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IMPACTS OF ALTERNATIVE AVIATION FUELS ON ENGINE CYCLE DESIGN AND AIRCRAFT MISSION CAPABILITY

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ABSTRACT

Recent 2050 net zero targets for aviation have sparked interest among the industry players to seek alternative aviation fuels as a pathway for the immediate alleviation of its carbon footprint. This paper aims to shed light on the opportunities and challenges that zero & low-carbon alternative fuels can provide from a technical standpoint. To address this aim, candidate fuels for aviation were selected from five broad classes of fuels. Then, a preliminary thermodynamic engine cycle design space exploration of a modern three spool turbofan is conducted to identify the fuel impact on cycle performance. Following that, an integrated Engine-Aircraft mission assessment for a Boeing 787 style aircraft with a three spool turbofan is conducted to assess performance at the mission level and explore opportunities and challenges for both powerplant and aircraft, accounting for fuel storage. Finally, an investigation of the opportunities available for the proposed fuels to be used as a heat sink is presented. The results indicate that zero-carbon fuels expand the design space for the powerplant cycle, allow for higher BPR, lower energy specific fuel consumption, lower peak cycle temperatures compared to the rest of the fuels, and provide significant cycle redesign opportunities. On a mission level, cryogenic fuels are penalized for block energy consumption due to the significant weight and size of the fuel storage system, while liquid alternative fuels are comparable to kerosene in terms of emissions and block energy consumption. Concerning Hydrogen, Methane, and Ammonia, the thermal power requirement for fuel conditioning (pressure and temperature rise) is calculated to be 2.2MW, 1.3MW, and 1MW respectively for a 240kN SLS thrust class engine during take-off.

Keywords: alternative aviation fuels, engine cycle design space, fuel conditioning, zero carbon fuels, Boeing 787

NOMENCLATURE

°C	Degree Celcius
η_{poly}	Polytropic Efficiency
ACARE	Advisory Council for Aviation Research in Europe
ASTM	American Society for Testing & Materials
atm	Standard Atmosphere
BPR	Bypass Ratio
CH4	Methane
CO2	Carbon Di Oxides
$CO2_{eq}$	CO2 equivalent
Cp	Specific Heat Capacity at constant pressure (J/kg.K)
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DME	Dimethylether
DOC	Direct Operating Cost
ECS	Environmental Control System
EU	European Union
FAR	Fuel Air Ratio
GWP	Global Warming Potential
HPC/IPC	High/Intermediate Pressure Compressor
HPT/IPT/LPT	High/Intermediate/Low Pressure Turbine
HY	Hydrogen
IATA	International Air Transport Association
ISA	International Standard Atmosphere
IPCC	Intergovernmental Panel on Climate Change
K	Kelvin
KE	Kerosene/Jet-A
kN	Kilo Newton
L	Liquid

LHV	Lower Heating Value
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MCL	Max-Climb
MCR	Mid-Cruise
MTO	Max-Takeoff
MTOW	Maximum Takeoff Weight
MW	MegaWatt
NASA	National Aeronautics and Space Administration
NH3	Ammonia
nm	Nautical Mile
NOx	Nitrogen Oxides
OEW	Operating Empty Weight
OPR	Overall Pressure Ratio
pax	Passenger
PR	Pressure Ratio
PtL	Power to Liquid
SAF	Sustainable Aviation Fuel
SFC	Specific Fuel Consumption (g/kN. s)
SLS	Sea-Level Static
SMR	Short-Medium-Range
T40	Combustor Outlet Temperature
T30	High Pressure Compressor Exit Temperature
TET	Turbine Entry Temperature
TOC	Top of Climb
TOW	Takeoff Weight
UK	United Kingdom
X_{H20}	Mole fraction of water
X_{CO2}	Mole fraction of carbon dioxide

1. INTRODUCTION

In 2011, ACARE set goals for the reduction of aviation CO_2 emissions by 75% and NO_x emissions by 90% relative to the year 2000 values [1]. In 2018, the IPCC report 'Global Warming of 1.5°C' indicated that by 2050, global CO_2 emissions must reduce to net zero to avoid unrecoverable climate change [2]. In 2019, EU commission implemented the Green Deal 2050 aiming for net zero emissions by 2050 across all industries and sectors including aviation [3]. In the UK, Jet Zero Council launched in 2020 as a partnership between industry and government aiming to deliver net zero aviation by 2050 [4] with an ambitious goal of achieving the first zero-emission commercial transatlantic passenger flight by 2025. In September 2020, AIRBUS announced hydrogen aircraft in response to tackle the emissions impact and achieve sustainable aviation. More recently, in October 2021, IATA member airlines agreed to transition their operations to net zero carbon emissions by 2050 to limit global warming to 1.5°C [5]. For addressing these objectives and targets, alternative fuels are considered or re-assessed for aviation applications.

Alternative fuels for aviation were investigated in the past mainly because of concerns over resource depletions and increasing demand. Brewer [6] performed assessments on liquid hydrogen for aviation during the 1990s with DOC as the figure of merit. The selected engine configuration for hydrogen included four heat exchangers out of which two used liquid hydrogen to cool the bleed air for ECS & turbine cooling flows, one used to cool the oil, and another to heat the hydrogen to the required combustor conditions from the exhaust system. The study concluded that hydrogen aircraft can be beneficial on an energy consumption basis for all mission ranges except very short ranges due to an increase in operating empty weight. Carson et al [7] reported the details of the study done for liquid methane fueled aircraft. The study concluded that methane aircraft can be beneficial on an energy consumption basis for all mission ranges except very short ranges. Brewer [6] compared liquid hydrogen, liquid methane, and kerosene powered long range subsonic aircraft. However, this comparison is made using the same engine thermodynamic cycle for all three fuels. The studies [6] & [7] scale the engine according to the aircraft thrust requirements by maintaining the same thermodynamic cycle and did not perform any emission studies. Seeckt and Scholz [8] assessed an ATR72 style freighter model aircraft with kerosene and hydrogen as fuel using turboprop and turbofan propulsion systems. Hydrogen variants are reported to provide significant benefits in terms of CO_2 and NO_x emissions. Water vapor emissions increased 2.5 times upon using hydrogen compared to kerosene, but this has a smaller climate impact compared to longer range aircraft due to lower cruise altitude leading to no contrails. However, the study scales the engine according to the thrust requirements keeping the same thermodynamic cycle. Verstraete [9] assessed hydrogen fuel for short, medium, and long range aircraft. The study reported that hydrogen for long range aircraft is beneficial in energy consumption by up to 12% when compared to kerosene. But for medium and short range aircraft, it reported a penalty of 5% and 18% respectively. However, the study scales the hydrogen engines according to the thrust requirements keeping the same thermodynamic cycle as the kerosene variant. Rompokos et al [10] assessed LNG as an alternative aviation fuel and reported environmental benefits in terms of CO_2 emission reduction of up to 16% but increased energy consumption per passenger mile due to the increased weight and drag of the aircraft. However, this study also followed the same approach of scaling the engines to match the aircraft thrust requirements while maintaining the same thermodynamic cycle. Zhuravlev [11] provided information regarding experimental activities and concepts where they explored LPG fueled aircraft. The paper stated that LPG is economically cheap and ecologically beneficial in terms of soot and emissions. It also provides information on the experimental TU-155 aircraft which successfully ran on liquid hydrogen and liquified natural gas in the late 1980s powered by experimental engines to demonstrate that it works. Lokesh et al [12] performed mission assessments for 100% blends of SAF sourced from 3 feedstocks namely

