWfuel,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$\dot{m}_f$ [lbm]')
title('Fuel flow rate vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'ABturbojet_pi_c2.eps'])

%------------------------------------------------------------------------
% 60,000 ft
%------------------------------------------------------------------------

% Setting up figure
figure('Position',[790 311 790 500])

% Specific thrust vs compressor pressure ratio off-design
subplot(2,2,1)
plot(perfData(1).pi_c,perfData(3).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$F/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% SFC vs pi_c
subplot(2,2,2)
plot(perfData(1).pi_c,perfData(3).SFC,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('SFC [(lbm/hr)/lbf]')
title('SFC vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Fn vs pi_c
subplot(2,2,3)
plot(perfData(1).pi_c,perfData(3).Fn,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$F_n$ [lbf]')
title('Net Thrust vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Fuel flow rate vs pi_c
subplot(2,2,4)
plot(perfData(1).pi_c,perfData(3).BrnWfuel,'-k','LineWidth',1.5)
xlabel('$\pi_c$')
ylabel('$\dot{m}_f$ [lbm]')
title('Fuel flow rate vs CPR')
set(gca,'XLim',[perfData(1).pi_c(1) perfData(1).pi_c(end)])

% Saving plot
set(gcf,'PaperPositionMode','auto')
```

```matlab
print(gcf, '-depsc', [ImgPath,'ABturbojet_pi_c3.eps'])

%=========================================================================
%% Plotting T_t4 hook (data sets 4 - 6)
%=========================================================================

% Plotting off design T_t4 vs design T_t4
figure
plot(perfData(4).T_t4,perfData(5).T_t4,'-k',...
    perfData(4).T_t4,perfData(6).T_t4,'--k','LineWidth',1.5)
xlabel('Design $T_{t4}$ [$^\circ$R]')
ylabel('Off Design $T_{t4}$ [$^\circ$R]')
lh = legend('40,000 ft','60,000 ft');
set(lh,'Location','East')

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'T_t4DesignVSoffDesign.eps'])

%-------------------------------------------------------------------------
% Design point
%-------------------------------------------------------------------------

% Setting up figure
figure('Position',[795 60 790 800])

% Specific Thrust vs T_t4
subplot(3,2,1)
plot(perfData(4).T_t4,perfData(4).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$F/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% SFC vs T_t4
subplot(3,2,2)
plot(perfData(4).T_t4,perfData(4).SFC,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('SFC [(lbm/hr)/lbf]')
title('SFC vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Fuel flow rate vs T_t4
subplot(3,2,3)
plot(perfData(4).T_t4,perfData(4).BrnWfuel,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$\dot{m}_{fB}$ [lbm/s]')
title('Main burner fuel flow rate vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% AB fuel flow rate vs T_t4
subplot(3,2,4)
plot(perfData(4).T_t4,perfData(4).ABrnWfuel,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$\dot{m}_{fAB}$ [lbm/s]')
title('AB fuel flow rate vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Nozzle throat area vs T_t4
```

```
subplot(3,2,5)
plot(perfData(4).T_t4,perfData(4).F080A,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('Nozzle throat area [in$^2$]')
title('Nozzle throat area vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Nozzle exit area vs T_t4
subplot(3,2,6)
plot(perfData(4).T_t4,perfData(4).F090A,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('Nozzle exit area [in$^2$]')
title('Nozzle exit area vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'ABturbojet_T_t41.eps'])

%---------------------------------------------------------------------------
% 40,000 ft
%---------------------------------------------------------------------------

% Setting up figure
figure('Position',[790 311 790 500])

% Specific thrust vs compressor pressure ratio off-design
subplot(2,2,1)
plot(perfData(4).T_t4,perfData(5).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$F/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs $T_{t4}$')
set(gca,'XLim',[perfData(5).T_t4(1) perfData(5).T_t4(end)])

% SFC vs pi_c
subplot(2,2,2)
plot(perfData(4).T_t4,perfData(5).SFC,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('SFC [(lbm/hr)/lbf]')
title('SFC vs $T_{t4}$')
set(gca,'XLim',[perfData(5).T_t4(1) perfData(5).T_t4(end)])

