Design Project: Overture Engine Concept

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Abstract

The goal of this project was to design a turbofan engine that would meet the requirements for Boom Technologies supersonic jet, Overture. Currently the Overture aircraft is set to fly with an engine designed by Rolls Royce. This report will outline an alternative engine option that may be used in its place if customers choose to do so. Some basic requirements for the engine include but are not limited to a cruise thrust of 80 kN at a cruise speed of mach 1.7 and a minimum takeoff thrust of 100 kN. In addition the engine needs to be as efficient and lightweight as possible in order for the Overture aircraft to meet its range requirement of 8000 km and maximum takeoff weight of 77 tons. For this report more emphasis will be placed on the overall engine performance rather than individual component performance. As such, efficiency values for components have been provided by UCI staff. Using these values and the fundamental equations for analyzing turbofan performance a number of factors, including maximum temperature, pressure ratio, bypass ratio, and fan pressure ratio, were analyzed to determine the best turbofan engine.

Introduction

For most of commercial aviation history planes have flown at subsonic speeds. However, there is an exception to this, the Concorde. The Concorde was able to fly at a cruising speed of around mach 2 and capable of making transatlantic crossings. Unfortunately, although the Concorde's engines were very efficient at its cruising speed their performance in the subsonic regime was suboptimal. This, among other problems associated with the plane resulted in high operating costs leading to the aircraft type being non economically viable. As such, the commercial aviation industry has stuck with slower, but more efficient, subsonic aircraft. However, in the past decades, advancements in technologies have opened the door for the potential return of commercial supersonic transports.

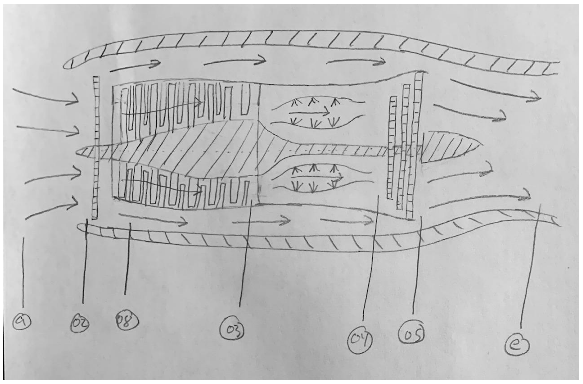
One such company is Boom Technologies. Their aircraft concept, Overture, is a small supersonic transport which has been designed to have a cruise speed of around mach 1.7, a passenger load, including crew, of 65, and a range of 8000 kilometers. The aircraft concept also aims to minimize the effects of the sonic boom generated by flying at subsonic speeds. The loud sonic boom was one of the features of the Concorde that limited where it could fly at its cruise speed. By limiting the intensity of the sonic boom the Overture aircraft concept aims to have an expanded cruise envelope. In order to achieve the cruise speed of mach 1.7 Boom Technologies intends to partner with Rolls Royce to produce a turbofan engine that can run efficiently at both the aircrafts cruising speed and subsonic speeds.

In this report an outline for an alternative engine will be presented. To help simplify some of the calculations that will need to be made. Component performance as a whole will be considered however, the components themselves have already been predetermined. As such, more attention can be made to optimizing the engine as a whole. To do this it is important to list out the design requirements for this alternative engine option. As discussed earlier the Overture aircraft aims to have a cruise speed of mach 1.7. In order to do this the aircraft requires 3 engines each producing a minimum 80 kN of thrust. For takeoff the thrust requirements are greater with the engines needing to produce a minimum thrust of 100 kN. With these constraints a limit is placed on the minimum achievable specific thrust and maximum thrust specific fuel consumption. There is also a 2 meter diameter limit on the inlet meaning that the mass flow through the engine is limited.

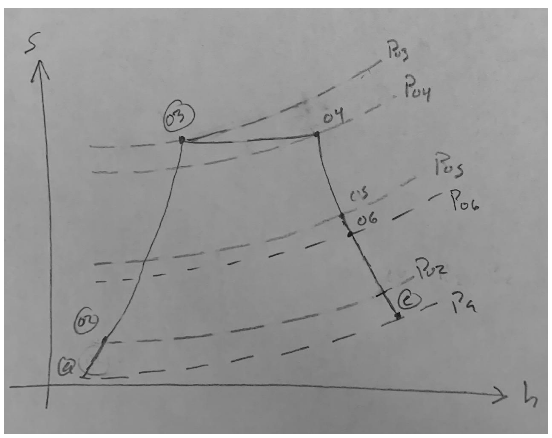
In order to choose the best design for the turbofan engine that will be proposed in this report four key factors and their effects will be examined. These factors are the maximum total temperature, the compressor compression ratio, the bypass ratio, and the fan pressure ratio. The max temperature being limited to 1800 K by material limits and the compressor compression ratio being limited by power output of the turbine. By varying these factors a complete spread of possible engines can be created. From these possibilities the engines that fit the design parameters can be chosen. From there comparisons can be made by looking at the efficiencies of the engines to result in a final design. The final engine, in theory, being a competitive option that could be used by Boom Technologies on their Overture aircraft.