Jatropha, Camelina, and Microalgae. The study reported that life cycle carbon savings of up to 70% were obtained with mission fuel burn savings of up to 3.8% for the same mission range. However, the engine thermodynamic cycle for SAF is kept the same as the kerosene counterpart for the study. SAF has the potential to reduce CO_2 emissions by up to 80% on a life cycle basis [13] given that its production is scaled up in a sustainable way to meet aviation demand. Rahmes et al [14] reported flight tests conducted in 2009 using up to 50% blends of SAF. The report highlights that increasing the blend ratio could provide both economic and environmental benefits. Zhang et al [15] provides information on flight tests conducted on various synthetic and biofuels for aviation from 2006 to 2016. Voigt et al [16] reported details of DLR-NASA aircraft campaigns that measured exhaust and contrail characteristics of an A320 burning kerosene and low aromatic SAF blends. It stated that burning SAF provides a 50%-70% reduction in soot and as a result lower contrails leading to lower climate impact from adopting SAF compared to standard jet fuel. ASTM standards [17] currently allow blending different forms of synthetic kerosene with Jet A from 10% to a maximum of 50% blending ratio. In 2021, Airbus A350 flew with 100% SAF in both the engines to measure emissions and provided promising results [18]. Earlier this year in 2023, as part of efforts to push for certifying 100% SAF use in flight, both flight and engine tests were conducted with 100% SAF [19–22]. Singh and Haglind [23] provide studies on the impact of hydrogen on aero engine performance and its NO_x reduction potential. The study highlights when switching to hydrogen, TET reduces more than 30K for a V2527-A5 turbofan engine for the same net thrust, or the net thrust increases when the TET is kept the same. This effect is due to the increased water content in the flow gases which has a higher Cp compared to CO_2. However, the study assumes fixed thrust for both hydrogen and kerosene engines which is not the case when aircraft thrust requirements are considered and only assesses for the same thermodynamic cycle. Corchero and Montanes [24] provide similar results with benefits in TET of 40K when switching to hydrogen and also discusses the influence of fuel injection temperature on performance. The study only assesses performance for the same thermodynamic cycle without considering hydrogen aircraft thrust requirements. Kailos [25] reports details of the study that was done for the US army during the 1960s for ammonia fueled helicopter and propeller driven aircraft. The study highlights the significant limitations of ammonia aircraft in the payload carrying capability especially since it was considered for a military application. Emissions were not an attribute that was investigated in this study and lacked an analysis of a turbofan engine. In the 1960s, Newhall and Starkman [26] investigated ammonia as a gas turbine fuel and reported that ammonia can provide superior thermal efficiencies up to 10% higher than hydrocarbons. However, the study is fundamental in nature and hence did not provide insights into turbofan engine performance and design. Recently, Otto et al [27] assessed ammonia for a B737-8 variant aircraft. Ammonia is carried in a liquid state in the wings. The liquid ammonia is used as a heat sink to enable system wide performance improvements. Since it is stored in -33°C, it is used for intercooling and bleed air cooling. The cracking unit converts gaseous ammonia into hydrogen before it is fed into combustion chambers. However, the study lacks a cycle and mission assessment. Goldmann et al [28] talk about electrofuels for aviation, a term assigned to fuels generated using renewable power. The work highlights the synthesis pathways for sustainable production of fuels, physico-chemical properties, and their impact on a turbine performance for a single operating point for an aero engine. The study highlights that alternative fuels generate more power with the consequence of higher engine speeds. However, the study does not provide mission assessment and turbofan engine cycle assessment for the alternative fuels. Rao et al [29] reviews energy carriers in aviation and looks at liquid hydrogen and liquefied natural gas as a dual fuel application with kerosene in a blended wing body concept aircraft. Florian et al [30] showcases a hydrogen powered long range concept aircraft Hyliner 2.0 and compares it to the contemporary kerosene variant. It is reported that hydrogen variant provides significant emission benefits in CO_2, NO_x, sulfur oxides and soot with 9% higher energy consumption. However, the hydrogen turbofan engine used for the study uses the same thermodynamic cycle as that of the baseline kerosene variant and is scaled to meet the thrust requirement of the aircraft. Jayant and Dan [31] assessed regional and short medium range hydrogen powered aircraft for entry into service 2035. It is reported that hydrogen powered aircraft could contribute to aviation's 2050 climate goals depending on the adoption of the hydrogen powered aircrafts into the fleets. However, the study keeps the same thermodynamic cycle as that of kerosene for the hydrogen powerplant and scales the engine to meet the aircraft thrust requirement.

From the discussions above, state-of-the-art studies on fuels suitable for aviation mostly boil down to hydrogen, and methane, with recent efforts for ammonia and SAF. To widen the research horizon, it is necessary to consider a broader class of fuels from which fuels deemed suitable for aviation can be down selected for further assessment. It is noted from the above studies that a comprehensive understanding of the impact of alternative fuels on both powerplant and aircraft is missing. This is understood from the limitations of the studies stated above as they look at the impact of alternative fuels on aircraft and powerplant individually rather than in an integrated manner. The originality of this paper is the knowledge contribution on the impact of alternative aviation fuels on powerplant design when alternative fueled aircraft influence is considered through an integrated engine-aircraft mission assessment approach. To quantify these impacts, initially, a preliminary thermodynamic engine cycle design space exploration is conducted to get a better overview of the possible efficiency gains and cycle redesign opportunities for different fuels. Then, an integrated engine-aircraft mission assessment, maintaining baseline airframe dimensions and fan size, is conducted to identify opportunities and challenges at both powerplant and aircraft level. The engine cycles are redesigned according to aircraft thrust requirements using a 3-point design method. Finally, a fuel conditioning assessment is performed to explore the opportunities available for the fuels to be used as a heat sink and enable unconventional cycles for future powerplant designs.

2. METHODOLOGY

In this section, the methods used for the assessments will be described.

2.1 Candidate Fuels

Five broad classes of fuels are recognized. These are alkanes, alcohols, ethers, non-hydrocarbons, and drop-in fuels. Following subsections briefly describe these classes of fuels and the selected candidates for further assessment.

2.1.1 Alkanes

Alkanes are a family of saturated hydrocarbons which are generally regarded as stable compounds. Methane is selected as it is the simplest alkane having only one carbon atom. It offers good thermal stability and clean combustion [32]. Butane is a gaseous fuel and can be stored as a liquid at 2 atm and 15°C. It has a higher boiling point which enables lower insulation requirements than methane and hence is selected due to storage advantages in aircraft. Octane is similar to jet fuel concerning physical properties. It is reported that octane has the potential to be used as a drop-in fuel. Only minor modifications to engines might be necessary [28] and its handling is expected to be similar to kerosene and hence is selected.

