

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**MIXED FLOW MILITARY TURBOFAN CONTROL
STRATEGIES**

MEHMET ENES YALÇIN

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ENERGY TECHNOLOGIES
APPLIED PROPULSION SYSTEM DESIGN AND
ENGINEERING FOR AEROSPACE TECHNOLOGIES
PROGRAM

ADVISOR: ASSIST. PROF. DR. FATİH USTA

JULY 2025

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**MIXED FLOW MILITARY TURBOFAN CONTROL
STRATEGIES**

MEHMET ENES YALÇIN

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ENERGY TECHNOLOGIES
APPLIED PROPULSION SYSTEM DESIGN AND
ENGINEERING FOR AEROSPACE TECHNOLOGIES
TECHNOLOGIES PROGRAM**

ADVISOR: ASSIST. PROF. DR. FATİH USTA

JULY 2025

T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

KARIŞIK AKIŞ ASKERİ TURBOFAN KONTROL
STRATEJİLERİ

MEHMET ENES YALÇIN

YÜKSEK LİSANS TEZİ
ENERJİ TEKNOLOJİLERİ ANABİLİM DALI
HAVACILIK VE UZAY TEKNOLOJİLERİNDE
UYGULAMALI İTKİ SİSTEMİ TASARIM
MÜHENDİSLİĞİ PROGRAMI

DANIŞMAN: DR. ÖĞR. ÜYESİ FATİH USTA

TEMMUZ 2025



MASTER of SCIENCE JURY APPROVAL FORM

A thesis submitted by Mehmet Enes, Yalçın, defended on 25/07/2025 before the jury formed with the 08/07/2025 date and 2025/35 numbered decision of the GTU Graduate Administration Board, has been accepted as a MASTER of SCIENCE thesis in the Department of Energy Technologies, Applied Propulsion System Design and Engineering Program for Aerospace Technologies.

JURY

MEMBER

(THESIS ADVISOR) : Assist. Prof. Dr. Fatih Usta

MEMBER

: Prof. Dr. Ali Ata

MEMBER

: Assist. Prof. Dr. Demet Balkan

APPROVAL

Gebze Technical University Graduate Administration Board

...../...../..... date and/..... numbered decision.

SIGNATURE/SEAL

ABSTRACT

Mixed flow turbofan engines are essential for the modern aerial combat and defense roles since they possess high thrust, good fuel efficiency and flexible operation. These engines present special control problems because of their complex aero thermal dynamics, numerous operating conditions and several performance constraints. This thesis is aimed at improving efficiency and operability of control approaches for modern turbofan engines.

First, engine design features, basic functioning, and the structure of mixed flow turbofan engines are reviewed. Off design simulation of the interaction between bypass and core flows is also presented. The performance and control of the engine are also evaluated based on various engine components such as variable geometry mechanisms and nozzles.

Additionally, the developed engine is evaluated for specific cases to determine the strengths and weaknesses of the control strategies implemented. The engine station pressure and temperature parameters are used to judge the control effectiveness of the engine and its response.

This thesis is partly based on the presentation of different control methods from the performance point of view. The study looks at how these approaches alter engine fan and exhaust system behaviors at certain times, how it improves performance during missions and maneuvers, and how it ensures the safety of the engine within its limitations.

The findings of this research are useful for the improvement of control theories for military turbofan engines with mixed flows and would help to improve the design of control systems for such engines. The results also show how to enhance the efficiency and power leverage of the engine in all the operating regimes for better reliability and durability.

Keywords: Turbofan, Control, Nozzle, Thrust, Afterburner

ÖZET

Karışık akışlı turbofan motorları, modern hava muharebe ve savunma uygulamalarında yüksek itki, yakıt verimliliği ve operasyonel esneklik arasında denge sağlayan kritik bileşenlerdir. Bu motorların kontrol kavramları, karmaşık aero-termal dinamikleri, çeşitli çalışma koşulları ve sıkı performans gereksinimleri nedeniyle önemli zorluklar içermektedir. Bu tez, modern turbofan motorları için kontrol yaklaşımlarını inceleyerek verimlilik ve işletilebilirliği artırmayı amaçlamaktadır.

Araştırma, öncelikle motor tasarım özellikleri, temel çalışma prensipleri ve karışık akışlı turbofan motorlarının mimarisinin analiz edilmesiyle başlamaktadır. Bypass ve çekirdek akışları arasındaki etkileşim, hem tasarım hem de tasarım dışı çalışma koşulları bağlamında incelenmektedir. Değişken geometrili mekanizmalar ve nozul seçimleri gibi çeşitli motor bileşenleri analiz edilerek, bunların performans ve kontrol üzerindeki etkileri değerlendirilmektedir.

Bunun yanı sıra, tasarlanan motor belirli platform manevraları altında incelenerek farklı kontrol stratejilerinin avantajları ve sınırlılıkları belirlenmektedir. Motorun istasyon basıncı ve sıcaklık parametreleri kullanılarak, motor kontrol performansı ve motor yanıt karakteristikleri değerlendirilmektedir.

Bu tezin temel odak noktalarından biri, çeşitli kontrol yaklaşımlarının performans açısından değerlendirilmesidir. Çalışma, bu yaklaşımların belirli çalışma koşullarında motor davranışını nasıl değiştirdiğini, dinamik görev profilleri ve manevralar içinde performansını nasıl optimize ettiğini ve operasyonel sınırlamalar dahilinde motor güvenliğini nasıl sağladığını ortaya koymaktadır.

Bu araştırmadan elde edilen bulgular, karışık akışlı askeri turbofan motorlarının kontrol stratejilerinin geliştirilmesine katkı sağlamakta olup, daha verimli ve çevik motor kontrol sistemlerinin oluşturulmasını desteklemektedir. Elde edilen sonuçlar, motor performansını ve işletilebilirliğini tüm operasyonel koşullar altında iyileştirme konusunda önemli bilgiler sunarak, motorların güvenilirliğini ve dayanıklılığını artırmayı amaçlamaktadır.

Anahtar Kelimeler: Turbofan, Kontrol, Egzoz, İtki, Art Yakıcı

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis advisor, Dr. Fatih Usta, for his continuous support, valuable guidance, and insightful feedback throughout the course of this study.

I am also thankful to Mr. Emrah Güllü from Tusas Engine Inc. for technical assistance and contributions, which played an important role in development of this thesis.

My heartfelt thanks go to my family for their endless support, patience, and encouragement during this journey.

I would also like to extend my appreciation on my colleagues Mehmet Yaşar Tekin , Melih İçinsel, Alper Yılmaz for their understanding and support, which helped me stay motivated and focused throughout the process.

Finally, I gratefully acknowledge the support provided by TEI – TUSAS Engine Industry Inc., whose contribution made the research possible.



TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	v
ÖZET	vi
ACKNOWLEDGEMENTS	vii
TABLE OF CONTENTS	viii
LIST OF SYMBOLS AND ABBREVIATIONS	x
LIST OF FIGURES	xii
LIST OF TABLES	xiv
1. INTRODUCTION	1
1.1. Fundamentals of Turbofan Engines	2
1.1.1. Basic Working Principles of Turbofan Engine	2
1.1.2. Engine Layout and Stations	3
1.2. Different Design Selection of Turbofans	4
1.2.1. Low Bypass and High Bypass Turbofan Engines	4
1.2.2. Mixed Flow and Unmixed Flow Turbofan Engines	6
1.2.3. Afterburner Operation of Turbofan Engines	8
1.2.4. Benchmark Engines	9
1.3. Turbofan Components	17
1.3.1. Fan	17
1.3.2. Compressor	18
1.3.3. Combustor	19
1.3.4. Turbine	20
1.3.5. Nozzle	21
1.3.6. Variable Components	22
2. STEADY STATE OPERATION OF TURBOFAN ENGINE	26
2.1. Parametric Cycle (On-Design) of Turbofans	26
2.1.1. Design Point Definition	27
2.1.2. Thermodynamic Cycle Definition	28
2.1.3. Cycle Design Parameters	29
2.1.4. Design Optimizations	30
2.2. Off - Design of Turbofan	30
2.2.1. Off Design Operation Concept	30
2.2.2. Operation Conditions and Mission Profile	32
2.2.3. Component Performance in Off Design	33
2.2.4. Performance Degradation and Health Monitoring	34
3. TRANSIENT OPERATION OF TURBOFAN ENGINE DESIGN	36
3.1. Engine Response Characteristics During Transient's Operation	37
3.2. Time Dependent Behavior of Key Engine Parameters	39
3.3. Limitation of Engine Response During Fast Operational Changes	40
3.4. Physical and Environmental Factors Influencing Transient Response	42
4. EXPERIMENT	43
4.1. Experiment Concepts and Requirements	44
4.1.1. Specific Fuel Consumption	45

4.1.2. Net Thrust	46
4.1.3. Surge Margin	48
4.1.4. High - Pressure Turbine Inlet Temperature (T4)	49
4.2. Comparison Parameters Definition	50
4.2.1. Engine Installation	50
4.2.2. Engine Deterioration	51
4.3. Engine Design	51
4.4. Engine Control Design Selection	53
4.5. Engine Control Outputs	54
4.5.1. Installed Deteriorated with AB Operation	54
4.5.2. Uninstalled Deteriorated with AB Operation	57
4.5.3. Installed New with AB Operation	60
4.5.4. Uninstalled New with AB Operation	62
4.5.5. Installed Deteriorated Without AB Operation	65
4.5.6. Uninstalled Deteriorated Without AB Operation	67
4.5.7. Installed New Without AB Operation	70
4.5.8. Uninstalled New Without AB Operation	72
5. EXPERIMENT RESULTS	75
6. CONCLUSIONS	81
REFERENCES	83
BIOGRAPHY	87

LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Annulus Area
AB	:	Afterburner
BPR	:	Bypass Ratio
CC	:	Combustor Chamber
CON-DI	:	Convergent - Divergent Nozzle
Core	:	Core Section
CPR	:	Compressor Pressure Ratio
DEEC	:	Digital Electronic Fuel Control
DECU	:	Digital Electronic Control Unit
Dry	:	Without Afterburner Operation
EASA	:	European Union Aviation Safety Agency
ECS	:	Electronic Control System
EGT	:	Exhaust Gas Temperature
EMU	:	Engine Monitoring Unit
EMS	:	Engine Monitoring System
EPR	:	Engine Pressure Ratio
FAA	:	Federal Aviation Administration
FADEC	:	Full Authority Digital Engine Control
Fan	:	Fan Section
F_N	:	Net Thrust
FPR	:	Fan Pressure Ratio
HPT	:	High Pressure Turbine
HPC	:	High Pressure Compressor
ICAO	:	International Civil Aviation Organization
IGV	:	Inlet Guide Vane
kN	:	kilo Newton
kg/s	:	Kilogram / second
kW	:	kilo Watt
K	:	Gain between fuel and spool response
LPT	:	Low Pressure Turbine
Ma/M	:	Mach Number
M13	:	Mach Number at Station 13
m_c	:	Corrected Mass Flow
m_f	:	Fuel Mass Flow
NATO	:	North Atlantic Treaty Organization
Nc02	:	Corrected Fan Speed
NGV	:	Nozzle Guide Vane
NPSS	:	Numerical Propulsion System Simulation
η_p	:	Propulsive Efficiency
η_{th}	:	Thermal Efficiency
OPR	:	Overall Pressure Ratio
P	:	Density
P3	:	Total Pressure at Station 3
P6	:	Total Pressure at Station 6
P16	:	Total Pressure at Station 16
Pt	:	Total Pressure
PSFC	:	Power to Specific Fuel Consumption
PTO	:	Power Take Off
R	:	Gas Constant
RQL	:	Rich Quench Lean

SFC	:	Specific Fuel Consumption
SM	:	Surge Margin
STOL	:	Short Take Off Landing
T2	:	Temperature at Station 2
T3	:	Temperature at Station 3
T4	:	Temperature at Station 4
TIT	:	Turbine Inlet Temperature
Tt	:	Total Temperature
TRF	:	Turbine Rear Frame
TSFC	:	Thrust to Specific Fuel Consumption
UAV	:	Unmanned Aerial Vehicle
V	:	Velocity
VAN	:	Variable Nozzle
Vdry	:	Velocity without Afterburner Operation
VIGV	:	Variable Inlet Guide Vane
VSV	:	Variable Stator Vane
W	:	Rotational Speed
Wet	:	With Afterburner Operation
Y	:	Specific Heat Ratio

LIST OF FIGURES

	<u>Page</u>
Figure 1.1: Basic layout of turbofan components.	2
Figure 1.2: Stations on a turbofan engine.	3
Figure 1.3: The relationship between DPR and SFC at different T4, OPR, propulsive efficiency [1].	6
Figure 1.4: Bypass stream and core stream mixing [2].	7
Figure 1.5: Mixed and Unmixed turbofan BPR vs. n_{th} with same n_p [1].	7
Figure 1.6: The mechanical components of afterburner [3].	8
Figure 1.7: Dry and wet (afterburner) operation effects on net thrust and SFC [1].	9
Figure 1.8: RB 199 Engine Layout [4].	10
Figure 1.9: F100 Engine with accessories and sensors [5].	12
Figure 1.10: F404 Engine [6].	13
Figure 1.11: AL-41 Engine [7].	14
Figure 1.12: General Electric F110 Engine [7].	16
Figure 1.13: EJ 200 Engine [8].	17
Figure 2.1: Ideal and real Brayton cycle [9].	28
Figure 2.2: The relation comparison of cycle design parameters such as OPR, TIT, SFC and thermal efficiency [10].	29
Figure 3.1: Transient behavior of engine when accelerating with limitation of W_f/Ps_3 and $\dot{N}$ [11].	38
Figure 4.1: Experiment Plan with Engine Features and Control Approach.	45
Figure 4.2: Flight Envelope of MHY16500.	53
Figure 4.3: Ins – Det – Thrust Comparison.	55
Figure 4.4: Ins – Det – SFC Comparison.	55
Figure 4.5: Ins – Det – T4 Comparison.	56
Figure 4.6: Ins – Det – Fan SM Comparison.	56
Figure 4.7: Ins – Det – CMP SM Comparison.	57
Figure 4.8: Un – Det – Thrust Comparison.	57
Figure 4.9: Un – Det – SFC Comparison.	58
Figure 4.10: Un – Det – T4 Comparison.	58
Figure 4.11: Un – Det – FAN SM Comparison.	59
Figure 4.12: Un – Det – CMP SM Comparison.	59
Figure 4.13: Ins – New – Thrust Comparison.	60
Figure 4.14: Ins – New – SFC Comparison.	60
Figure 4.15: Ins – New – T4 Comparison.	61
Figure 4.16: Ins – New – FAN SM Comparison.	61
Figure 4.17: Ins – New – CMP SM Comparison.	62
Figure 4.18: Un – New – Thrust Comparison.	62
Figure 4.19: Un – New – SFC Comparison.	63
Figure 4.20: Un – New – T4 Comparison.	63
Figure 4.21: Un – New – FAN SM Comparison.	64
Figure 4.22: Un – New – CMP SM Comparison.	64
Figure 4.23: Ins – Det – Thrust Comparison.	65
Figure 4.24: Ins – Det – SFC Comparison.	65
Figure 4.25: Ins – Det – T4 Comparison.	66
Figure 4.26: Ins – Det – FAN SM Comparison.	66
Figure 4.27: Ins – Det – CMP SM Comparison.	67

Figure 4.28: Un – Det – Thrust Comparison.	67
Figure 4.29: Un – Det – SFC Comparison.	68
Figure 4.30: Un – Det – T4 Comparison.	68
Figure 4.31: Un – Det – FAN SM Comparison.	69
Figure 4.32: Un – Det – CMP SM Comparison.	69
Figure 4.33: In – New – Thrust Comparison.	70
Figure 4.34: In – New – SFC Comparison.	70
Figure 4.35: In – New – T4 Comparison.	71
Figure 4.36: In – New – FAN SM Comparison.	71
Figure 4.37: In – New – CMP SM Comparison.	72
Figure 4.38: Un – New – Thrust Comparison.	72
Figure 4.39: Un – New – SFC Comparison.	73
Figure 4.40: Un – New – T4 Comparison.	73
Figure 4.41: Un – New – FAN SM Comparison.	74
Figure 4.42: Un – New – CMP SM Comparison.	74
Figure 5.1: Thrust Outputs from different nozzle control methods.	77
Figure 5.2: T4 Outputs from different nozzle control methods.	77
Figure 5.3: CMP SM Outputs from different nozzle control methods.	78
Figure 5.4: New – AB Engine Configuration with installation case effects on T4.	78
Figure 5.5: Installed – AB Engine Configuration with deterioration effects on T4.	79
Figure 5.6: AB Engine both installation and deterioration effects on T4.	80

LIST OF TABLES

	<u>Page</u>
Table 1.1: Station numbering of a turbofan engine.	3
Table 4.1: Design Parameter of Engine.	52
Table 5.1: Experiment Outputs with AB version (Min – Max).	75
Table 5.2: Experiment Outputs without AB version (Min – Max).	76



1. INTRODUCTION

In the aviation world, different types of power sources are used, such as on-utilized air platforms such as helicopters, airplanes, or UAVs. These power sources are divided for the purpose of usage platforms. Therefore, the widely used power sources are turbo engines, such as turbofans, turbojets, and turboshaft engines. All these turbo engines have working principles based on compression and combustion, but their designs are specialized for each other.

Turbofan engines are the most popular engines used in modern aviation. It provides more thrust with low specific fuel consumption thanks to bypassing flow. The bypassing flow is only pressurized at the fan and not in the core engine, where compression and combustion operations occur. These engines are preferred in both commercial and military platforms.

Turbofan engines are classified based on their design, such as low-bypass and high-bypass configurations, each designed to meet specific aircraft requirements. High-bypass turbofan engines are commonly used for commercial purposes due to their good fuel efficiency. Unlike the high-bypass configuration, low-bypass turbofans are primarily used in military aircraft, which require higher thrust-to-weight ratios and supersonic operations. Furthermore, these configurations are further categorized based on design selection requirements, such as mixed-flow or unmixed-flow configurations, nozzle selection, integrated variable geometry components, and the use of an afterburner.

In this thesis, Mixed Flow Military Turbofan Engines are the primary focus. Initially, the fundamentals of turbofan engines will be analyzed, including the historical evolution of turbofan technology, basic working principles, critical design selections, differences between military and commercial applications, and benchmark examples of turbofan engines.

1.1. Fundamentals of Turbofan Engines

1.1.1. Basic Working Principles of Turbofan Engine

The working principles of turbofan engine to the basic level are compression, combustion and expansion. For these operations, turbofan engine has components which are divided into cold and hot components according to their operating region. The cold region is mainly related to the non-combustion part of the engine namely intake, fan, splitter, compressor and bypass duct. However, the hot region of the engine consists of combustion chamber, HPT, LPT, mixer, exhaust and afterburner sections as shown in **Figure 1.1**, the demonstration basic layout of Turbofan.

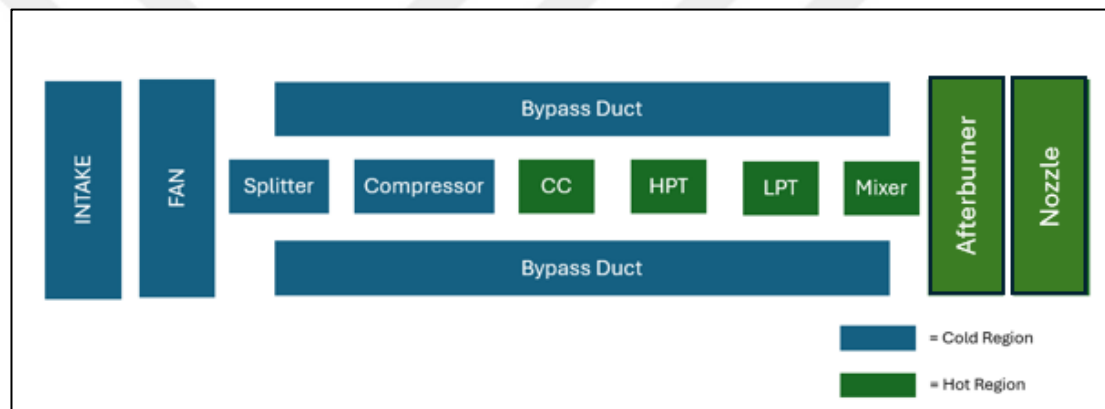


Figure 1.1: Basic layout of turbofan components.

The turbofan engine has two separate flows of mass: the bypass flow and the core flow. Both are responsible for the overall thrust generation. The bypass flow is the portion of the incoming air divided by the splitter and then sent to the bypass duct. The selected bypass ratio will determine the mass flow, and the air velocity of the bypass stream can be optimized through efficient design.

The core flow is the air which remains after the splitter and enters the engine. This flow is first compressed in the compressor section, then mixed with fuel and burned in the combustion chamber and then expanded through the turbine section to produce mechanical work.

To make the turbofan engine have the capability to operate continuously, the rotating components are joined by means of integrated shafts called spools. These are usually divided into a high-pressure spool, which has the high-pressure turbine connected to

the high-pressure compressor, and a low-pressure spool, which has the low-pressure turbine connected to the fan module.

1.1.2. Engine Layout and Stations

In Engine parts, designers are named specific regions as stations. These stations are simple clarification to understanding component thermodynamic specifications. As demonstrated in **Table 1.1** as well as **Figure 1.2**.

Table 1.1: Station numbering of a turbofan engine.

Station Number	Name
0	Ambient
20	Fan Inlet
13	Fan Outer Exit
21	Fan Inner Exit
25	HPC Inlet
27	HPC Interstage
30	HPC Exit
40	HPT NGV Inlet
43	HPT Rotor Exit
45	LPT Rotor Inlet
50	LPT Rotor Exit
60	Core Exit
16	TRF Bypass Exit
70	Nozzle Inlet
80	Nozzle Throat
90	Nozzle Exit

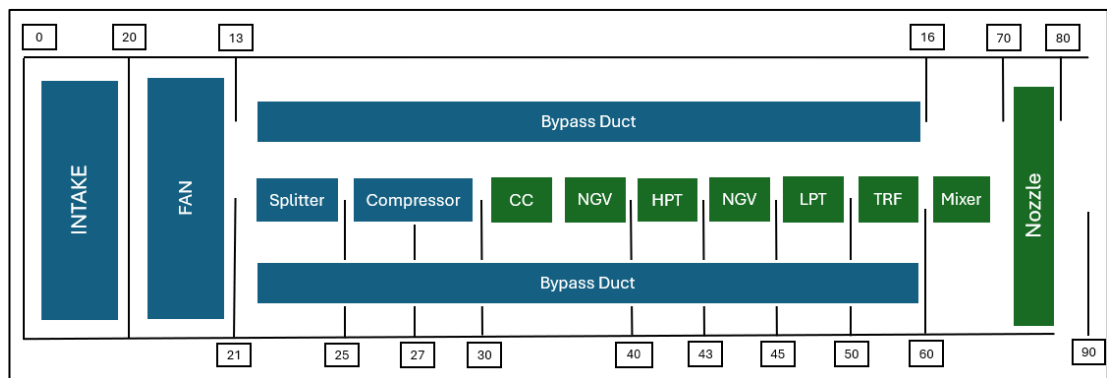


Figure 1.2: Stations on a turbofan engine.

1.2. Different Design Selection of Turbofans

The classification of turbofan engines depends on their intended use between commercial and military operations and their design aspects which include bypass ratio levels (high or low) and flow configuration types (mixed or unmixed).

The fundamental design choices determine both engine architecture and operational performance capabilities. Commercial turbofan engines optimize their design for low specific fuel consumption with high bypass ratios to improve fuel efficiency. Military turbofan engines operate with higher specific fuel consumption rates and reduced bypass ratios since they need to deliver maximum thrust and compactness for combat and high-performance flight capabilities.

1.2.1. Low Bypass and High Bypass Turbofan Engines

Bypass ratio is the key parameter of the design of turbofan engine. According to the usage of turbofan engine, designers have simulated engine thermodynamics and aerodynamics conditions with specific requirements like thrust, SFC and operational altitude.

The main mass flow enters the fan where it is pressurized the air and go through splitter component. Therefore, splitter work as knife cut the air through bypass duct and core engine so bypass ratio is the ratio of the mass flow rate of air bypassing the engine core to the mass flow rate of air passing through the core.

$$\text{BPR} = \frac{m_{\text{bypass}}}{m_{\text{core}}} \quad (1.1)$$

m_{bypass} = the mass flow rate of air that bypass the engine core

m_{core} = the mass flow rate of air that passes through the engine core

SFC and Thrust requirements of platform are the main criteria for selection of BPR. If the platform aims to operate for long distances and good fuel consumption, BPR shall be higher for using low jet velocity. These concepts emphasize propulsive efficiency. Propulsive efficiency formula is;

$$n_p = \frac{2}{1 + \frac{V_j}{V_0}} \quad (1.2)$$

n_p = propulsive efficiency

V_j = jet velocity

V_0 = aircraft velocity

At high BPR, bypass mass flow is higher than core mass flow, so this means that air velocity is nearly same as jet velocity. Moreover, the engine has used fuel more efficiently, but the thrust level of engine is subsonic because Jet velocity is low.

At low BPR, bypass mass flow is lower than core mass flow, so jet velocity is much higher than aircraft velocity. This causes more fuel and generates more thrust for platforms. Aircraft would use this jet velocity for specific maneuvers at short time period with supersonic speed.

As design selection BPR, military and commercial aircraft have diverse requirements for operationally. Commercial aircraft have been used in transportation with low fuel usage and limited maneuverability, so high bypass ratio turbofan engines are good selection for commercial applications.

On the other hand, military aircraft are designed to meet performance demands such as high thrust generation, rapid acceleration, and operational flexibility required for dogfighting, air-to-air, and air-to-ground combat missions. Considering these requirements, low bypass ratio turbofan engines are more appropriate, as they provide higher specific thrust at the expense of fuel efficiency.

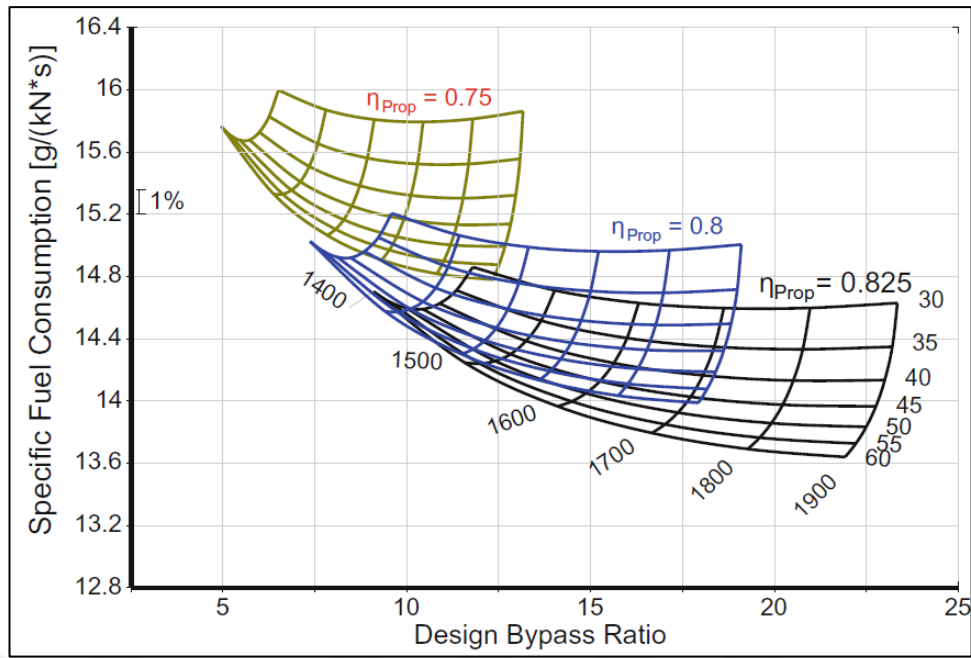


Figure 1.3: The relationship between DPR and SFC at different T4, OPR, propulsive efficiency [1].

According to Kurzke and Halliwell (1), at **Figure 1.3**, SFC and design bypass ratio are examined different T4 and propulsive efficiency. By increasing design bypass ratio at same Overall Pressure Ratio (OPR) demonstrates the specific fuel consumption changes. Moreover, increasing the BPR reflects the advantages of decreasing specific fuel consumption which approve those commercial applications prefers high bypass turbofan engine.

However, decreasing design bypass ratio causes higher specific fuel consumption with lower propulsive efficiency. With continued decreasing thermal efficiency, military applications have located left corner region figure.

1.2.2. Mixed Flow and Unmixed Flow Turbofan Engines

Mixing Flow concepts related to core and bypass flow relation. The basic definition of the mixing is combining bypass flow and core flow before entering region of nozzle as can be seen from **Figure 1.4**. Besides mixing flow, unmixed flow does not merge and extract with using two different nozzles. This design selection is changeable for design requirements of platforms such as dimension of nozzle, material selection of nozzle, weight and using afterburner strategies.

Furthermore, core and hot flows merge at mixer region with assumption of $P_{16}/P_6 = 1$. This means that pressures of these region equal one to mixing efficiency. Although, the merged flow has extracted at one nozzle with good thermal balance. Also, If the platform requires afterburner operation, mixing concepts shall be used.

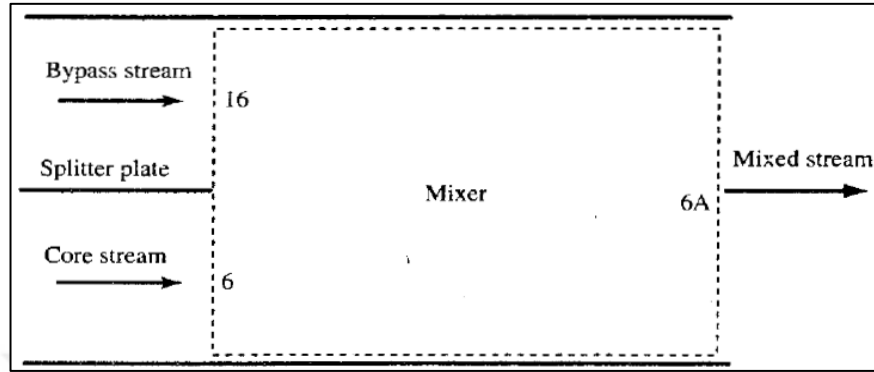


Figure 1.4: Bypass stream and core stream mixing [2].