Design Method/Equations

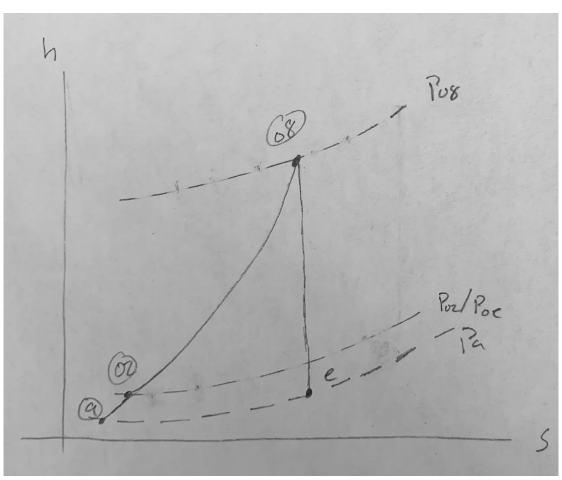
Sketch of Turbofan Engine Configuration



Sample h-s Diagram for Turbofan Engine Core Gas Generator



Sample h-s Diagram for Turbofan Engine Bypass Section



Variables

$\dot{m} = Mass\ Flow\ Rate$
$\delta_0 = Dimensionless\ Constant$
$\theta_0 = Dimensionless\ Constant$
$\gamma = Specific\ Heat\ Capacity\ Ratio$
$c_p = Specific\ Heat\ Capacity\ Constant\ Pressure$
$R = Ideal\ Gas\ Constant$
$\beta = Bypass\ Ratio$
$Q_r = Fuel\ Heating\ Value$
$T_0 = Total\ Temperature\ at\ a\ Station$
$P_0 = Total\ Pressure\ at\ a\ Station$
$\eta_p = Polytropic\ Efficiency$
$\eta = Adiabatic\ Efficiency$
$\eta_{th} = Thermal\ Efficiency$
$\eta_p = Propulsive\ Efficiency$
$\eta_o = Overall\ Efficiency$
$\pi = Total\ Pressure\ Ratio$
$T = Thrust$
$u = Flow\ Speed$
$ST = Specific\ Thrust$
$TSFC = Thrust\ Specific\ Fuel\ Consumption$
$\Delta KE = Change\ in\ Kinetic\ Energy$

Fundamental Equations and Conversions

$$\dot{m} = 238.1A\frac{\delta_0}{\sqrt{\theta_0}} = \dot{m}_a(1 + \beta)$$

$$\delta_0 = \frac{P_{02}}{P_{a,ST}}$$

$$\theta_0 = \frac{T_{02}}{T_{a,ST}}$$

$$\pi_{adiabatic} = \left(\frac{T_{02}}{T_{01}}\right)^{\frac{\eta_p\gamma}{\gamma-1}}$$

$$\eta_{adiabatic} = \frac{\pi^{\frac{\gamma-1}{\gamma}}-1}{\pi^{\frac{\eta_p\gamma}{\gamma-1}}-1}$$

$$T = \frac{T_{bare}}{1.04+.01\beta^{1.2}}$$

Turbofan Equations

$$T_{0a} = T_a\left(1 + \frac{\gamma-1}{\gamma}M^2\right)$$

$$P_{0a} = P_a\left(1 + \frac{\gamma-1}{\gamma}M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$T_{02} = T_{0a}$$

$$P_{02} = P_a(1 + \eta_d(\frac{T_{02}}{T_{0a}} - 1))^{\frac{\gamma}{\gamma-1}}$$

$$T_{08} = T_{02}(1 + (\pi_f^{\frac{\gamma-1}{\gamma}} - 1)/\eta_f)$$

$$P_{08} = P_{02}\pi_f$$

$$u_{ef} = \sqrt{2\eta_f \frac{\gamma}{\gamma-1} RT_{08}(1 - (\frac{P_a}{P_{08}})^{\frac{\gamma-1}{\gamma}})}$$