2.1.2 Alcohols

Alcohols are a family of hydrocarbon oxygenates and are generally stable and clean burning fuels. Since alcohols are liquids, from a storage point of view, they present an advantage for the aircraft. The densities of alcohols are also very similar to Jet-A. Mendez et al [33] reported that blending Butanol with Jet-A for gas turbines reduced the NOx and CO emissions. It is also the alcohol with the highest LHV in the first four carbon number group which can provide benefits for aircraft mission performance. Hence, butanol is selected.

2.1.3 Ethers

Ethers are a family of hydrocarbon oxygenates and are known to burn cleanly. Lee et al [34] investigated the use of DME which is a gaseous fuel for gas turbines and found that it is a very clean and efficient fuel. Its oxygen content enables smoke free (no soot) combustion [35,36]. Its handling properties are very similar to LPG and present storage advantages with lower insulation requirements due to a higher boiling point. Hence DME is selected.

2.1.4 Non-Hydrocarbons

Hydrogen and Ammonia were grouped under Non-Hydrocarbons. Hydrogen and Ammonia are zero carbon fuels that produce only water as combustion products on complete combustion. They are selected automatically due to their relevance to decarbonizing aviation.

2.1.5 Drop-in

SAF sourced from Jatropha is selected since based on the study from Lokesh et al [12], the inflight emissions were lowest for the fuel based on this feedstock.

Hence, 3 liquid and 5 gaseous fuels are selected as follows:
Liquid fuels: Butanol, Octane, and SAF
Gaseous fuels: Hydrogen, Ammonia, DME, Methane, and Butane
Their respective boiling points are indicated the Table 1. Note that SAF has been assumed to have the same boiling point as that of Jet-A for this study.

Table 1: Boiling point of candidate fuels (a:[28]**, b:**[37])

Fuels	Boiling Point (°C) at 1 atm
Jet-A/SAF	176[a]
N-Octane	126[a]
Butanol	118[b]
N-Butane	-0.5[b]
DME	-24.8[b]
Ammonia	-33[a]
Methane	-162[a]
Hydrogen	-252[a]

2.2 Engine cycle design space exploration and integrated engine-aircraft mission assessment

To tackle this objective, a methodology based on the EPIDOSYS (Engine Preliminary Integrated Design Optimization SYStem) platform of Cranfield University is utilized as shown in Figure 1. Alternative fuels that needed to be investigated were added to this platform. EPIDOSYS platform is built in a Python environment.

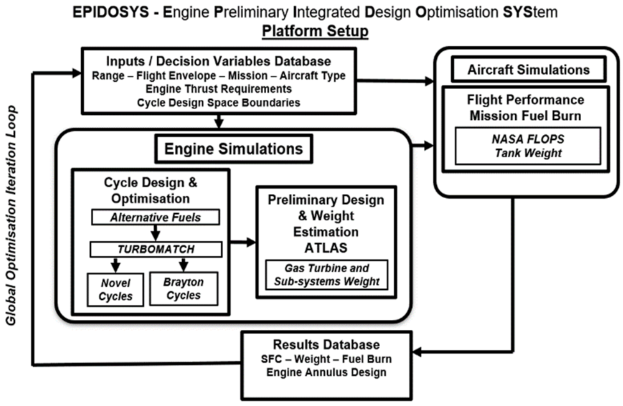

Figure 1: EPIDOSYS Platform

Preliminary thermodynamic engine cycle design space exploration is achieved using Fortran based TURBOMATCH [38]. TURBOMATCH is an in-house gas turbine performance software of Cranfield University. It can assess both steady state and transient analysis. Due to its modular structure, it can simulate conventional and unconventional engine cycles. For aircraft performance, Fortran based NASA FLOPS is utilized. The FLight OPtimisation System (FLOPS) is a multidisciplinary aircraft preliminary design and analysis package developed by the NASA Langley Research Center [39]. It is used for defining aircraft performance enabling the engine cycle assessment at the mission level. The size and weight of the turbomachinery components are estimated using the in-house tool Fortran based ATLAS [40]. ATLAS uses the cycle performance outputs from TURBOMATCH for performing engine component design and sizing allowing the estimation of the engine weights.

3-point engine cycle design method as shown in Figure 2 is utilized to redesign the engine cycles according to the aircraft thrust requirements. The 3 points based on which the engine cycles are designed in this paper are namely mid-cruise, top of climb & take-off point. Mid-cruise point is where the aircraft flies most of the time and it is the design point, top of climb point is the sizing point for the fan as the non-dimensional speeds are highest at this point and take-off is the highest power setting for a powerplant which determines the highest cycle temperature.

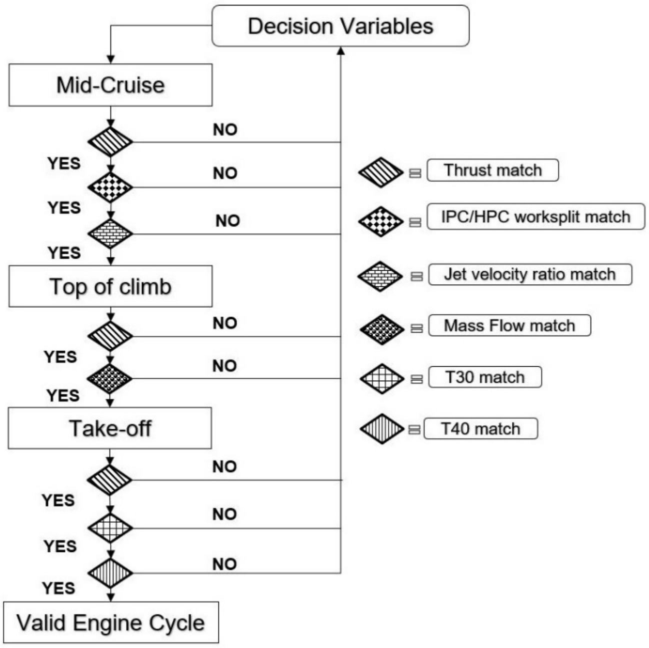

Figure 2: 3-point cycle design flowchart

The decision variables to match the constraints in the flowchart of Figure 2 are shown in Table 2.

Table 2: 3-point design decision variables and constraints

Decision Variables	Constraints
Mid-cruise T40	Take-off T40
IPC PR	Take-off T30
HPC PR	IPC/HPC Worksplit
Fan Tip PR	TOC Massflow
Mid-Cruise BPR	Jet Velocity Ratio

In this paper, 3-point design is performed for the same take-off T40s as the baseline to have the maximum cycle temperatures, the same take-off T30s as the baseline to have the maximum HPC blade exit temperatures, the same core worksplit as the baseline, the same fan size (diameter) as the baseline and a range of jet velocity ratios to minimize the specific fuel consumption while respecting the above constraints. The technology levels for the powerplant considered for the assessments in this paper are provided in Table 3.

Table 3: Technology levels for the assessments

Technology	Value
T40 (K)	1758
T30 (K)	891
$\eta_{poly,Fan}$	0.91

$\eta_{poly,IPC}$	0.92
$\eta_{poly,HPC}$	0.90
$\eta_{poly,HPT}$	0.89
$\eta_{poly,IPT}$	0.895
$\eta_{poly,LPT}$	0.90

Gravimetric efficiency/index is used to consider fuel storage implications on aircraft wherever appropriate for mission fuel burn assessments. Its definition is as follows:

$$\eta_{grav} = \frac{M_f}{M_f + M_t} \quad (1)$$

where η_{grav} is the gravimetric tank efficiency/gravimetric index (GI); M_f is the mass of fuel; M_t is the mass of the tank.

