Thrust and Performance Analyses of the Pratt & Whitney JT3D Turbofan Engine

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The Pratt & Whitney JT3D engine is a low-bypass turbofan with a long flight history on both civilian and military aircraft. In this report, the design of the JT3D is presented both qualitatively and quantitatively, with analyses conducted to determine performance and thrust at nominal flight conditions and otherwise. Results are compared to publicly available performance specifications.

Nomenclature

B	=	Bypass ratio
M	=	Mach number
P_{0x}	=	Total (stagnation) pressure at stage x
P_a	=	Ambient pressure
P_{rc}	=	Compressor (overall) pressure ratio
P_{rf}	=	Fan pressure ratio
T_{0x}	=	Total (stagnation) temperature at stage x
T_a	=	Ambient temperature
TIT	=	Tubine inlet temperature (engine maximum temperature)

I. Introduction

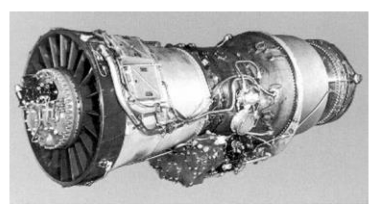

Figure 1 - P&W J57 Turbojet[2]

THE Pratt & Whitney JT3D was the company's first production turbofan, borrowing much of its core from the successful J57 turbojet (pictured right). It promised to provide 50% more takeoff thrust, 25% more climbing power, and 20% more power at cruise. The JT3D entered service in June 1960, fitted to a Boeing 707. It continued to power this aircraft and, not long after, the McDonnell Douglas DC-8 for decades to come. In the military sector, its TF33 variant powered such heavy cargo platforms as the Boeing B-52H Stratofortress (the H variant being the only model to be fitted with turbofan engines), the Lockheed C-141 Starlifter, and the Boeing C-135B Stratolifter. The design thrust of the JT3D ranges from 16,000 lbf (71.17 kN) to 22,500 lbf (75.62 kN, designed for the unbuilt Boeing 707-820).[3]

As a comparably older jet engine model, the JT3D does not enjoy some of the efficiency and performance advances that a newer engine may feature; its low turbine inlet temperature (1150 K) suggests the use of materials that are not as heat-tolerant as the materials used in more modern engines. Being a low-bypass turbofan, the JT3D generates a sizeable fraction of its thrust via the turbojet subsystem, as opposed to the more efficient, higher bypass turbofans of more recent times. Additionally, the use of a two-stage fan indicates a lack of advancement in the field of transonic fan design. Though these factors make the JT3D seem inefficient and underpowered, its proliferation and long

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[2] https://www.navalhistory.org/2010/04/16/flightdeck-friday-douglas-f4d-skyray-part-1

[3] Wikipedia, https://en.wikipedia.org/wiki/Pratt_%26_Whitney_JT3D

operational history testify to its effectiveness—the TF33 is expected to remain in service on the B-52H through 2040[4], eighty years after its introduction to the industry.

Figure 2 - The JT3D turbofan engine, TF33 military variant[5]

II. Performance and Thrust Analyses

An analysis was conducted using the publicly available information on the P&W JT3D—design bypass ratio (BPR), fan pressure ratio (FPR), turbine inlet temperature (TIT), and overall pressure ratio (OPR), to name a few parameters of interest. Fortunately, an engine with such a long history has much of these parameters publicly available. The analysis contained herein studied both the civilian and military variants of the JT3D. Taking the production models with the most information available led to the JT3D-1 (used on six different Boeing 707 variants and four McDonnell Douglas DC-8 variants) and the TF33-P-7 (employed by the Boeing B-52H variant). Design data for these are as follows:

Table 1 - Design Values

	Thrust (dry) [kN]	TSFC [kg/kN·s]	Compressor Pressure Ratio	Fan Pressure Ratio	Bypass Ratio	TIT (K)
JT3D-1	76	0.022	13	1.66	1.42	1150
TF33-P-7	93	0.016	16	1.9	1.21	1228

Using these starting parameters and the following values for the adiabatic efficiencies and specific heat ratios at various points of the engine, the analysis could be performed to verify the given values for thrust and SFC.