$$T_{03} = T_{02}(1 + (\pi_c^{\frac{\gamma-1}{\gamma}} - 1)/\eta_c)$$

$$P_{03} = P_{02}\pi_c$$

$$P_{04} = P_{03}\pi_b$$

$$T_{05} = T_{04} + T_{02} - T_{03} - \beta(T_{08} - T_{0a})$$

$$P_{05} = P_{04}(1 - (1 - \frac{T_{05}}{T_{04}})/\eta_t)^{\frac{\gamma}{\gamma-1}}$$

$T_{06} = T_{05}$ *(Non Afterburning Engine)*

$P_{06} = P_{05}$ *(Non Afterburning Engine)*

$$u_e = \sqrt{2\eta_n \frac{\gamma-1}{\gamma} RT_{06}(1 - (\frac{P_a}{P_{06}})^{\frac{\gamma-1}{\gamma}})}$$

Turbofan Efficiency Equations

$$f = \frac{\frac{T_{04}}{T_{03}} - 1}{\frac{Q_r\eta_b}{c_pT_{03}} - \frac{T_{04}}{T_{03}}}$$

$ST = (1 + f)u_e + \beta u_{ef} - (1 + \beta)u_a$ *(Use to find engine Thrust)*

$ST_{alternate} = \frac{T}{\dot{m}_a(1+\beta)}$ *(Use for minimum ST and Total ST of Engine)*

$TSFC = f/ST$

$\Delta KE =$

$$\eta_{th} = \frac{\Delta KE}{\dot{m}_f Q_r}$$

$$\eta_p = \frac{Tu_a}{\Delta KE}$$

$$\eta_o = \eta_{th}\eta_p$$

Design Method

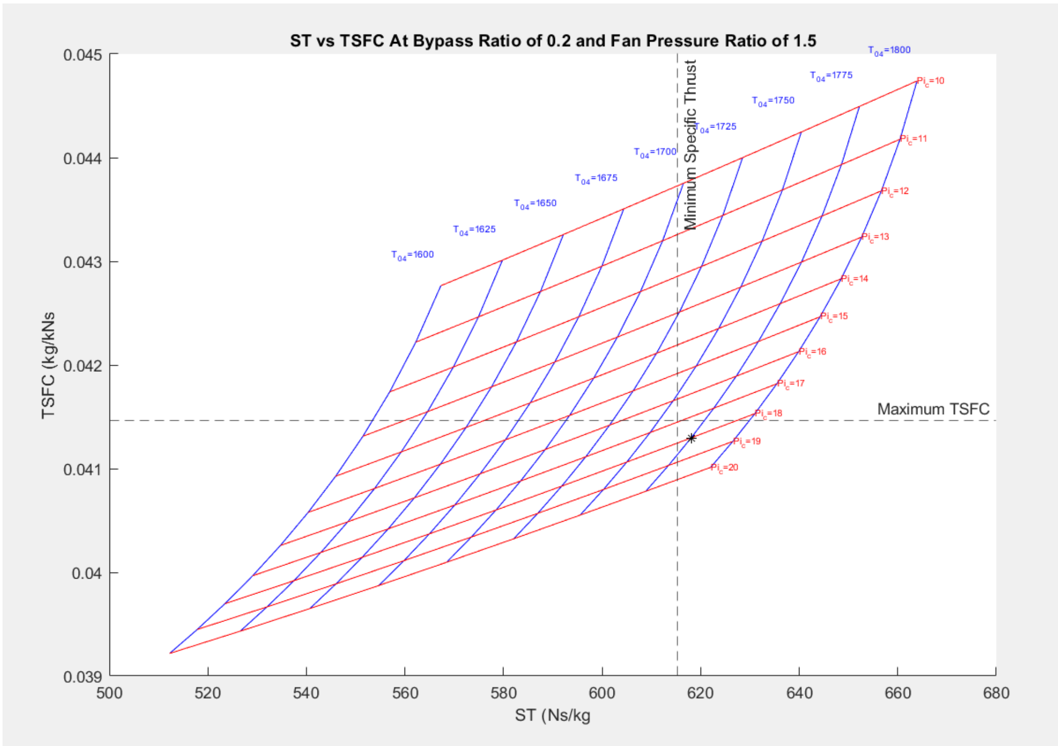
The first step in designing the proposed engine is to determine the inlet parameters of the engine. By doing this the mass flow rate through the engine will be set allowing for the simplification of calculations further along in the design process. By choosing an inlet diameter the drag induced by the engine can also be taken into account allowing for more accurate calculations when it comes to the efficiency of the engine. All of this can be achieved using the first section of equations listed above.