2.3 Fuel conditioning and exhaust gas properties

The method to achieve the fuel conditioning assessment objective is to utilize the REFPROP package [41]. It is software that has thermophysical properties of fluids over a wide range of conditions. The thermodynamic cycle data from TURBOMATCH provide fuel flow rates which coupled with the data from REFPROP for certain tank storage conditions in aircraft to combustor injection conditions will provide fuel conditioning requirements in terms of thermal power. The exhaust gas properties are also shown in this paper to explain the effects of alternative fuels on engine performance. To achieve this objective, the Fortran based CEA package is utilized. CEA [42] is a software that can calculate the thermodynamic and transport properties of products in chemical equilibrium with each other.

3. RESULTS AND DISCUSSION

3.1 Preliminary engine cycle design space exploration

It is known that alternative fuels have different LHVs. This will lead to different FAR inside the combustor of the powerplant. This can affect the exhaust gas's thermodynamic properties. Typically, for turbofan engines utilizing kerosene as fuel, FAR is approximately 0.0213, which is lean combustion since FAR for stoichiometric combustion is 0.068. To get the FAR for alternative fuels, the following relation is used:

$$FAR_{fuel} = \frac{FAR_{KE} * LHV_{KE}}{LHV_{fuel}} \quad (2)$$

where FAR_{fuel} is the Fuel Air Ratio of the alternative fuel; FAR_{KE} is the Fuel Air Ratio of kerosene; LHV_{KE} is the Lower Heating Value of kerosene; LHV_{fuel} is the Lower Heating Value of the alternative fuel.
The FAR_{fuel} and mole % of product composition for alternative fuels is shown in Table 4.

Table 4: FAR for alternative fuels

Fuel	LHV (MJ/kg)	FAR_{fuel}	X_{H20} (%)	X_{CO2} (%)
NH3	18.61	0.0495	11.435	0.029
HY	120	0.0076	10.462	0.03
CH4	50.05	0.0184	6.438	3.25
DME	28.8	0.0320	5.805	3.901
Butanol	33.1	0.0278	5.27	4.247
Butane	45.77	0.0201	4.896	3.948
Octane	44.78	0.0205	4.591	4.112
SAF	44.3	0.0208	4.533	4.176
KE	43.124	0.0213	4.168	4.38

For the FAR shown in Table 4, Cp is evaluated as this term appears in the fundamental definitions of enthalpy and entropy used for gas turbine performance simulations**.** The effects are shown in Figure 3.

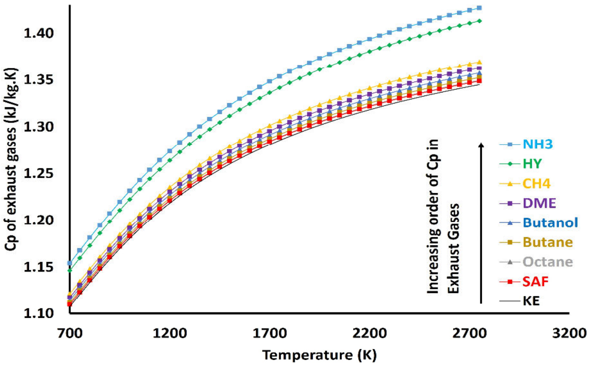

Figure 3: Exhaust gases Cp for a range of temperatures

From Figure 3, it is found that exhaust gases contain different heat capacities. This can be attributed to the amount of water content in the exhaust gases as shown in Table 4. Water is known to have higher Cp than CO_2.

It is known that the turbine work equation is:

$$W_t = \dot{m} C_p dT \quad (3)$$

where W_t is the turbine work; $\dot{m}$ is the mass flow rate of exhaust gases; C_p is the heat capacity of exhaust gases at constant pressure; dT is the temperature drop across the turbine.

Therefore, higher Cp values can lead to increased turbine work. As shown previously, in Table 4, FAR is different for alternative fuels due to different LHVs. Goodger [43] reports that a fuel that has components such as nitrogen and oxygen, reduces its LHV. Hence, the exhaust gas mass flow rate $\dot{m}$ will also be different in equation 3. To quantify the cumulative effect on a turbofan

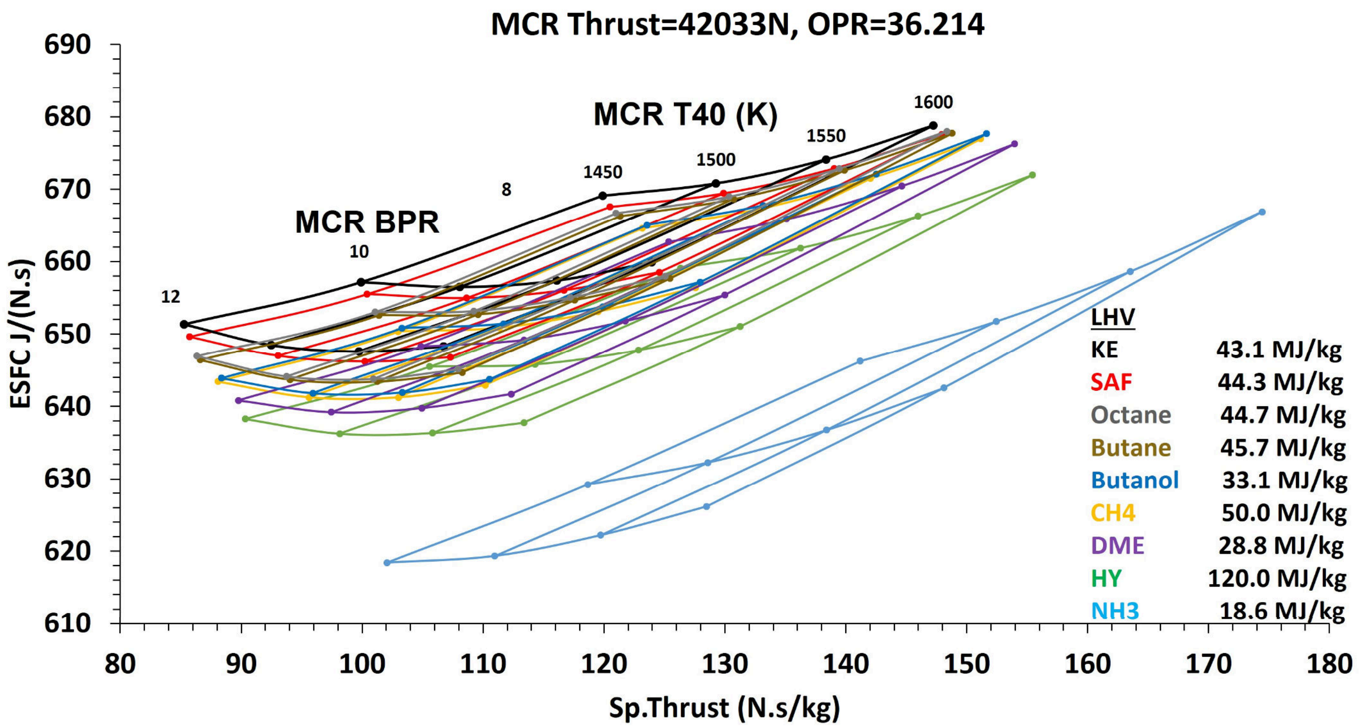

Figure 4: ESFC vs Specific Thrust

engine, a preliminary thermodynamic engine cycle design space exploration is performed for fixed thrust requirements. The test case chosen is a 240 kN SLS thrust class three spool turbofan engine architecture. The analysis is done using TURBOMATCH for the following design MCR and off design MTO conditions as shown in Table 5.