Against mixing strategies, unmixed options have simple design but require bigger nozzle. Thus, thermal strength of divided nozzle is critical for life calculation of components because bypass flow outside of nozzle and core flow inside of nozzle. The interaction of cold and hot gas on nozzle decreases the nozzle mechanical endurance entire mechanical life. Even if nozzle material is modified, this brings more weight and more cost.

As comparison of two different design selection, Thrust is essential parameter. enormous thrust change is observed at same propulsive efficiency thermodynamically.

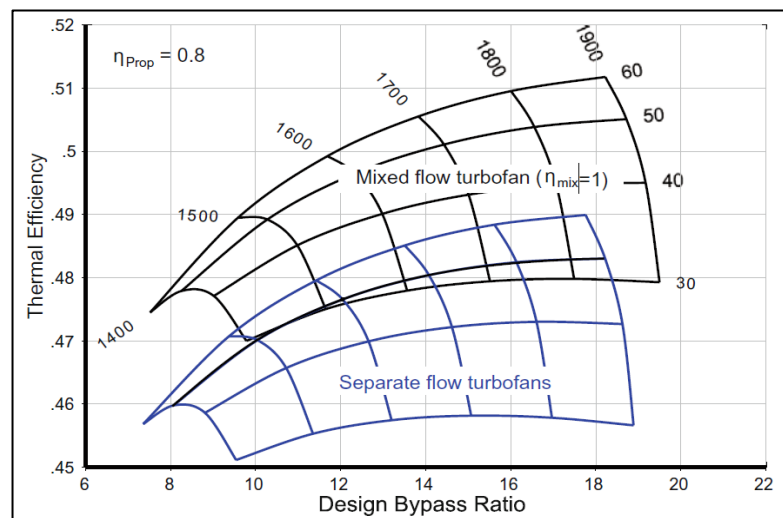


Figure 1.5: Mixed and Unmixed turbofan BPR vs. n_{th} with same n_p [1].

In conclusion, commercial aircraft generally prefer unmixed turbofan design as more basic and durability. However, for military aircraft, mixed turbofan is sufficient as more thrust requirement and the chance of afterburner usage.

1.2.3. Afterburner Operation of Turbofan Engines

The afterburner system, shown in **Figure 1.6**, known as reheat systems functions as secondary combustion chambers which attach to gas turbine engine exhaust streams for military aircraft usage. The main purpose of afterburners is to generate a large and fast thrust boost that serves military aircraft during takeoff, combat flight and supersonic operations. The afterburner burns additional fuel in turbine exhaust oxygen to boost exhaust velocity while operating outside the safety constraints of the main combustor but according to (24), the combustion chamber only burns 25 percent of air then the afterburner can burn up the remaining 75 percent of the initial air, but fuel consumption has raised three or five times of normal consumption. This case was caused by unpressurized air at the afterburner section beside the combustion chamber. Therefore, the afterburner opens short period of time operation like acceleration, takeoff, climb, sudden accelerations, and maximum speed.

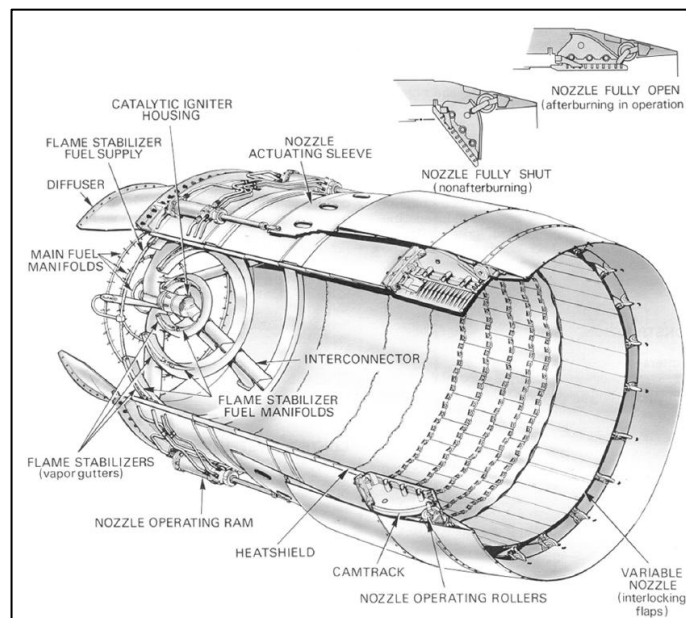


Figure 1.6: The mechanical components of afterburner [3].

Generally, Dry operation represents a non-afterburner operation as engine use only heat addition at combustion chamber. Although, wet operation includes only afterburner operation.

$$\Delta F = (m_{total})(V_{afterburner} - V_{dry}) \quad (1.3)$$

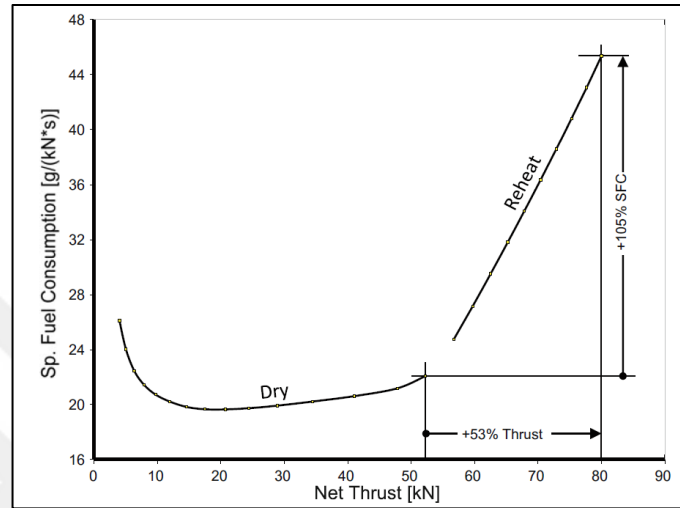


Figure 1.7: Dry and wet (afterburner) operation effects on net thrust and SFC [1].

The advantages of thrust generation from afterburners exist within specific operational limitations. The system produces poor specific fuel consumption rates, as can be observed from **Figure 1.7**, and creates elevated thermal stress on engine parts while producing stronger infrared and acoustic signals. The operation of afterburner systems demands sophisticated hardware components including variable-area nozzles to handle the enlarged hot gases.

1.2.4. Benchmark Engines

1.2.4.1. RB199 Turbofan Engines

The RB199 turbofan engine, demonstrated in **Figure 1.8**, emerged from development by Turbo-Union which was a joint venture of Rolls-Royce (UK), MTU (Germany) and Fiat Aviazione (Italy) for the Panavia Tornado multirole combat aircraft during the 1970s. The main purpose of this development aimed to produce a compact high-performance versatile propulsion system which would fulfill operational requirements

of NATO air forces. The engine was created to support supersonic flight and provide STOL capabilities while enabling various combat missions. Its modular design served as a strategic technical decision for fast maintenance and direct field replacement.

The three-spool configuration of the RB199 includes low-pressure (LP), intermediate-pressure (IP) and high-pressure (HP) compressors and turbines which operate on separate shafts. The design allows for increased efficiency while providing better control of the rotational dynamics. The engine breaks down into nine separate maintenance modules which include the fan and compressor stages and turbines and afterburner and nozzle assemblies. The afterburner section combines mixed-flow operation between core and bypass flows prior to heat combustion for efficient thrust enhancement. A multi-flap variable geometry nozzle system exists for flow control optimization in a compact design. Single-crystal turbine blades and thermal barrier coatings made of titanium and nickel-based alloys enhance durability under extreme temperatures and thermal stress.

The RB199 engine provides high specific thrust through its low bypass ratio of 1:1. The dry-operating engine produces 8000 lbf (35.6 kN) thrust but afterburner activation leads to a thrust output of 16000 lbf (71.2 kN). The engine produces more than 23:1 pressure ratio and operates turbine inlet temperatures beyond 1600 K and afterburner exhaust temperatures that exceed 1900 K. The engine's thrust-to-weight ratio of about 8:1 along with its 3.2 m length and 0.87 m diameter provides major integration benefits for aircraft fuselage integration. These design features made the RB199 a leading-edge and operationally successful turbofan engine during its time period.

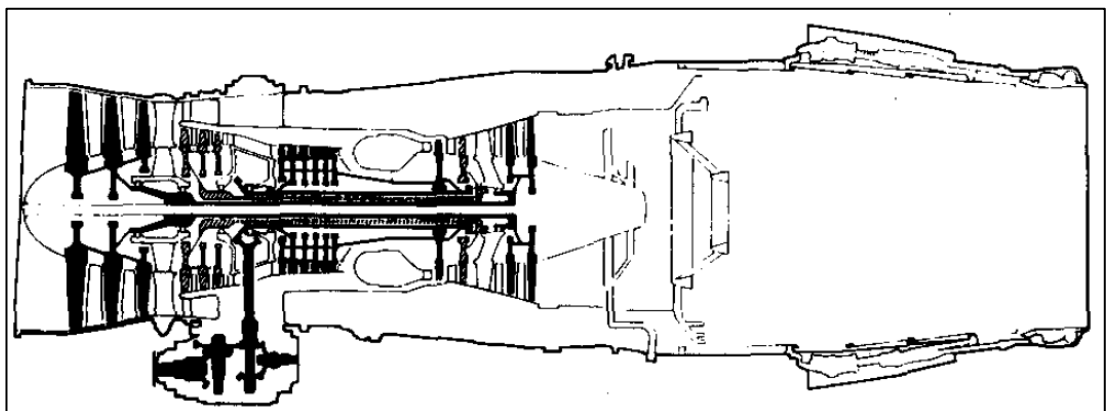


Figure 1.8: RB 199 Engine Layout [4].

1.2.4.2. F100 Turbofan Engine

As depicted in **Figure 1.9**, the F100 turbofan engine was produced by Pratt and Whitney to meet the requirement of the United States Air Force for a high thrust supersonic propulsion system for the F-15 Eagle and F-16 Fighting Falcon aircraft. The emphasis was on high thrust to weight ratio, rapid response to throttle movements and reliability for combat flying in high dynamic conditions (39).

The engine is characterized by a low bypass ratio, two spool axial flow configuration with an integrated afterburner system and digital electronic fuel control (DEEC in later variants). The fuel control system is modular and is highly reliable and includes functions like fan speed limitation, acceleration/deceleration scheduling and automatic flame out detection with relight capability. The multi-function fuel control unit of the engine is one of the engine's standout features; it controls fuel to the combustor and afterburner and controls the variable geometry inlet guide vanes and nozzle. The fuel system is designed to ensure that there is proper mixing in the afterburner section, where the core and bypass flows are mixed before combustion, and then expanded through a variable area convergent-divergent nozzle to provide supersonic exhaust velocity when required.

The F100 engine produces dry thrust more than 65 kN and afterburner thrust of about 105–130 kN depending on the variant. The fuel control system is critical to the efficiency of the engine and in preventing compressor stalls and in controlling the heat load on critical turbine components. Full-authority digital control enables the engine to vary thrust output to meet the pilot's precise demands within the constraints of turbine inlet temperature limits, fan surge margins and overall thrust schedules. Furthermore, the system's modularity supports on-condition maintenance strategies, decreasing overhaul frequency and improving fleet readiness. Thus, the F100 can be considered as one of the best examples of a modern turbofan design that combines performance, control and maintainability in one combat engine.

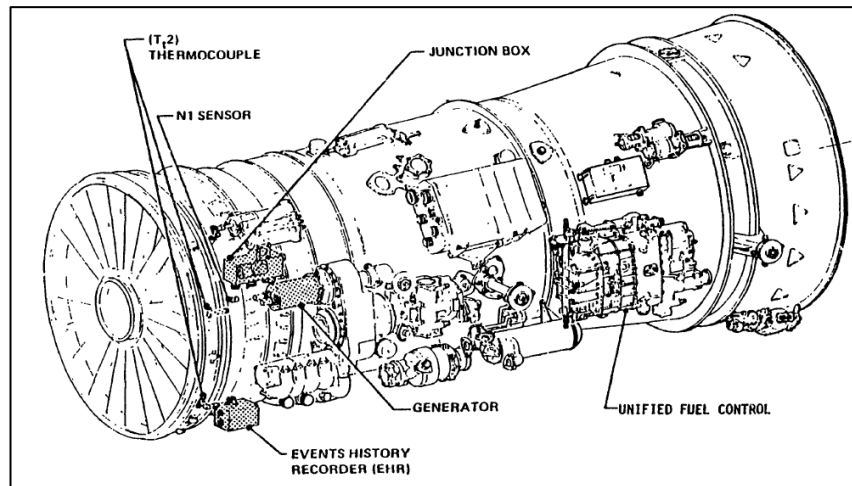


Figure 1.9: F100 Engine with accessories and sensors [5].

1.2.4.3. F404 Turbofan Engine

The General Electric F404-GE-400 engine, indicated in **Figure 1.10**, became part of the F/A-18 Hornet program as the United States Navy sought lightweight turbofans for multi-role combat operations. The F404 program took its starting point from the YJ101 experimental engine used in the YF-17 prototype while making operational durability and reliability its top priorities alongside maintainability rather than raw performance alone. The engine needed to perform well under combat conditions where it would experience rapid throttle changes and multiple acceleration cycles and maintainability demand.

The F404 operates as a “leaky turbojet” because it has a low bypass ratio of 0.34:1 rather than functioning as a traditional high-bypass turbofan. The engine uses a two-spool axial arrangement with three fan stages and seven high-pressure compressor stages that result in a total pressure ratio of 25:1. The engine achieves single high-pressure and low-pressure turbine stages. Moreover, the afterburner system makes use of circumferential spray bars together with pilot-main bar sequencing and a variable-area nozzle which allows thrust control and stability in supersonic flight.

The F404 engine generates 10,600 lbf dry thrust before its afterburner system raises output to 16,000 lbf. Aircraft agility benefits significantly from the F404 engine's compact design and lightweight construction which produces a thrust-to-weight ratio of 7.3. The F404 outperforms the TF30 engine by delivering improved fuel economy

and throttle reaction and easier maintenance accessibility through on-condition design of its components.



Figure 1.10: F404 Engine [6].

1.2.4.4. AL 41 Turbofan Engine

The AL-41 engine known as izdeliye 20 emerged from NPO Saturn during the late Soviet period as part of the MFI fifth-generation multirole fighter program. The AL-41 engine, illustrated in **Figure 1.11**, known as izdeliye 20 emerged from NPO Saturn during the late Soviet period as part of the MFI fifth-generation multirole fighter program. During the late 1970s the MFI (Mnogofunktsionalniy Frontovoy Istrebitel) program launched its mission to develop an advanced air superiority fighter that would replace both MiG-29 and Su-27 aircraft platforms. The AL-41F functioned as a future fighter powerplant for the I-90 experimental aircraft. The engine focused heavily on attaining super cruise ability together with exceptional thrust-to-weight ratios while representing an important strategic technological development for Soviet defense manufacturing. The program ended in 1997 due to Soviet dissolution and financial instabilities even though only 28 engines underwent limited testing.

The AL-41F utilized a variable bypass low-bypass turbofan configuration which enabled pilots to reach Mach 1.5 without activating afterburners for supercruise. Operation at 1,915 K (1,642°C) turbine inlet temperature exceeded the previous AL-31 engine by 250°C. The structure used a one-stage high-pressure turbine while featuring an advanced compressor-fan system designed for maximum efficiency at

high speeds. Modern thermal barrier coatings combined with advanced alloys helped the engine function at elevated temperatures for extended operational periods. The engine integrated stealth technology by using radar-absorbing intake guide vanes and separated exhaust nozzles.

The AL-41 generated 177 kN (40,000 lbf) of thrust power during afterburner operation and produced a remarkable thrust-to-weight ratio of 11.1 for its class and time period. The AL-41 never reached mass production status but its technological advancements became the foundation for Russian aerospace engines which power the Su-57 Felon with AL-41F1 and the upcoming Su-75 "Checkmate" using the AL-51 (izdeliye 30) engine. The subsequent evolutionary stages provide 6.4% higher specific thrust and 9% reduced fuel usage and a 19% increased thrust-to-weight ratio compared to the initial AL-41 design. The AL-41 program established an essential milestone in Soviet and Russian aeroengine development even though it did not see extensive operational deployment and continues to affect fifth and sixth-generation fighter propulsion systems.



Figure 1.11: AL-41 Engine [7].

1.2.4.5. F110 Turbofan Engine

As shown in **Figure 1.12**, the General Electric F110 turbofan engine was developed as a high-thrust alternative to the Pratt and Whitney F100, with the first application for the F-16 Fighting Falcon and the subsequent application to the F-14 Tomcat and F-15 Eagle. The F110 was originally developed from the F101 DFE (Derivative Fighter

Engine) program to be used in single- and twin-engine fighter aircraft and provide higher reliability, no restriction on throttle operation and better maintainability. The engine family also included the F110-GE-100, -129, and -132 variants, with each version being improved incrementally through a low-risk derivative development process [24].

Technically, the F110 series is a low-bypass, two-spool axial flow engine with a three stage fan, nine stage high pressure compressor, annular combustor, and 1+2 stage high- and low-pressure turbines. The F110-GE-132 variant introduced significant advancements including a three-stage long-chord blisk fan, radial augments and lightweight filament-wound composite fan duct, all of which contributed to thrust gains and part durability. The Engine Monitoring System (EMS) developed for the F110-GE-100 gathers real time flight data, evaluates engine limit exceedances, supports trending of long-term performance, and simplifies maintenance planning by tying into USAF ground computing infrastructure. These systems offer the pilots automated feedback and assist in the reduction of in-flight failures and overhaul frequencies [48].

In terms of performance, the F110 variants produce thrust between 16,000 and 34,000 lbf based on the configuration and afterburner mode. The F110-GE-132 has a maximum augmented thrust of 34,000 lbf of power, which is possible due to optimized control schedules that can operate automatically based on flight conditions like Mach number and altitude without requiring pilot input [7]. The thrust-to-weight ratio reaches up to 7.4, and durability features like laser shock peening, single-crystal hot section components, and reduced part count in the blisk fan contribute to exceptional field reliability. The F110's balance between power, efficiency, and adaptability has made it a reference propulsion system in modern fighter aviation and a candidate for future engine upgrades across multiple platforms.

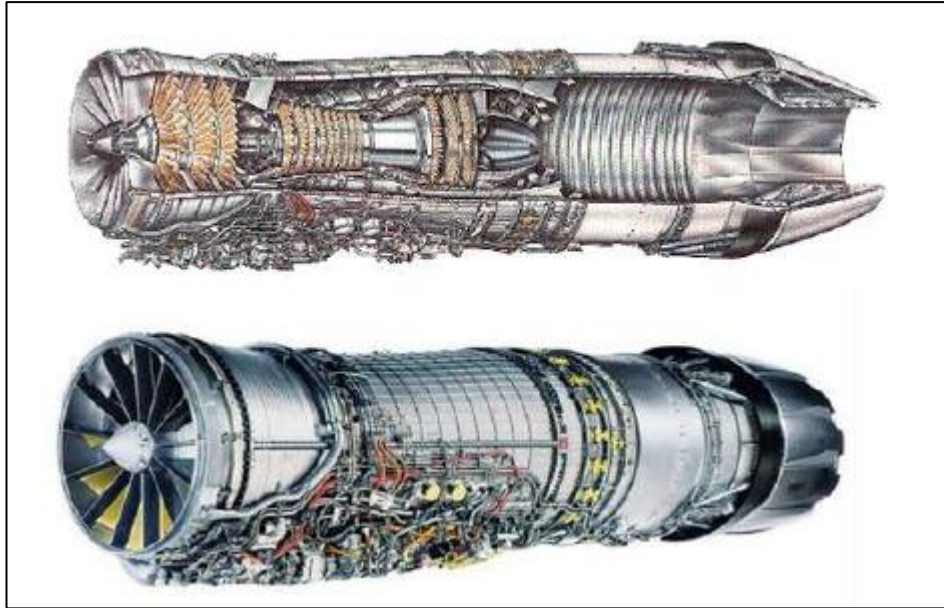


Figure 1.12: General Electric F110 Engine [7].

1.2.4.6. EJ200 Turbofan Engine

Eurofighter Typhoon adopted the Eurojet EJ200 engine, presented in **Figure 1.13**, as its main power source because it had to satisfy the extreme flight demands of air combat and multirole duties. The Rolls-Royce (UK), MTU Aero Engines (Germany), ITP (Spain) and Avio (Italy) European consortium created this technological achievement by applying the lessons learned from the Tornado/RB199 program [26]. The main objectives of the development program were to ensure a handling system that did not require pilot intervention to generate thrust, while also achieving high thrust-to-weight ratio and low life-cycle costs for integrating with aircraft digital controls and weapons systems.

The EJ200 operates as a low-bypass two-spool turbofan engine with three-stage low-pressure compressor and five-stage high-pressure compressor (featuring blisk construction in the first three stages) and single-stage high- and low-pressure turbines using single-crystal air-cooled blades. The modular design facilitates maintenance operations as well as on-conditioning service. Advanced technologies include a full-authority digital engine control unit (DECU), engine monitoring systems (EMU), and brush seals for improved internal sealing. The reheat system includes radial hot stream burners in addition to hydraulically actuated convergent-divergent nozzles that provide independent control over hot and cold streams [28]. Future enhancements will include

thrust vectoring and integrated diagnostics/prognostics and surge control systems as described by [21].

The EJ200 delivers 60 kN of dry thrust and 90 kN with afterburner while achieving a thrust-to-weight ratio of approximately 9:1 with projected growth potential up to 10:1 according to [26]. High turbine inlet temperatures above 200°C compared to previous generation engines combined with advanced cooling systems optimize specific fuel consumption (SFC). The EJ200 outperforms the F404 and RB199 engines with its reduced part count by 30% that leads to enhanced reliability and lower maintenance needs [28]. Future variants of the engine will provide 10–20% higher dry thrust and enhanced SFC while integrating into UCAV systems through derivative or new engine architectures to maintain cost-effectiveness and expand mission adaptability [21].



Figure 1.13: EJ 200 Engine [8].

1.3. Turbofan Components

1.3.1. Fan

The fan section is located on the front of engine as both a propulsion component and drives essential engine operations. The fan draws big amounts of air which is pressurized before directing part of this air into the engine core while the remaining air moves bypass duct. The fan functions similarly to a low-pressure axial compressor yet maintains distinct design characteristics and operational behavior and pressure transformation capabilities. The fan operates at reduced compression levels than core compressors to enable bigger and wider rotating blades that focus on high mass flow instead of high-pressure rise.

The design of the fan combines mechanical and aerodynamic features that adjust according to application requirements. The fan component in military turbofan engines maintains a compact design that generates high specific thrust through its low bypass ratio and fast throttle response. The following stator structure directs airflow toward the compressor stages that follow the fan. Commercial turbofan engines implement wide-chord blades on large-diameter fans to handle massive airflow through higher bypass ratios. The design strategy optimizes propulsive efficiency and reduces noise levels to fulfill civil aviation requirements for fuel economy and acoustic compliance.

Although, it generates two separate airflow paths with different pressure levels through thermodynamic operations. The inner fan exits pressure ratio (P_{21}/P_2). The core receives its flow from the core while the outer fan exit pressure ratio (P_{13}/P_2) represents the bypass stream. The fan pressure ratio (FPR) depends on these parameters to determine both engine core mass flow and turbofan engine net thrust output. The fan design requires a careful trade-off between aerodynamic performance and thermal considerations and mechanical strength and environmental compliance to determine the engine's acoustic characteristics.

1.3.2. Compressor

The compressor component of turbofan engines duty to increase air pressure before the combustion chamber through compression. Air compression allows the Brayton cycle to achieve better fuel combustion efficiency and thermal performance. Engine performance factors like thrust generation along with fuel efficiency are directly affected by how compressors behavior [28].

Gas turbine engines use two main compressor varieties which include axial compressors and radial centrifugal compressors. Gas turbine engines utilize axial compressors which consist of stationary and rotating blade arrangements that perform successive air compression along their longitudinal direction. These compressors operate widely throughout civil and military engine applications because they provide high air flow capabilities and adaptable scalability. The pressure ratio of each stage in centrifugal compressors exceeds axial compressors but these devices remain more suitable for auxiliary power units (APUs) and small turbojets and some military UAVs because of their bulkier design.

Engine design constraints together with mission profile determine whether an axial or centrifugal compressor should be used. Military engines require both high thrust-to-weight ratios and compact designs, which leads to the adoption of axial-centrifugal compressor combinations. Civil aviation engines use multiple-stage axial compressors because these configurations maximize bypass and thermal efficiency when operating at extended durations during cruise flights [1].

The design of compressors requires special attention to prevent stall and surge which represent two distinct aerodynamic instabilities. When blades experience an angle of attack that exceeds safe limits the airflow detaches from the surface resulting in performance deterioration. The compressor experiences an extreme instability called surge which leads to reversed or oscillating airflow resulting in immediate pressure drop and potential mechanical stress. Variable stator vanes together with bleed valves and multi-spool designs work to stabilize airflow during different operating conditions [2].

1.3.3. Combustor

The combustion chamber of a turbofan engine is the core of the thermodynamic process where the chemical energy of fuel is converted into high temperature and high-pressure gas that activates the turbine stages. The goal of the combustion chamber is to liberate the maximum amount of energy with the least possible pressure loss, so that the expansion in the turbine can be efficient. This can be achieved by the combustion system supporting stable, complete and low-emission combustion over a wide range of operating conditions. The design must also have a high combustion efficiency of more than 99%, especially during cruise conditions [42,12].

The three main combustion chamber configurations used in gas turbines are the can type, annular, and can annular. Can type chambers are made of several flame tubes that are parallel to each other which makes them easy to maintain and modular but heavy and space consuming. Annular combustors, which are single continuous liner in ring shape are the most used in the current civil aviation engines due to their compactness and uniformity of temperature. Can annular designs combine the advantages of both and are commonly used in high power military engines to provide structural rigidity and improved thermal [19,37].

Engine efficiency, specific fuel consumption (SFC) and turbine durability are influenced by the performance of the combustion chamber. One of the most important design issues is the restriction of the total pressure loss across the chamber (4–8%) and the uniformity of temperature at the turbine inlet (T_4). This is because non-uniform temperature distribution causes stress on the turbine blades and decreases the life of the turbine. To solve these, current combustors apply advanced swirlers, staged fuel injections, and film or effusion cooling techniques. Due to environmental concerns, low emission technologies such as lean direct injection (LDI) and rich-quench-lean (RQL) combustion have been integrated into civil engines [51,1].

The operational requirements of the engines influence the design of military versus civil engines. The chambers are compact, high thermal, and have good throttle response, which is why they are used in military engines where they have to withstand large changes in pressure and temperature. Such systems are normally designed to work with afterburners. On the other hand, civil engines are concerned with fuel consumption, durability and less emissions of NO_x and CO. This calls for advanced control systems and optimized combustor geometries to meet the international noise and emissions standards stipulated by ICAO [10].

1.3.4. Turbine

A turbofan engine's turbine section functions as the main component that completes the energy transformation process. After combustion the hot high-pressure gases flow through turbine stages that generate mechanical power to activate the fan and compressor systems. The conversion process needs to operate with maximum efficiency while minimizing losses under the extreme thermal and mechanical conditions. The turbine design needs to perform energy extraction functions while ensuring stable flow and component integrity throughout all flight phases of the engine [29].

Engine turbines exist in two main categories: high-pressure turbines (HPT) and low-pressure turbines (LPT) with two structural variants: axial and centrifugal. Modern turbofan engines contain one-stage high-pressure turbine that drives the compressor and multiple-staged low-pressure turbine that drives both fan and low-pressure compressor. The axial flow turbine remains preferred for civil and military operations

because it provides higher efficiency along with better capabilities to handle large mass flow rates. Advanced LPT designs that use variable geometry stator vanes enhance efficiency across different engine operating speeds and flight altitudes [34].

The thermal efficiency of turbines depends on turbine inlet temperature (TIT), blade cooling performance and aerodynamic optimization. Modern turbines require TIT above 1600 K which demands complex air-cooled blade designs that incorporate internal serpentine passages together with film cooling holes and thermal barrier coatings. The implemented methods defend blades from thermal fatigue along with oxidation while allowing the expansion process to stay efficient. Single-crystal superalloys and ceramic coatings serve as materials that help increase component lifespan under harsh thermal conditions [43]. Guide vanes function as essential components because they form and quicken the flow before reaching the rotor and their design determines how efficiently the flow will pass through and how much pressure will be recovered [32].

Although, the main difficulty for the future will be to reconcile the aerodynamic performance of the turbines with the material survivability. Both Weir [52] and Williams [54] stress the need for component integration, especially between combustion, turbine, and nozzle systems, to reduce installation losses and maintain high propulsive efficiency. The development of turbine design will remain a function of materials engineering, thermal protection technologies, and advanced computational design tools aimed at minimizing cooling air usage while maximizing aerodynamic performance.

1.3.5. Nozzle

A turbofan engine's final aerodynamic and thermodynamic component transforms remaining thermal energy into fast jet flow through the nozzle to produce thrust. The nozzle operates as an exhaust exit that people commonly overlook but it actively affects engine efficiency and turbine loading and thrust production. The nozzle influences both the engine's sound extraction and the uniformity of airflow. The proper pressure equilibrium between engine components and atmospheric conditions results from efficient nozzle design which reduces total pressure losses and improves propulsive efficiency [42,37].

The two common main nozzle types include convergent and convergent-divergent (ConDi) designs. Civil aircraft engines use convergent nozzles since they maintain exhaust velocities below the speed of sound while adjusting the flow to match atmospheric conditions. Military aircraft with afterburners utilize ConDi nozzles to produce supersonic jet velocity.

A nozzle affects engine performance through its operational effects. An optimally designed nozzle enhances specific fuel consumption (SFC) through better momentum transfer while reducing kinetic energy losses. The turbine back pressure depends on the nozzle exit pressure and area measurements which determine the energy extraction process. Modern military engines incorporate variable-geometry nozzles to dynamically change their configuration during flight operations which help counteract performance-diminishing effects while maintaining optimal cycle operation [37,27].

Civilian turbofan engines use fixed-area low-noise nozzles with acoustic liners to meet noise regulations and reduce environmental impact during operation. Military engines focus on performance capabilities and adaptability through their use of ConDi or thrust-vectoring nozzles which enable better maneuverability and afterburner compatibility. The design of stealth military platforms leads to nozzle shape modifications that create reduced infrared and radar detectability [13].