The next step in the engine design is going to be an analysis of the performance of the engine gas generator. This is essentially the core of the engine. It is important to note that there are many different ways in which the core engine gas generator can be designed. As such a wide range of engine parameters will be altered and their effects on engine performance will be examined to determine the best options. This will be done by ranging the maximum internal temperature and compressor compression ratio.

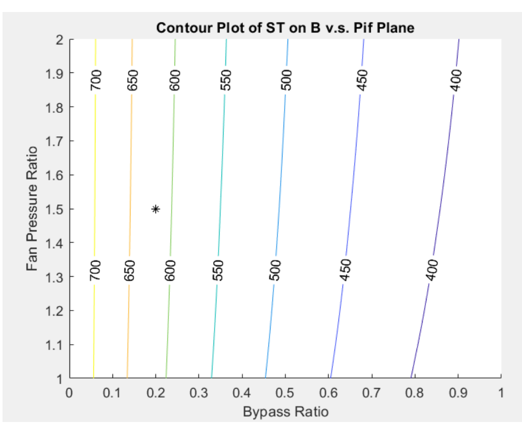
The next step will be to determine the bypass and fan pressure ratios for the outer portion of the engine. By adding a fan to the front of the engine more energy can be extracted from the hot gas created from the core gas generator thus improving efficiency. However, this requires additional power to be drawn from the hot gas and less mass flow rate through the core engine. As such a balance needs to be achieved. In order to find the ideal balance for the flight conditions and requirements laid out in this project a range of bypass and fan pressure ratios will be examined.

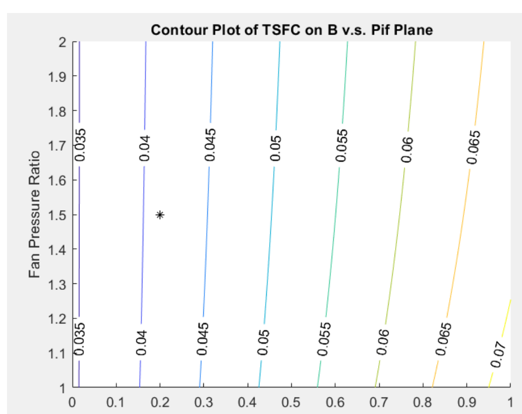
The final step is to analyze the efficiency of the engine. By creating contour plots using the performance parameters mentioned above a wide range of efficiencies can be analyzed. Ideally the values that these performance parameters are set to will yield the highest possible efficiency values while meeting the design requirements stated in this report so that the engine can be competitive on the market.

Results and Analysis



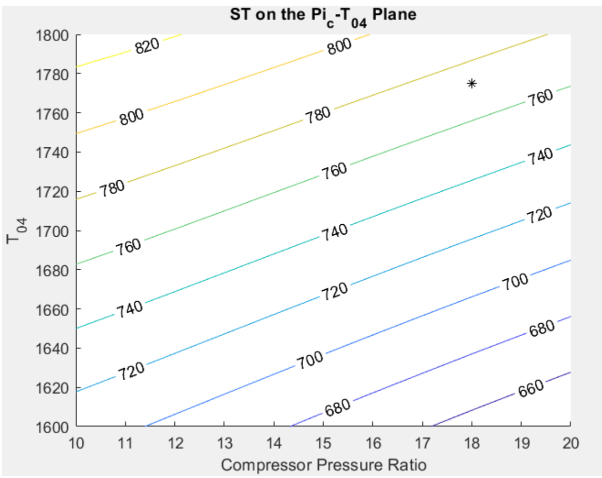
The carpet plot above shows the potential operating conditions of the turbofan engine at varying maximum temperatures and compressor compression ratios while at a fixed bypass and fan pressure ratio. Included in the plot are the maximum allowable thrust specific fuel consumption and minimum allowable specific thrust at the desired cruise conditions. Included is this report's choice of max temperature and compressor compression ratios, 1775 K and 18 respectively. It is important to note that the inlet diameter was set to 1.6 meters to minimize drag.