Table 5: On design and Off design conditions

MCR Altitude	35,000 ft
MCR Mach	0.85
MCR ISA dev	0
MCR Thrust	42,033 N
MCR BPR	8, 10, 12
MCR T40 (K)	1450, 1500, 1550, 1600
MCR OPR	36.214
MTO Altitude	0 ft
MTO Mach	0.25
MTO ISA dev	15
MTO Thrust	178,710 N

Hence, the overall effect on the engine cycle performance when operating with alternative fuels is shown in Figure 4.

The relationship between overall efficiency and the energy consumption is as follows:

$$\eta_o = \frac{V_o}{ESFC} \tag{4}$$

where η_o is the overall efficiency; V_o is the flight speed; $ESFC$ is the energy specific fuel consumption (SFC * LHV).

From Figure 4, for a given specific thrust (constant propulsive efficiency), as we move from long chain hydrocarbons to zero carbon fuels, the carpet plot shifts down i.e., ESFC reduces. One should note that every design point in the carpet plot has been optimized for minimum SFC by optimizing the FPR. Overall efficiency is a product of thermal, propulsive, and transfer efficiency. For a given specific thrust, propulsive efficiency is approximately fixed, while transfer efficiency is fixed for fixed isentropic efficiency of LP spool components. Thus, since flight speed is kept constant, any changes in ESFC are directly linked to changes in thermal efficiency. Hence, it is found that alternative fuels increase thermal efficiency leading to lower energy specific fuel consumption for a given thrust condition. It is also observed that the carpet plot tends to shift towards the right, indicating higher optimum specific thrust values and ultimately, smaller engine sizes for a given set of thrust requirements and technology constraints. Hence, utilizing alternative fuels for turbofan engines can lead to comparatively smaller engines. Alternatively, if the same specific thrust is desired, then engines can be run at reduced T40s or increased BPR. It is observed that Hydrogen and Ammonia provide an ESFC benefit of approximately 3% and 6% respectively when compared to kerosene. The off-design effects of utilizing alternative fuels for max take-off conditions are shown in Figure 5.

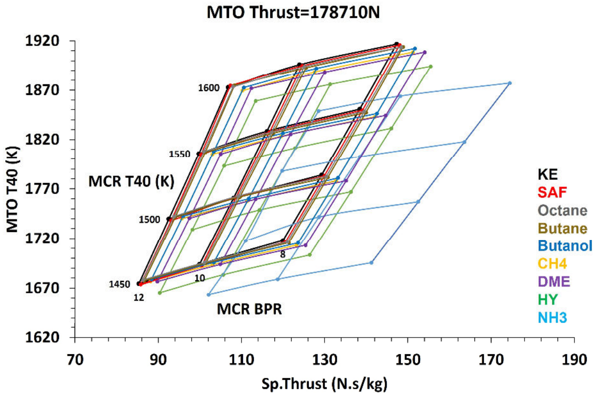

Figure 5: Take-off T40 effects of alternative fuels

It is observed that there are take-off T40 benefits for alternative fuels compared to the baseline kerosene. Due to the increased heat capacities in the exhaust gases for alternative fuels, they generate more power. Hence, for the same takeoff thrust condition, lower T40s are observed. The maximum reduction in T40 observed is approximately 40K and 20K for Ammonia and Hydrogen respectively compared to baseline kerosene. Therefore, utilizing alternative fuels for aero engines can result in engine life benefits due to reduced peak cycle temperatures.

3.2 Integrated engine-aircraft mission assessment

Boeing B787/3 style aircraft is the selected platform to accomplish this objective. For the SMR category mission, it is assumed that a wide body aircraft would be apt to store the cryogenic fuels inside the fuselage. The Boeing 787/3 is supposed to be a wide body aircraft capable of carrying more passengers for SMR category missions. In this paper, the mission assessment is a retrofit exercise meaning there are no external modifications done to the airframe. Hence, for fuels that need to be stored inside the fuselage, the passenger capacity is reduced to accommodate the fuel tanks instead of extending the fuselage. The engine cycles are designed for the same fan diameter to keep the airframe as it is without any modifications. Table 6 shows the design conditions for which the test case aircraft is modeled.

Table 6: Aircraft design conditions

Design Conditions	
Cruise Mach	0.85
Cruise Altitude (ft)	35000
Design Range (nm)	3050
MTOW (tons)	170.24
Maximum Fuel Capacity (tons)	38.98
PAX	330

The 3-point thrust requirements which are considered for the baseline kerosene aircraft are provided in Table 7.

Table 7: 3-point thrust requirements

3 Point Thrust Requirements	
MCR	42 kN ISA 0
MCL	50.4 kN ISA 10
MTO	178.7 kN ISA 15

The assessments in this paper are made for a target design range of 3050 nm where possible and never exceeding the MTOW to be within the structural limitations. The 3-point thrust requirements for alternative fuels are the result of an iteration process shown in Figure 6. Initially, the mission is flown with a baseline cycle. Then, new 3-point thrust requirements are obtained as a result of changes in TOW where applicable. The take-off thrust is changed for a fixed thrust-weight ratio as baseline aircraft. Using 3-point cycle design method, engine cycles are redesigned. The insulation tank weights are calculated from the gravimetric index definition. The engine weights are updated, and the mission is flown again. This process is repeated until the relative change in mission fuel compared to the previous iteration comes within a tolerance value.

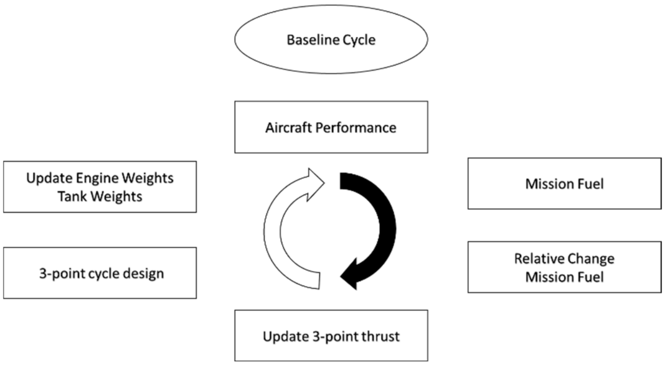

Figure 6: 3-point thrust requirements iteration process

As a result of this process, the aircraft weight breakdown along with the passenger capacity for alternative fuels is shown in Figure 7. It should be noted that Hydrogen, Methane, Butane, Octane, and SAF fly at the same range as the kerosene aircraft whereas Ammonia, DME, and Butanol fly at a reduced range. This is discussed further in the upcoming mission assessments section.