[4] United Technologies, http://www.utc.com/News/PW/Pages/Pratt-Whitneys-TF33-Engine-Celebrates-its-55th-Year-with-a-Promise-of-Many-Mor.aspx

[5] http://www.aero-news.net

Table 2 - Component Efficiencies and Specific Heat Ratios

Component	Efficiency, η	Specific-heat ratio, γ
Diffuser	0.97	1.4
Compressor	0.85	1.37
Burner	1	1.35
Turbine	0.9	1.33
Turbojet-nozzle	1	1.36
Fan	0.85	1.4
Fan-nozzle	1	1.4

A. Calculation of Thrust and SFC at Sea Level Conditions

In conducting the turbofan analysis as outlined in *Hill & Peterson, Mechanics and Thermodynamics of Propulsion, 2e*, we find the total pressures and temperatures at various stages of the both the civilian and military variants as follows:

Table 3 - Stagnation Pressures and Temperatures

At Sea Level	P_a (kPa)	P_{02}	P_{03}	P_{04}	P_{05}	P_{06}	P_{08}
JT3D-1	101.33	160.4	2084.7	2084.7	177.3	177.3	266.2
TF33-P-7	101.33	160.4	2565.8	2565.8	188.6	188.6	304.7
	T_a (K)	T_{02}	T_{03}	T_{04}	T_{05}	T_{06}	T_{08}
JT3D-1	288.2	329.8	717.4	1150	676.5	676.5	390.2
TF33-P-7	288.2	329.8	762.2	1228	701.1	701.1	407.9

These values usher along the analysis up to the point at which thrust and specific fuel consumption are obtained.

Table 4 - Thrust & SFC

	JT3D-1, given	JT3D-1, calculated	Error	TF33-P-7, given	TF33-P-7, calculated	Error
Thrust (dry) [kN]	76	72.1	5.1%	93	90.9	2.2%
TSFC [kg/kN·s]	0.022	0.031	41%	0.016	0.029	81%

The overall efficiency η_o is found to be 21.0% for the JT3D-1, and 21.9% for the TF33-P-7.

B. Optimization Analyses at Cruise Conditions

Varying different design parameters gave insight to how the JT3D's performance fares in terms of optimizing thrust and fuel consumption. All analyses in this section are taken for the JT3D-1 variant, at a cruise altitude of 40,000 feet at a flight Mach number of 0.85. All other values were taken as the nominal values given in Tables 1, 2, and 3. Nominal design parameters are indicated by a dashed green line.