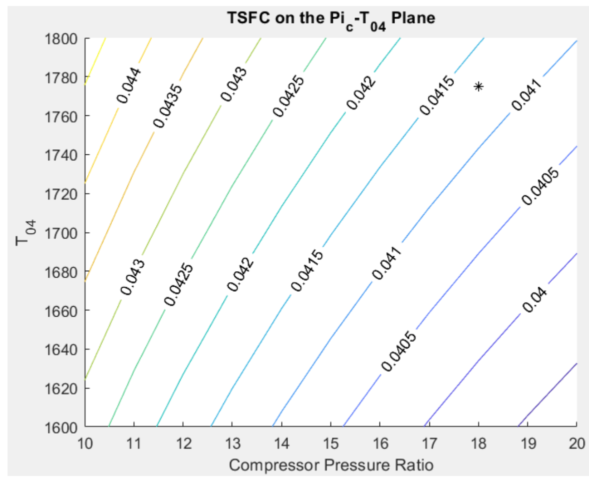




In the above two contour plots the effects of bypass ratio and fan compression ratio on the specific thrust and thrust specific fuel consumption. As shown in the plots, as the bypass ratio is increased beyond .2 the specific thrust starts to decrease rapidly. Likewise at bypass ratios above .4 the thrust specific fuel consumption starts to increase rapidly. It is also shown that as the fan compression ratio increases its effects on specific thrust and thrust specific fuel consumption are not as drastic. However, it is worth noting that at higher fan pressures than displayed too much power would be drawn from the hot gas by the turbine resulting in exhaust exit velocities in the complex plane. Something that is not physically possible. Using this information it was decided that a bypass ratio of .2 and fan pressure ratio of 1.5 would be chosen for the proposed turbofan engine.

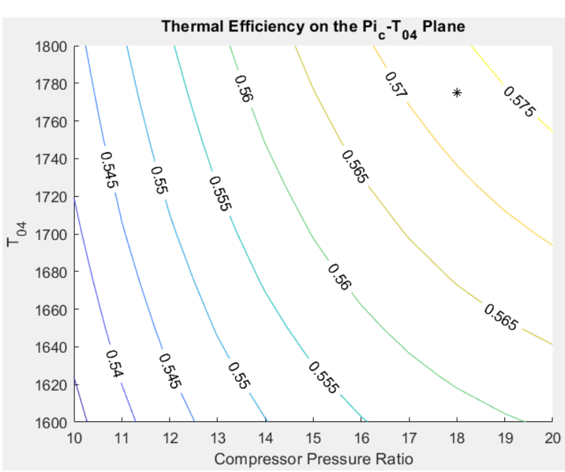
Contour Plots of ST and TSFC on the $\pi_c - T_{04}$ Plane

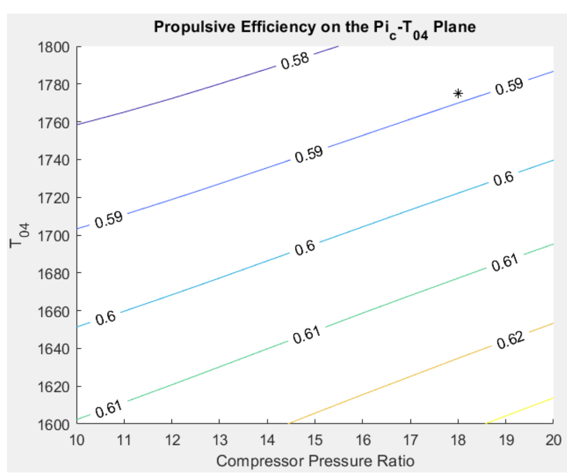


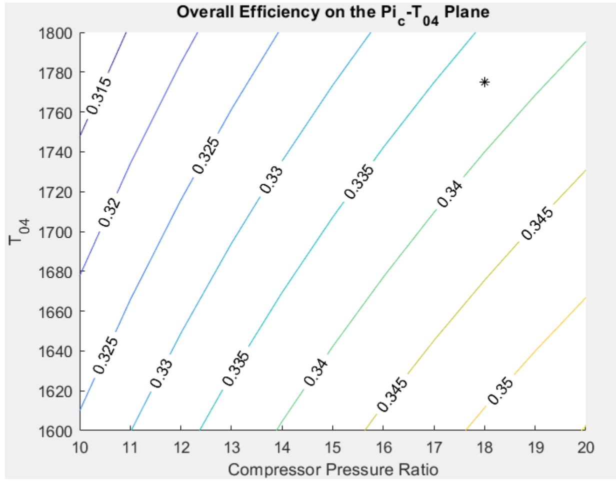


Above are contour plots of the turbofan specific thrust and thrust specific fuel consumption on the $\pi_c - T_{04}$ plane. In addition there is a black dot on both graphs indicating this reports chosen maximum temperature and compressor compression ratio values. These values, 1775 K and 18 respectively, result in the proposed turbofan engine having a specific thrust of 618.07 Ns/kg and a thrust specific fuel consumption of 0.0413 kg/kNs.