% Fn vs pi_c
subplot(2,2,3)
plot(perfData(4).T_t4,perfData(5).Fn,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$F_n$ [lbf]')
title('Net Thrust vs $T_{t4}$')
set(gca,'XLim',[perfData(5).T_t4(1) perfData(5).T_t4(end)])

% Fuel flow rate vs pi_c
subplot(2,2,4)
plot(perfData(4).T_t4,perfData(5).BrnWfuel,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$\dot{m}_f$ [lbm]')
title('Fuel flow rate vs $T_{t4}$')
set(gca,'XLim',[perfData(5).T_t4(1) perfData(5).T_t4(end)])

% Saving plot
```

```
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'ABturbojet_T_t42.eps'])


%--------------------------------------------------------------------------
% 60,000 ft
%--------------------------------------------------------------------------

% Setting up figure
figure('Position',[790 311 790 500])

% Specific thrust vs compressor pressure ratio off-design
subplot(2,2,1)
plot(perfData(4).T_t4,perfData(6).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$F/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% SFC vs pi_c
subplot(2,2,2)
plot(perfData(4).T_t4,perfData(6).SFC,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('SFC [(lbm/hr)/lbf]')
title('SFC vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Fn vs pi_c
subplot(2,2,3)
plot(perfData(4).T_t4,perfData(6).Fn,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$F_n$ [lbf]')
title('Net Thrust vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Fuel flow rate vs pi_c
subplot(2,2,4)
plot(perfData(4).T_t4,perfData(6).BrnWfuel,'-k','LineWidth',1.5)
xlabel('$T_{t4}$ [$^\circ$R]')
ylabel('$\dot{m}_f$ [lbm]')
title('Fuel flow rate vs $T_{t4}$')
set(gca,'XLim',[perfData(4).T_t4(1) perfData(4).T_t4(end)])

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'ABturbojet_T_t43.eps'])

%==========================================================================
%% Plotting Throat Area Hook (data sets 7 - 9)
%==========================================================================

%--------------------------------------------------------------------------
% 40,000 ft
%--------------------------------------------------------------------------

% Sorting the data so it is in the correct order
plotData = [perfData(8).F080A perfData(8).Fn ...
    perfData(8).Fnqmdot0 perfData(8).SFC];
plotData = sortrows(plotData,1);
```

```
% Setting up figure
figure('Position',[940 50 560 770])

% Net thrust vs throat area
subplot(3,1,1)
plot(plotData(:,1),plotData(:,2),'-k','LineWidth',1.5)
xlabel('$A_{th}$ [in$^2$]')
ylabel('$F_n$ [lbf]')
title('Net thrust vs throat area')

% Specific thrust vs throat area
subplot(3,1,2)
plot(plotData(:,1),plotData(:,3),'-k','LineWidth',1.5)
xlabel('$A_{th}$ [in$^2$]')
ylabel('$F_n/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs throat area')

% Specific fuel consumption vs throat area
subplot(3,1,3)
plot(plotData(:,1),plotData(:,4),'-k','LineWidth',1.5)
xlabel('$A_{th}$ [in$^2$]')
ylabel('SFC [(lbm/s)/lbf]')
title('SFC vs throat area')

% Saving plot
set(gcf,'PaperPositionMode','auto')
print(gcf, '-depsc', [ImgPath,'Ath40k.eps'])

%-------------------------------------------------------------------------
% 60,000 ft
%-------------------------------------------------------------------------

% Setting up figure
figure('Position',[940 50 560 770])

% Net thrust vs throat area
subplot(3,1,1)
plot(perfData(9).F080A,perfData(9).Fn,'-k','LineWidth',1.5)
xlabel('$A_{th}$ [in$^2$]')
ylabel('$F_n$ [lbf]')
title('Net thrust vs throat area')

% Specific thrust vs throat area
subplot(3,1,2)
plot(perfData(9).F080A,perfData(9).Fnqmdot0,'-k','LineWidth',1.5)
xlabel('$A_{th}$ [in$^2$]')
ylabel('$F_n/\dot{m}_0$ [lbf/(lbm/s)]')
title('Specific thrust vs throat area')