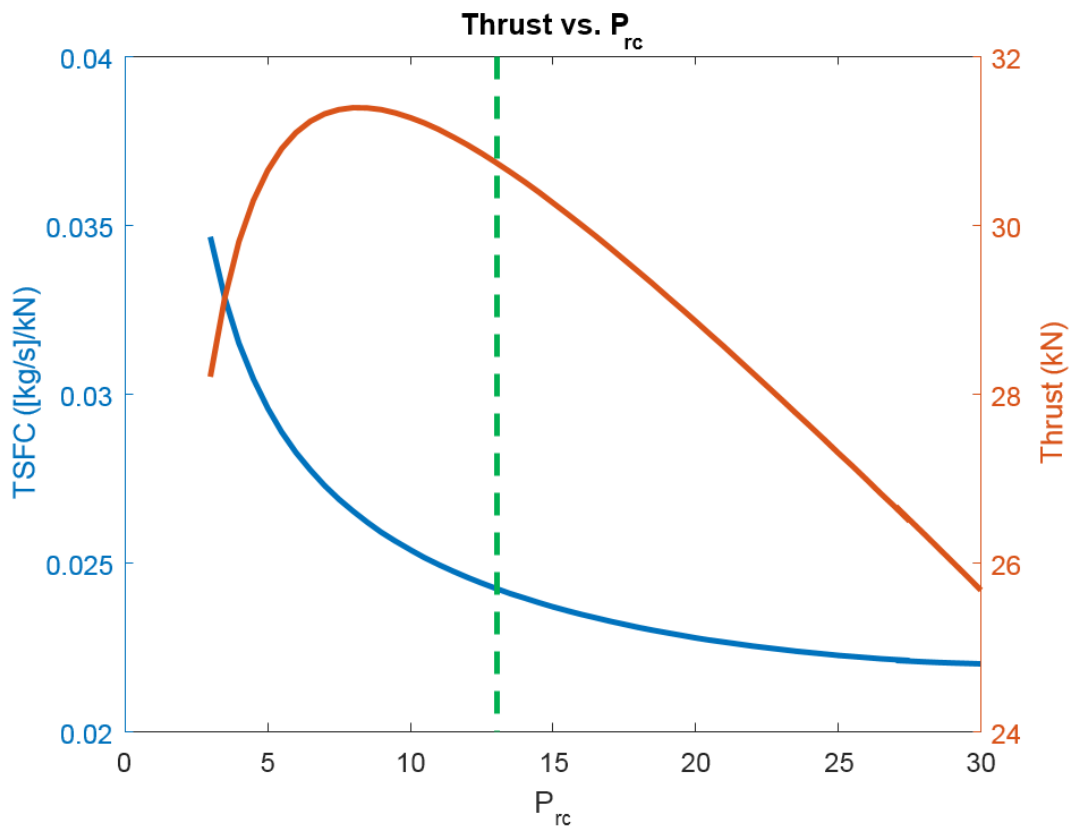

Figure 3 - Varying Compressor Pressure Ratio

Figure 3 shows the variation of thrust and specific fuel consumption with the compressor pressure ratio. The figure demonstrates an optimal choice for P_{rc}, where thrust is maximized while specific fuel consumption is minimized.