Contour Plots of Efficiencies on the $\pi_c - T_{04}$ Plane







Above are contour plots in the $\pi_c - T_{04}$ plane showing the thermal, propulsive, and overall efficiencies of the turbofan engines. Included in the plots are this report's chosen maximum temperature and compressor compression ratio for the proposed turbofan engine. The thermal, propulsive, and overall efficiencies of the proposed engine are 57.27%, 58.89%, and 33.73% respectively.

Potential Social and Economic Impact

The engine performance that is predicted by the calculations done in this report for the proposed turbofan engine exhibit performance characteristics that, although lower, are similar to those found on modern day aircraft. Typical modern aircraft engines have overall efficiencies of around 40%. This is in comparison to this report's proposed engine with an efficiency of 33%. However, this lower efficiency is expected as the aircraft that it is designed to be used on will fly at much higher speeds. These lower efficiency values mean that the operating costs will be higher than those of typical engines. This is the tradeoff made when dealing with supersonic transports. It is also worth noting that due to the Overture aircrafts limited passenger capabilities the service this aircraft provides will most likely only be available to more wealthy customers rather than the average traveller. As such, much like the Concorde, the Overture aircraft may not revolutionize the commercial aviation industry.

Summary

The goal of this report was to provide an alternative engine option to Boom Technologies commercial supersonic aircraft concept, Overture. The aircraft requires 3 engines to operate each producing a minimum thrust of 100 kN of thrust at takeoff and 80 kN of thrust at a cruise speed of mach 1.7. The aircraft also required a passenger capacity, including crew, of 65 and a maximum takeoff weight of 77 tons. The aircraft also needs to be capable of flying a minimum of 8,000 km. As such the proposed alternative engine needs to be fairly efficient. It is believed that the engine proposed in this report meets or exceeds the design requirements provided by Boom Technologies. This report's proposed engine option produces a theoretical thrust of 80.362 kN of thrust at mach 1.7 and a maximum takeoff thrust of 361.5 kN with an inlet diameter of 1.6 meters. The specific thrust at this cruise speed is 618 Ns/kg and the thrust specific fuel consumption is 0.0413 kg/kNs. The thermal, propulsive, and overall efficiencies of the engine at cruise speed are 57.27%, 58.89%, and 33.73% respectively. These efficiencies are slightly below those of current subsonic transports. However, this is expected due to the more intense requirements for this engine. Overall, the proposed alternative engine option in this report represents a viable option for the Overture aircraft.

References

Hill, Philip Graham, and Carl R. Peterson. Mechanics and Thermodynamics of Propulsion. Dorling Kindersley, 2014.

“Read ‘Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions’ at Nap.edu.” National Academies Press: OpenBook, https://www.nap.edu/read/23490/chapter/6#46.

“Concorde Olympus 593.” Heritage, https://www.heritageconcorde.com/concorde-olympus-593-mk610-engines.