1.3.6. Variable Components

1.3.6.1. Variable Inlet Guide Vane (VIGV)

The Inlet Guide Vanes (IGVs) are stationary or variable-angle aerodynamic surfaces located in front of the first rotating stage in a turbofan engine compressor or fan section. The main purpose of IGVs is to turn the incoming flow so that it is parallel to the rotor blade angles to get the best possible incidence and minimize flow distortion. IGVs are very important for compressor stability, especially during transients such as start-up, deceleration, or rapid throttle changes by making sure that the flow angles are favorable and that separation is minimized [46].

There are two basic types of IGVs; fixed and variable. Fixed IGVs are typical in engines that operate within relatively small performance ranges, for example, in commercial airliners. On the other hand, Variable Inlet Guide Vanes (VIGVs) can

change their angle of attack in real time and thus provide dynamic control of the airflow entering the compressor. Visser and Wernet [49] state that VIGVs enhance part load efficiency and increase surge margin, thus protecting the compressor from unstable operation during off design conditions.

The effects of IGVs on performance are not limited to one aspect. They help to optimize the aerodynamic load on the rotor blades, decrease pressure losses, and increase compressor adiabatic efficiency. Also, IGVs affect the temperature distribution of the downstream blades which in turn affect the turbine cooling requirements and thermal fatigue. In military applications, VIGVs enable the engine to work over a wide range of throttle settings, afterburner operations, and fast changes in altitude. Civil engines, however, prefer the simplicity, reliability, and low maintenance of fixed vanes, especially considering the emphasis on long-term fuel efficiency and noise regulations [15].

1.3.6.2. Variable Stator Vane (VSV)

The Variable Stator Vanes (VSVs) function as essential flow control elements that reside within the axial compressor stages of contemporary turbofan engines. The stator blades located between rotor stages have a rotating axis which enables them to change air flow angles before the next rotor stage. The main goal of these components is to enhance compressor efficiency through optimal rotor blade incidence angles which prevent flow separation and surge [38].

VSVs function differently from fixed stators because they enable the engine to make automatic adjustments based on speed changes and load variations and altitude fluctuations. Technology holds special importance in multi-spool engine designs because shaft speeds operate independently. The engine control system uses flight condition inputs including throttle position and altitude and temperature to set optimal vane positions through an actuating ring which controls the variable stator vane angles in real time. Volponi and Sheldon [50] explain that VSVs become more effective when used correctly because they improve compressor stall margin and startability and part-load efficiency.

The impact of VSVs on engine performance stands as a vital factor. The technology decreases off-design losses while improving fuel efficiency and broadens the operating

range of the compressor. Military engines require VSVs to achieve fast throttle transitions which lead to better acceleration and improved maneuverability. The VSVs in civil aviation operations enable smoother engine control during climb and descent and cruise transitions which leads to better fuel efficiency and lower emissions. The integration of VSVs with Full Authority Digital Engine Control (FADEC) systems enables precise automatic vane angle modulation which enhances both performance and safety [16].

1.3.6.3. Variable Nozzle Configuration

Turbofan military engines heavily rely on variable nozzles as essential components. Variable nozzles differ from fixed nozzles since they adjust their throat and exit area dynamically while in flight. The engine gains optimal expansion ratios with back-pressure control and thrust output because of its flexible design which works across various operating conditions. The ability to modulate the nozzle area is crucial for afterburner engines since it enables stable exhaust volume changes to maintain efficient flow [18].

The ConDi design of variable nozzles includes mechanical or fluidic control systems that enable adjustments to throat and exit diameters. The exhaust Mach number and pressure matching between engine exhaust and surrounding atmosphere becomes possible through their exact design parameters. The ability to modify nozzle thrust efficiency stands as a crucial element for maintaining engine performance when switching between dry thrust and augmented thrust in afterburning engines according to [45]. The specific fuel consumption (SFC) of an engine along with its turbine back pressure control depends directly on the variable nozzle area.

The implementation of variable nozzles leads to better engine performance characteristics including flexibility, acceleration, and maneuverability. The thrust vectoring ability of these nozzles allows for directional control of exhaust jets which benefits STOVL aircraft as well as modern fighter jets. According to Whitford [53], thrust vectoring nozzles provide both improved post-stall maneuverability and agility which are essential features in air superiority platforms. The adjustable nozzles help decrease infrared signatures by modifying the hot exhaust mixture with ambient air or bypassed air.

The operation of civil turbofan engines relies on fixed convergent nozzles because their design needs are basic, and they operate under limited conditions at lower costs. The development of adaptive cycle engines for future aircraft has led to renewed interest in variable nozzle technologies for civil aircraft applications that require multi-mission capabilities and improved cruise-to-climb performance transitions [31].



2. STEADY STATE OPERATION OF TURBOFAN ENGINE

2.1. Parametric Cycle (On-Design) of Turbofans

The preliminary design of turbofan engines requires parametric cycle analysis as a fundamental step. The framework enables performance evaluation of engine operation at cruise or take-off conditions through systematic changes of bypass ratio (BPR), overall pressure ratio (OPR) and turbine inlet temperature (TIT). The modified Brayton cycle that powers turbofan propulsion systems depend on these three fundamental variables [37].

The dual-stream Brayton cycle of turbofan engines divides air into two streams where one stream goes through the engine core and the other stream bypasses it. The core stream receives compression and combustion and turbine expansion to extract work while the bypass stream uses fan acceleration to generate thrust with reduced fuel usage. The engine configuration improves propulsive efficiency because it decreases jet exhaust velocity which results in reduced kinetic energy losses [13].

Several primary variables are essential to determine the on-design cycle behavior as Bypass Pressure Ratio (BPR), Overall Pressure Ratio (OPR) and Turbine Inlet Temperature (TIT) and Thrust-Specific Fuel Consumption (TSFC).

Overall Pressure Ratio is the ratio of total pressure at compressor exit to that inlet pressure.

$$OPR = \frac{Pt_3}{Pt_2} \quad (2.1)$$

This parameter is totally related to thermal efficiency which as;

$$n_{th} = 1 - \left(\frac{1}{OPR^{(\gamma-1)/\gamma}} \right) \quad (2.2)$$

OPR expresses the overall pressure ratio, and γ is demonstrated specific heat ratio.

Although, Turbine Inlet Temperature determines the thermal energy available to drive turbines. Higher TIT increases specific thrust but also imposes thermal constraints requiring advanced materials and cooling technologies [36].

Moreover, other key parameter is thrust – specific fuel consumption (TSFC);

$$TSFC = \frac{m_f}{F} \quad (2.3)$$

Where m_f is the mass flow rate of fuel, and F is the net thrust. Better fuel efficiency results from lower TSFC values. The BPR increase leads to higher TSFC values until it reaches a saturation point where drag and engine size become major factors that reduce overall performance gains. The specific thrust increases with TIT but TSFC typically rises unless advanced turbine design is used for management.

Designers use GasTurb and NPSS tools to execute sensitivity analyses and performance mapping and trade-off studies. The analysis of BPR and OPR variations against TSFC and thermal efficiency enables designers to identify suitable operating points. The tools enable designers to rapidly examine design possibilities before starting detailed component development and system integration work [22].

2.1.1. Design Point Definition

A turbofan engine design point represents a particular flight condition which combines altitude with Mach number and ambient temperature and thrust requirements for optimal thermodynamic cycle and component geometry performance. The engine sizing process and performance benchmarking require this point to be established before starting any off-design or transient performance analysis [51].

The design point for commercial transport aircraft exists at max climb conditions which occur at 11 km altitude and Mach 0.8 because these conditions create the most demanding thermal conditions and spool speed requirements and thrust needs. Military engines operate at either high-speed or high-load segments which include combat thrust at sea level or supersonic cruise based on mission requirements [37].

The engine operates at the design point under steady-state conditions where the overall pressure ratio (OPR), bypass ratio (BPR), and turbine inlet temperature (TIT) are fully

defined. The inputs allow for precise calculations of thermodynamic station values including total temperature T_t and total pressure P_t and mass flow m which are used to size the fan, compressors, turbines, and nozzle. A commonly used form of the continuity equation at the engine inlet is:

$$m = \rho * A * V = \frac{P_t}{R * T_t} * A * M * \sqrt{\gamma * R * T_t} \quad (2.4)$$

Where M is the Mach number, γ is the specific heat ratio, R is the gas constant and A is the annulus area. The equation shows how the engine face area is calculated from design point conditions [42].

2.1.2. Thermodynamic Cycle Definition

A turbofan engine operates through the Brayton cycle thermodynamic process which has been modified to support its dual-stream airflow system. The Brayton cycle serves as the fundamental analytical framework for studying energy transformations, thermal efficiency and thrust generation in gas turbine engines.

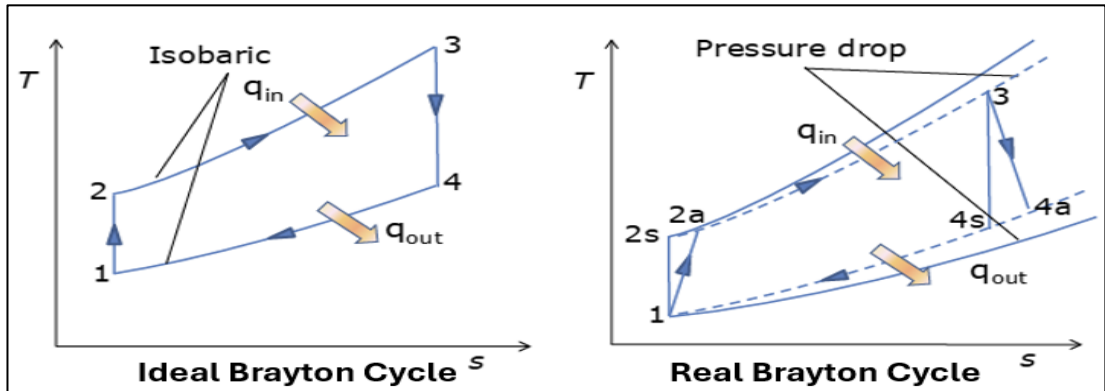


Figure 2.1: Ideal and real Brayton cycle [9].

The ideal Brayton cycle consists of four stages which include isentropic compression followed by constant-pressure heat addition then isentropic expansion and finally constant-pressure heat rejection, as can be seen in **Figure 2.1**. The turbofan cycle becomes more complex in practical applications because it contains multiple spool components and bypass streams and component inefficiencies. The engine draws in air through its inlet before the axial compressors compress the fluid. The combustion

chamber receives compressed air at constant pressure to add fuel which causes the temperature to increase. The hot gases expand through turbines to generate mechanical work that powers both compressors and the fan. Besides the ideal Brayton cycle, the real Brayton cycle includes thermodynamic and mechanical losses.

2.1.3. Cycle Design Parameters

The thermodynamic cycle of a turbofan engine is fundamentally shaped by a set of core design parameters, which dictate its performance under on-design conditions. These parameters—such as Overall Pressure Ratio (OPR), Bypass Ratio (BPR), Fan Pressure Ratio (FPR), and Turbine Inlet Temperature (TIT)—form the backbone of engine architecture and performance prediction. The correct selection and optimization of these parameters directly affect the thrust-specific fuel consumption (TSFC), thermal efficiency, specific thrust, and environmental characteristics of the engine as observed in **Figure 2.2**. Knowledge of their individual roles and interdependence is crucial for engine designers who want to meet mission-specific requirements while maintaining manufacturability and operational reliability.

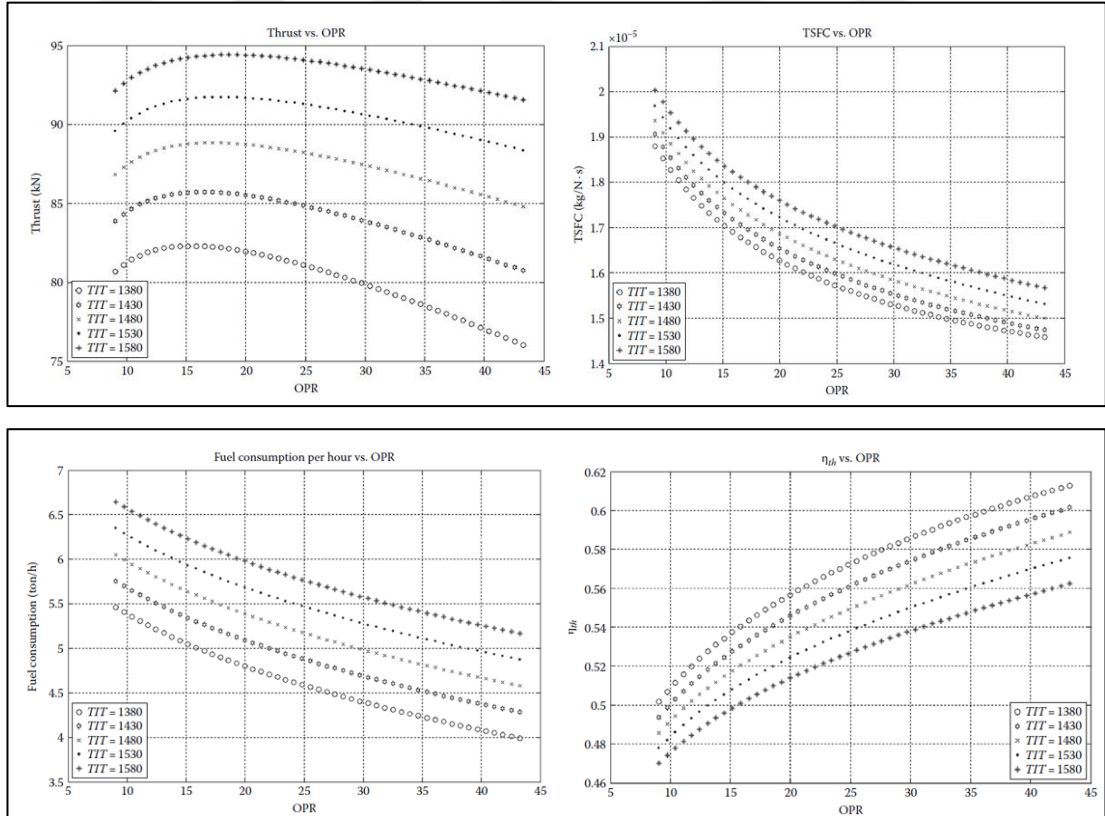


Figure 2.2: The relation comparison of cycle design parameters such as OPR, TIT, SFC and thermal efficiency [10].

2.1.4. Design Optimizations

The development of turbofan engines requires design optimization as a core phase which combines thermodynamic modeling with performance prediction and system-level trade-offs to create optimal engine configurations. Modern propulsion systems face multiple challenges regarding efficiency and emission standards and noise levels and weight constraints which require optimization to extend beyond basic parameter adjustments into a systematic multi-objective problem-solving framework. The optimization method serves both military and commercial engines to find the best possible design parameter settings including Overall Pressure Ratio (OPR), Bypass Ratio (BPR), Fan Pressure Ratio (FPR) and Turbine Inlet Temperature (TIT) under different mission constraints [42].

2.2. Off - Design of Turbofan

Off-design performance stands as a major difficult aspect when analyzing and designing turbofan engines. Engine operation in real conditions extends beyond the design point because it handles various off-nominal operating conditions which include takeoff and climb phases as well as descent and throttle and atmospheric changes. The comprehension of off-design behavior remains crucial because it enables performance prediction and ensures operational reliability and fuel efficiency and control system robustness across the entire engine mission profile.

The combination of flight altitude changes and Mach number variations produces deviations in mass flow rate and corrected shaft speeds and component pressure ratios. The changes in the thermodynamic cycle disrupt the equilibrium between core and bypass flow streams. Engine mass flow decreases when air density becomes lower at high altitudes which causes the fan and compressor operating points to move beyond their design map lines.

2.2.1. Off Design Operation Concept

The design and operational aspects of turbofan engines depend on off-design operation which describes all engine behaviors beyond the established design parameters. The design point receives careful optimization for cruise or maximum thrust conditions,

yet actual flight operations produce extensive variations between altitude and Mach number and ambient temperature and throttle position. The complete comprehension of off-design behavior remains essential to guarantee engine efficiency and stability and responsiveness throughout all flight regimes [18].

The engine operates in off-design conditions during flight phases such as takeoff and climb and descent and loiter where engine components experience different corrected speeds and mass flow rates than the design point conditions. The performance maps of compressors and turbines shift during these operational regimes which creates potential mismatches between flow and pressure distribution. The decrease in inlet pressure during high altitude flight operations causes corrected flow parameters to change which moves the compressor operation toward the surge line. The variations in operating conditions impact both engine thrust production and component durability and thermal performance capabilities.

Engineers solve nonlinear equations that couple mass conservation with momentum conservation and energy conservation to model off-design conditions thermodynamically. The fundamental concept involves using corrected parameters including corrected mass flow rates (m_{corr}), which enables component maps to be scaled across different atmospheric and spool speed conditions. The corrected mass flow is defined by the equation:

$$m_{\text{corr}} = \frac{m^* \sqrt{T_0}}{P_0} \quad (2.5)$$

Where T_0 and P_0 are ambient total temperature and pressure. The relations can be applied across compressors, turbines, and nozzles to obtain accurate estimates of thrust, specific fuel consumption (SFC), and exhaust gas temperature (EGT) for any off-design scenario [40].

The operation outside design parameters needs adaptive control methods to preserve component matching and prevent system instability. The risk of surge or thermal overload is reduced by using variable stator vanes (VSVs) and bleed valves and variable area nozzles (VANs) to dynamically control mass flow and pressure ratios. The mechanisms play a vital role during fast throttle changes and altitude shifts because operating lines rapidly shift across the compressor map.

Off-design performance analysis provides a complete understanding of engine behavior across the entire mission envelope whereas on-design operation focuses on limited optimization. Through this analysis engineers gain knowledge about efficiency versus responsiveness tradeoffs which helps them make better decisions for future propulsion systems. The reliable performance of a turbofan engine depends on both its peak operational capabilities and its ability to function dependably in various off-design operating conditions.

2.2.2. Operation Conditions and Mission Profile

The military mixed-flow turbofan engine operates under mission profile conditions together with operational conditions to determine both its thermodynamic responses and control approaches. The engines require reliable operation under conditions that include extreme changes in altitude and Mach number and throttle settings and flight load during maneuvers. A single mission requires the engine design to support operation across various flight conditions which include both low speed loiter and high-speed dash or combat engagements. The demanding requirements create major hurdles when developing control laws and performance boundaries.

A typical mission sequence includes five distinctive operational segments including takeoff, climb, cruise, loiter and acceleration phases followed by combat and descent phases. Each operational phase creates separate requirements for engine operation. Combat maneuvers need high thrust output in brief periods with afterburner activation while loiter and cruise operations require maximum fuel efficiency. The turbofan engine requires the ability to shift between operational modes without crossing operational boundaries and without putting mechanical components under excessive stress.

Environmental operating conditions are equally critical. Engine performance depends heavily on changes in ambient temperature and pressure as well as humidity levels. Operations at high altitudes with low atmospheric pressure demand the compressor to operate within its surge margin while delivering adequate pressure ratio. Flight operations at low altitude and high speed create inlet distortion and thermal loading problems which require advanced component design and variable geometry mechanisms to solve [29].

The operation conditions and mission profile of a military turbofan engine require an integrative design approach which combines aerothermodynamic design with control system logic. The accurate modeling of these profiles remains crucial for both performance prediction and limiter validation and variable geometry scheduling and mission readiness validation across all flight envelopes.

2.2.3. Component Performance in Off Design

The design of turbofan engines operates best at design points which match cruise conditions. Real-world operations require engine performance across multiple off-design operating conditions which include different altitudes and speeds and throttle positions. The analysis of component behavior under off-design operating conditions serves as a vital factor for maintaining engine reliability and efficiency together with extending its lifespan.

Fan and Compressor Performance: The aerodynamic performance of fans and compressors get substantially affected when operating under off-design conditions. Engine stability becomes compromised when design-point airflow deviates because it causes stall or surge problems. Modern engines use variable stator vanes and bleed valves to control airflow angles and pressure ratios for maintaining optimal performance across different operating conditions.

Combustor Behavior: The combustor demonstrates high sensitivity to off-design operational changes in pressure and temperature and airflow conditions. Low power settings together with high altitudes create air density conditions that make flame stability more difficult to maintain thus increasing the risk of blowout. Modern combustor designs use staged combustion systems and advanced ignition systems to maintain stable operation across multiple operating conditions

Turbine Adaptability: The turbine requires adaptation to handle mass flow and temperature variations that occur during off-design operational conditions. The efficiency and structural integrity of the turbine get affected by these changes. The implementation of cooling methods together with materials that resist high temperatures helps preserve turbine operation and protects it from damage when operating outside design parameters [57].

Nozzle Functionality: The nozzle functions as a critical exhaust flow controller especially when operating under off-design conditions. Engine operating condition changes produce exhaust gas pressure and temperature variations which require nozzle geometry modifications to achieve optimal thrust and prevent backpressure problems. The implementation of variable-area nozzles allows engines to adjust their performance efficiently when operating under different conditions [57].

2.2.4. Performance Degradation and Health Monitoring

Long engine operation together with severe environmental exposure and mechanical component deterioration leads to performance degradation of turbofan engines. Engine operation generates fouling along with erosion and thermal fatigue that results in measurable performance losses of thrust together with efficiency and responsiveness. Engine reliability maintenance depends on understanding and fixing this degradation while minimizing costs and ensuring operational safety primarily in high-performance military and commercial applications [41].

The main signs of engine degradation appear when engine pressure ratios shift, and specific fuel consumption rises while compressor or turbine operational efficiency decreases. The erosion of compressor blades generates changed airflow, which decreases compression performance while turbine blade cooling inefficiency creates temperature increases that put stress on turbine components [35]. Flight data analysis along with trend monitoring systems enable the measurement of these changes.

Engine Health Monitoring (EHM) systems were created to identify early warning signs of engine malfunction through their health monitoring capabilities. The systems use a combination of model-based diagnostic approaches alongside data-driven analytical techniques. Model-based diagnostics apply established physical equations which compare real-time engine performance with predicted responses from fuel flow and shaft speed inputs to exhaust temperature outputs. Data-driven techniques identify anomalies and forecast failures through statistical or machine learning algorithms which receive training from historical data [14].

The widespread application of Kalman filtering in health estimation allows real-time estimation of compressor or turbine efficiency which is an unmeasurable health parameter. The integration of physics-based constraints with these estimators produces

robust degradation tracking results for a wide range of flight conditions [14]. Research today supports the usage of functional principal component analysis together with k-nearest neighbors' regression for RUL estimation of turbofan components which leads to improved predictive maintenance [35].

EHM systems show increasing capabilities, but developers still face various implementation obstacles. Engine operations dynamics together with sensor inaccuracies and measurement noise and engine operational variability create degradation signal obscuration. The integration of health monitoring frameworks into current engine architecture requires major computational power together with strict validation procedures to prevent both false alerts and undetected issues. The implementation of hybrid diagnostic models combined with advanced prognostic algorithms drives continuous improvements in aircraft engine lifecycle management and maintenance operations [41].

3. TRANSIENT OPERATION OF TURBOFAN ENGINE DESIGN

The operation of turbofan engines in transient mode describes the non-steady-state conditions which exist when the engine moves from one equilibrium state to another. The engine experiences these transitions through pilot throttle inputs and automatic flight management commands and environmental variations. Rapid changes occur in engine parameters like fuel flow, turbine inlet temperature, spool speeds and pressure ratios which generate a complicated dynamic situation for engine components together with control systems. Both military and commercial aviation require reliable and safe operation during transient conditions because improper handling methods can result in compressor instability and thermal stress and thrust unavailability.

Kurzke and Halliwell [1] base their description of transient response on the significance of fuel scheduling together with control logic for engine-safe point-to-point operation. According to their approach, the engine responds differently to fuel input changes because mechanical inertia and air path delays and thermodynamic inertia cause time-delayed responses in various engine components. The accurate modeling of transient behavior requires first-order lag models along with the analysis of air mass accumulation in volumes and thermal effects despite using simplified mathematical expressions [1].

The latest research shows that thermal aspects have the most significant impact on how engines behave during transients. The research by Yang et al. [56] demonstrates that internal engine component temperatures remain constant after fast power setting changes during takeoff roll and go-around maneuvers. The heat retention characteristics of metal materials cause their clearances to change because of thermal inertia effects. The heating of turbine casings produces changes in tip clearances which affects both compressor efficiency and surge margin [56]. The thermal effects on sensors decrease their accuracy to the point where control system decisions become impaired during fast transitions.

Khalid and Hearne [30] perform an additional study, which reveals that thermal behavior in transients is influenced by four fundamental processes: Heat transfer between gas and metal surfaces, Alterations in cooling flow ratios, Temperature-induced delays in sensor measurements, and Short-term structural deformations that

modify internal part clearances. According to their research the combined effects of these phenomena result in major discrepancies between predicted and actual engine responses during both demanding flight operations and abnormal situations [30]. The identification and mitigation of these deviations remain essential for developing robust transient control laws.

The control systems require unique approaches during transient periods to sustain system integrity. The control system needs to regulate fast fuel increases to prevent temperature limits violations at turbine inlet and to prevent compressor instability during rapid throttle reductions. Transient control logic needs to account for fast actuator reactions together with slow thermal feedback responses. EASA together with FAA set standards for transient engine performance during certification testing which require compliance with thrust response duration and stability restrictions.

3.1. Engine Response Characteristics During Transient's Operation

The operation of turbofan engines under flight conditions requires them to enter transient operation regimes when they experience rapid changes such as takeoff and throttle adjustments and maneuvering. For instance, the change in the parameters of the engine compressor during the acceleration maneuver, which is a transient condition, is as shown in **Figure 3.1**. The engine operates in transient regimes through brief periods of non-steady state behavior which causes essential parameters including spool speed and turbine inlet temperature and fuel flow and pressure ratio to adjust because of external inputs. The engine requires exceptional ability to handle fast performance changes because this capability determines mission success in modern military aircraft and high-performance aircraft.

The main difficulty during transient operation arises from the slow reaction time of engine components to control commands. Kurzke and Halliwell [1] explain this phenomenon through a basic first-order model which shows the main time difference between fuel control and mechanical system output. The delay between throttle increases and thrust output results from rotating component inertia and internal air volume compressibility. This behavior can be represented as:

(3.1)

$$T * \frac{dW}{dt} + w = K * m_f$$

where T denotes the spool time constant, w is the rotational speed, m_f is the change in fuel mass flow, and K is the gain between fuel and spool response. The equation shows how mechanical inertia together with airflow dynamics limit the speed at which the engine can respond to input requirements [31].

The transient behavior of the engine is influenced by both mechanical lag and thermal response characteristics. The engine structures including turbine blades and casings absorb heat at a slower rate than the surrounding gas flow changes during power transitions according to Walsh and Fletcher [51]. The process of heat soakage occurs because thermal equilibrium becomes temporarily out of sync. The resulting delay affects component clearances—particularly in the high-pressure turbine—and may influence airflow efficiency and stability during transients [51].

The propagation of flow dynamics between engine components plays an essential part in the overall system. Cumpsty [19] explains that pressure and velocity changes made in the combustion chamber do not reach all downstream components at the same time. The staged progression of airflow through compressors and turbines creates time-based differences in response which result in delayed pressure changes and energy distribution. The total delay in thrust buildup requires thorough analysis because these phase delays accumulate during performance prediction and design assessment [19].

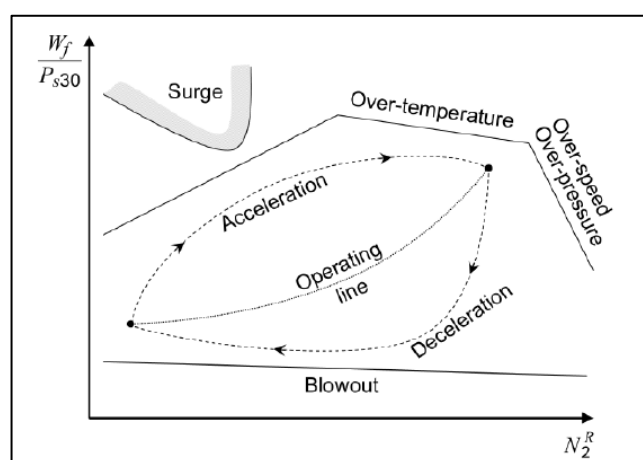


Figure 3.1: Transient behavior of engine when accelerating with limitation of W_f/P_{s3} and $\dot{N}_{dot}$ [11].

The transient response of a turbofan engine emerges from the combination of mechanical inertia together with thermal lag and internal flow dynamics. The different time-based factors which affect engine subsystems create transient behavior as a system-wide phenomenon rather than a localized effect. The correct comprehension of these characteristics serves as a vital requirement for both engine power transition safety and component longevity and performance margin preservation across the entire operational range.

3.2. Time Dependent Behavior of Key Engine Parameters

The physical dynamics of turbofan engine core parameters determine how they change during transient events such as throttle modulation or altitude transitions across specific time periods. The evaluation of turbine inlet temperature (TIT), compressor pressure ratio (CPR), exhaust gas temperature (EGT), fuel mass flow m_f and surge margin (SM) behavior over time remains essential for predicting transient operability and preventing limit violations while ensuring performance integrity.

Turbine Inlet Temperature: The response time of TIT exceeds mechanical variables because of thermal inertia. According to Yang et al. [55] TIT reaches stability after tens of seconds because combustion gases transfer heat to metal structures which affects tip clearances and thermal stress levels.

Compressor Pressure Ratio: The aerodynamic state of the compressor affects CPR that adjusts at an intermediate timescale. The combustion pressure step moves through various compressor stages that produces temporary overshoots or undershoots before the system reaches stability. The preservation of surge margin during fast speed changes depends heavily on CPR according to transient control studies.

Exhaust Gas Temperature: The temperature of exhaust gases follows TIT patterns but includes turbine expansion and heat loss effects. EGT follows TIT trends in thermal equilibrium development with a time constant of tens of seconds which makes it essential for thermal protection logic and maintenance limits.

Fuel Mass Flow Rate: The engine control electronics receive fuel flow commands right away, but actual injectors and manifolds create hydraulic lag. Transient studies found m_f ramping delays affect spool response and propagate into CPR and TIT dynamics as 0.5 – 1 second [1].

Surge Margin: The compressor operates between its operating point and surge line through surge margin. The transient surge margin reduces its value when the compressor experiences fast acceleration because steady-state SM depends on design maps. The total surge margin constraint needs to include two separate stacks according to Csank and Thomas [20]. The uncertainty stack functions to address both environmental and modeling-related uncertainties. The transient stack functions to protect against surge risk when the throttle moves rapidly.