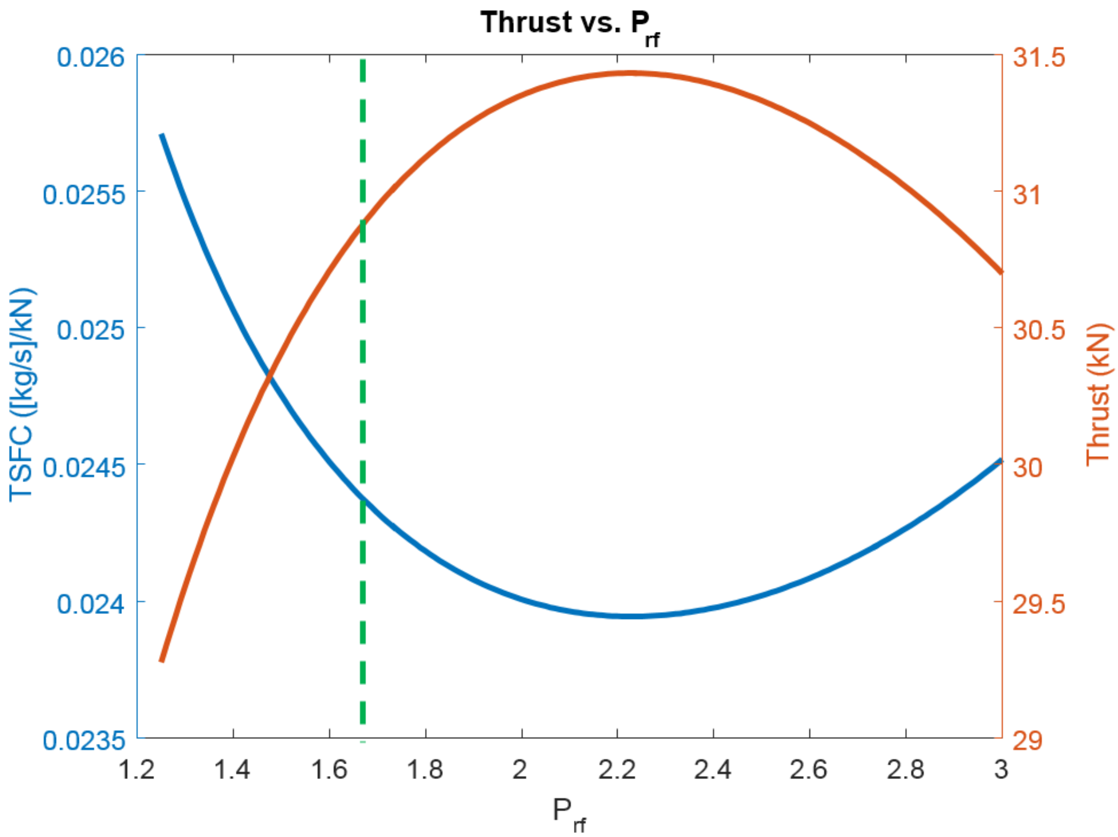

Figure 4 - Varying Fan Pressure Ratio

In taking the case of varying fan pressure ratio, however, we clearly see that the nominal P_{rf} is not optimally situated. A higher pressure ratio across the fan would result in higher thrust output and lower specific fuel consumption. This design choice may not be a choice at all, but rather a limitation imposed by the available technology at the time. As stated before, Pratt and Whitney had not conducted extensive research into transonic fans, and given that the JT3D-1 was the first turbofan they had produced, it would stand to reason that there were limitations, both material and otherwise, on the engineering team to design a highly optimal fan.

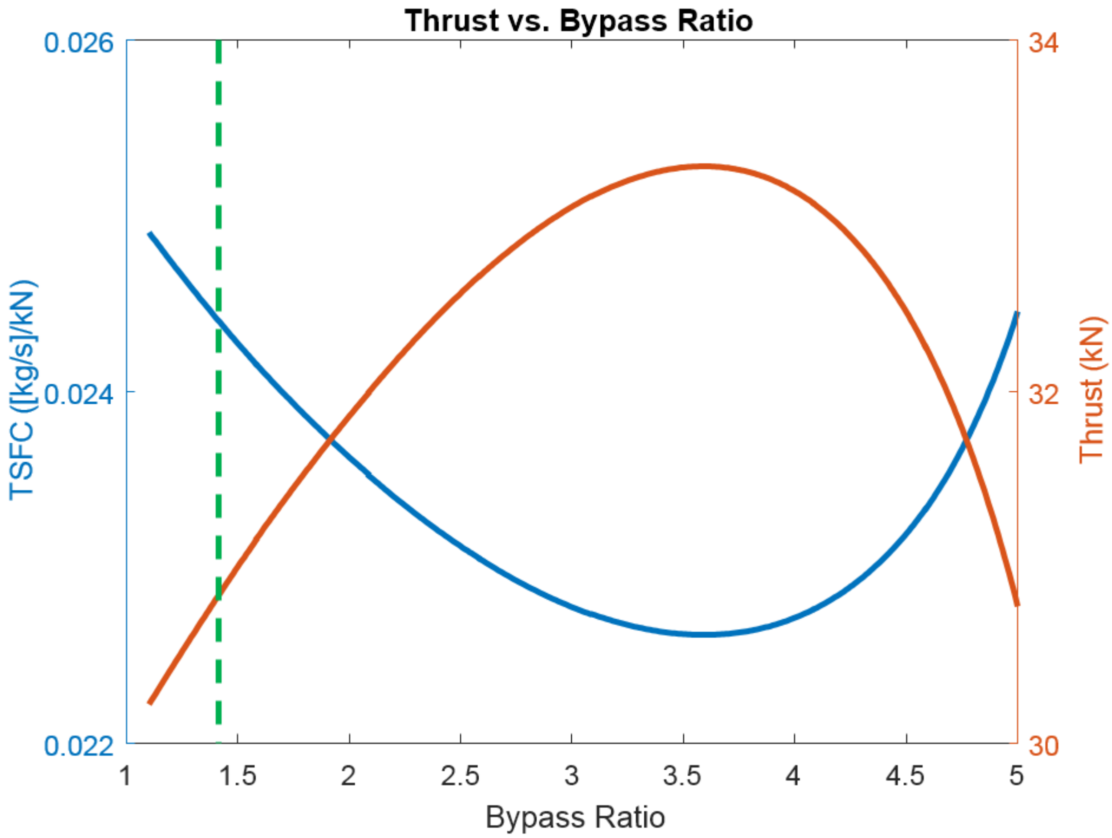

Figure 5 - Varying Bypass Ratio

This conundrum appears again when the turbofan's bypass ratio is varied—the nominal design bypass ratio is placed such that thrust is near minimal and specific fuel consumption is at a high. While this may also be attributed to technological hindrances, it may also be noted that a lower bypass ratio provides better performance at supersonic flight, so that may be another driving factor in this choice.