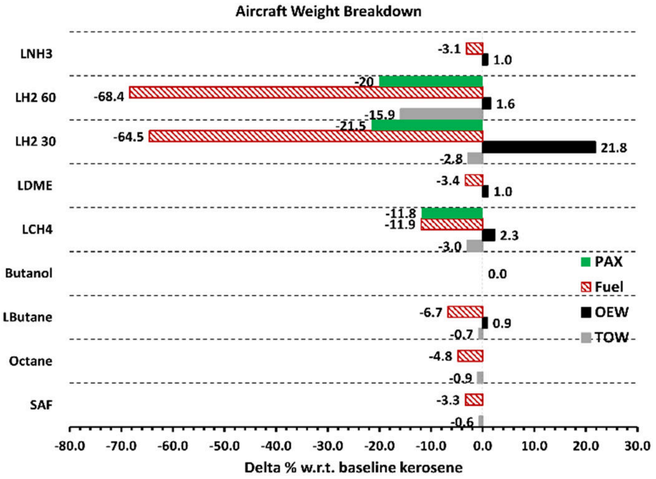

Figure 7: Aircraft Weight Breakdown

LH_2 30 and LH_2 60 are assessments made for hydrogen aircraft that utilize different tank technology i.e. 30% gravimetric index (heavier tank) and 60% gravimetric index (lighter tank) respectively. It is seen that for cryogenic fuels such as Hydrogen and Methane where the fuel is stored inside the fuselage, the passenger capacity must be reduced to accommodate the cryogenic tanks. This is 71 and 66 passengers for LH_2 30 and LH_2 60 respectively whereas, for methane, it is 39 passengers. The OEW has increased compared to baseline due to the heavy tanks associated with cryogenic fuels, but MTOW has been respected. It can be seen for higher boiling point fuels such as Ammonia, DME, and Butane, the OEW increases are lower due to lighter tanks as the insulation requirements are lower compared to cryogenic fuels. The higher LHV fuels such as Hydrogen, Methane, Butane, Octane, and SAF have lower TOW and mission fuel requirements. Reduced LHV fuels such as Ammonia, DME, and Butanol are within the same MTOW to be within the structural limits for the aircraft. Hence, the following subsections discuss the working assumptions relating to the storage of fuels in the aircraft modeled. Note that the 3-point thrust requirements deduced from aircraft performance based on the different aircraft weights are provided in the Apendix section A.1.

The kerosene aircraft is referred to as the baseline from here onward.

3.2.1 SAF Aircraft

SAF is a drop in fuel that is very much like kerosene with slightly higher LHV, reduced carbon content, and lower aromatics which leads to lower soot emissions. A 100% blend is used for this study. It is stored in the wings like the baseline.

3.2.2 LH_2 Aircraft

Hydrogen needs to be stored in a liquid state to maximize its density and reduce the volume it occupies. It exists as a cryogenic liquid at 20.35K at ambient pressure. However, it's preferable to store it at a slightly higher pressure than ambient, 1.2 bar, to prevent leakage of air into the tanks [44]. It is assumed to be stored inside the fuselage in cylindrical tanks with hemispherical caps as this geometry has the least surface/volume ratio that minimizes heat leakage [45]. To consider cryogenic tank weights, gravimetric index as a tech factor is assumed. The CleanSky report [46] assumes a gravimetric index of 37% for the SMR segment while Verstraete et al [47] and Brewer [6] reported values in the ranges between 50% and 70%. Hence, two scenarios, conservative 30% and optimistic 60% values are assessed. Passenger capacity is reduced to place the tanks inside the fuselage.

3.2.3 LCH_4 Aircraft

Like LH_2, Methane also needs to be stored in a liquid state to maximize density and reduce the volume occupied. It exists as a mild cryogenic liquid at 111.55K at ambient pressure. However, it is preferable to store it at a slightly higher pressure than ambient, 1.2 bar, to prevent air leakage into the tanks. Rompokos et al [10] and Carson et al [7] reported a gravimetric index of approximately 90%. Being conservative due to installation losses, 85% value is selected for the assessment. One should also note that liquid Methane will require lower insulation due to its higher boiling point compared to liquid hydrogen, and this will lead to a higher gravimetric index in comparison to liquid hydrogen. Liquid methane is stored inside the fuselage in a cylindrical tank with hemispherical cap ends and the passenger capacity is reduced appropriately.

3.2.4 LButane Aircraft

Butane has a boiling point of 272.65K at ambient pressure. It can also exist as a liquid under ambient temperatures and 2 atm pressures. However, it is proposed to be stored inside the wings under a subcooled state as this provided maximum density (601.63 kg/m3). Since the boiling point is a high value, a gravimetric index of 97% is assumed to account for the very low insulation required compared to cryogenic fuels. Since the fuel is stored in the wings, the passenger capacity is preserved.

3.2.5 Octane Aircraft

Octane is an alternative fuel similar in characteristics to kerosene. Since it is a liquid fuel, it is proposed to be stored inside the wings like the baseline.

3.2.6 Butanol Aircraft

Butanol is a liquid fuel and has high densities like kerosene fuel. Since it is a liquid fuel, it is proposed to be stored inside the wings like the baseline.

3.2.7 LDME Aircraft

DME has a boiling point of 248.15K at ambient pressure. Its handling properties are very similar to LPG. Hence, it can also exist as a liquid under moderate pressures of 4-5 atm at ambient temperatures. However, it is proposed to be stored inside the wings under a subcooled state as this provided maximum density (735 kg/m3). Since the boiling point is a high value, gravimetric index of 97% is assumed to account for the very low insulation required compared to cryogenic fuels. Since the fuel is stored in the wings, the passenger capacity is preserved.

3.2.8 LNH3 Aircraft

Ammonia has a boiling point of 239.85K at ambient pressure. However, it can also exist as a liquid under moderate pressure of 8 bar and ambient temperatures. Herein, it is proposed to be stored inside the wings under a subcooled state as this provided maximum density (682 kg/m3). Since the boiling point is a high value, gravimetric index of 97% is assumed to account for the very low insulation required compared to cryogenic fuels. Since the fuel is stored in the wings, the passenger capacity is preserved.

3.2.9 Engine Cycle Designs

The cycles were optimized for minimum energy consumption for alternative fuels with relevant thrust requirements. Figure 8 shows the engine cycle differences at the design mid-cruise operating point when powered by the proposed alternative fuels. Note that the discussion here is for a three spool turbofan engine architecture.