The authors demonstrate through their dynamic analysis of a geared turbofan with VAFN that compressor stall or performance loss becomes possible when surge margin is not actively maintained, especially during throttle ramps. The authors suggest that surge margin preservation should be achieved through control limiters and area scheduling to prevent acceleration demands from surpassing system capabilities [20].

3.3. Limitation of Engine Response During Fast Operational Changes

Turbofan engines face physical and control-imposed limitations across multiple parameters when experiencing rapid throttle transitions or abrupt flight condition changes. The limitations establish safe operating envelopes while determining the structure of real-time control systems. The parameters include turbine inlet temperature (T4), high-pressure compressor exit temperature (T3), pressure at compressor exit (P3), compressor pressure ratio (CPR), exhaust gas temperature (EGT), fuel flow rate m_f , and surge margin (SM) are especially critical during such fast operational changes.

The T4 (High-Pressure Turbine Inlet Temperature) represents the thermal limit of the engine's hot section. A sudden increase in fuel flow raises combustor temperature which poses a risk of thermal stress damage to turbine blades. Csank and Thomas [20] state that T4 excursions during transients need to be actively limited through fuel flow scheduling or active cooling because turbine materials have specific short-duration temperature limits. Exceeding these limits could result in reduced creep life or structural deformation of the high-pressure turbine.

The T3 (HPC Exit Temperature) also imposes limitations, especially during fast accelerations. Abdelwahab [11] showed experimentally that sudden temperature

spikes at T3 between 60-70 Kelvin. The compressor-turbine matching can be disturbed by the disturbances, and the engine can be brought closer to surge conditions. T3 is a critical monitored variable for fast throttle scheduling in engines with high pressure ratios. Moreover, it is so critical to limit the engine mechanically. Static pressure of station is commonly used in flow control such as W_f / P_{s3} schedule.

P3 (HPC Exit Pressure) should be kept in a narrow range to avoid flow instability. Abdelwahab [11] also observed that transient pressure fluctuations at P3 caused by distorted fan inlet temperatures could lead to surge or rotating stall. Control systems mitigate this by modulating bleed valves or using inlet guide vane scheduling to absorb pressure variation during transients.

Compressor Pressure Ratio (CPR) is bounded by both surge and choke conditions. Yu et al. [58] observed that CPR overshoots are common during fast throttle increases, often reaching aerodynamic limits unless stator vanes or bleed flows are adjusted in real time. These CPR excursions pose a direct risk to compressor operability, particularly in low-altitude, high-thrust scenarios.

EGT (Exhaust Gas Temperature), while derivative of T4, presents an additional constraint due to its direct connection with the engine's exhaust system and thermal monitoring architecture. Yang et al. [55] point out that EGT overshoots during transients are typically controlled by temporary fuel flow reduction, especially in engines using T4-based control loops. Sustained EGT overshoots can trigger maintenance actions or induce blade surface erosion.

Fuel Mass Flow Rate cannot be executed throttle commands at the same speed as the operator. The system experiences physical delays because fuel metering units need time to respond hydraulically and combustion stabilization needs time to stabilize thermally. According to Yang et al. [55], control systems enforce specific rate constraints on $\dot{m}_f$ during transients to prevent over fueling, sudden temperature jumps, or compressor stall, especially when operating near the surge boundary.

The engine cycle simulation through fan and compressor map characteristics determines the maximum Surge Margin available. Several methods exist for designers to determine this value. The surge behavior of an engine represents a fatal operational safety risk. The acceptable surge margin value must be determined for all operational

conditions across the entire envelope during transient operations at different altitude and temperature settings.

3.4. Physical and Environmental Factors Influencing Transient Response

The transient operation of turbofan engines depends on both internal control algorithms and hardware reaction speed yet remains heavily influenced by surrounding physical conditions and environmental factors. The ability of the engine to perform acceleration and deceleration along with maintaining operability depends heavily on ambient temperature conditions as well as altitude and inlet distortion and component degradation factors.

The density of incoming air decreases when the aircraft rises in altitude and when it operates under high ambient temperatures. The reduction in available mass flow through the engine causes compressor pressure rise to decrease and results in reduced operational surge margin. According to Walsh and Fletcher [51] engine pressure and temperature buildup during acceleration slow down dramatically in the low-pressure compressor and fan stages because of these changes. The authors explain that engines operating at “hot and high” conditions need to receive more cautious throttle transients to prevent compressor stall and thrust shortfall.

The engine inlet receives distorted airflow because of atmospheric variables that include wind, turbulence and sudden aircraft movements. Cumpsty [19] demonstrates that compressor blade loading becomes non-uniform when distortions occur thus resulting in reduced pressure rise and potential surge line proximity. High angle-of-attack flight and engine-airframe integration conditions make these effects more critical because boundary layer ingestion disrupts inlet flow uniformity.

Recurring exposure to atmospheric particles such as sand dust and salt leads to compressor surface fouling and erosion that decreases both efficiency and airflow capability. Walsh and Fletcher [51] demonstrate that moderate surface degradation makes the engine operating line approach closer to the surge limit. Engine transient fuel scheduling becomes limited because fuel flow increases now exceed the decreased surge margin leading to possible stability issues or stall conditions.

The operation of engines generates temporary thermal expansion which affects turbine casings and rotors. According to Cumpsty [19] blade tip clearances change temporarily because of thermal effects which modify the flow area and result in changes to the effective pressure ratio. The aerodynamic performance between turbine stages becomes affected when clearance measurements experience small changes because these changes directly impact efficiency during steady operation and throttle response during transient periods. Thermal effects remain poorly assessed in transient scheduling, but they become essential factors for engines with narrow tolerances and complex cooling system



4. EXPERIMENT

4.1. Experiment Concepts and Requirements

The study's experimental section includes the development of a mixed-flow military turbofan engine that uses fundamental design principles from previous chapters. This design serves as the basis for analyzing thrust and exhaust control under various influencing factors.

Any control-oriented investigation requires the establishment of a steady-state engine design. The initial design emerges from combining on-design and off-design parameters. The engine design process depends on platform requirements which include thrust output targets together with specific fuel consumption requirements and flight altitude needs. Engine designers follow the requirements which platform interfaces provide for guiding their work.

Open-source data enabled thermodynamic cycle analysis for the experimental case study. The engine's platform requirements have been established through a set of properly justified assumptions that are detailed in the following list:

Design Requirements:

- The engine shall need to generate a max dry thrust output of 60 kN.
- The engine design shall need to include an afterburner system for delivering increased thrust.
- The engine shall need to generate a max wet thrust output of 73 kN.
- The specific fuel consumption at maximum dry thrust shall not exceed 50 g/(kN·s).
- The engine shall be capable of being operational at 45,000 feet
- The engine's highest operational speed shall be set at 1.6 Ma.
- The engine intake shall provide 70 kg/s of air through its intake system.
- The engine shall deliver 280 kW of power for accessory operation together with platform systems.
- The engine shall need to supply 0.5 kg/s of bleed air which will be used by the platform.

$$SFC = \frac{m_f}{\text{net thrust (kN) or shaft power (kW)}} \quad (4.1)$$

Where m_f is fuel mass flow and the selection.

TSFC is the specific fuel consumption relevant to engines that generate thrust, such as turbojets and turbofans. It is defined as the fuel flow rate divided by the net thrust produced by the engine:

$$TSFC = \frac{m_f}{F_N} \quad (4.2)$$

Where F_N is net thrust. The unit of TSFC is typically expressed as grams per kilonewton-second ($\text{g}/(\text{kN}\cdot\text{s})$). Lower TSFC values indicate higher propulsion efficiency and improved range performance. According to [42], TSFC is influenced by design parameters such as bypass ratio, turbine inlet temperature, and compressor pressure ratio. High-bypass turbofan engines generally demonstrate lower TSFC due to enhanced propulsive efficiency.

PSFC applies to engines that produce shaft power, including turboshaft and turboprop engines. It is defined as the fuel flow rate per unit of shaft power output:

$$PSFC = \frac{m_f}{\text{Power}_{\text{shaft}}} \quad (4.3)$$

PSFC is commonly measured in grams per kilowatt-hour ($\text{g}/(\text{kW}\cdot\text{h})$). The PSFC must be minimized in industrial gas turbines, marine propulsion systems and auxiliary power units to maintain operational efficiency. As Boyce [12] pointed out, PSFC is sensitive to turbine efficiency, part-load operation, and environmental conditions, and is a key indicator in performance diagnostics and health monitoring strategies. In this thesis, TSFC is focused as SFC comparison.

4.1.2. Net Thrust

The forward motion of aircraft depends on net thrust which results from the unbalanced force that emerges when air accelerates through the engine. The evaluation

of turbojet and turbofan engine effectiveness depends on net thrust as the most important parameter which determines aircraft acceleration and climb rate and cruise capabilities. The development and control of military and civilian propulsion systems heavily depend on precise net thrust prediction and optimization methods.

The theoretical basis of net thrust comes from applying Newton's second law of motion to a control volume that includes the engine. The momentum equation shows how to calculate net thrust for an ideal one-dimensional steady flow system that excludes external work and heat exchange as follows:

$$F_N = m_e * V_e - m_0 * V_0 + (P_e - P_0) * A_e \quad (4.4)$$

Where F_N is the net thrust (N), m_e is the exhaust mass flow rate (kg/s), V_e is the exhaust velocity (m/s), m_0 is the inlet air mass flow rate (kg/s), V_0 is the freestream velocity of the aircraft (m/s), P_e and P_0 are the exhaust and ambient static pressure (Pa) and A_e is the exhaust exit area (m^2). The term $(P_e - P_0) * A_e$, representing pressure thrust can be ignored under perfectly expanded nozzle conditions in practical applications. The simplified momentum thrust becomes:

$$F_N = m_0 * (V_e - V_0) \quad (4.5)$$

This equation shows that net thrust is primarily a function of the mass flow rate and the difference in velocities between the exhaust and the freestream. In turbofan engines, the total net thrust must account for both core (combustion products) and bypass (fan flow) streams:

$$F_N = m_{core} * (V_{core} - V_0) + m_{fan} * (V_{fan} - V_0) \quad (4.6)$$

High bypass ratio engines generate 80% of their total net thrust from the bypass stream during subsonic cruise operations. The bypass stream enhances propulsive efficiency and reduces specific fuel consumption when compared to turbojets [2]. The military engine uses afterburners to produce higher exhaust temperatures and velocities which results in a major boost in V_e and thus in net thrust. The afterburner operation results

in significant increases of specific fuel consumption and thermal loads which restrict its use to particular flight phases including takeoff and combat maneuvers [44].

The critical factors include both altitude and Mach number. The increase in altitude results in decreased air density and engine mass flow rate which produces reduced net thrust. The freestream velocity increases as flight Mach numbers rise while the engine mass flow rate decreases at higher flight Mach numbers.

The freestream velocity V_0 increases which reduces the $V_e - V_0$ term and diminishes net thrust accordingly. Advanced inlet designs work to maximize ram recovery for improving total pressure recovery at the compressor face [27].

The accurate modeling of net thrust under off-design conditions is essential for mission performance analysis and engine control. The thrust output changes substantially due to deviations in turbine inlet temperature and pressure losses and nozzle efficiency which makes it a critical metric for full-envelope engine simulations and digital control frameworks [47].

4.1.3. Surge Margin

The modern gas turbine engine with axial compressors depends on surge margin to achieve aerodynamic stability and engine durability and safe operation in steady-state and transient conditions. The system-level instability known as compressor surge results in a complete failure of flow reversal throughout the compressor. The occurrence of surge produces loud noises and vibrations together with thrust loss and possible structural harm. The operational buffer between the current engine operating point and surge onset defines surge margin which serves as a critical element in engine design and performance monitoring and control systems.

The mathematical definition of surge margin depends on compressor maps at constant corrected speed:

$$SM = \frac{m_{cmp\ opline} - m_{cmp\ surge\ limit\ with\ same\ SL}}{m_{cmp\ opline}} * 100\% \quad (4.7)$$

This expression provides a normalized percentage indicating how far the operating point is from the surge boundary. A higher surge margin denotes safer operation, while a lower margin increases the risk of instability.

Moreover, surge margin of Fan is calculated same way with using map characteristic of inner fan and outer fan. The surge margin management in military turbofan engines becomes more complex because of fast throttle movements and afterburner activation and flight at high altitudes. The FADEC system requires surge maps and engine deterioration models and control logic to maintain sufficient margin during aggressive operating conditions [44].

4.1.4 High - Pressure Turbine Inlet Temperature (T₄)

The High-Pressure Turbine Inlet Temperature represents a vital thermodynamic parameter which shows the total temperature of gas flow when it enters the first stage of the high-pressure turbine. The engine's thermal efficiency together with specific thrust and power output depends on this parameter because it determines the amount of enthalpy drop available for turbine work extraction. The Brayton cycle analysis shows that T₄ increases will boost cycle efficiency by expanding the useful temperature differential across turbine sections [42].

The material strength of turbine components along with cooling system efficiency restricts the maximum possible increase of T₄. Boyce [12] explains that modern gas turbines need advanced blade cooling methods including internal convective cooling and film cooling and thermal barrier coatings to maintain metal temperatures below their allowable limits when operating at 1400–1700 K. These cooling methods enable the gas path temperature to rise above the melting point of uncooled materials by multiple hundred degrees. Beside Boyce [12], in this thesis, the design high pressure turbine inlet temperature is selected as 1850 K. Therefore, cooling effectiveness and cooling efficiency of turbine blade is assumed to be advanced with using Nickel-Based Single-Crystal Superalloy with Gadolinium Zirconate TBC [59].

The T₄ value in high-performance military turbofan engines requires optimization for maximum thrust while also meeting specific mission requirements including acceleration and fuel economy and altitude adaptability. The book by Kurzke and Halliwell [1] explains that higher T₄ values produce better net thrust during

afterburning but these conditions reduce turbine lifespan and increase fuel usage [1]. The trade-off between performance and durability becomes more significant when the engine operates through throttle bursts or altitude changes.

4.2. Comparison Parameters Definition

4.2.1. Engine Installation

The installation of turbofan engines on military aircraft faces stricter aerodynamic and structural limitations than civil aircraft since they need to perform high maneuvers while operating at supersonic speeds and maintaining compact fuselage designs. The installation constraints increase the effects of propulsion performance degradation through intake distortion and external drag and off-design operability. The engine integration process with the airframe through short inlets and S-duct geometries and embedded configurations produces non-uniform total pressure distribution at the fan face. The distorted pressure distribution creates areas that are prone to stall while decreasing fan efficiency and increasing the risk of surge during transient throttle operations [42].

The controlled extraction of high-pressure, high-temperature air from intermediate or high-pressure compressor stages of a gas turbine engine is known as customer bleed air. The extracted air comes from the main engine flowpath to supply external aircraft systems including cabin pressurization and environmental control systems (ECS) and anti-icing systems and pneumatic actuation or fuel tank systems.

The extraction of mechanical power from the engine spool through an accessory gearbox enables the operation of external aircraft systems including hydraulic pumps generators avionics and fuel systems. The mechanical power from either the high-pressure or low-pressure shaft moves through a power take-off shaft (PTO) and gearbox module to transfer energy.

In this thesis, Engine installation concepts are conducted with customer bleed and power off take concepts. Intake efficiency losses and intake distortion are neglected.

4.2.2. Engine Deterioration

The deterioration of engines occurs through continuous performance reduction of gas turbine and turbofan engines because of component wear and fouling and erosion and corrosion. The accumulation of particles on compressor blades through fouling causes decreased airflow and reduced pressure ratio and compressor efficiency,

The deterioration of turbine components especially in the high-pressure turbine (HPT) causes major performance degradation and operational issues for gas turbines. The deposition of particles and erosion on HPT vanes causes a reduction in effective throat area which results in decreased mass flow and increased core gas temperature that elevates downstream losses and stresses the system and shortening low-cycle fatigue life [17].

For the purposes of this thesis, a uniform 1% reduction in efficiency is applied to both the high-pressure turbine (HPT) and the low-pressure turbine (LPT) to account for performance degradation.

4.3. Engine Design

The first step to establish effective control strategies demands designing a mixed-flow military turbofan engine. The specified engine requires integration with particular unmanned aerial vehicles (UAVs) and military aircraft platforms. The main goal of this work includes validating control methods through simulations of an accurately modeled propulsion system which allows for dependable observation and analysis. The engine is named as MHY16500.

The Gasturb software became the first tool used for preliminary thermodynamic design work during the initial phase of design. The modeling process for engines becomes faster when users input essential design parameters. During this stage designers assumed standard atmospheric conditions for the engine operation at sea level and static environment.

Multiple essential design parameters need to be established at the beginning of the design process including turbine inlet temperature (T_4) and overall pressure ratio (OPR) and mass flow rate and bypass ratio. Military engine requirements drove the design of a low-bypass-ratio engine with high OPR because such features are typical

of combat engines. The architectural dimensions of military turbofans need to be more compact when compared to civil turbofans while operating at lower fan pressure ratios. The operational flexibility of the engine depends on an afterburner system which affects both control dynamics and thrust modulation performance

The parameters underwent a series of thermodynamic cycle iterations through the Gasturb software. The design team focused on achieving the correct P16/P6 ratio because this parameter controls the balance between thrust output and fuel consumption. The P16/P6 ratio needed to reach approximately 1 to ensure operational stability of the design. Engine simulation is performed multiple iterative adjustments until they achieved a design cycle which satisfied all requirements. The validation of final input parameters and design cycle was achieved through multiple iterative steps.

Table 4.1: Design Parameter of Engine.

Design Parameters at Sea Level Static	Value
Design Point Condition	SLS - Standard Day
Mass Flow Rate	70 kg/s
By Pass Ratio	0.3
Fan Stages	3
Fan Efficiency	85%
Fan Pressure Ratio	nearly 4.2
Compressor Stages	6
Compressor Efficiency	0.87
Compressor Pressure Ratio	6.50
Cooling LPT NGV	5%
Cooling LPT Rotor	3%
Cooling HPT NGV	14%
Cooling HPT Rotor	7%
T4	1850 K
HPT Stages	1
HPT Efficiency	0,87
LPT Stages	1
LPT Efficiency	0.88
HPT RPM	18000
LPT RPM	12000
P16/P6	1

The second development phase produced a digital engine model to simulate performance during on-design and off-design operating conditions. The second stage focused on analyzing engine thermodynamic responses throughout different operating

situations. The Numerical Propulsion System Simulation (NPSS) platform served as the simulation tool for this purpose. NPSS enables precise engine performance predictions for various mission profiles by utilizing its comprehensive gas turbine engine component libraries for detailed modeling.

The NPSS environment requires performance maps of individual engine components to study engine behavior during off-design conditions. The required maps were extracted from publicly accessible data sources. The F100 engine provided fan map data which NASA E3 program data served to create compressor and turbine maps. The engine model depends heavily on the distinctive features present in these maps for both accuracy and fidelity.

The selection of open-source performance maps followed because detailed proprietary maps from real engine programs were not available. The fan map data originated from [25] while the compressor and turbine maps came from the NPSS maps library that contains NASA E3 program data.

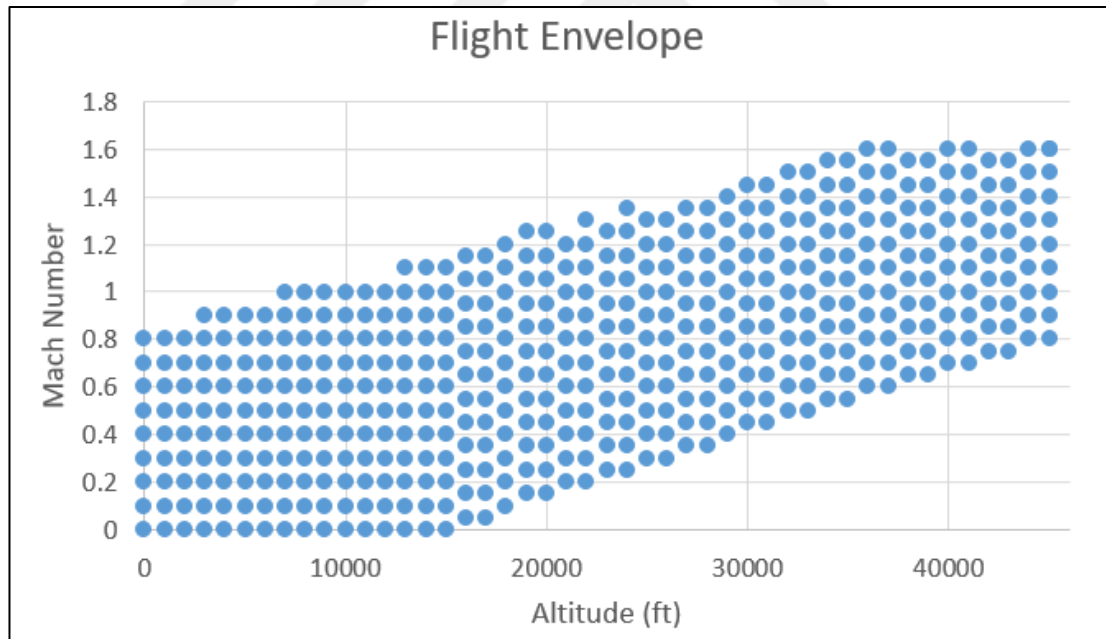


Figure 4.2: Flight Envelope of MHY16500.

4.4. Engine Control Design Selection

The control aspects of the propulsion system gained increasing importance after completing the engine design stage. The initial study focused on steady-state engine

management, yet it failed to address transient behavior which describes the time-dependent engine responses during this stage of analysis.

The determination of thrust-governing parameters along with exhaust system dynamic control methods represents a fundamental requirement for engine control systems. Engine manufacturers employ diverse methods to handle this requirement, which stems from their product design approaches and operational demands.

The main thrust control methods use either fan speed as a function of inlet temperature or engine pressure ratio (EPR). The choice of control parameter requires evaluation based on its ability to keep the engine operating within its designated limits across different operating scenarios. EPR serves as an effective control method for nozzle control systems. Using the same control parameter such as EPR for thrust and exhaust control makes system implementation more complex.

The thesis implements thrust control through fan speed which depends on fan rotational speed and engine inlet temperature. The selection of EPR for exhaust control purposes makes sense because it produces a more stable engine response in these applications.

Literature and practice present multiple functional relationships for exhaust control implementation. The control system uses three main functional relationships which include the corrected fan speed and Mach number at station 13, the relationship between corrected fan speed and engine pressure ratio and EPR depends directly on inlet temperature. The control functions will be tested through various engine conditions that include afterburning versus non-afterburning operation and aged versus new engine condition and installed versus uninstalled configurations. Each function will receive evaluation based on its performance to maintain engine operability while delivering consistent results across these multiple operational conditions.

4.5. Engine Control Outputs

4.5.1. Installed Deteriorated with AB Operation

Installed Deteriorated Engine with AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.3** to **Figure 4.7**.

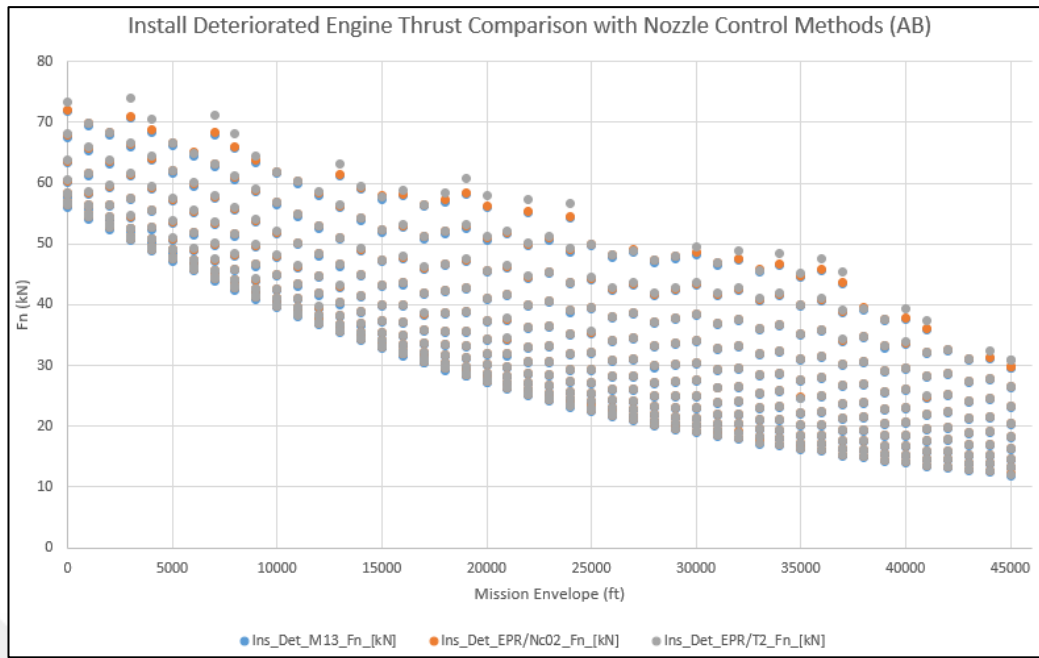


Figure 4.3: Ins – Det – Thrust Comparison.

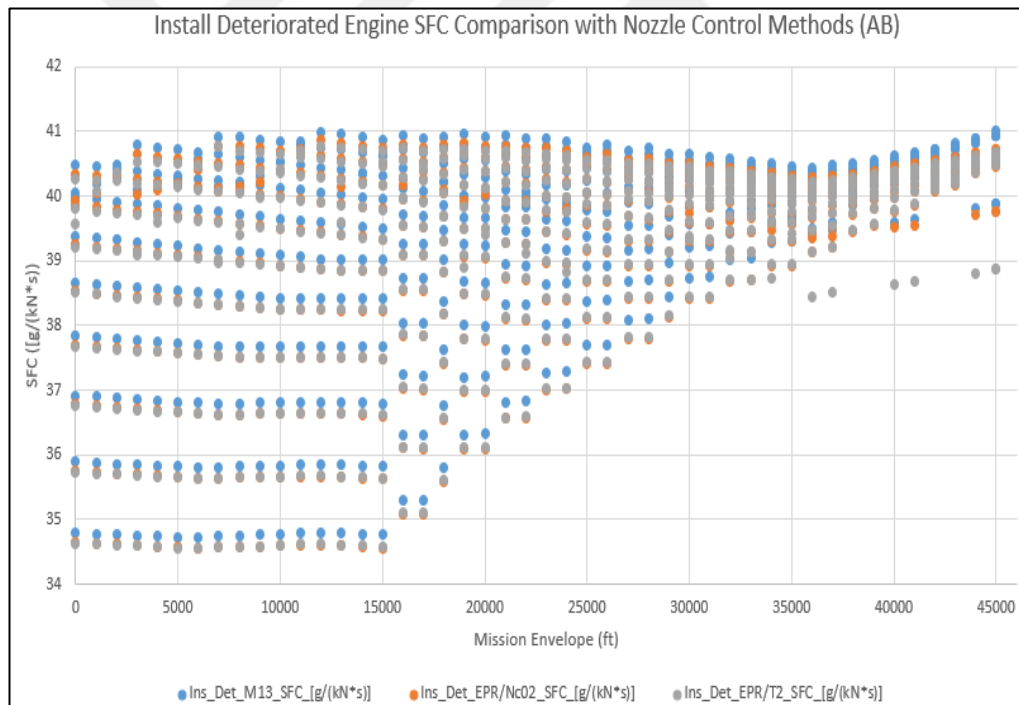


Figure 4.4: Ins – Det – SFC Comparison.

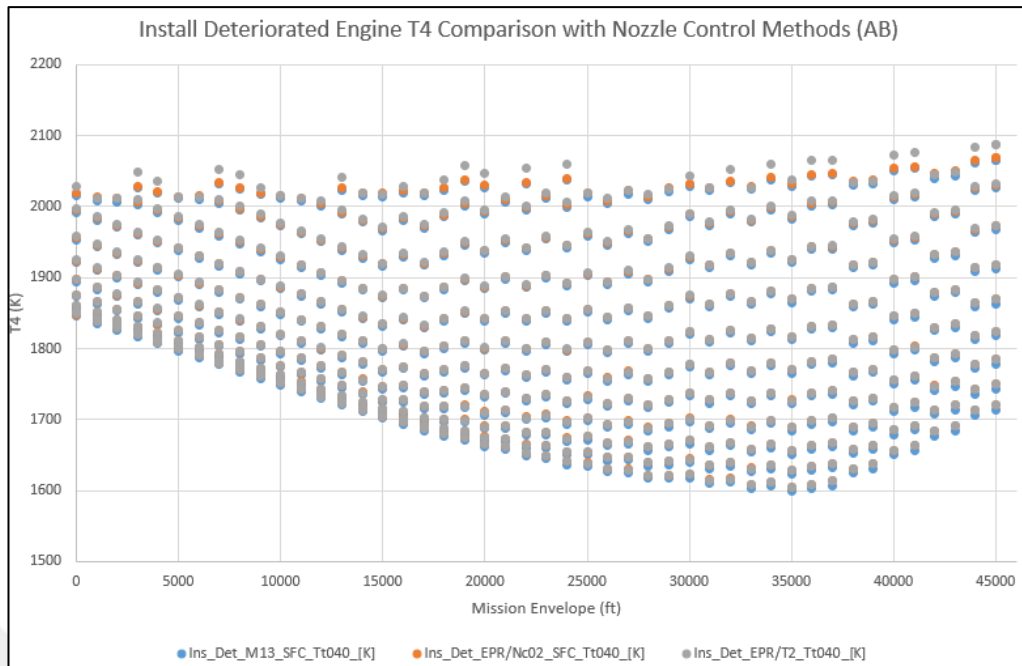


Figure 4.5: Ins – Det – T4 Comparison.