C. Thrust Performance at Varying Altitude

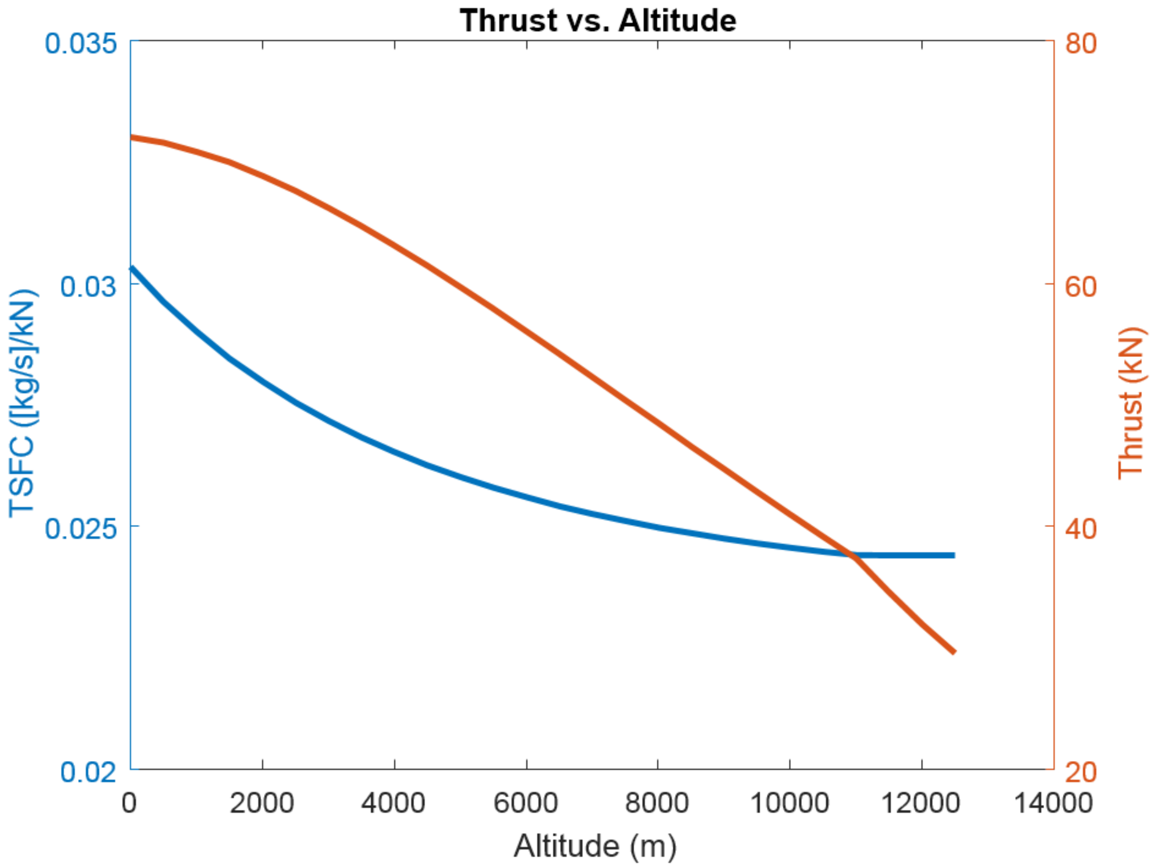

Figure 6 - Thrust Performance During Climb

Plotting our thrust output and specific fuel consumption against time, we find that the overall thrust decreases with altitude, but that fuel consumption decreases, until it levels off around 8000-9000 meters, about cruise altitude. Our maximum thrust at sea level, found earlier, can be clearly viewed on this plot as well.