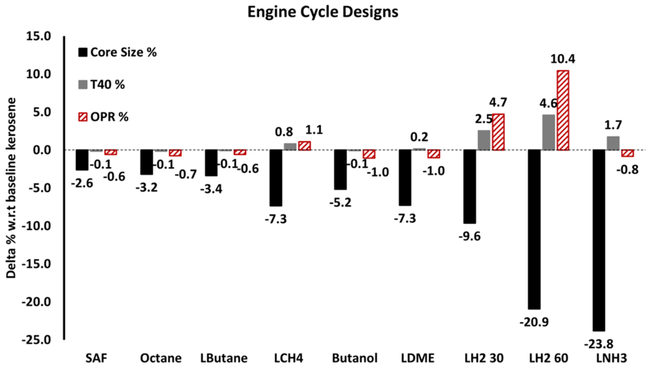

Figure 8: Alternative fuel engine cycles at mid cruise

It is found that when powered by alternative fuels, for the same fan size, the core size starts reducing with a maximum reduction of up to 23.8% as seen in the case of an Ammonia powerplant. This is followed by a 21% and 10% reduction for Hydrogen powerplants depending on the cryogenic tank technology. The reduction in take-off T40 when operated with alternative fuels provides opportunities to resize the core for a given peak cycle temperature. This leads to different bypass ratio designs for the same fan diameter. The take-off power for a given thrust-weight ratio starts to reduce due to the impact of the increased LHV fuels on TOW for a given mission range as shown earlier in Figure 7. This provides the opportunity to downsize the core for a given peak cycle temperature further. This applies to SAF, Octane, Butane, Methane, and Hydrogen. The differences in T40 and OPR to satisfy take-off T40 and T30 constraints can be attributed to the different thrust ratings between take-off and mid-cruise as obtained from the mission assessment**.** Figure 9 shows the differences in ESFC (a measure of overall powerplant efficiency), specific thrust, and bypass ratio.

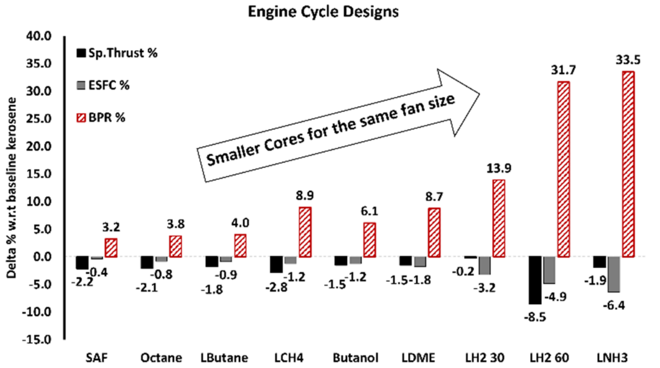

Figure 9: Overall efficiency of the engine cycles at mid cruise

Since higher LHV fuels will require reduced power as the TOW reduces to lower levels resulting in a lighter aircraft, when the fan size is kept the same, a lower specific thrust design is obtained. Based on the mission assessment thrust requirements, maintaining the same fan size can alter the specific thrust for reduced LHV fuels. It is found that the maximum ESFC benefit for the Ammonia powerplant is up to 6.4% and for the Hydrogen powerplant is 3.2% and 4.9% depending on the cryogenic tank technology. The rest of the fuels offer ESFC benefits providing improved overall efficiencies at the engine cycle level.

3.2.10 Mission Assessments

At the mission level, the H_2O and CO_2 emissions compared to baseline on a pax.nm basis are presented in Table 8. Note that NO_x emissions are not assessed for different fuels since it depends on the flame temperatures and combustor modeling which is outside the scope of the present study. Ammonia has the potential to reduce thermal NO_x due to its low adiabatic flame temperature, however, due to its fuel bound nitrogen, fuel NO_x can be generated. The fuel NO_x highly depends on the air-fuel equivalence ratio and can be kept low as reported in [28].

Table 8: Emissions of alternative fuel aircraft

Alternative Fuel	%delta vs baseline (H_2O)	%delta vs baseline (CO_2)
SAF	10	-2
Octane	12	-3
LButane	19	-7
Butanol	31	2
LDME	46	-5
LCH_4	76	-14
LH_2 60	193	-100
LNH_3	200	-100
LH_2 30	235	-100

From Table 8, it is observed that as alternative fuels are utilized, inflight CO_2 emissions are reduced except for Butanol. However, on the downside, the H_2O emissions are increasing from high to low/zero carbon fuels. To get the total impact of both CO_2 and

H_2O emissions, their global warming impact is quantified. CO_2 and H_2O emissions are combined to give a CO_2 equivalent through the use of GWP. The definition for GWP [46] and the resulting CO_2 equivalent equation used is as follows:

$$GWP = \frac{radiative\ forcing\ of\ 1\ kg\ of\ pollutant}{radiative\ forcing\ of\ 1\ kg\ of\ CO2} \tag{5}$$

$$\frac{CO2eq\ (kg)}{pax.nm} = \frac{CO2\ (kg)}{pax.nm} + (\ GWP * \frac{H2O\ (kg)}{pax.nm}) \tag{6}$$

GWP value for water vapor at 35,000 ft is assumed to be 0.29 from data reported by Khandelwal et al [45]. Water vapor causes global warming effect from 10 km altitude onwards and hence the effects of water vapor are considered only for the cruise segment. The effects of contrails are not considered in this study. Figure 10 presents the block energy consumption and global warming impact of the proposed fuels on a pax.nm basis.

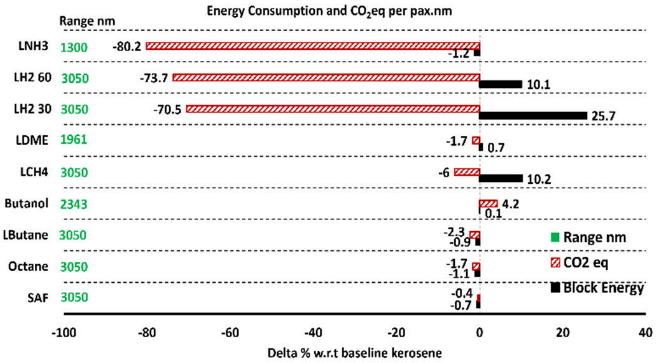

Figure 10: Block energy consumption and Global warming impact

It is observed that zero carbon fuels, Hydrogen, and Ammonia provide the least global warming impact. Cryogenic fuels, Hydrogen, and Methane are penalized in block energy consumption due to the size and weight of the fuel storage system (which causes reduced passenger numbers and increased OEW). For Hydrogen, depending on the tank technology, this can be from 10 to 25%. The rest of the fuels are comparable to kerosene on block energy consumption. Fuels such as Ammonia, DME, and Butanol are penalized in mission range because of less energy in the tanks for a fixed MTOW due to their reduced LHV. The maximum penalty is seen in the case of ammonia which is up to 58% reduced range compared to the baseline.

3.3 Fuel handling and conditioning assessments

An assessment is made to investigate the amount of thermal power needed to condition the fuel to satisfactory levels for the proper performance of the powerplant.