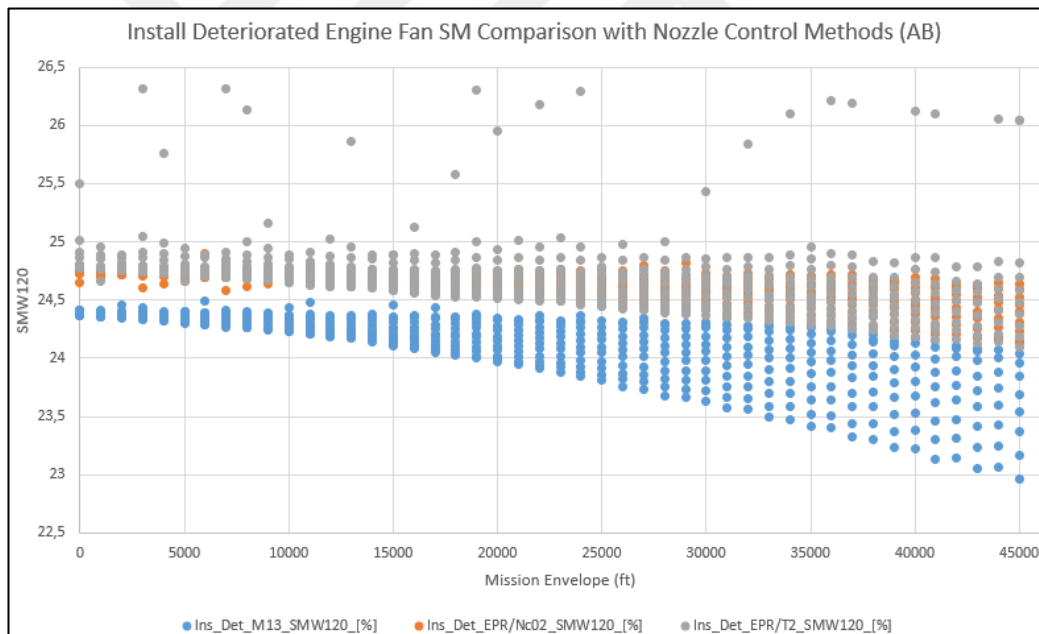


Figure 4.6: Ins – Det – Fan SM Comparison.

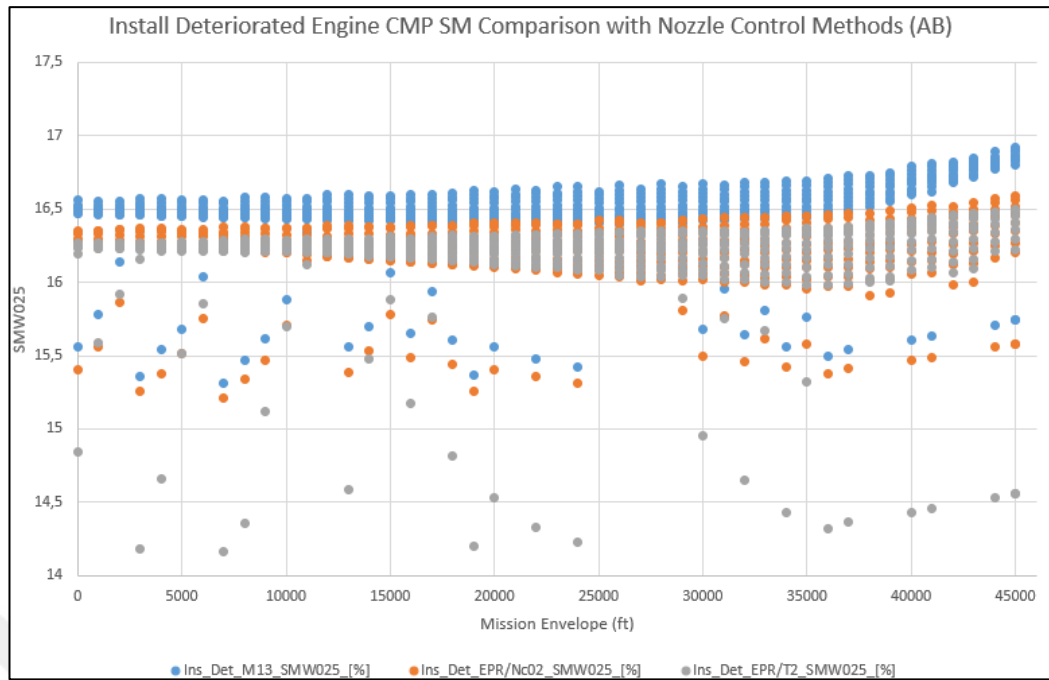


Figure 4.7: Ins – Det – CMP SM Comparison.

4.5.2. Uninstalled Deteriorated with AB Operation

Uninstalled Deteriorated Engine with AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.8** to **Figure 4.12**.

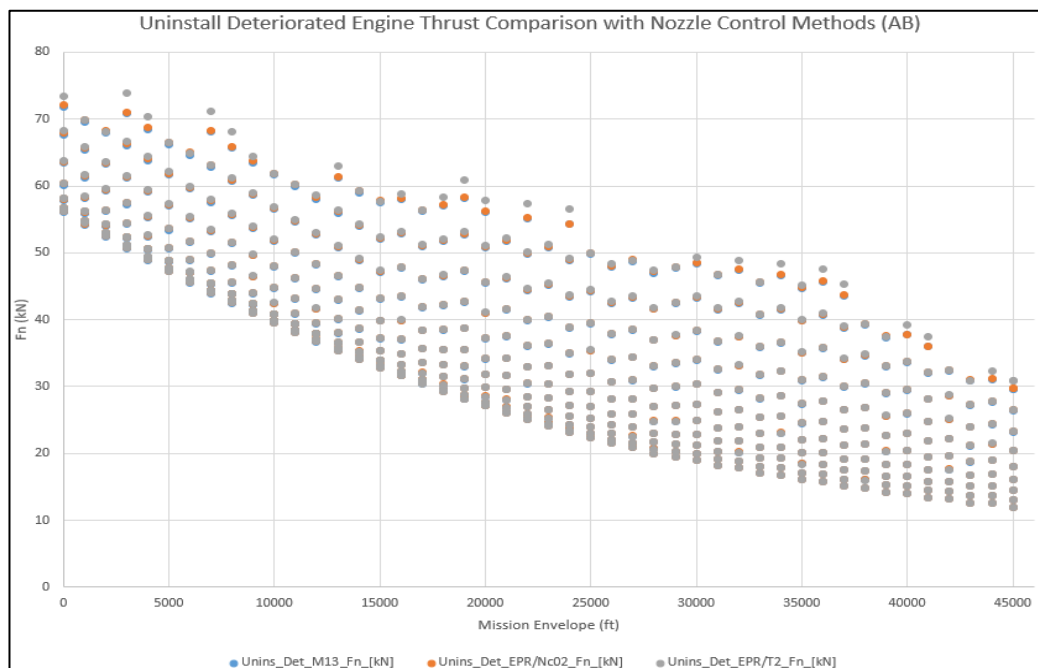


Figure 4.8: Un – Det – Thrust Comparison.

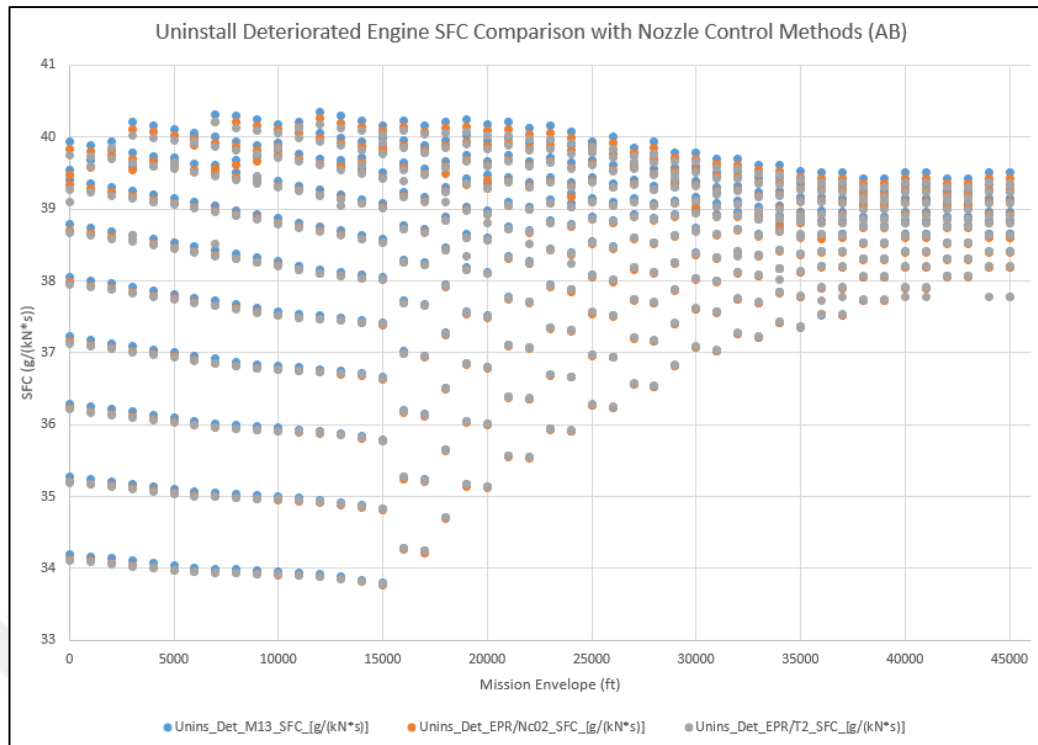


Figure 4.9: Un – Det – SFC Comparison.

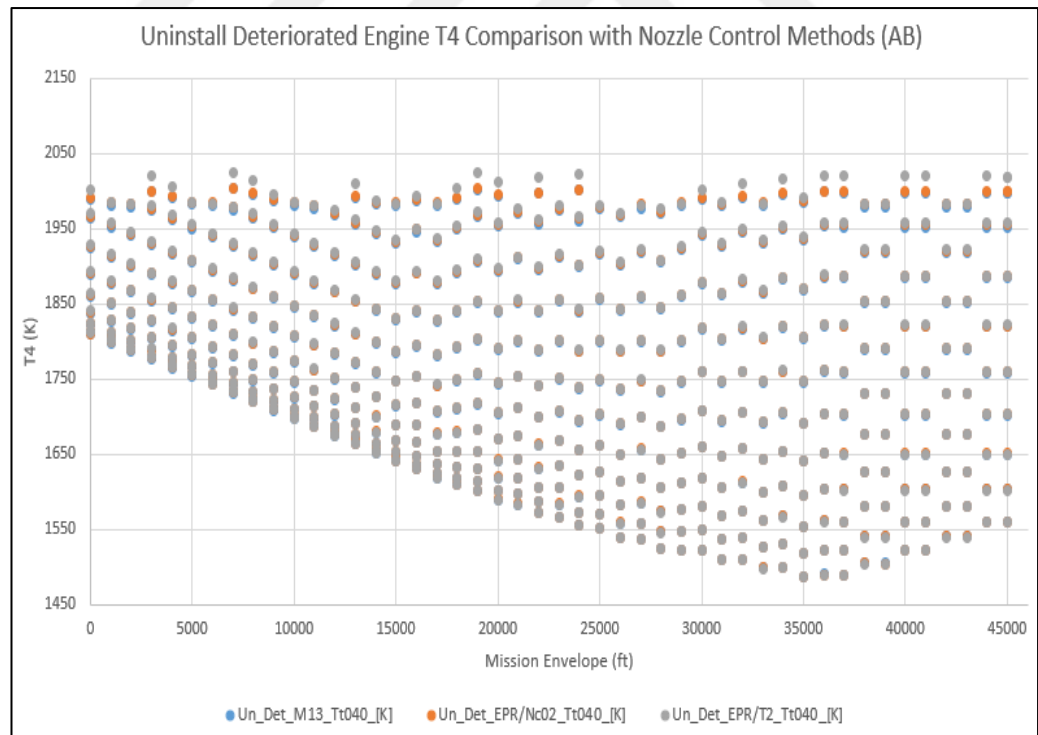


Figure 4.10: Un – Det – T4 Comparison.

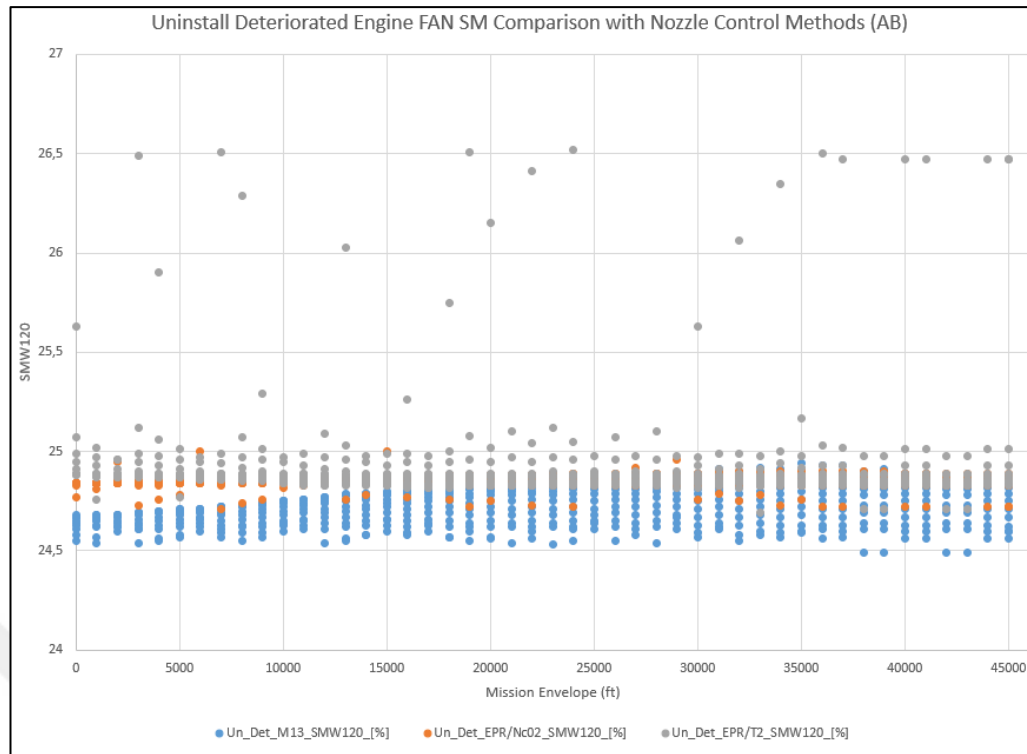


Figure 4.11: Un – Det – FAN SM Comparison.

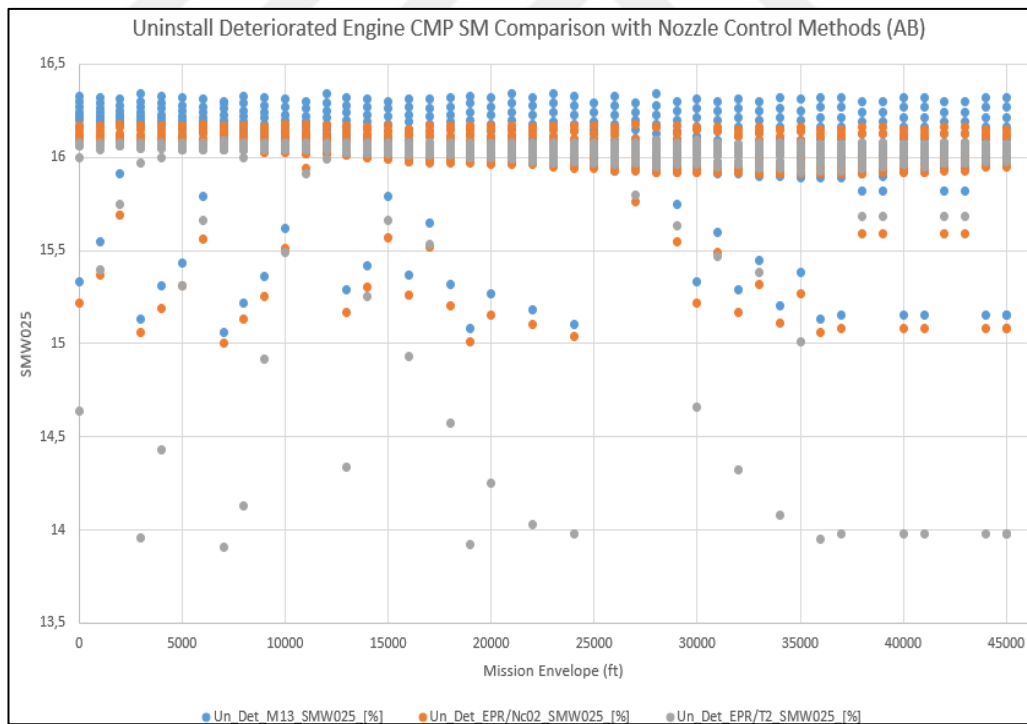


Figure 4.12: Un – Det – CMP SM Comparison.

4.5.3. Installed New with AB Operation

Installed New Engine with AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.13** to **Figure 4.17**.

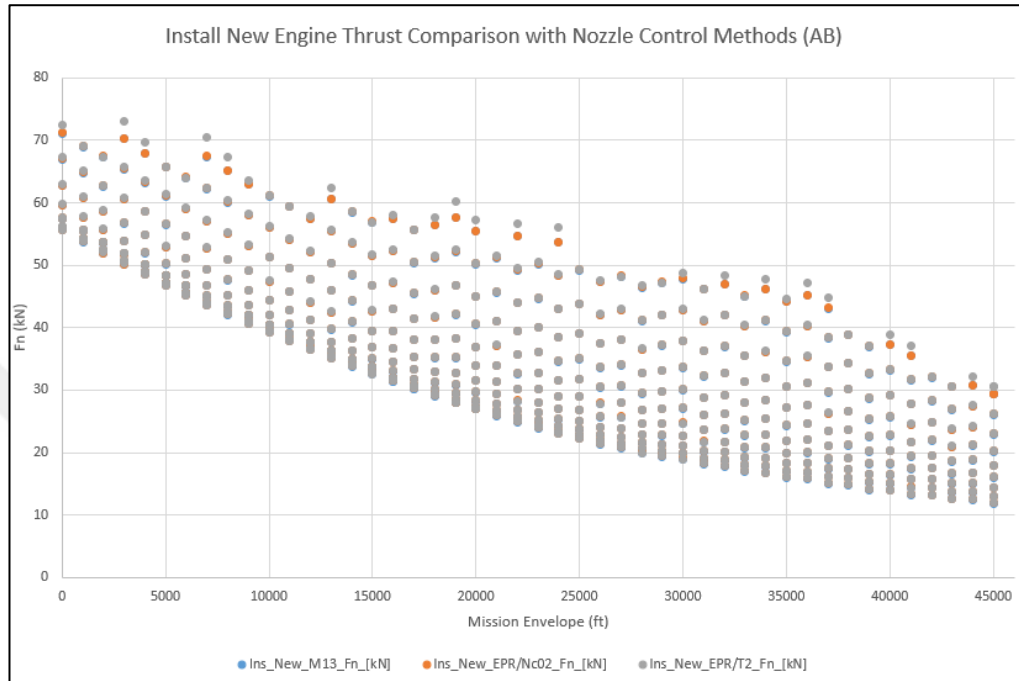


Figure 4.13: Ins – New – Thrust Comparison.

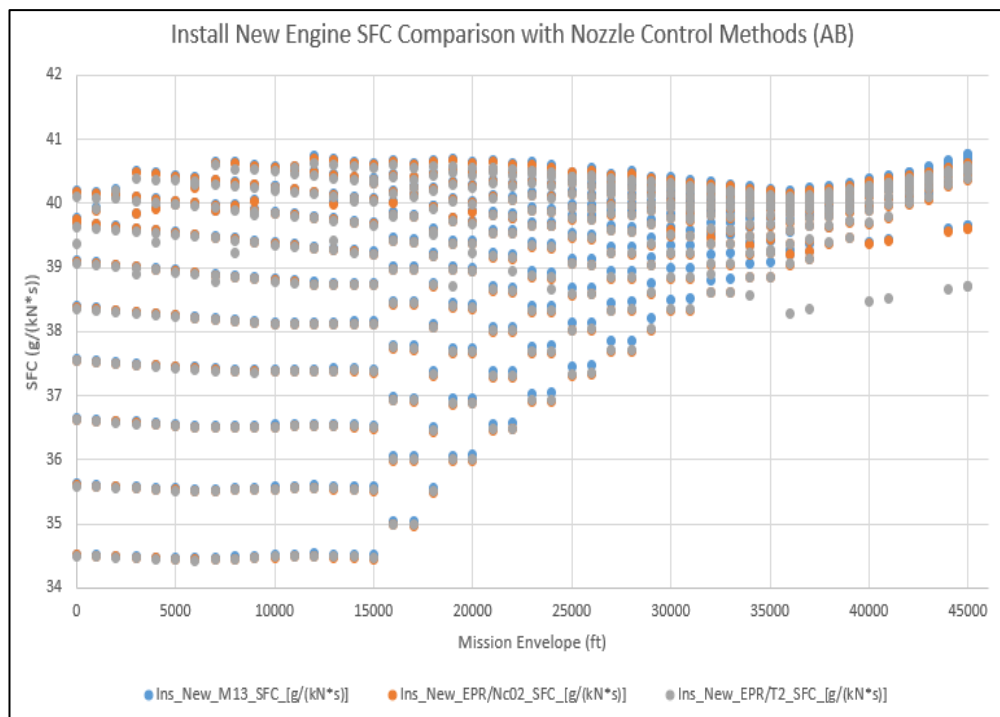


Figure 4.14: Ins – New – SFC Comparison.

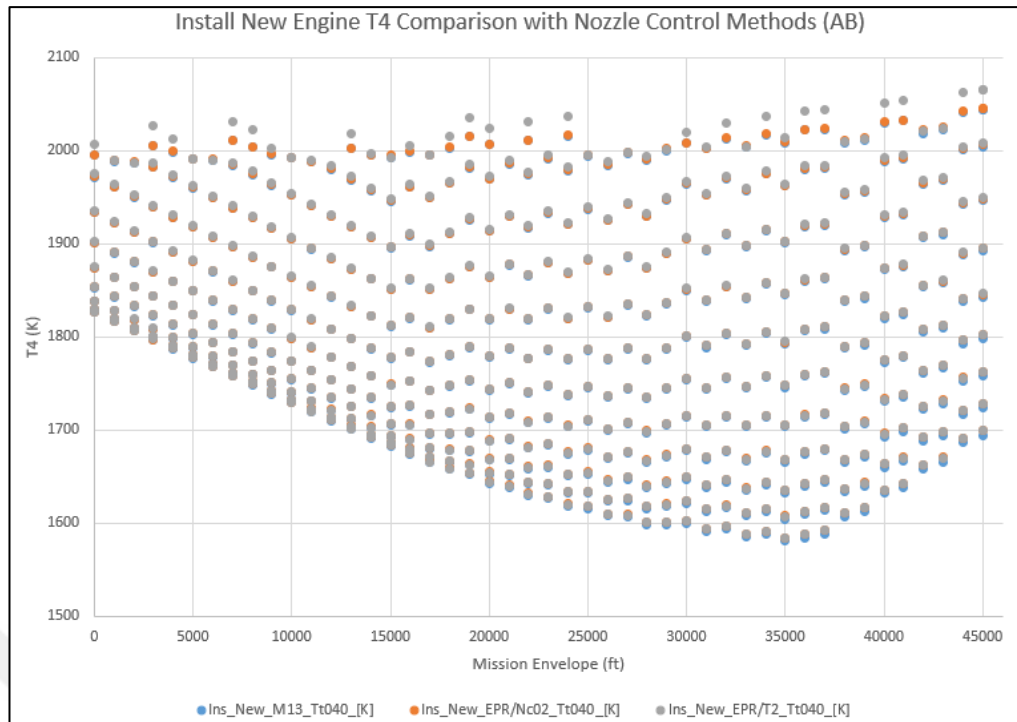


Figure 4.15: Ins – New – T4 Comparison.

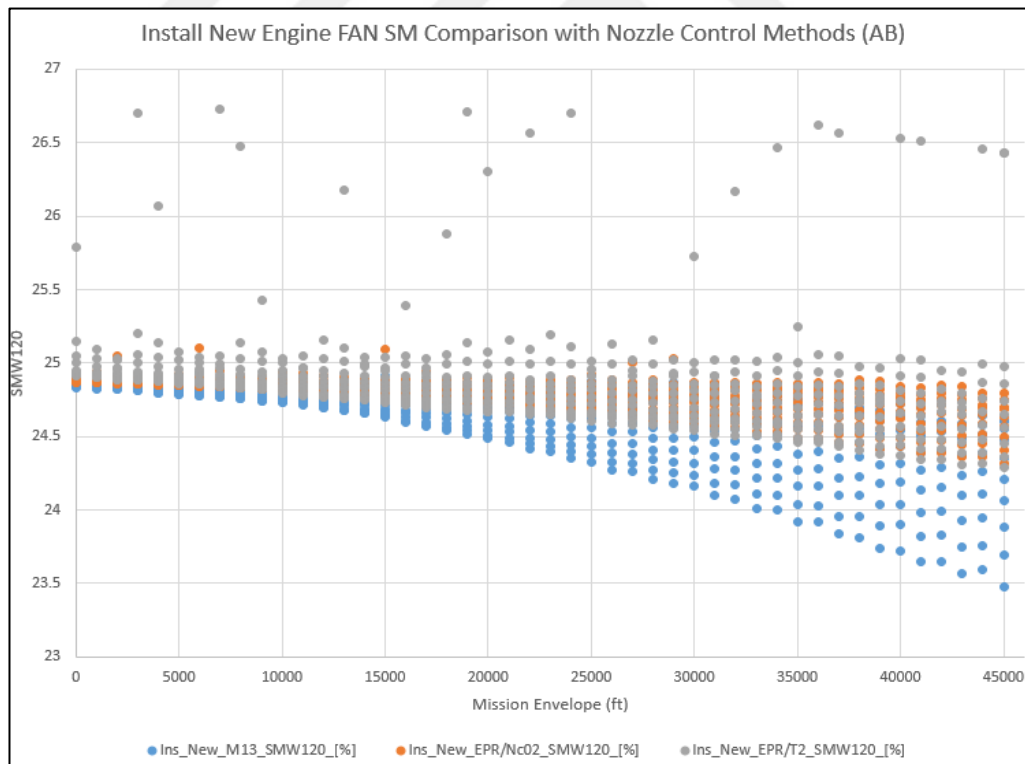


Figure 4.16: Ins – New – FAN SM Comparison.

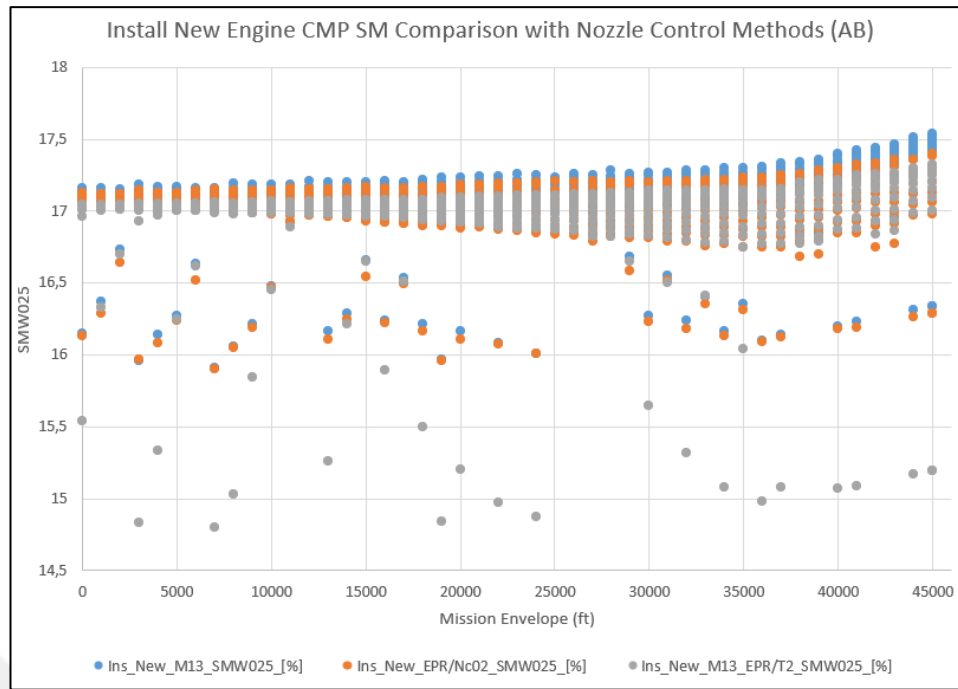


Figure 4.17: Ins – New – CMP SM Comparison.

4.5.4. Uninstalled New with AB Operation

Uninstalled New Engine with AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.18** to **Figure 4.22**.

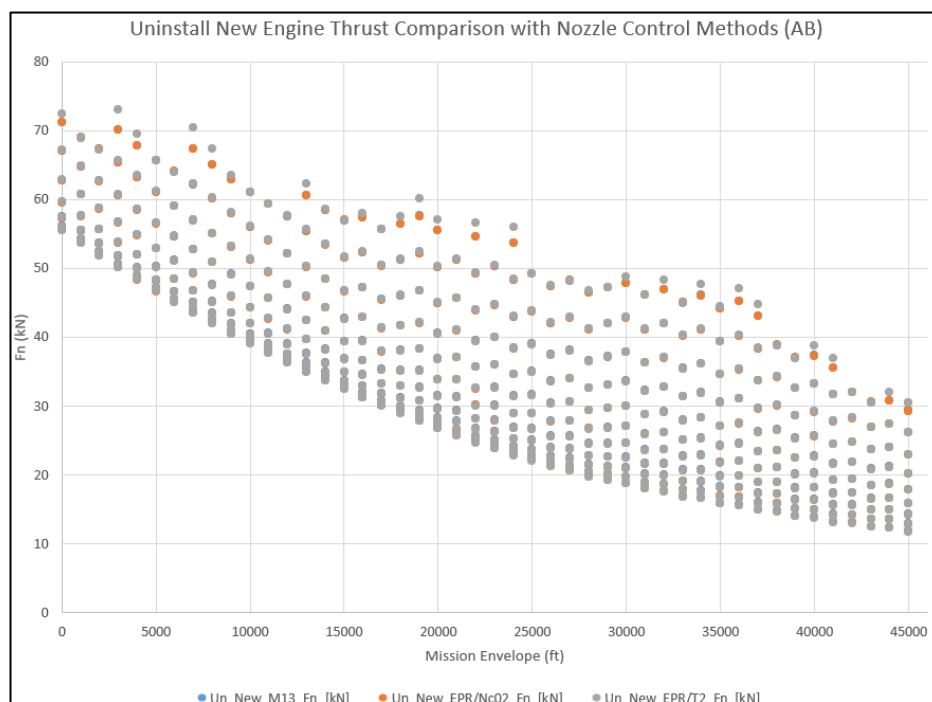


Figure 4.18: Un – New – Thrust Comparison.