III. Conclusions

Analysis was performed on the JT3D engine and its variants to verify the nominal design parameters given by Pratt and Whitney. Thrust output was found to be in family with the expected values, but thrust specific fuel consumption was calculated to be greater than the nominal values.

Optimization analyses showed that while the JT3D-1's compressor pressure ratio was well-suited to Mach 0.85 cruise at 40,000 feet, its fan pressure ratio and bypass ratio are not as optimal for this flight condition. This may be due to a lack of available fan technology and research at the time of development, or to a design choice that favors supersonic flight (which is unlikely, given the proliferation of the engine on passenger aircraft).

Thrust analysis at various altitudes demonstrates an optimal cruise height of about 40,000 feet, where thrust specific fuel consumption is minimized while preserving total thrust output.

Appendix (MATLAB Code)

```
function values = JT3D_murray_ms
%%  AEM-508
%   John Murray

% JT3D-1 Variant at Sea Level
[TSFC, thrust, n_o] = find_thrust_efficiency(1.66, 1.42, 1150, 13, 101.325e3,
288.15, 196);
values = [TSFC, thrust, n_o];

% TF33-P-3 Variant at Sea Level
[TSFC, thrust, n_o] = find_thrust_efficiency(1.9, 1.21, 1228, 16, 101.325e3,
288.15, 225.9);
values = [values; TSFC, thrust, n_o];

% Vary JT3D-1 compressor pressure ratio at cruise altitude (~40k ft)
thrust_varPRC = [];
for P_rc = 3:0.5:30
    [TSFC, thrust, n_o] = find_thrust_efficiency(1.66, 1.42, 1150, P_rc,
18.75e3, 216.7, 196*.246);
    thrust_varPRC = [thrust_varPRC; P_rc, TSFC, thrust, n_o];
end

figure
[hAx,hLine1,hLine2] = plotyy(thrust_varPRC(:,1),
thrust_varPRC(:,2),thrust_varPRC(:,1), thrust_varPRC(:,3));
title('Thrust vs. P_{rc}')
xlabel('P_{rc}')
ylabel(hAx(1),'TSFC ([kg/s]/kN)') % left y-axis
ylabel(hAx(2),'Thrust (kN)') % right y-axis


% Vary JT3D-1 fan pressure ratio at cruise altitude (~40k ft)
thrust_varPRF = [];
for P_rf = 1.25:0.01:3.0
    [TSFC, thrust, n_o] = find_thrust_efficiency(P_rf, 1.42, 1150, 12.5,
18.75e3, 216.7, 196*.246);
    thrust_varPRF = [thrust_varPRF;P_rf, TSFC, thrust, n_o];
end

figure
[hAx,hLine1,hLine2] = plotyy(thrust_varPRF(:,1),
thrust_varPRF(:,2),thrust_varPRF(:,1), thrust_varPRF(:,3));
title('Thrust vs. P_{rf}')
xlabel('P_{rf}')
ylabel(hAx(1),'TSFC ([kg/s]/kN)') % left y-axis
ylabel(hAx(2),'Thrust (kN)') % right y-axis


% Vary JT3D-1 Bypass ratio at cruise altitude (~40k ft)
thrust_varBPR = [];
```

```
for B = 1.1:0.01:5
    [TSFC, thrust, n_o] = find_thrust_efficiency(1.66, B, 1150, 12.5,
18.75e3, 216.7, 196*.246);
    thrust_varBPR = [thrust_varBPR; B, TSFC, thrust, n_o];
end

figure
[hAx,hLine1,hLine2] = plotyy(thrust_varBPR(:,1),