% Specific fuel consumption vs throat area
subplot(3,1,3)
plot(perfData(9).F080A,perfData(9).SFC,'-k','LineWidth',1.5)
xlabel('$A_{th}$ [in$^2$]')
ylabel('SFC [(lbm/s)/lbf]')
title('SFC vs throat area')

% Saving plot
set(gcf,'PaperPositionMode','auto')
```

```
print(gcf, '-depsc', [ImgPath,'Ath60k.eps'])

close all
```

# Appendix D

# NPSS Code for Final Engine

```

//   File Name: Turbojet.run
//   Date: April 2013
//
//
//-----------------------------------------------------------------------------

#include <InterpIncludes.ncp> // file contains unit names, socket types, error ...
    statements, and some constants

//-----------------------------------------------------------------------------
//                          Set Thermodynamic Package
//-----------------------------------------------------------------------------

setThermoPackage("GasTbl");  // air properties, developed by Pratt and Whitney

//-----------------------------------------------------------------------------
//                          User-Defined Elements
//-----------------------------------------------------------------------------


//-----------------------------------------------------------------------------
//                    User-Defined Tables and Functions
//-----------------------------------------------------------------------------

// User-defined functions
#include "user.fnc"

//-----------------------------------------------------------------------------
//                            Model Definition
//-----------------------------------------------------------------------------

// Load the that file contains the model definition (element instantiations, ...
    links, and solver variables)
#include "Turbojet.mdl"

// Load the CaseRowViewer file
#include "EngResultsRow.view"
// Save run results in output file EngDesign.txt
```

```
os_EngResultsRow.filename = "ABTJ_Results.dat"; // set the viewer output file name

//-----------------------------------------------------------------------------
//                          Running the Model
//-----------------------------------------------------------------------------
cout << endl;
cout << "======================================= \n";
cout << "=====    RUNNING DESIGN POINT     ===== \n";
cout << "======================================= \n";
cout << endl;


// Set up design point run
#include"Design.inp"
setupDesign();
Amb.alt_in = 0;
Amb.MN_in = 0;
Fn_req = 38000;
run();
printResults();
CASE++;
EngResultsRow.update();

cout << endl;
cout << "============================================== \n";
cout << "=====    RUNNING OFF DESIGN - 40k ft     ===== \n";
cout << "============================================== \n";
cout << endl;

// Off design point 1 - 40,000 ft
setupOffDesign();
FusABrn.Wfuel = 0.0;
Amb.alt_in = 40000;
Amb.MN_in = 0.9;
Fn_req = 1000000;
real NozAthDes = NozPri.AthCold;
NozPri.AthCold = NozAthDes * 0.9;
run();
printResults();
CASE++;
EngResultsRow.update();

cout << endl;
cout << "============================================== \n";
cout << "=====    RUNNING OFF DESIGN - 60k ft     ===== \n";
cout << "============================================== \n";
cout << endl;

// Off design point 2 - 60,000 ft
setupOffDesign();
FusABrn.Wfuel = 0.0;
Amb.alt_in = 60000;
Amb.MN_in = 2.2;
Fn_req = 10000000;
NozPri.AthCold = NozAthDes * 0.9;
run();
printResults();
CASE++;
EngResultsRow.update();
```

```
//------------------------------------------------------------------------
//                             Model Definition
//------------------------------------------------------------------------

// Instantiating the Ambient element
Element Ambient Amb{}

// Instantiating the InletStart element

Element InletStart FsEng{

    AmbientName = "Amb";                    // Name of the Ambient element
    W_in = 100.;                            // lbm/s - input airflow rate

}

// Instantiating the Inlet element

Element Inlet InEng{

    eRamBase = 0.995;                       // Ram pressure recovery

}

// Instantiating the Low Pressure Compressor element

Element Compressor CmpL{

    effDes = 0.9;                           // Design point efficiency

    // Load file that instantiates a subelement and plugs into compressor ...
        socket (S_map)
    #include "lpcE3.map";                   // Refer to subelement by its ...
        socket name: S_map