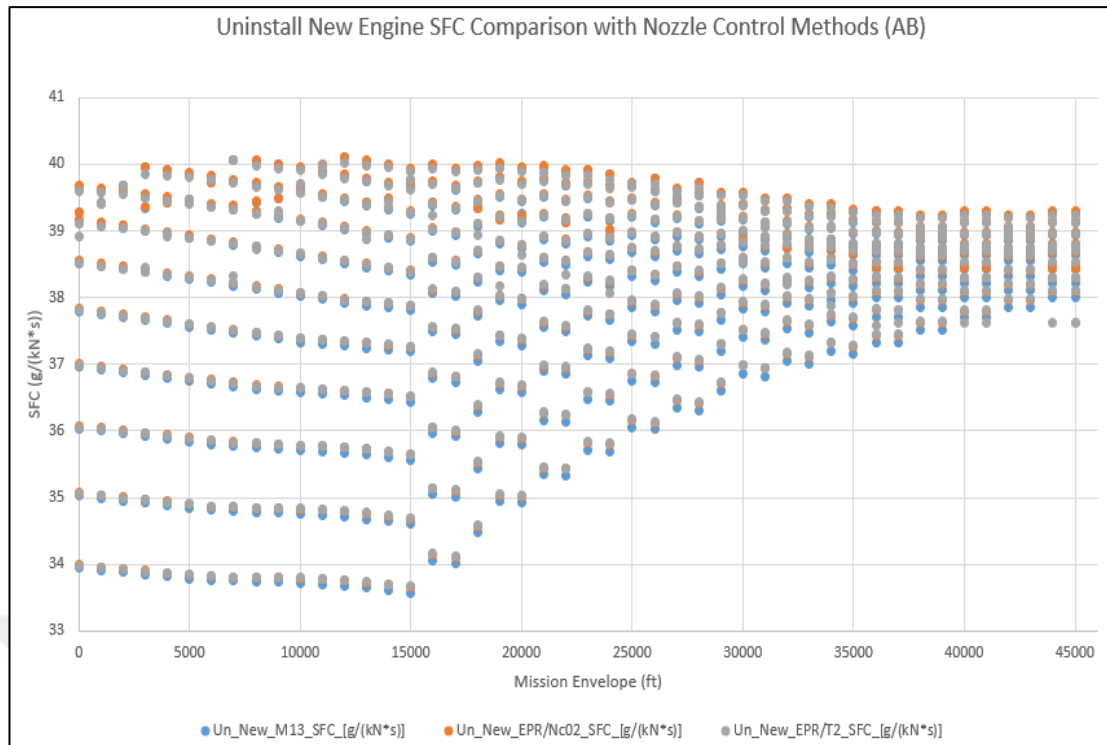


Figure 4.19: Un – New – SFC Comparison.

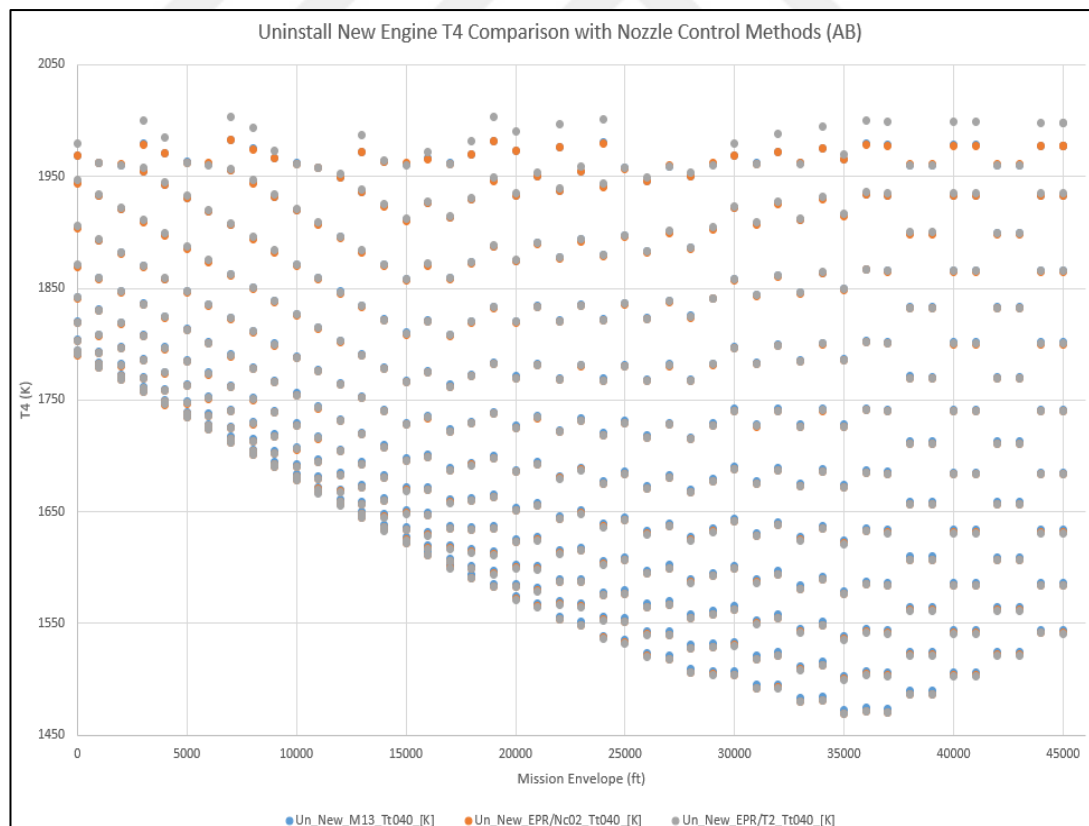


Figure 4.20: Un – New – T4 Comparison.

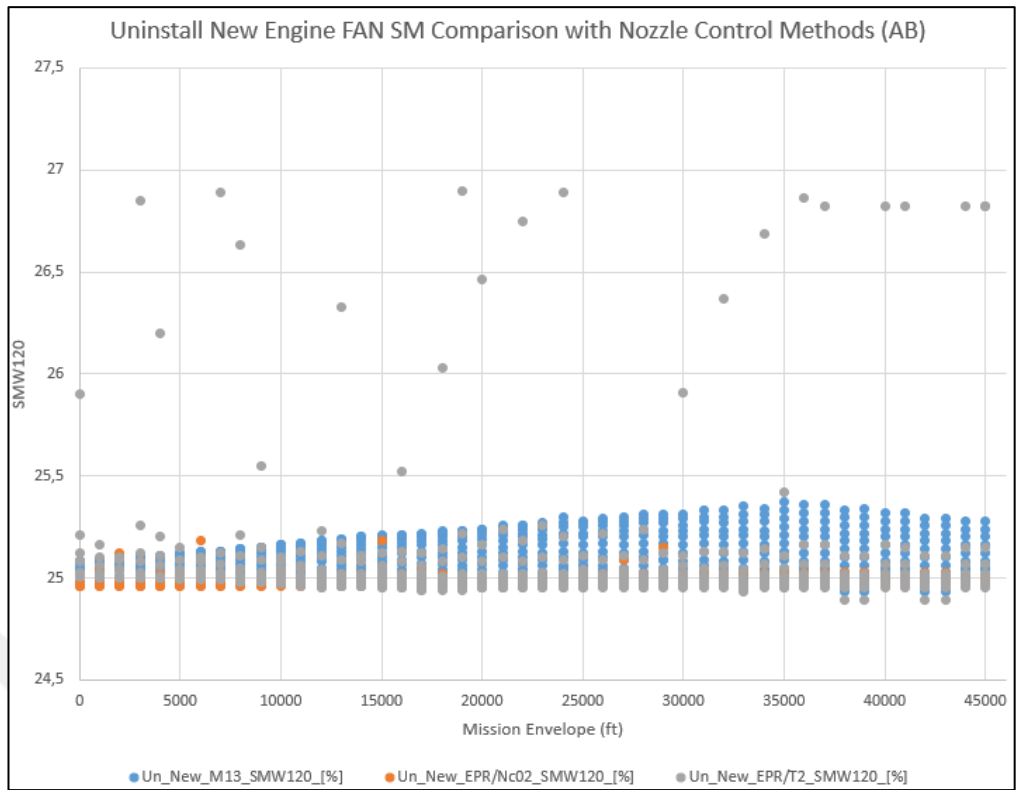


Figure 4.21: Un – New – FAN SM Comparison.

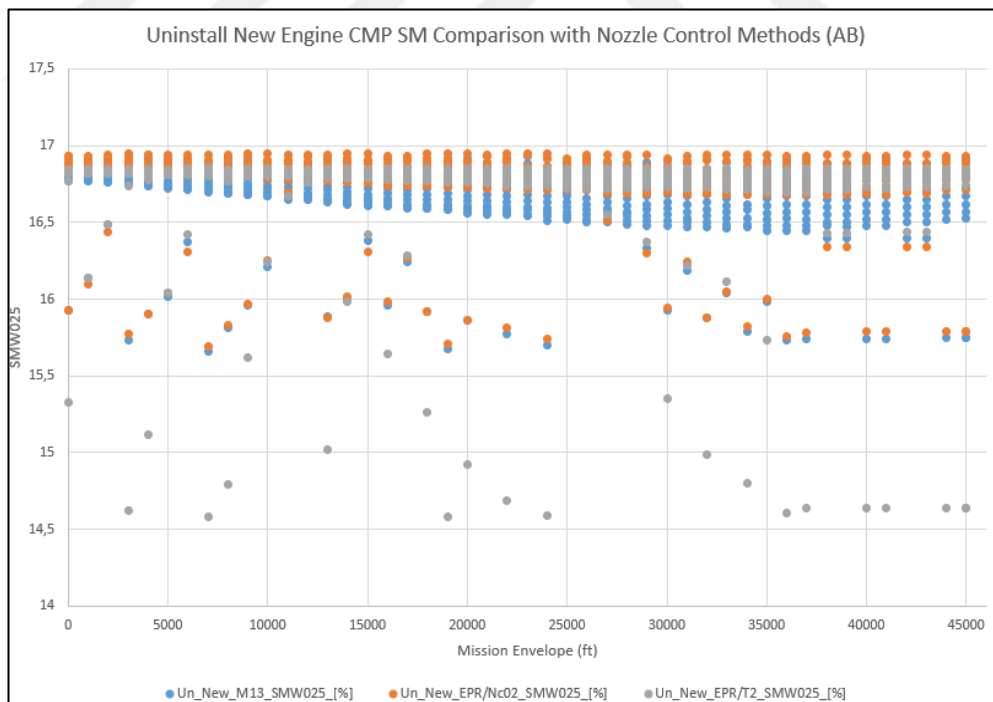


Figure 4.22: Un – New – CMP SM Comparison.

4.5.5. Installed Deteriorated Without AB Operation

Installed Deteriorated Engine without AB have simulated with Thrust, SFC, T4, Fan SM and Compressor SM under nozzle control techniques through **Figure 4.23** to **Figure 4.27**.

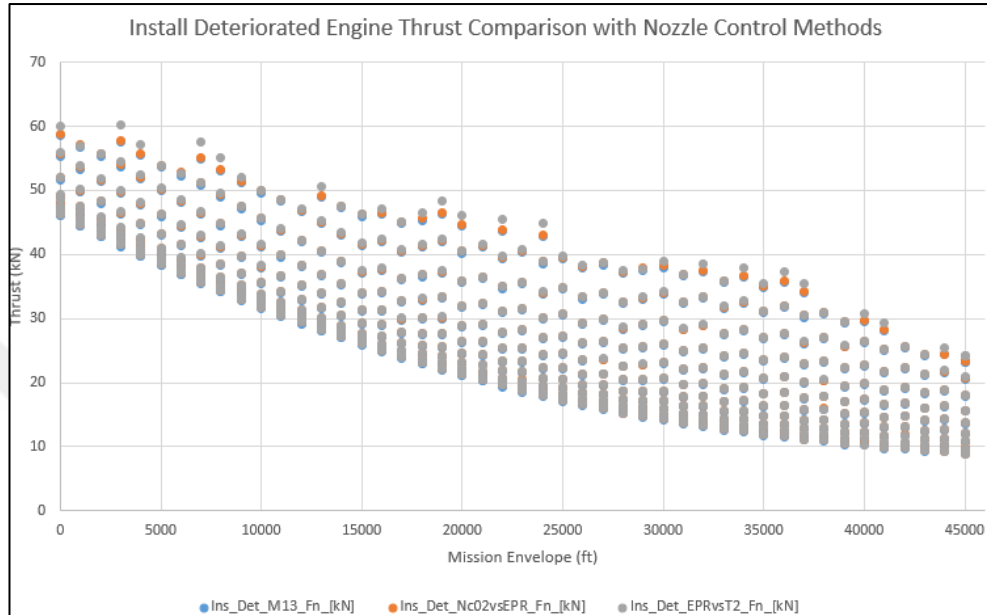


Figure 4.23: Ins – Det – Thrust Comparison.

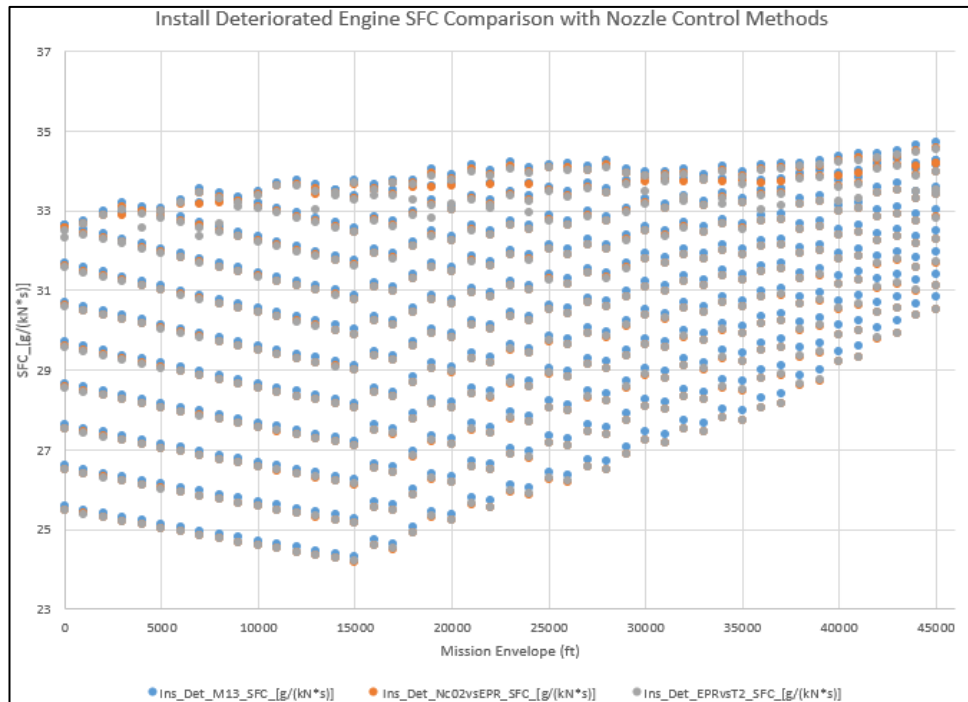


Figure 4.24: Ins – Det – SFC Comparison.

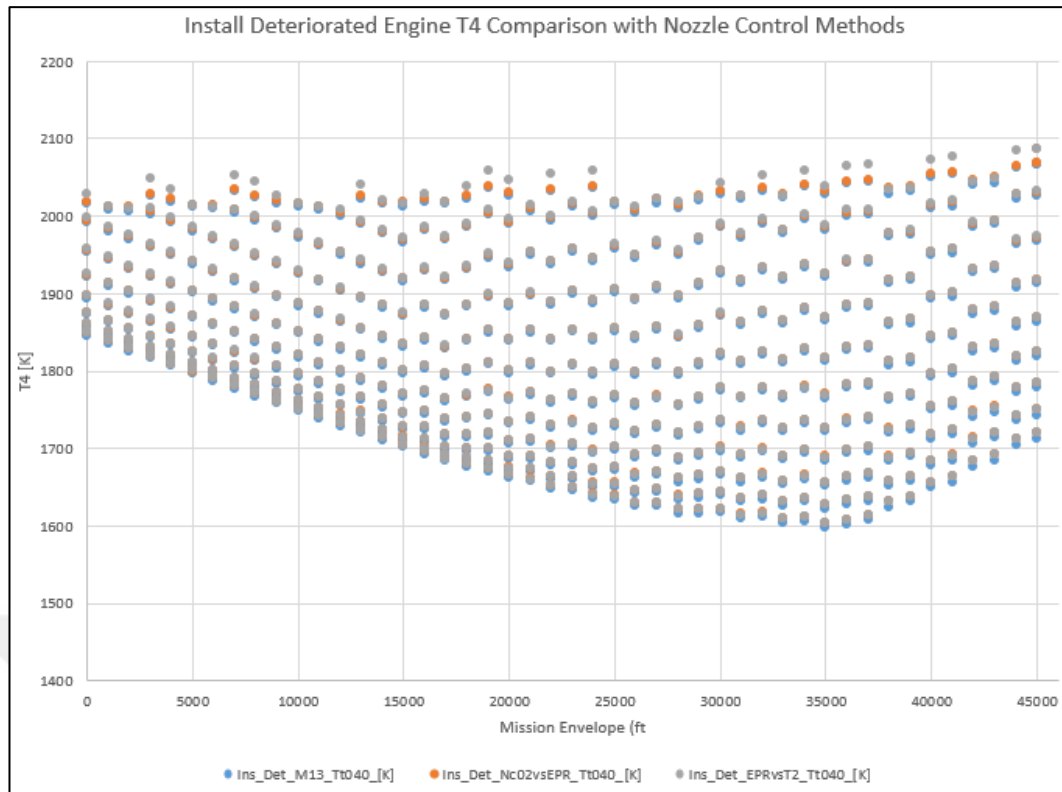


Figure 4.25: Ins – Det – T4 Comparison.

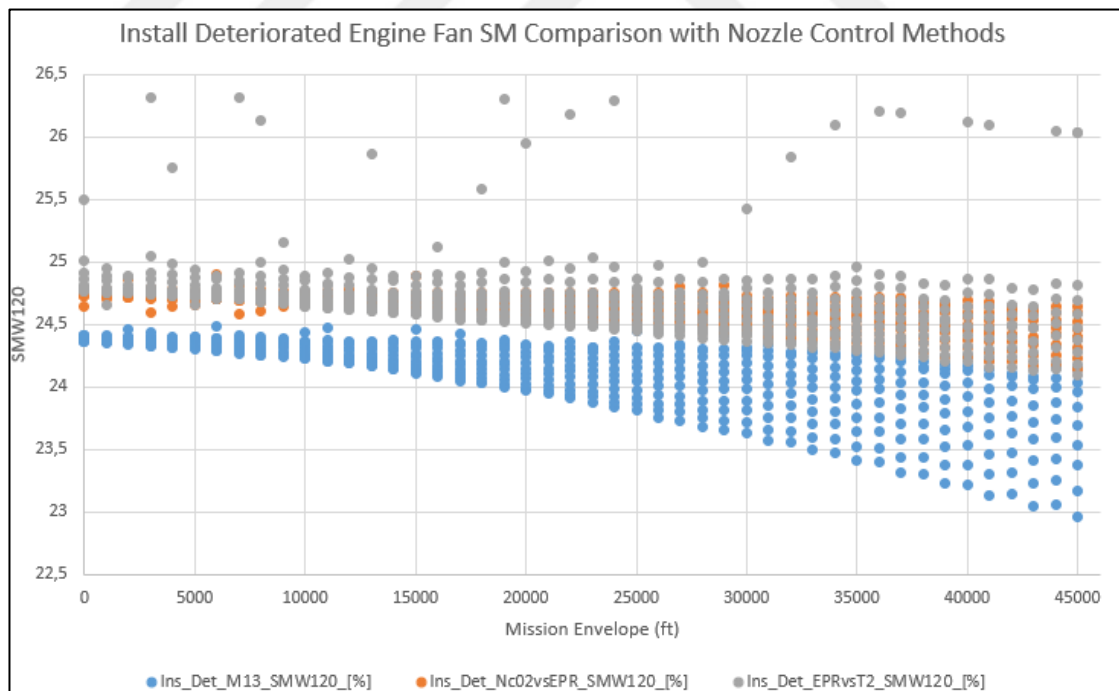


Figure 4.26: Ins – Det – FAN SM Comparison.

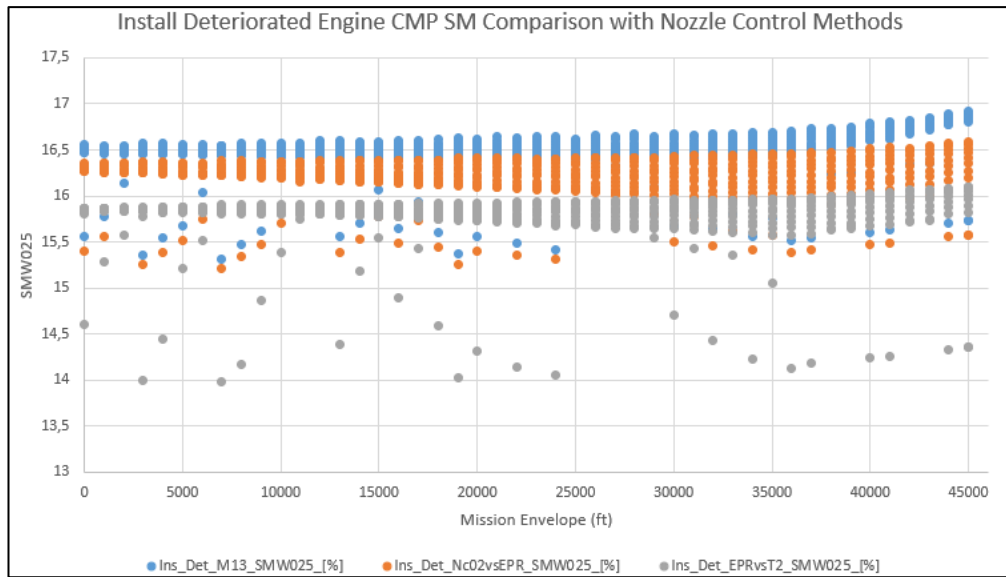


Figure 4.27: Ins – Det – CMP SM Comparison.

4.5.6. Uninstalled Deteriorated Without AB Operation

Uninstalled Deteriorated Engine without AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.28** to **Figure 4.32**.

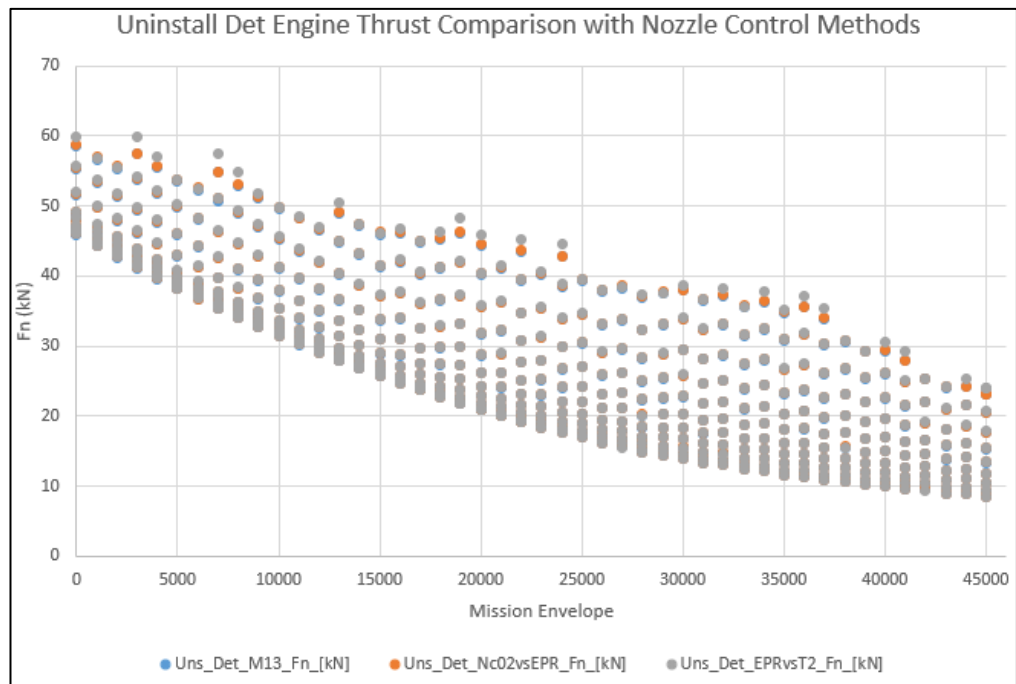


Figure 4.28: Un – Det – Thrust Comparison.

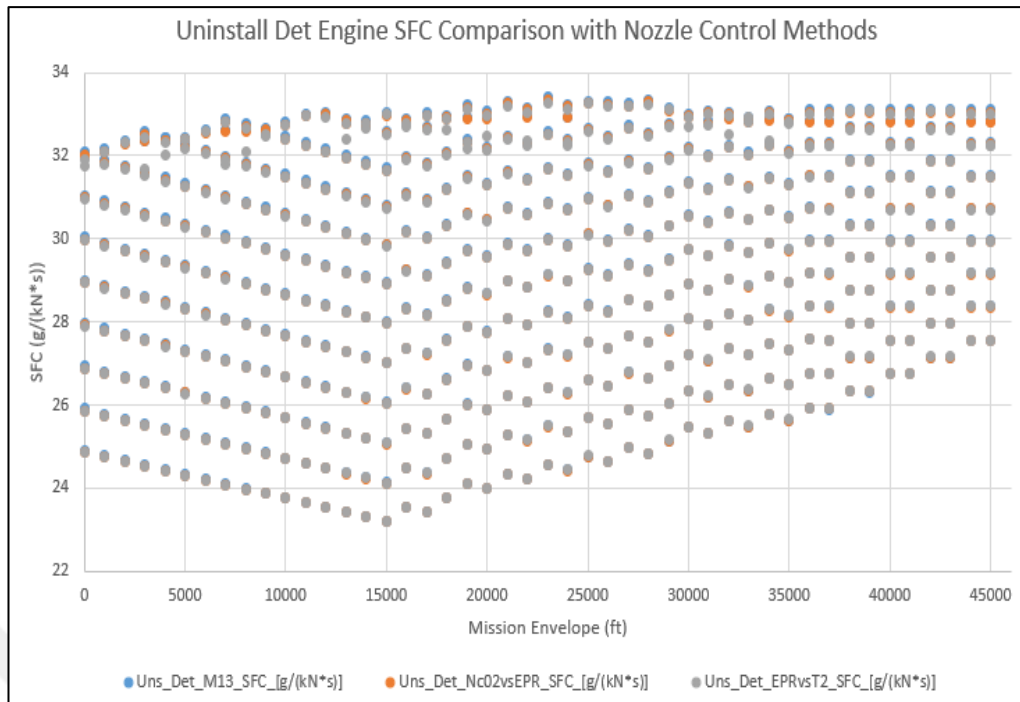


Figure 4.29: Un – Det – SFC Comparison.

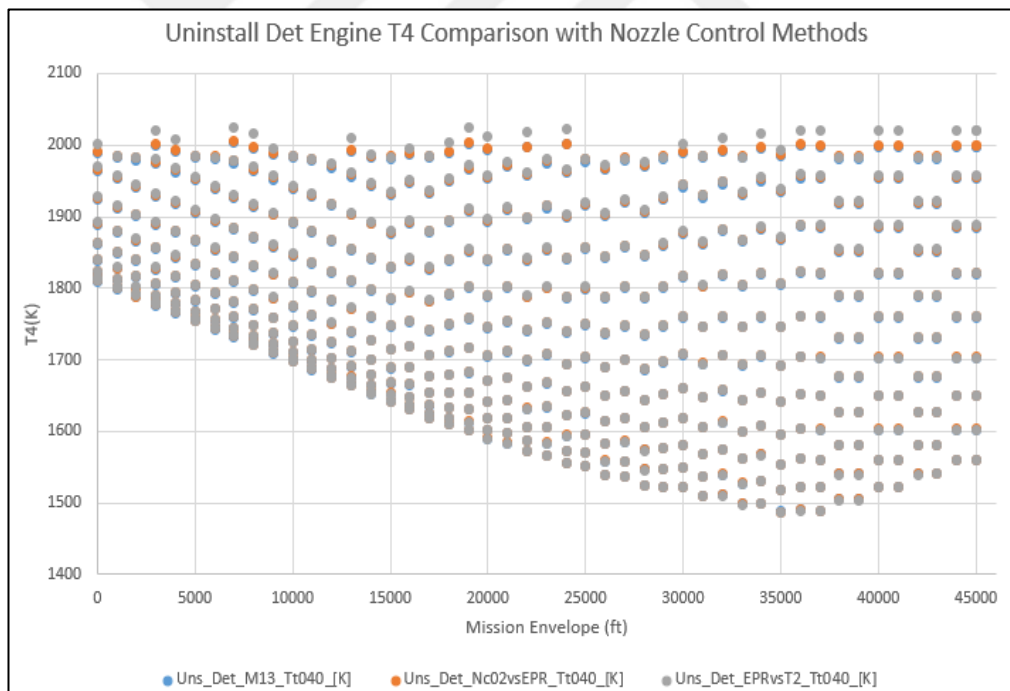


Figure 4.30: Un – Det – T4 Comparison.