thrust_varBPR(:,2),thrust_varBPR(:,1), thrust_varBPR(:,3));
title('Thrust vs. Bypass Ratio')
xlabel('Bypass Ratio')
ylabel(hAx(1),'TSFC ([kg/s]/kN)') % left y-axis
ylabel(hAx(2),'Thrust (kN)') % right y-axis


load flight.mat
altitude = [];
list_thrust = [];
list_TSFC = [];
for ii = 1: length(flight_info)
    [TSFC, thrust, n_o] = find_thrust_efficiency(1.66, 1.42, 1150, 12.5,
flight_info(ii,3)/100e3, flight_info(ii,2), 196*flight_info(ii,4));
    list_thrust = [list_thrust; thrust];
    list_TSFC = [list_TSFC; TSFC];
    altitude = [altitude; flight_info(ii,1)];
end


figure
[hAx,hLine1,hLine2] = plotyy(altitude,list_TSFC ,altitude, list_thrust);
title('Thrust vs. Altitude')
xlabel('Altitude (m)')
ylabel(hAx(1),'TSFC ([kg/s]/kN)') % left y-axis
ylabel(hAx(2),'Thrust (kN)') % right y-axis

function [TSFC, thrust, n_o] = find_thrust_efficiency(P_rf, B, T_04, P_rc,
P_a, T_a, m_a)


%% Initial parameters
gamma = 1.4;
% B = 1.42;
% P_rc = 12.5;
% T_04 = 1150; % K
% P_rf = 1.50;
Qr = 45000e3;
M = 0.85;
R = 287;

% Turbojet component efficiencies
% Diffuser
n_d = 0.97;
gamma_d = 1.40;
% Compressor
n_c = 0.85;
```

```
gamma_c = 1.37;
% Burner
n_b = 1.00;
gamma_b = 1.35;
% Turbine
n_t = 0.90;
gamma_t = 1.33;
% Nozzle
n_n = 0.98;
gamma_n = 1.36;

% Bypass fan component efficiencies
% Diffuser
n_d = 0.97;
gamma_d = 1.4;
% Fan
n_f = 0.85;
gamma_f = 1.4;
% Fan nozzle
n_fn = 0.97;
gamma_fn = 1.4;



%%  Turbojet calculations
% 1. Compressor inlet conditions
T_02 = T_a*(1 + ((gamma-1)/2)*M^2);
P_02 = P_a*(1 + n_d*((T_02/T_a)-1))^(gamma_d/(gamma_d-1));

% 2. Compressor outlet conditions
P_03 = P_02*P_rc;
T_03 = T_02*(1+(1/n_c)*(P_rc^((gamma_c - 1)/gamma_c) - 1));

% 3. Burner fuel-air ratio
Cp = R*(gamma_b/(gamma_b-1));
f = ((T_04/T_03) - 1)/((Qr/(Cp*T_03)) - (T_04/T_03));

% 4. Turbine inlet pressure
P_04 = P_03; % roughly

%% Turbofan calculations
% 6. Fan outlet conditions
P_08 = P_02*P_rf;
T_08 = T_02*(1 + (1/n_f)*(P_rf^((gamma_f-1)/gamma_f) - 1));

% 7. Fan nozzle exit velocity
u_ef = sqrt(2*n_fn*(gamma_f/(gamma_f-1))*R*T_08*(1-(P_a/P_08)^((gamma_f-
1)/gamma_f)));

% 8. Turbine outlet conditions
T_0a = T_a*(1+((gamma - 1)/2)*M^2);
T_05 = T_04 - (T_03 - T_02) - B*(T_08 - T_0a);
P_05 = P_04*(1 - (1/n_t)*(1 - (T_05/T_04)))^(gamma_t/(gamma_t-1));

% 9. Nozzle inlet conditions
```

```
T_06 = T_05;
P_06 = P_05;

% 10. Nozzle exit conditions
u_e = sqrt(2*n_n*(gamma_n/(gamma_n-1))*R*T_06*(1 - (P_a/P_06)^((gamma_n-
1)/gamma_n)));

%% Thrust conditions
u = M*sqrt(gamma*R*T_a);
Th_sp = (1 + f)*u_e + B*u_ef - (1+B)*u;
TSFC = (f/((1+f)*u_e + B*u_ef - (1+B)*u));

%% Overall efficiency
n_o = Th_sp*u/(f*Qr);


TSFC = TSFC*1000; % convert to kg/(kN-s)
Th_sp = Th_sp/1000; % convert to (kN-s)/kg

thrust = Th_sp*m_a; % kN
```