Appendix

Code Used to Perform Calculations

```
close all; clear,clc;

%Ambient Variables

Qr=45e6;
ThrustMin=80e3;
ThrustMax=100e3;
Ta=216.5;
Pa=7232.6004;
Tst=288;
Pst=10.13e4;
R=287;
M=1.7;
To4=1600:25:1800;
D=1.6;
A=((D/2)^2)*pi;

gammasub=@(gam) (gam-1)/2;
gammadiv=@(gam) gam/(gam-1);
cp=@(gam) (R*gam)/(gam-1);
poly2adiabatic=@(etap,pi,gam) (pi.^((gam-1)/gam)-1)/(pi.^((gam-1)/(gam*etap))-1);
TBare=@(Tact,Beta) Tact*(1.04+(.01*Beta^1.2));
TAct=@(Tbare,Beta) Tbare/(1.04+(.01*Beta^1.2));
mdoth=@(mdot,Beta) mdot/(1+Beta);

%Engine Performance Variables

gamma=1.4;
gammad=1.4;
gammac=1.37;
gammaf=1.4;
gammab=1.35;
gammat=1.33;
gamman=1.36;

B=.2;
etaf=.92;
pif=1.5;
etanf=.99;
etad=.95;
pic=10:1:20;
etab=.97;
etatp=.92;
pib=.95;
etan=.99;

%%
clc;
```

```
Toa=Ta*(1+gammasub(gamma).*M.^2);
ua=M.*sqrt(gamma*R*Ta);

To2=Ta*(1+gammasub(gamma).*M.^2);
Po2=Pa*(1+(etad.*((To2./Ta)-1))).^(gammadiv(gammad));

del0=Po2/Pst;
theta0=To2/Tst;
mdot=231.8*A*(del0/sqrt(theta0));
mdota=mdoth(mdot,B);

STMin=ThrustMin/mdot;

Po8=Po2.*pif;
To8=To2.*(1+((pif^(1/gammadiv(gammaf))-1)./etaf));
uef=sqrt(2*etanf*(gammadiv(gammaf))*R*To8.*(1-(Pa/Po8).^(1/gammadiv(gamman))));

for m=1:size(To4,2)
  for n=1:size(pic,2)

    etac(m,n)=poly2adiabatic(.9,pic(n),gammac);
    To3(m,n)=To2.*(1+((pic(n).^(1/gammadiv(gammac))-1)/etac(m,n)));
    Po3(m,n)=Po2.*pic(n);

    Po4(m,n)=Po3(m,n).*pib;

    To5(m,n)=To4(m)+To2-To3(m,n)-(B*(To8-Toa));
    pit(m,n)=(To5(m,n)/To4(m))^((etatp*gammab)/(gammab-1));
    etat(m,n)=poly2adiabatic(.92,pit(m,n),gammab);
    Po5(m,n)=Po4(m,n).*(1-((1-(To5(m,n)./To4(m)))./etat(m,n))).^(gammadiv(gammat));

    To6(m,n)=To5(m,n);
    Po6(m,n)=Po5(m,n);


ue(m,n)=sqrt(2*etan*gammadiv(gamman)*R*To6(m,n).*(1-(Pa/Po6(m,n)).^(gammadiv(gamman)^-
1)));

    a=(To4(m)/To3(m,n))-1;
    b=((Qr*etab)/(cp(gammab)*To3(m,n)))-(To4(m)/To3(m,n));
    f(m,n)=a/b;
    ST(m,n)=(((1+f(m,n))*ue(m,n))+(B*uef)-((1+B)*ua));
    Thrust(m,n)=mdota*ST(m,n);
    TAct1(m,n)=TAct(Thrust(m,n),B);
    ST2(m,n)=TAct1(m,n)/mdot;
    TSFC(m,n)=(f(m,n)*1000)/ST2(m,n);
    KE(m,n)=.5*mdota*(((1+f(m,n))*ue(m,n)^2)+(B*uef^2)-((1+B)*ua^2));
    etath(m,n)=KE(m,n)/(f(m,n)*mdota*Qr);
    etap(m,n)=(Thrust(m,n)*ua)/KE(m,n);
    etao(m,n)=etath(m,n)*etap(m,n);

  end
end
```

```
TSFCMax=f(m,n)*1000/STMin;
[a,b]=ValFinder(To4,pic,1775,18);

figure(1)

for m=1:size(ST,1)
    hold on
    plot(ST2(m,:),TSFC(m,:),'b') %Constant Temp

text(ST2(m,1)-10,TSFC(m,1)+.0003,['T_0_4=',num2str(To4(m))],'Color','b','FontSize',6);
    title(append('ST vs TSFC ','At Bypass Ratio of ',num2str(B),' and Fan Pressure
Ratio of ',num2str(pif)));
    xlabel('ST (Ns/kg');
    ylabel('TSFC (kg/kNs');
end

for n=1:size(ST,2)
    hold on
    plot(ST2(:,n),TSFC(:,n),'r') %Constant Pressure Ratio
    text(ST2(end,n),TSFC(end,n),['Pi_c=',num2str(pic(n))],'Color','r','FontSize',6);
end

xline(STMin,'--','Minimum Specific Thrust');
yline(TSFCMax,'--','Maximum TSFC');
plot(ST2(a,b),TSFC(a,b),'*','Color','k');

hold off