}

// Instantiating the High Pressure Compressor element

Element Compressor CmpH{

    effDes = 0.9;                           // Design point efficiency

    // Load file that instantiates a subelement that plugs into compressor ...
        socket (S_map)
    #include "hpcE3.map";                   // Refer to subelement by its ...
        socket name: S_map

}

// Starting the fuel

Element FuelStart FusEng{

    Wfuel = 2.0;                            // lbm/s - fuel flow rate
```

```

}

// Instantiating the Burner element

Element Burner BrnPri{

    dPqP_dmd = 0.05;                        // user input friction relative ...
        pressure drop
    effBase = 0.99;                         // adiabatic efficiency
    switchBurn = "WFUEL";                   // FUEL, WFUEL, or FAR

}

// Instantiating the High Pressure Turbine element

Element Turbine TrbH{

    effDes = 0.9;                           // design efficiency
    PRbase = 4.5;                           // Initial guess for pressure ratio

    // Loading file that instantiates a subelement and plugs into turbine socket
    #include "hptE3.map";

}

// Instantiating the Low Pressure Turbine element

Element Turbine TrbL{

    effDes = 0.9;                           // design efficiency
    PRbase = 4.5;                           // Initial guess for pressure ratio

    // Loading file that instantiates a subelement and plugs into turbine socket
    #include "lptE3.map";

}

// Starting the fuel for the afterburner

Element FuelStart FusABrn{

    Wfuel = 2.0;                            // lbm/s - fuel flow rate

}

// Instantiating the Afterburner element

Element Burner ABrn{

    dPqP_dmd = 0.05;                        // user input friction relative ...
        pressure drop
    effBase = 0.99;                         // adiabatic efficiency
    switchBurn = "WFUEL";                   // FUEL, WFUEL, or FAR

}

// Instantiating the Nozzle element

```

```
Element Nozzle NozPri{

    PsExhName = "Amb.Ps";                     // Name of ambient static pressure
    switchType = "CON_DIV";                   // Setting nozzle to conic

}

// Instantiating the Low Pressure Shaft element

Element Shaft ShL{

    ShaftInputPort Sh_ICmp;                   // Port for connection between CmpL ...
        and shaft
    ShaftInputPort Sh_ITrb;                   // Port for connection between TrbL ...
        and shaft
    Nmech = 5000.;                            // rpm
}

// Instantiate the High Pressure Shaft element

Element Shaft ShH{

    ShaftInputPort Sh_ICmp;                   // Port for connection between CmpH ...
        and shaft
    ShaftInputPort Sh_ITrb;                   // Port for connection between TrbH ...
        and shaft
    Nmech = 10000.;                           // rpm

}

// Ending flow of air

Element FlowEnd FePri{
}

// Instantiating the EngPerf element
Element EngPerf Perf{
}

//-----------------------------------------------------------------------
// Linking fluid ports
//-----------------------------------------------------------------------

// Ambient to inlet
linkPorts("FsEng.Fl_O",         "InEng.Fl_I",           "F0");

// Inlet to low pressure compressor
linkPorts("InEng.Fl_O",         "CmpL.Fl_I",            "F020");

// Low pressure compressor to high pressure compressor
linkPorts("CmpL.Fl_O",          "CmpH.Fl_I",            "F025");

// High pressure compressor to burner
linkPorts("CmpH.Fl_O",          "BrnPri.Fl_I",          "F030");

// Burner to high pressure turbine
linkPorts("BrnPri.Fl_O",        "TrbH.Fl_I",            "F040");

// High pressure turbine to low pressure turbine
```

```
linkPorts("TrbH.Fl_O",          "TrbL.Fl_I",            "F045");

// Low pressure turbine to afterburner
linkPorts("TrbL.Fl_O",          "ABrn.Fl_I",            "F050");

// Afterburner to nozzle
linkPorts("ABrn.Fl_O",          "NozPri.Fl_I",          "F070");

// Nozzle to atmosphere
linkPorts("NozPri.Fl_O",        "FePri.Fl_I",           "F090");


//-------------------------------------------------------------------------
// Linking fuel ports
//-------------------------------------------------------------------------
linkPorts("FusEng.Fu_O",        "BrnPri.Fu_I",          "Fu_In");
linkPorts("FusABrn.Fu_O",       "ABrn.Fu_I",            "ABFu_In");