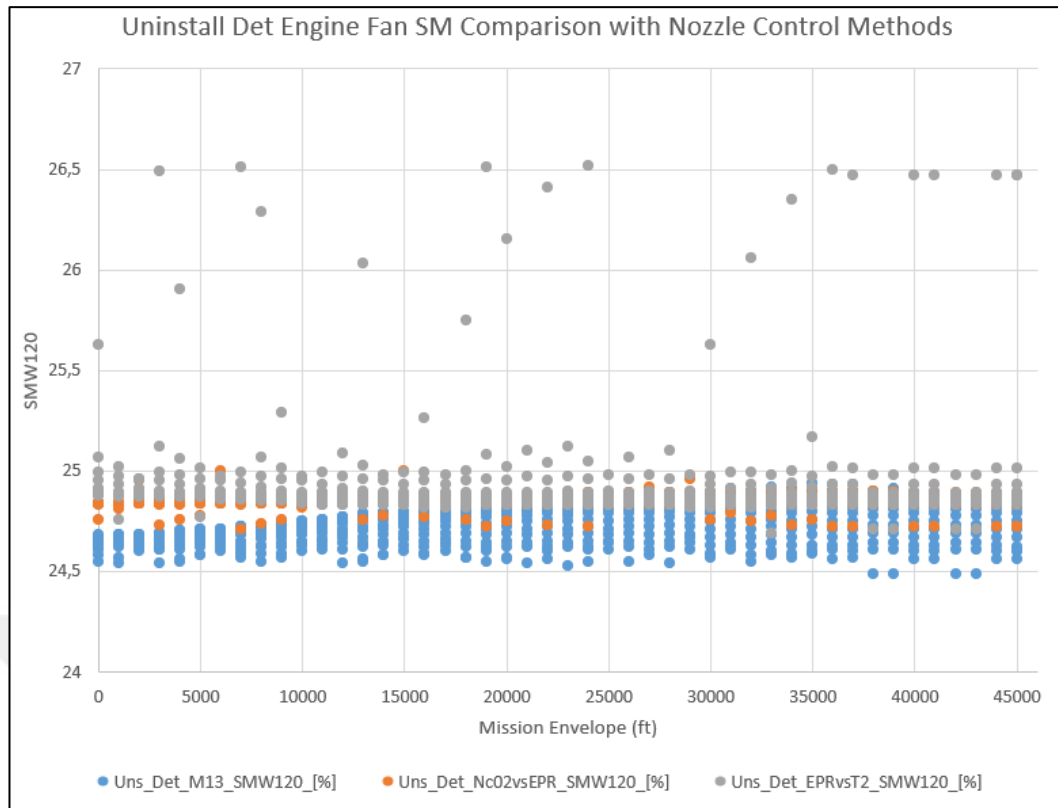


Figure 4.31: Un – Det – FAN SM Comparison.

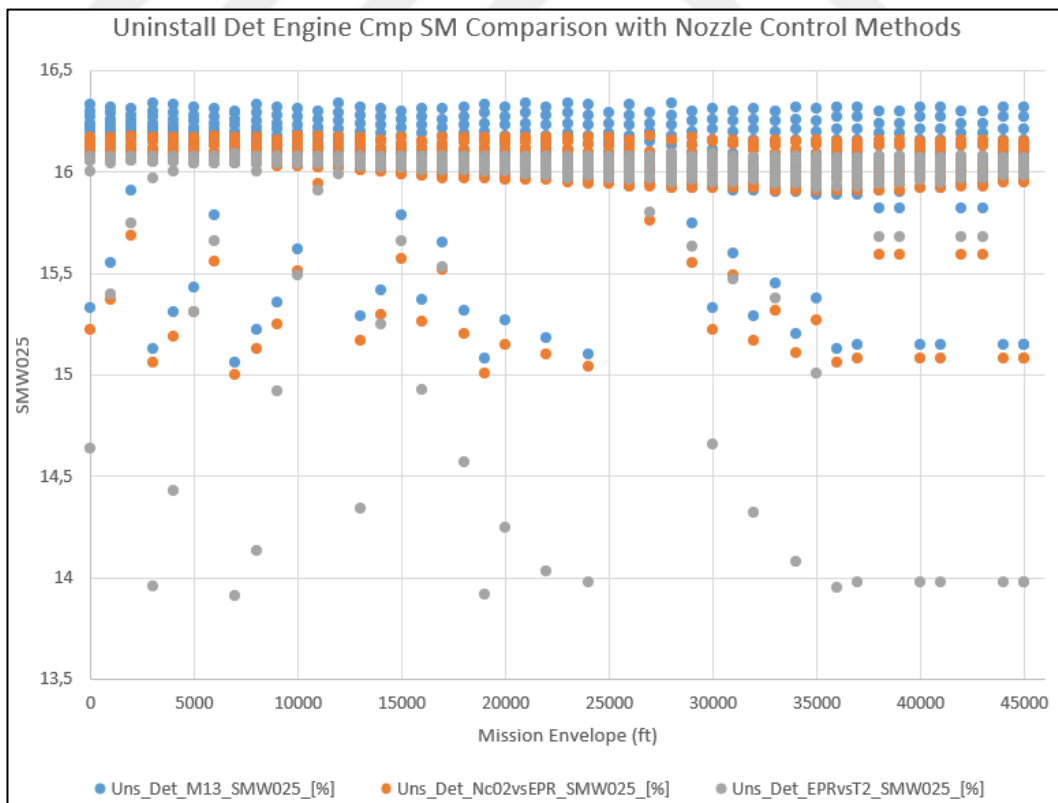


Figure 4.32: Un – Det – CMP SM Comparison.

4.5.7. Installed New Without AB Operation

Installed New Engine without AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.33** to **Figure 4.37**.

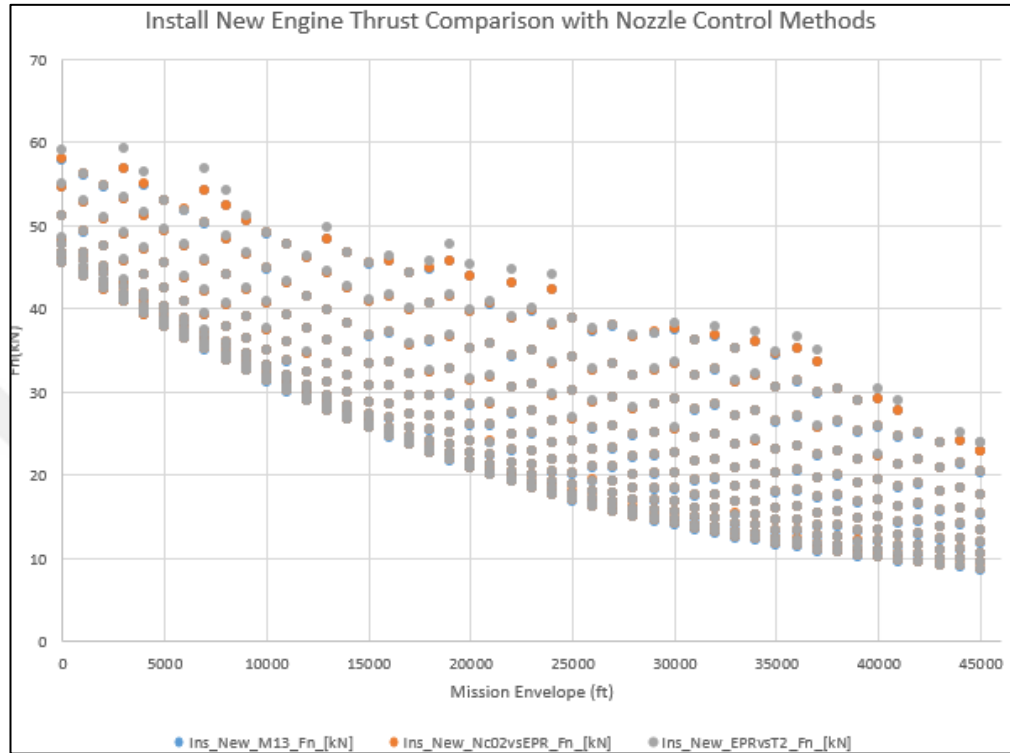


Figure 4.33: In – New – Thrust Comparison.

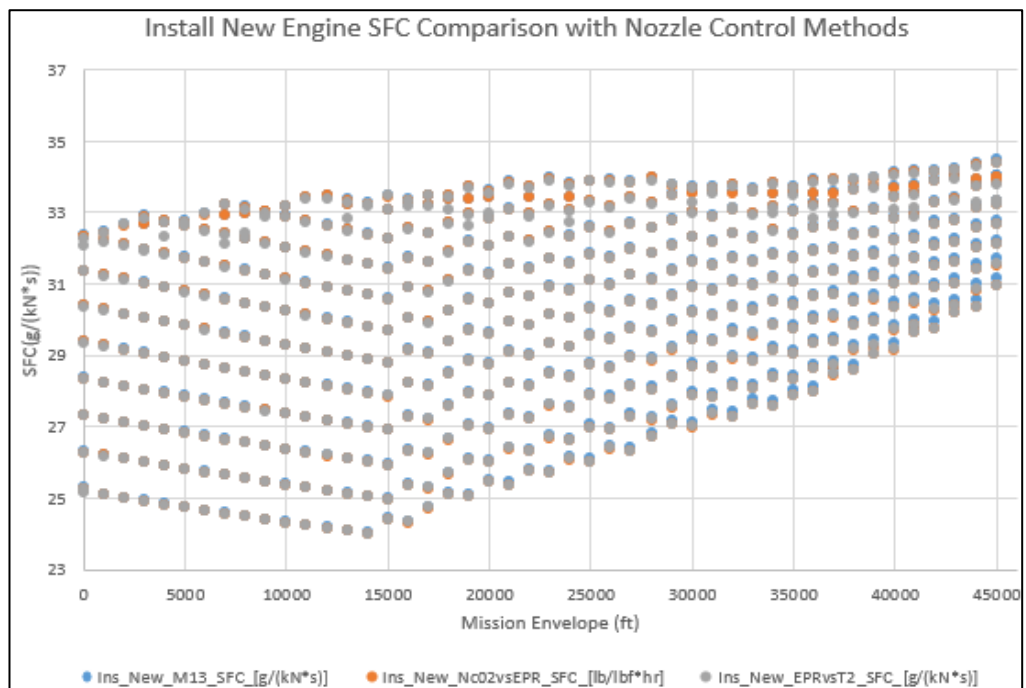


Figure 4.34: In – New – SFC Comparison.

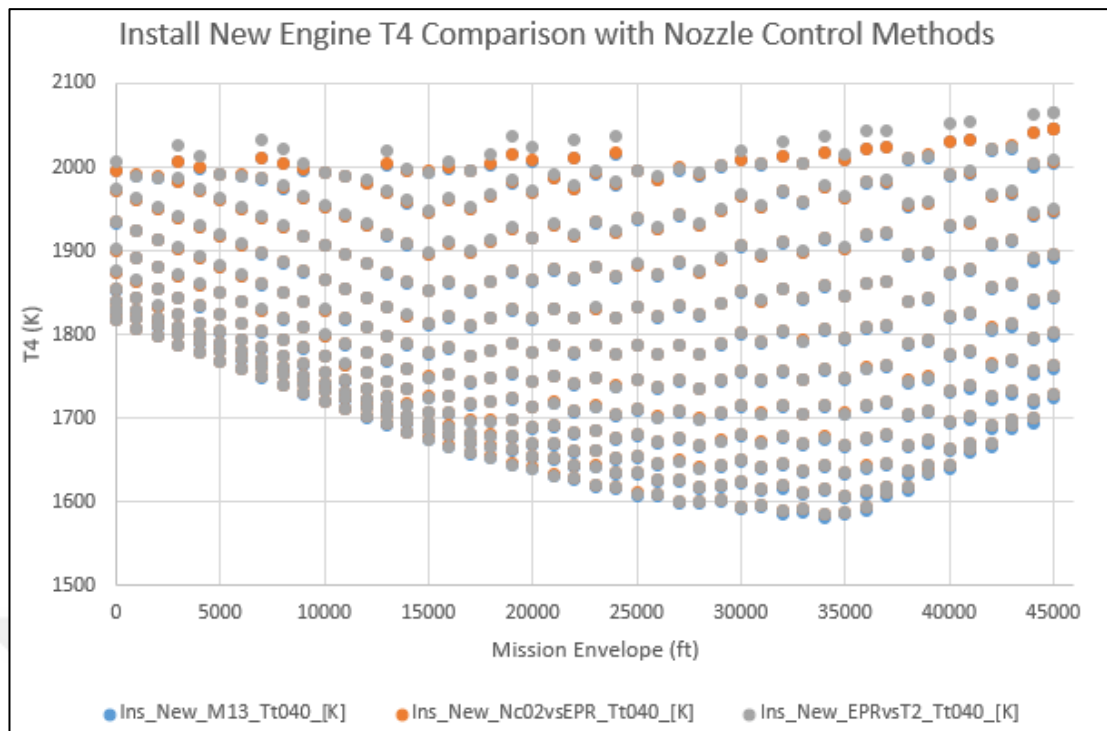


Figure 4.35: In – New – T4 Comparison.

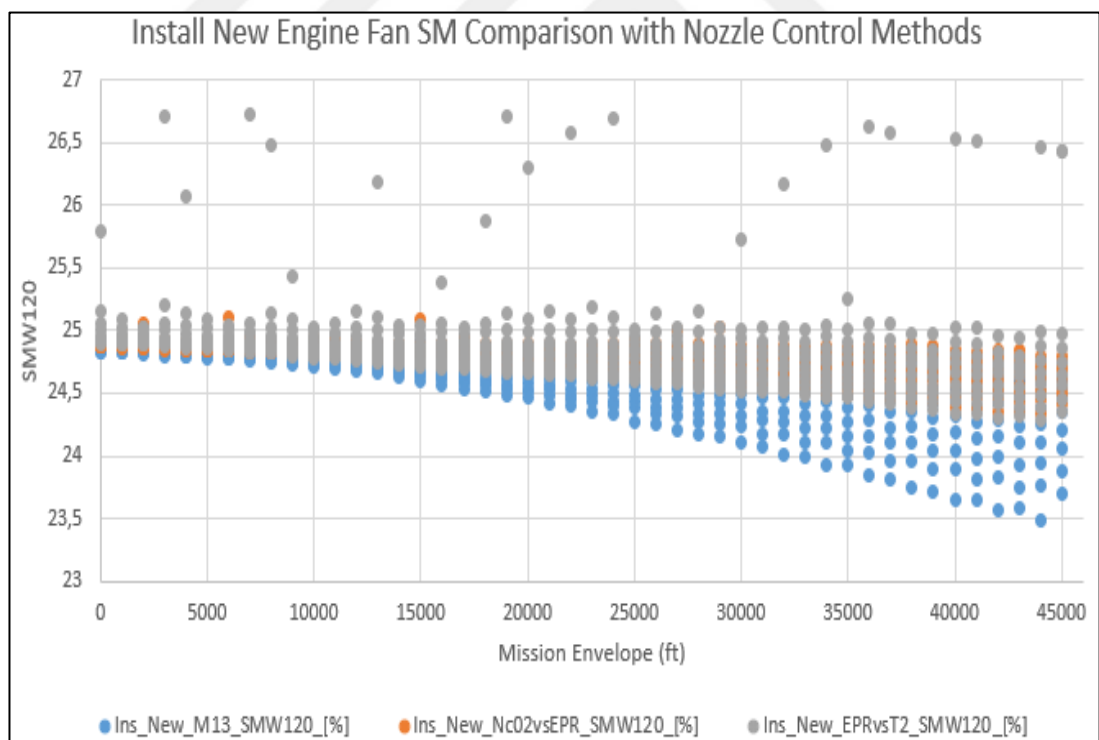


Figure 4.36: In – New – FAN SM Comparison.

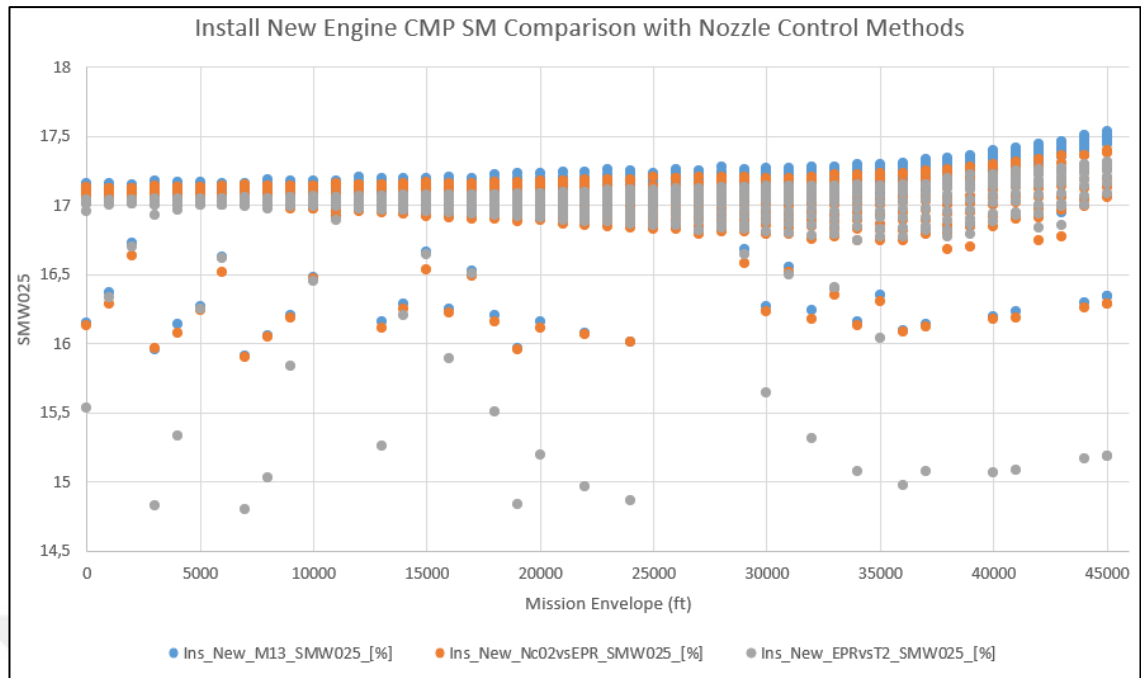


Figure 4.37: In – New – CMP SM Comparison.

4.5.8. Uninstalled New Without AB Operation

Uninstalled New Engine without AB have simulated with Thrust, SFC, T4, FAN SM and Compressor SM under nozzle control techniques through **Figure 4.38** to **Figure 4.42**.

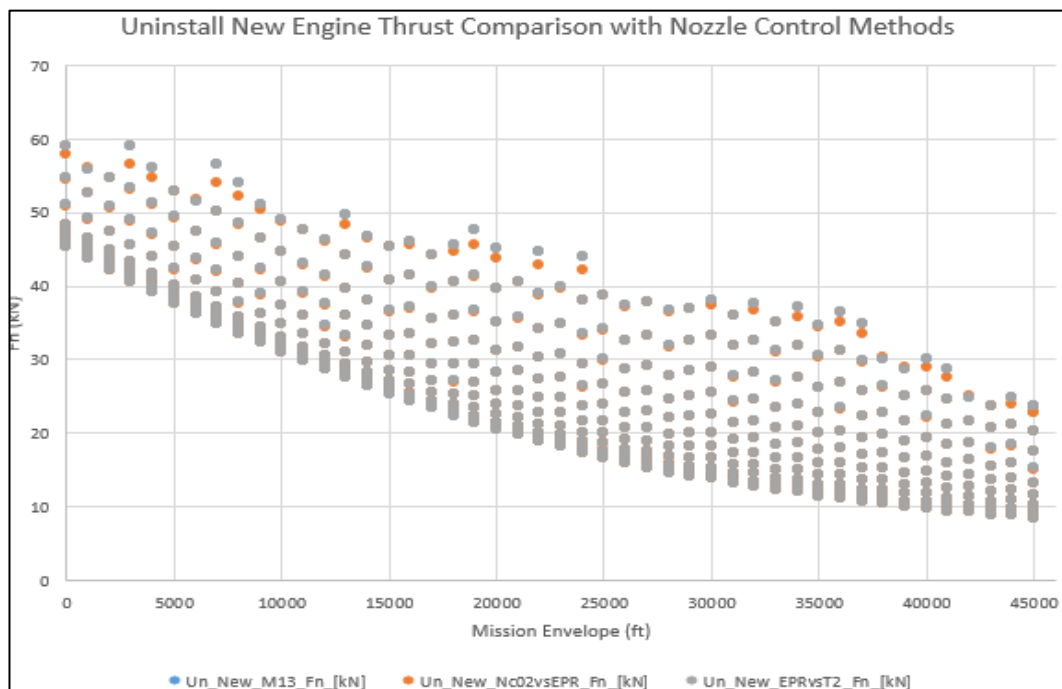


Figure 4.38: Un – New – Thrust Comparison.

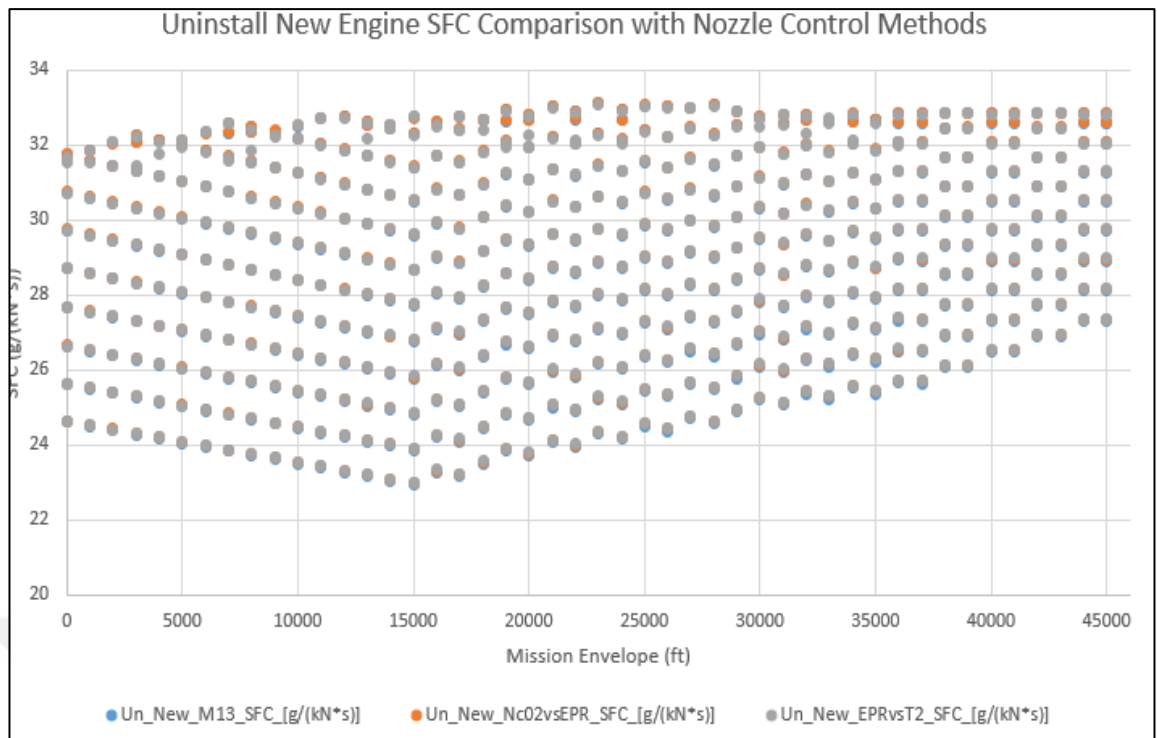


Figure 4.39: Un – New – SFC Comparison.

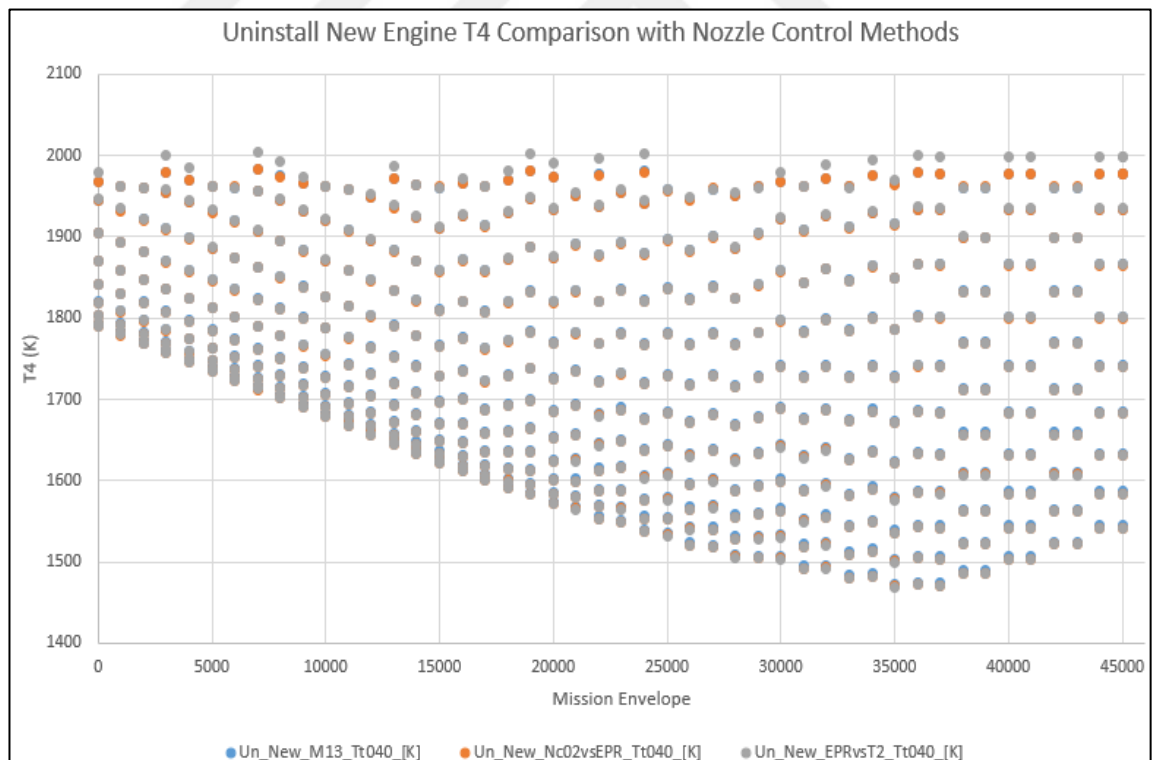


Figure 4.40: Un – New – T4 Comparison.

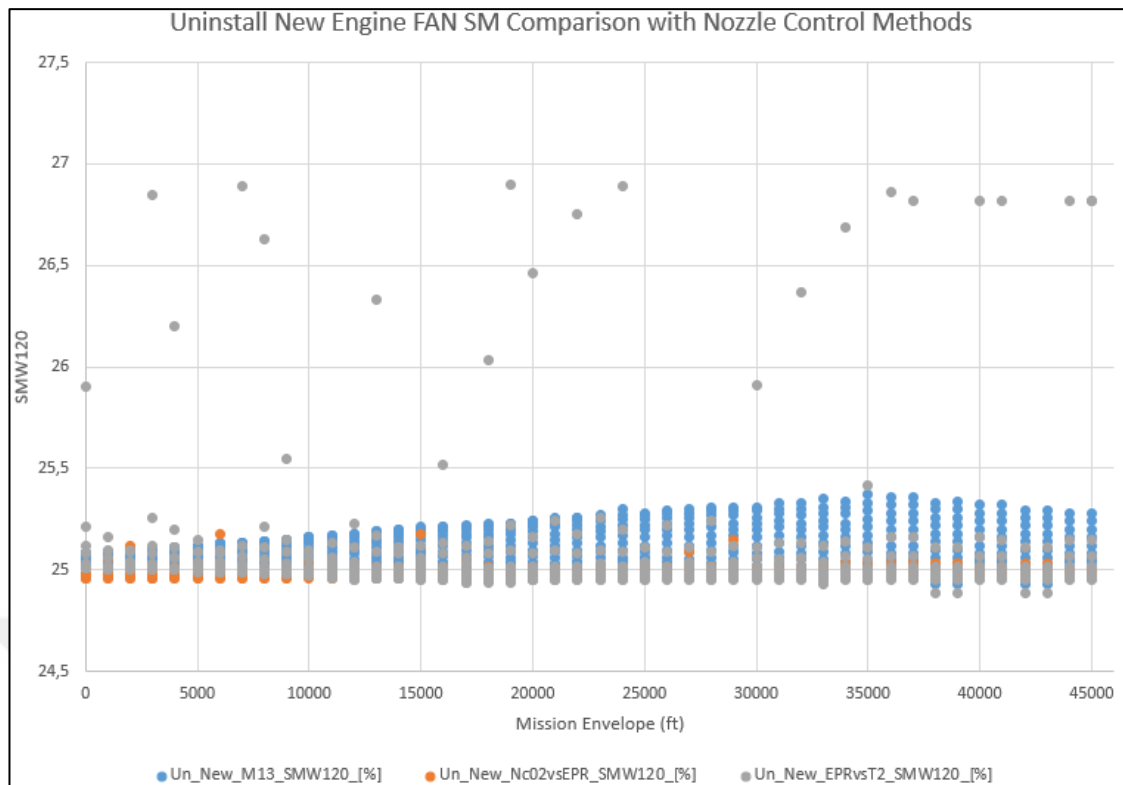


Figure 4.41: Un – New – FAN SM Comparison.

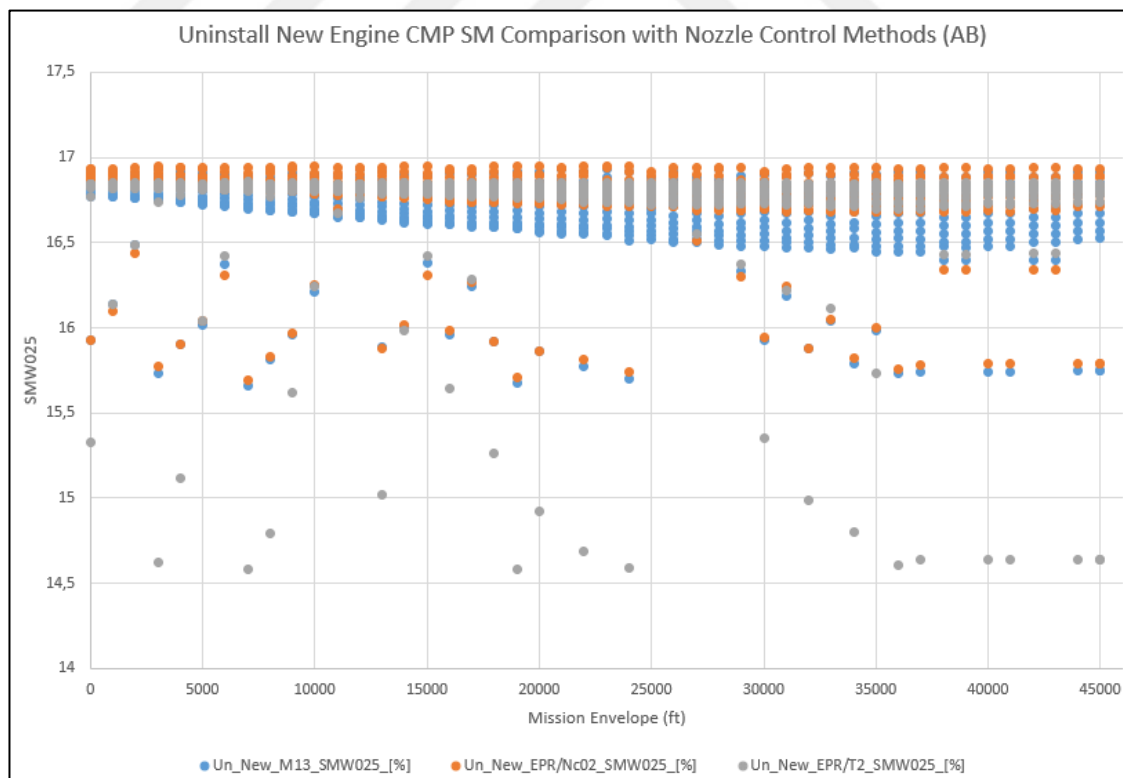


Figure 4.42: Un – New – CMP SM Comparison.