%%
clc;

NewPo4=Po3(a,b).*pib;
NewB=0:.05:1;
Newpif=1:.05:2;
m=1;
n=1;

for m=1:size(NewB,2)
  for n=1:size(Newpif,2)

    NewPo8(m,n)=Po2.*Newpif(n);
    NewTo8(m,n)=To2.*(1+((Newpif(n)^(1/gammadiv(gammaf))-1)./etaf));

Newuef(m,n)=sqrt(2*etanf*(gammadiv(gammaf))*R*NewTo8(m,n).*(1-(Pa/NewPo8(m,n)).^(1/gam
madiv(gamman))));

    NewTo5(m,n)=To4(a)+To2-To3(a,b)-(NewB(m)*(NewTo8(m,n)-Toa));
    Newpit(m,n)=(NewTo5(m,n)/To4(a))^((etatp*gammab)/(gammab-1));
    Newetat(m,n)=poly2adiabatic(.92,Newpit(m,n),gammab);

NewPo5(m,n)=NewPo4.*(1-((1-(NewTo5(m,n)./To4(a)))./Newetat(m,n))).^(gammadiv(gammat));

    NewTo6(m,n)=NewTo5(m,n);
```

```
    NewPo6(m,n)=NewPo5(m,n);


Newue(m,n)=sqrt(2*etan*gammadiv(gamman)*R*NewTo6(m,n).*(1-(Pa/NewPo6(m,n)).^(gammadiv(
gamman)^-1)));

    Newmdota(m,n)=mdoth(mdot,NewB(m));
    NewST1(m,n)=(((1+f(a,b))*Newue(m,n))+(NewB(m)*Newuef(m,n))-((1+NewB(m))*ua));
%Bare ST
    NewThrust(m,n)=Newmdota(m,n)*NewST1(m,n);
%Bare T
    NewTAct(m,n)=TAct(NewThrust(m,n),NewB(m));
%Actual T
    NewST2(m,n)=TAct(NewThrust(m,n),NewB(m))/mdot;
%Actual ST
    NewTSFC(m,n)=(f(a,b)*1000)/NewST2(m,n);

  end
end

[c,d]=ValFinder(NewB,Newpif,B,pif);

figure(2)
hold on
plot(NewB(c),Newpif(d),'*','Color','k');
contour(NewB,Newpif,NewST2','ShowText','on');
xlabel('Bypass Ratio');
ylabel('Fan Pressure Ratio')
title('Contour Plot of ST on B v.s. Pif Plane')

figure(3)
hold on
plot(NewB(c),Newpif(d),'*','Color','k');
contour(NewB,Newpif,NewTSFC','ShowText','on')
xlabel('Bypass Ratio');
ylabel('Fan Pressure Ratio')
title('Contour Plot of TSFC on B v.s. Pif Plane')

%%
clc;

figure(4)
hold on
plot(pic(b),To4(a),'*','Color','k');
contour(pic,To4,ST,'ShowText','on');
xlabel('Compressor Pressure Ratio');
ylabel('T_0_4');
title('ST on the Pi_c-T_0_4 Plane');

figure(5)
hold on
plot(pic(b),To4(a),'*','Color','k');
contour(pic,To4,TSFC,'ShowText','on');
xlabel('Compressor Pressure Ratio');
```

```
ylabel('T_0_4');
title('TSFC on the Pi_c-T_0_4 Plane');

figure(6)
hold on
plot(pic(b),To4(a),'*','Color','k');
contour(pic,To4,etath,'ShowText','on');
xlabel('Compressor Pressure Ratio');
ylabel('T_0_4');
title('Thermal Efficiency on the Pi_c-T_0_4 Plane');

figure(7)
hold on
plot(pic(b),To4(a),'*','Color','k');
contour(pic,To4,etap,'ShowText','on');
xlabel('Compressor Pressure Ratio');
ylabel('T_0_4');
title('Propulsive Efficiency on the Pi_c-T_0_4 Plane');

figure(8)
hold on
plot(pic(b),To4(a),'*','Color','k');
contour(pic,To4,etao,'ShowText','on');
xlabel('Compressor Pressure Ratio');
ylabel('T_0_4');
title('Overall Efficiency on the Pi_c-T_0_4 Plane');

%%

function [a,b]=ValFinder(Array1,Array2,Chosen1,Chosen2)

  %From while loop above if any Variables are needed use the a and b values (a=rows
and b=columns)
  %Constant values: To4, To5, Po5, To6, Po6, f, pic
  a=1;
  b=1;
  c=0;

  while c==0
    if Array1(a)==Chosen1 && Array2(b)==Chosen2
      c=1;

    elseif b==size(Array2,2)
      b=1;
      a=a+1;
    else
      b=b+1;
    end
  end
end
```