Table 9: Fuel storage and delivery conditions

Fuel	$P_{storage}$ (atm)	$T_{storage}$ (°C)	$P_{injection}$ (atm)	$T_{injection}$ (°C)	Fuel Flows (kg/s)
Jet A	1	25	43.97	120	1.85
SAF	1	25	43.98	120	1.77
Octane	1	25	43.99	126	1.75
Butanol	1	25	44.00	118	2.38
LButane	1	-0.6	44.00	25	1.71
LDME	1	-25.1	43.99	25	2.72
LNH3	1	-33.9	44.10	25	3.98
LCH4	1.18	-159.4	70.32	25	1.59
LH2 30	1.18	-252.3	70.27	-23.15	0.61
LH2 60	1.18	-252.3	69.83	-23.15	0.51

The fuel storage and delivery conditions used for the assessments are presented in Table 9. The fuel flows presented in Table 9 correspond to the engine cycles presented in section 3.2.9 at the take-off operating point. For liquid fuels, the delivery pressure into the combustor is assumed to be 25% more than the HPC exit pressure whereas, for gaseous fuels, it is assumed to be 2 times more than the HPC exit pressure based on [44]. Gaseous fuels such as Ammonia, DME, and Butane exist in a subcooled liquid state for the powerplant conditions. Hence, they are injected into the combustor at pressures 25% more than the HPC exit pressure. The storage temperatures are based on the discussions in sections 3.2.1 – 3.2.8. Jet-A is assumed to be injected at temperatures lower than its boiling point to avoid coking of the fuel. This is also the case assumed for SAF. The rest of the liquid fuels, Octane and Butanol, it is assumed to be injected at their boiling points. The injection temperatures for gaseous fuels have been considered to be 300K (25°C) to ensure stable combustion. Hydrogen is assumed to be injected at a slightly lower temperature of 250K based on [23].

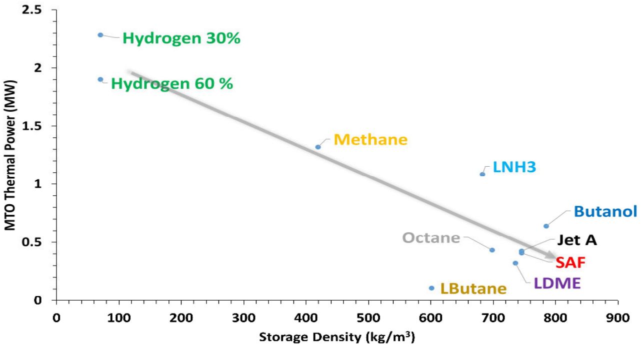

Figure 11: MTO Thermal Power

Figure 11 presents the thermal power required to condition the fuel for satisfactory performance of the powerplant under the conditions stated in Table 9.

It is observed from Figure 11 that as the storage density in the aircraft increases, the thermal power requirement to condition the fuel decreases. Note that the graphical arrow simply acts as a guideline and is not based on any equation. For a 240kN SLS class engine, at take-off, Hydrogen requires 2.2 MW, Methane requires 1.3MW and Ammonia requires 1 MW (all compared to approximately 15 MW of propulsive power) with the rest of the fuels showing similar needs as that of kerosene. Cryogenic fuels such as Hydrogen and Methane exist as supercritical fluid under powerplant conditions at combustor entry. This indicates challenging handling conditions when considering fuel management system. High boiling point fuels such as Butane, Ammonia, and DME exist as sub-cooled liquids under powerplant conditions. This indicates favorable handling conditions when considering fuel management system. The high thermal power requirement for cryogenic fuels Hydrogen and Methane and high boiling point fuel Ammonia indicates that there exist opportunities for utilizing these three fuels as heat sinks to enable powerplant designs having heat exchanger cycles and improve powerplant performance.

4. CONCLUSION

A candidate list of zero/low carbon alternative fuels is investigated for aviation with an integrated engine-aircraft assessment approach. An engine cycle design space exploration of a modern three spool turbofan engine utilizing the proposed alternative fuels highlighted the benefits of implementing alternative fuels for the powerplant i.e, improved overall efficiency, lower peak cycle temperatures, and significant cycle redesign opportunities. An ESFC benefit of 3% for Hydrogen and up to 6% for Ammonia for fixed thrusts are observed.

An integrated engine-aircraft mission assessment highlighted the following points for the powerplant and aircraft:

- For a given peak cycle temperature and compressor blade exit temperature at take-off and a given fan size, the powerplant utilizing alternative fuels can be significantly redesigned. For zero carbon fuels, a core size reduction of up to 23.8% for Ammonia and up to 21% is observed for Hydrogen leading to different bypass ratio powerplant designs.
- Alternative fuels that have higher LHV compared to baseline kerosene offer lighter aircraft leading to lower take-off power for a given thrust-weight ratio. As a result, the core size (gas generator) can be reduced further leading to improved design point fuel efficiencies apart from the thermal efficiency benefits arising from using alternative fuels. Low carbon fuels such as Octane, Butane, Methane, and zero carbon fuel Hydrogen which are higher LHV fuels compared to kerosene offer this opportunity with ESFC benefits ranging from 0.8% to 4.9%. This is especially important for hydrogen aircraft from a cryogenic tank technology perspective since lighter advanced composite tanks will allow the industry to take advantage of the lightness of hydrogen fuel to the maximum by pushing the core sizes down further. This is especially showcased by LH2 30 and LH2 60. From the current assessment, SAF also provides core size reduction opportunities due to variation in LHV as it is sourced from bio-feedstock and also because a 100% blend is assessed. Particularly for SAF produced from PtL, if the LHVs are not identical to kerosene, similar core sizing opportunities can be envisaged.
- Cryogenic fuels penalize block energy consumption due to the size and weight of the fuel storage system. Passenger capacity needs to be reduced to make space for the tanks. The weight contributes to the increase in OEW. However, high boiling point fuels are comparable in block energy consumption to kerosene due to their flexibility to be stored in the wings.
- Alternative fuels reduce inflight CO_2 emissions but increase H_2O emissions. Zero carbon fuels provide the best reduction in global warming impact, whereas SAF, Octane, Butane, DME, and Methane offer only modest reductions (0-6 %) in global warming impact per pax.nm respectively when CO_2 and H_2O are assumed to be greenhouse gases. Butanol increases the global warming impact by 4%. These numbers are inflight emissions and not on a life cycle emission basis and don't account for the effect of contrails.
- Ammonia, DME, and Butanol are limited in mission capability due to reduced range.
- For take-off operating point, cryogenic fuels, Hydrogen, and Methane are perceived to be challenging for handling considerations (fuel management system) since they exist in a supercritical state whereas high boiling point fuels Ammonia, Butane, and DME are perceived to be easier since they exist as a subcooled liquid at combustor entry.
- As the storage density of the fuel increases, the thermal power requirement to condition the fuel decreases. For a 240kN SLS class engine, at take-off, the thermal power requirements to condition the fuel are 2.2MW, 1.3, and 1MW for Hydrogen, Methane, and Ammonia respectively (all compared to 15MW of propulsive power). This proves that there exist opportunities for heat exchanger cycles to be envisaged if the powerplant is to be powered by Hydrogen, Methane, and Ammonia since the fuel conditioning requirements are significant.

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APPENDIX

A.1 3 Point Thrust Requirements

Fuel	MCR kN ISA 0	MCL kN ISA 10	MTO kN ISA 15
Jet A	42	50.4	178.7
SAF	41.1	49.4	177.5
Octane	41.19	49.43	177.1
Butanol	41.44	49.73	178.7
LButane	41.3	49.58	177.3
LDME	41.44	49.73	178.7
LNH3	41	49.4	178.7
LCH4	40.9	49.1	173.9
LH2 30	42.6	46.9	174.4
LH2 60	39.1	43	152.6

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