//-------------------------------------------------------------------------
// Linking shaft ports
//-------------------------------------------------------------------------

// Low pressure compressor shaft to low pressure shaft input
linkPorts("CmpL.Sh_O",          "ShL.Sh_ICmp",          "MeCmpL");

// Low pressure turbine shaft to low pressure shaft
linkPorts("TrbL.Sh_O",          "ShL.Sh_ITrb",          "MeTrbL");

// High pressure compressor shaft to high pressure shaft
linkPorts("CmpH.Sh_O",          "ShH.Sh_ICmp",          "MeCmpH");

// High pressure turbine shaft to high pressure shaft
linkPorts("TrbH.Sh_O",          "ShH.Sh_ITrb",          "MeTrbH");

//-------------------------------------------------------------------------
//                           Solver Variables
//-------------------------------------------------------------------------

// Create alias F080 to represent nozzle throat conditions
setAlias("NozPri.Fl_Th", "F080");

// Specifying the Mach number at the compressor face so that area can be determined
F020.MN = 0.5;

real T4_req = 3000.;                    // Rankine - desired T_t4
real T7_req = 3400.;                    // Rankine - desired T_t7
real Fn_req = 38000.;                   // lbf - desired thrust
real NmechL_max = 5200.;                // rpm - max allowable rpm for low ...
    pressure shaft
real NmechH_max = 11000.;               // rpm - max allowable rpm for high ...
    pressure shaft
real T4_max = 3600;                     // Max allowable T_t4

// Solver independent variable that varies fuel flow rate
Independent ind_Wfuel{
    varName = "FusEng.Wfuel";
}

// Solver independent variable that varies fuel flow rate for afterburner
```

```
Independent ind_ABWfuel{
    varName = "FusABrn.Wfuel";
}

// Solver independent that varies air flow rate
Independent ind_Wair{
    varName = "FsEng.W_in";
}

// Solver dependent variable for required T_t4
Dependent dep_T4{
    eq_lhs = "F040.Tt";                        // actual T_t4
    eq_rhs = "T4_req";                         // desired T_t4
}

// Solver dependent variable for required T_t7
Dependent dep_T7{
    eq_lhs = "F070.Tt";                        // actual T_t7
    eq_rhs = "T7_req";                         // desired T_t7
}

// Solver dependent variable for required net thrust
Dependent dep_Fn{
    eq_lhs = "Perf.Fn";                        // actual value
    eq_rhs = "Fn_req";                         // desired Fn
}

//-------------------------------------------------------------------------
//                           Solver Constraints
//-------------------------------------------------------------------------

// Solver dependents that limits shaft speeds
Dependent dep_NmechL_max{
    eq_lhs = "ShL.Nmech";                      // variable to be constrained
    eq_rhs = "NmechL_max";                     // max allowable low pressure shaft rpm
}

Dependent dep_NmechH_max{
    eq_lhs = "ShH.Nmech";                      // variable to be constrained
    eq_rhs = "NmechH_max";                     // max allowable high pressure ...
        shaft rpm
}

Dependent dep_T4_max{
    eq_lhs = "F040.Tt";
    eq_rhs = "T4_max";
}

// Applying the constraints on the shaft RPM
dep_Fn.addConstraint("dep_NmechL_max","MAX");
dep_Fn.addConstraint("dep_NmechH_max","MAX");
dep_Fn.addConstraint("dep_T4_max","MAX");
```

```
// Design point input values

// Set some design point values
Amb.alt_in = 0; // ft, altitude
```

```
Amb.MN_in = 0; // Mach number
FsEng.W_in = 350; // lbm/s, initial guess, engine total flow rate
ShL.Nmech = 5000; // shaft speed
ShH.Nmech = 10000; // shaft speed
CmpL.PRdes = 3; // low pressure compressor pressure ratio
CmpH.PRdes = 5; // high pressure compressor pressure ratio
Fn_req = 38000; // lbf, requested net thrust
T4_req = 3300; // R, requested turbine inlet temperature
T7_req = 3600;
```