5. EXPERIMENT RESULTS

The engine simulation studies investigated installation effects and performance deterioration specifically through thrust and exhaust control analysis. The engine pressure ratio (EPR) proved to be the dominant control parameter for exhaust management rather than fan rotational speed for thrust regulation. The FADEC system requires separate parameters for thrust and exhaust regulation because using the same parameter would create complexity and efficiency losses. The primary thrust control parameter selected was fan speed.

The evaluation of eight different engine configurations used three distinct control strategies for exhaust control. The evaluation of these configurations used performance metrics obtained from graphical results and min–max parameter tables. The evaluation of exhaust control behavior across different engine health states and installation conditions helps determine which control approach works best.

Table 5.1: Experiment Outputs with AB version (Min – Max).

		AB							
		Installed - New		Installed - Det		Uninstalled - New		Uninstalled - Det	
		Min	Max	Min	Max	Min	Max	Min	Max
M13 vs Nc020	Thrust (kN)	11.84	71.13	11.94	71.75	11.84	71.30	11.93	71.78
	SFC (g/(kN*s))	34.46	40.77	34.72	41.00	33.57	40.10	33.80	40.35
	T4 (K)	1580	2044	1598	2065	1472	1983	1488	2003
	FAN SM (%)	23.48	24.93	22.96	24.49	24.93	25.37	24.49	24.94
	CMP SM (%)	15.91	17.54	15.31	16.92	15.66	16.93	15.06	16.34
Nc020 vs EPR	Thrust (kN)	11.99	71.21	12.16	72.11	11.79	71.16	11.94	72.05
	SFC (g/(kN*s))	34.43	40.70	34.54	40.85	33.65	40.10	33.77	40.25
	T4 (K)	1584	2045	1600	2070	1469	1982	1487	2004
	FAN SM (%)	24.32	25.01	24.14	24.90	24.96	25.18	24.71	25
	CMP SM (%)	15.90	17.04	15.21	16.59	15.69	16.95	15	16.18
EPR vs T2	Thrust (kN)	11.98	73.11	12.15	73.95	11.78	73.07	11.93	73.88
	SFC (g/(kN*s))	34.43	40.61	34.55	40.76	33.67	40.05	33.79	40.21
	T4 (K)	1584	2065	1604	2087	1468	2003	1487.5	2024
	FAN SM (%)	24.29	26.73	24.10	26.32	24.89	26.90	24.69	26.52
	CMP SM (%)	14.8	17.32	14.16	16.5	14.58	16.86	13.91	16.09

Table 5.2: Experiment Outputs without AB version (Min – Max).

		Without AB							
		Installed - New		Installed - Det		Uninstalled - New		Uninstalled - Det	
		Min	Max	Min	Max	Min	Max	Min	Max
M13 vs Nc020	Thrust (kN)	8.65	57.91	8.76	58.56	8.44	58	8.59	58.10
	SFC (g/(kN*s))	24.02	34.47	24.31	34.73	22.93	33.13	23.20	33.40
	T4 (K)	1580	2044	1598	2065	1472	1983	1488	2003
	FAN SM (%)	23.48	24.93	22.96	24.49	24.93	25.37	24.49	24.94
	CMP SM (%)	15.91	17.54	15.31	16.92	15.66	16.93	15.06	16.34
Nc020 vs EPR	Thrust (kN)	8.77	57.9	8.93	58.87	8.45	57.93	8.59	58.71
	SFC (g/(kN*s))	23.98	34.41	24.18	34.58	22.98	33.13	23.18	33.33
	T4 (K)	1584	2045	1604	2068	1469	1982	1487.7	2004
	FAN SM (%)	24.33	25.1	24.14	24.9	24.96	25.18	24.71	25
	CMP SM (%)	15.9	17.4	15.21	16.59	15.94	16.95	15	16.18
EPR vs T2	Thrust (kN)	8.76	59.28	8.92	60.12	8.44	59	8.58	58.94
	SFC (g/(kN*s))	23.99	34.36	24.19	34.58	22.99	33.07	23.19	33.27
	T4 (K)	1584	2065	1604	2087	1468	2004	1487.4	2024
	FAN SM (%)	24.29	26.73	24.1	26.32	24.89	26.90	24.69	26.52
	CMP SM (%)	14.8	17.32	13.98	16.1	14.58	16.86	13.91	16.09

For single engine configuration, three different control strategies, namely M13 vs. Nc020, Nc020 vs. EPR, and EPR vs. T2, were analyzed. These control techniques were evaluated under both after-burning (AB) and non-afterburning configurations, using uninstalled and deteriorated engines. The comparative assessment revealed that the behavior of both engines under these configurations was approximately similar. Among the analyzed performance parameters on single engine to understand the effect of nozzle control techniques, the impact of control technique variation on Specific Fuel Consumption (SFC) was found to be negligible; fuel consumption remained nearly constant for both AB and non-AB configurations. However, notable differences were observed in thrust output in min-max comparison even if envelope behaviors of control strategies looks as same as **Figure 5.1** and **Figure 5.2**. In the EPR vs. T2 method, thrust increased by approximately up to 2%, accompanied by a 20 K rise in turbine inlet temperature (T4). Both of differences are observed from **Table 5.1** and **Table 5.2**. Despite these gains, the compressor surge margin decreased up to 1.5% seemed by **Figure 5.3**. Based on simulation results and min–max tabulated data, it is evident that the choice of control technique must be tailored to the platform type and material constraints. For example, in the case of the MHY16500 engine, designed for a UAV platform with minimal transient and maneuvering demands, the EPR vs. T2 technique can be employed to maximize thrust output. Conversely, for a more maneuverable fighter aircraft platform, the same engine is better controlled using the Nc020 vs. EPR

approach. These behavioral characteristics were found to be consistent across other engine configurations as well.

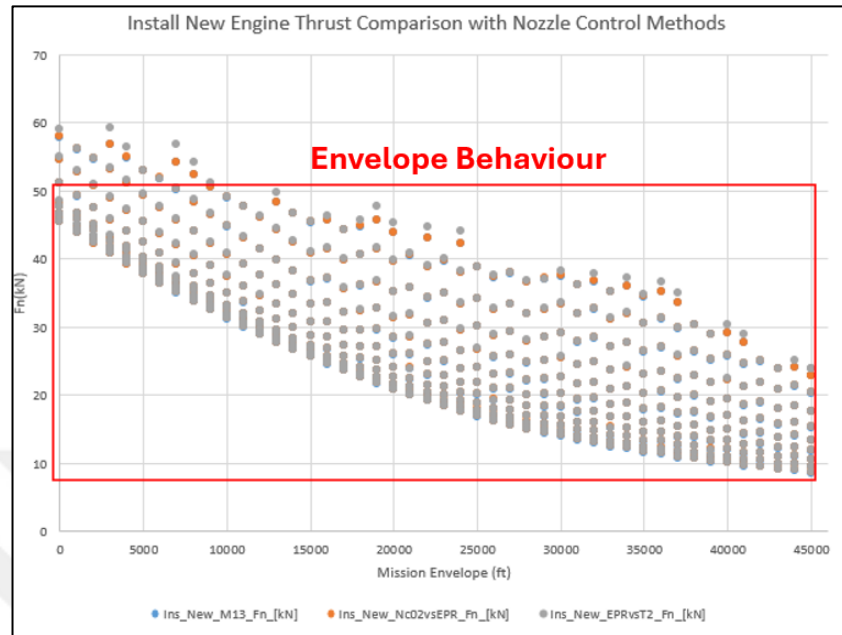


Figure 5.1: Thrust Outputs from different nozzle control methods.

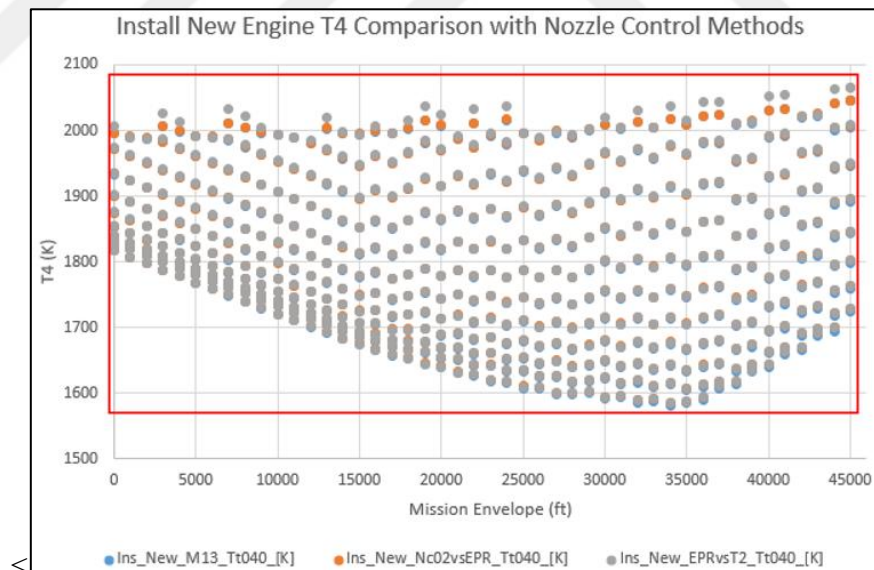


Figure 5.2: T4 Outputs from different nozzle control methods.

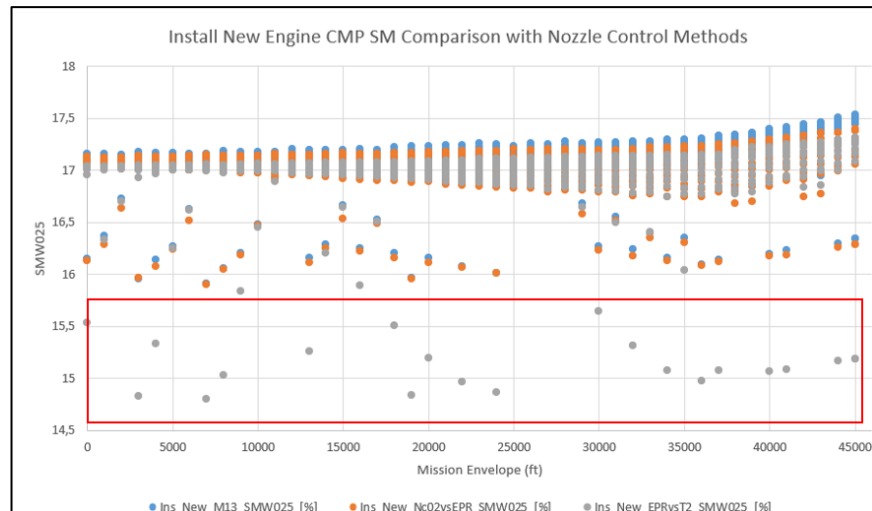


Figure 5.3: CMP SM Outputs from different nozzle control methods.

To assess the impact of engine installation, simulations were conducted for both installed and uninstalled new engine models, in AB and non-AB modes. Across all three control techniques, integration was associated with a reduction in thrust and an increase in SFC, averaging a 50 K increase in T4 from Table 5.1 and **Figure 5.4**. The inclusion of customer bleed and 200 kW power offtake notably influenced engine behavior. Among all configurations, the EPR vs. T2 technique exhibited the largest increase in T4, whereas Nc020 vs. EPR demonstrated the most stable behavior within the operating envelope.

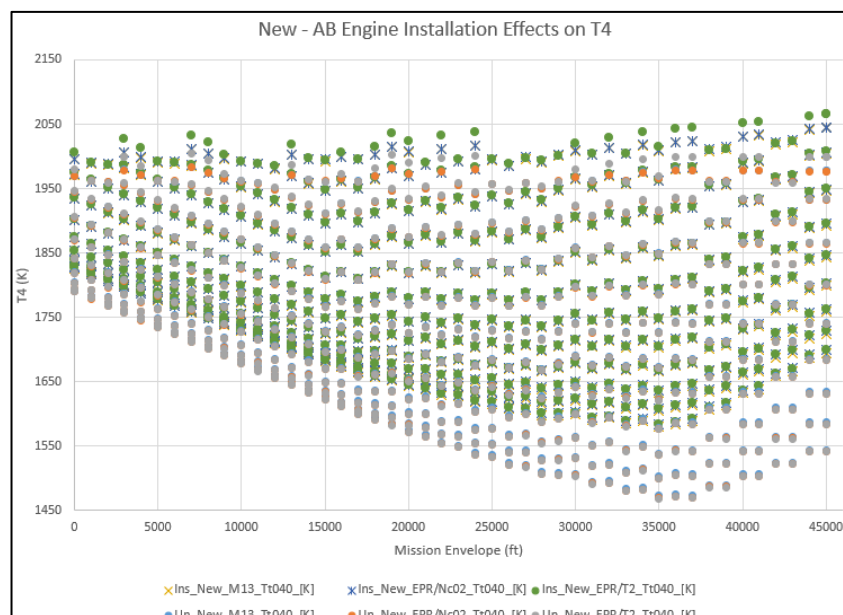


Figure 5.4: New – AB Engine Configuration with installation case effects on T4.

The impact of engine deterioration was evaluated by comparing uninstalled new and uninstalled deteriorated engine models across both AB and non-AB scenarios. Across all three control strategies, engine deterioration led to increased SFC and decreased thrust. This was accompanied by an approximate 20 K rise in T4 as **Figure 5.5**, attributable to reduced turbine efficiencies, which forced the engine to operate at higher temperatures. Consequently, the elevated thermal loads pose a risk to component life through increased fatigue and creep.

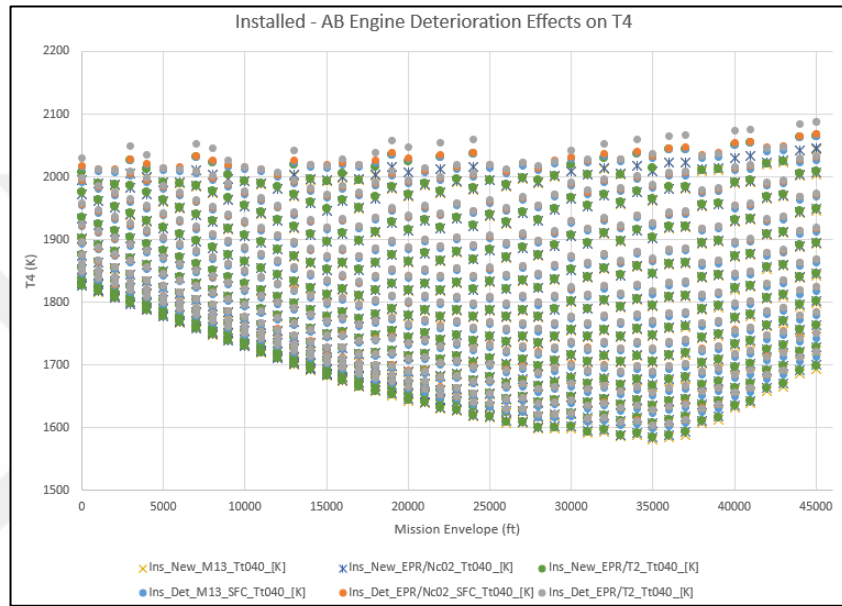


Figure 5.5: Installed – AB Engine Configuration with deterioration effects on T4.

When both installation and deterioration effects were considered, simulations were conducted comparing an integrated deteriorated engine with an uninstalled new engine, across three control strategies and two AB modes. The integrated deteriorated engine exhibited increased thrust, increased SFC, and an approximate 80 K rise in T4. These increases were coupled with a decline in fan and compressor surge margins, highlighting the performance trade-offs introduced by long-term degradation and platform coupling. Particularly, EPR vs. T2 showed the most severe surge margin loss. Based on this behavior, the suitability of Nc020 vs. EPR may vary depending on the platform’s transient maneuvering requirements.

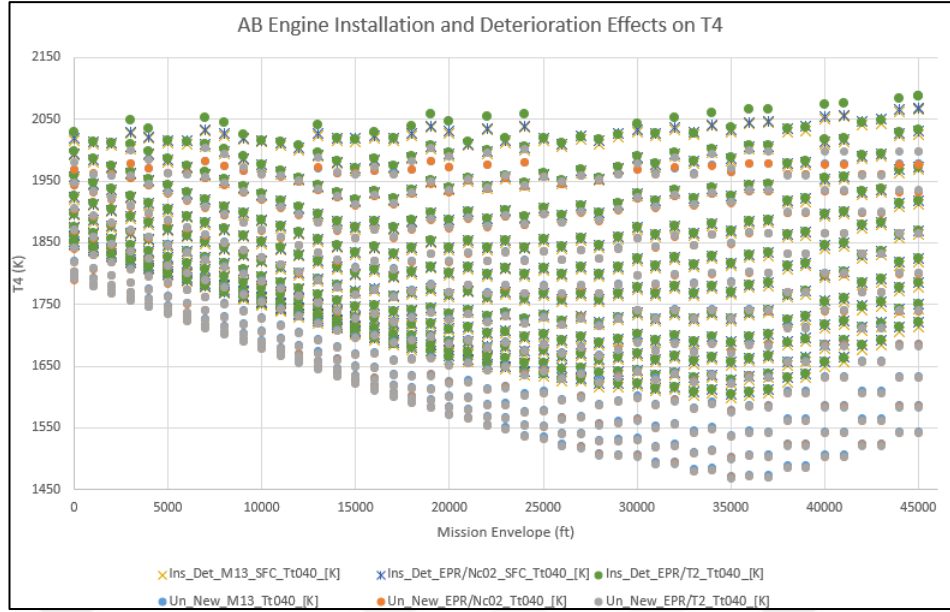


Figure 5.6: AB Engine both installation and deterioration effects on T4.

In summary, among the three control strategies analyzed, Nc020 vs. EPR and EPR vs. T2 emerged as the most viable options. The relative advantages of each strategy vary depending on platform requirements and engine growth potential. In general, for platforms that are not maneuver intensive and aim to maximize thrust at constant SFC, EPR vs. T2 is a favorable control technique. On the other hand, for applications requiring better surge margin management and transient operability with slightly lower thrust gain, Nc020 vs. EPR is recommended.

6. CONCLUSIONS

The research examined various control approaches for mixed-flow military turbofan engines specifically focusing on thrust management together with nozzle regulation systems. The research employed an engine model that researchers created specifically for evaluating steady-state and off-design operational performance under different operating conditions. The modeling process incorporated realistic component maps—sourced from open literature and NPSS libraries—including F100 fan data and NASA E3 compressor and turbine characteristics. Gasturb served as the tool for design operations while NPSS handled both dynamic simulation and control analysis tasks.

The research evaluated different control parameter pairs for their effectiveness in thrust and exhaust modulation systems. The study evaluated three control strategies that included M13 vs. Nc020, Nc020 vs. EPR, and EPR vs. T2 while testing different engine configurations including afterburning vs. non-afterburning and installed vs. uninstalled and new vs. deteriorated engines. The SFC measurements showed minimal variation based on control strategy selection although thrust output alongside surge margin and turbine inlet temperature (T4) exhibited noticeable variations between the different control methods.

The EPR vs. T2 approach delivered approximately 2% higher thrust performance along with greater T4 readings which indicated advantages for UAV platforms with constrained transient operating requirements. Nc020 vs. EPR control strategy demonstrated better surge margin stability which made it suitable for fighter aircraft that need to operate under intense transient conditions.

Research analyzed the impact of engine-airframe integration and engine deterioration effects on system performance. High-power operations led to increased turbine inlet temperatures and decreased surge margin when engine components operated as part of integrated systems. The decrease in turbine efficiency through deterioration led to elevated fuel usage and heat stress on the engine thus proving the requirement for adaptive control systems to ensure long-term engine operational stability.

The research demonstrates the need to adapt control systems according to platform requirements along with engine condition status. Among the studied approaches EPR vs. T2 and Nc020 vs. EPR presented the most promising control strategies for thrust

and nozzle management. The research suggests additional studies should investigate transient control performance along with adaptive FADEC implementation and engine health monitoring system integration for improving propulsion system resilience throughout the entire mission envelope.



REFERENCES

- [1] Kurzke, J., Halliwell, I., (2018), “Propulsion and Power”, Springer International Publishing.
- [2] Mattingly, J.D., (2010), “Elements of Gas Turbine Propulsion”, 1st Edition, TATA McGraw-Hill.
- [3] Flack, R. D., (2005), “Combustors and afterburners, in Fundamentals of Jet Propulsion with Applications”, Cambridge University Press, ch. 9, pp. 440–470.
- [4] Lewis, G. M., (1984), “The next European engine for combat aircraft”, Aeronautical Journal, 88 (879), 91–114.
- [5] National Research Council, (1983), “Final Report on the Fuel Control System of the F100 Engine”, National Academy Press.
- [6] GE Aviation, (2020), “F404 Turbofan Engine Family Data Sheet: A Versatile Engine for Front Line Fighters and Trainers Around the Globe”, GE Aviation.
- [7] Benini, E., Mistry, C. S., Wadia, A. R., (2024), “Historical retrospective on technology advances in military aeroengines”, Proc. Int. Soc. for Air-Breathing Engines (ISABE), Paper ISABE-2024-130, Sept.
- [8] EUROJET Turbo GmbH, (2019), “EJ200 Superior Military Turbofan: Engine Overview and Technical Brochure”, [Online]. Available: <https://www.eurojet-turbo.com/en/engines/ej200>, Accessed: 01.07.2025.
- [9] Roy, B., Pradeep, A. M., (n.d.), “Lect-6: Brayton cycle and its variants”, Dept. Aerosp. Eng., IIT Bombay, [Online]. Available: <https://www.aero.iitb.ac.in>, Accessed: 01.07.2025.
- [10] El-Sayed, A. F., (2017), “Aircraft Propulsion and Gas Turbine Engines”, 2nd ed., CRC Press.
- [11] Abdelwahab, M., (1981), “Effects of Fan Inlet Temperature Disturbances on the Stability of a Turbofan Engine”, NASA Tech. Memo. 82699.
- [12] Boyce, M. P., (2006), “Gas Turbine Engineering Handbook”, 3rd ed., Elsevier.
- [13] Bradley, R., (2012), “Stealth Technologies and Radome Design for Low Observable Aircraft”, AIAA Education Series.
- [14] Brennan, S., Khorasani, K., (2003), “Aircraft Turbofan Engine Health Estimation Using Constrained Kalman Filtering”, NASA Tech. Rep.
- [15] Brun, K., Kurz, R., Simons, S., (2015), “Aerodynamics and Design of Turbomachinery”, ASME Press.

- [16] Camus, E., Ardema, M., Schmitz, P., (2011), “Control strategies for variable geometry in gas turbine engines”, *J. Aerosp. Eng.*, 225 (5), 519–533.
- [17] Casari, N., Pinelli, M., Montomoli, F., (2018), “Deposition, erosion and detachment on high pressure turbine vanes”, *J. Turbomach.*, 140 (2), 021014.
- [18] Chandler, P. R., Hall, S. R., (1991), “Design and control considerations for variable-area exhaust nozzles”, *J. Propuls. Power*, 7 (3), 456–463.
- [19] Cumpsty, N., (2003), “Jet Propulsion”, 2nd ed., Cambridge University Press.
- [20] Csank, J. T., Thomas, G. L., (2023), “Dynamic analysis for a geared turbofan engine with variable area fan nozzle”, *AIAA J.*
- [21] Ehrlich, H., Kurz, K.-H., Rued, K.-P., Lauer, W., (2003), “Trends in military aero-engine design – from EJ200 to future manned and unmanned vehicle propulsion”, *Proc. AIAA/ICAS Int. Air and Space Symp. and Exposition*, July.
- [22] Fanzago, B., (2019), “Performance of Modern Unmixed Turbofan Engines: Simulation and Optimization Using GasTurb Software”, M.S. thesis, Università degli Studi di Padova.
- [23] Flack, R. D., (2005), “Fundamentals of Jet Propulsion with Applications”, Cambridge University Press.
- [24] General Electric, (1984), “F110 Development: Program Summary and Propulsion Characteristics (GEAE-F110)”, U.S. Air Force Publication.
- [25] Hendrick, P., Bourdiaudhy, K., Herbiet, J.-F., (2008), “A flight thrust deck for the F100 turbofan of the F-16 aircraft”, *Proc. 26th Int. Congr. Aeronaut. Sci. (ICAS)*.
- [26] Herrmann, P., (1999), “The EJ200 – Engine development and full certification for production release with Eurofighter 2000”, *Proc. 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. Exhibit*, Paper AIAA-99-2661.
- [27] Hill, P. G., Peterson, C. R., (1992), “Mechanics and Thermodynamics of Propulsion”, 2nd ed., Addison-Wesley.
- [28] Hilton, D., (1999), “The Eurojet EJ200”, *Air and Space Europe*, 1 (3), 66–73.
- [29] Jaw, L. C., Mattingly, J. D., (2009), “Aircraft Engine Controls: Design, System Analysis, and Health Monitoring”, *AIAA Education Series*.
- [30] Khalid, M., Hearne, S., (2021), “A review of transient thermal and fluid effects in gas turbine engines”, *NCBI PMC*.
- [31] Koff, B., Epstein, A., Sanger, N., (2018), “The adaptive versatile engine technology development”, *J. Propuls. Power*, 34 (2), 243–251.

- [32] Lakshminarayana, B., (1995), “Turbine Aerodynamics: Axial-Flow and Radial-Flow Turbine Design and Analysis”, Cambridge University Press.
- [33] Leishman, J. G., (2022), “Introduction to Aerospace Flight Vehicles”, Embry-Riddle Aeronautical University.
- [34] MacDonald, D. J., Morris, M. W., (2002), “Design guidelines for variable geometry turbine stages in military engines”, *J. Propuls. Power*, 18 (6), 1231–1240.
- [35] Mallamo, J., Azarian, M., (2023), “Identifying key factors in turbofan engine health degradation using data-driven methods”, *Proc. Prognostics and Health Management Society Conf.*
- [36] Marek, C. J., Liew, K. H., Urip, E., Yang, S. L., (2005), “A Parametric Cycle Analysis of a Separate-Flow Turbofan with an Interstage Turbine Burner”, NASA Tech. Rep.
- [37] Mattingly, J. D., Heiser, W. H., Pratt, D. T., (2002), “Aircraft Engine Design”, 2nd ed., AIAA.
- [38] Mazzawy, R. S., (1977), “Stator vane angle scheduling for multistage axial-flow compressors”, *J. Eng. Power*, 99 (3), 461–468.
- [39] National Research Council, (1983), “Final Report on the Fuel Control System of the F100 Engine”, National Academy Press.
- [40] NASA, (2005), “Performance (Off-Design) Cycle Analysis for a Turbofan Engine with Interstage Turbine Burner”, NASA Tech. Rep.
- [41] Qin, H., Zhao, J., Ren, L., Li, B., Li, Z., (2022), “Performance degradation evaluation of low bypass ratio turbofan engine based on flight data”, *Sustainability*, 14 (13), 8052.
- [42] Saravanamuttoo, H. I. H., Cohen, H., Rogers, G. F. C., (2001), “Gas Turbine Theory”, 5th ed., Pearson Education.
- [43] Schilke, P. W., (2010), “Development of Advanced Materials for Turbine Blades and Vanes in Gas Turbine Engines”, NASA Tech. Memo. 2010-216732.
- [44] Torenbeek, E., Wittenberg, H., (2009), “Flight Physics: Essentials of Aeronautical Disciplines and Technology”, Springer.
- [45] Treager, I. E., (2004), “Aircraft Gas Turbine Engine Technology”, 3rd ed., McGraw-Hill.
- [46] Turner, M. G., Annis, M. R., (2001), “Compressor flow control using variable inlet guide vanes”, *Proc. ASME Turbo Expo: Power for Land, Sea, and Air*, vol. 4.

- [47] Turns, S. R., (2000), "An Introduction to Combustion: Concepts and Applications", 2nd ed., McGraw-Hill.
- [48] USAF, (1990), "F110-GE-100 Engine Monitoring Unit (EMU) Operational Guide", United States Air Force Technical Manual.
- [49] Visser, W. P. J., Wernet, M. P., (2006), "Compressor surge margin improvement with variable guide vanes", *J. Propuls. Power*, 22 (5), 1055–1063.
- [50] Volponi, A. J., Sheldon, D. W., (2000), "Performance benefits of variable stator vanes in aero engines", *Proc. ASME Int. Gas Turbine and Aeroengine Congr. and Exhibition*.
- [51] Walsh, P. P., Fletcher, P., (2004), "Gas Turbine Performance", 2nd ed., Blackwell Science Ltd.
- [52] Weir, R. H., (1962), "High performance turbine engines", *J. Roy. Aeronaut. Soc.*, 66 (621), 537–550.
- [53] Whitford, R., (2000), "Design for Air Combat", Janes Information Group.
- [54] Williams, M. R., (1984), "Large turbofans to the year 2000", *Aeronaut. J.*, 88 (873), 419–423.
- [55] Yang, Y., Nikolaidis, T., Jafari, S., (2023), "Gas turbine engine transient performance and heat transfer effect modelling: A comprehensive review", *Appl. Therm. Eng.*, 236, 121523.
- [56] Yang, Y., Zhang, L., Liu, X., (2024), "Transient performance analysis of turbofan engines considering thermal response effects", *Appl. Therm. Eng.*, 226, 121523.
- [57] Yin, F., Rao, A. G., (2017), "Off-design performance of an interstage turbine burner turbofan engine", *J. Eng. Gas Turbines Power*, 139 (8), 082603.
- [58] Yu, B., Cao, C., Shu, W., Hu, Z., (2020), "Transient characteristics of compressor during throttle transients", *Energies*, 13 (19), 5107.
- [59] Zhang, Y., Zhu, D., Ghosn, L. J., Miller, R. A., (2018), "Thermal barrier coatings for gas turbine blade applications", *Surf. Coatings Technol.*, 337, 76–85

BIOGRAPHY

The author, Mehmet Enes YALÇIN, started his career as Software and Hardware Test Engineer in the Commercial and Military Industry. He is currently working as an Gas Turbine Performance Modelling Engineer in the Aviation and Defense Industry.

