



European Fuel Blend Development

Final Report

ESTEC Contract Number 4000113544/15/NL/AD
ESA Technical Officer(s): F. Valencia Bel, ESTEC, Noordwijk

**A.E.H.J. Mayer, TNO,
Rijswijk, The Netherlands**

**I. Waugh, NAMMO Westcott,
Westcott, United Kingdom**

**M. Poucet, Bradford Engineering,
Heerle, The Netherlands**

Date: 8 June 2018
Document ref. no. TNO 2018 R10640

**EUROPEAN SPACE AGENCY
CONTRACT REPORT**

The work described in this report was done under ESA contract. Responsibility for the contents resides in the author or organisation that prepared it.

ABSTRACT

Nitrous Oxides Fuel Blend (NOFB) propellants are re-emerging and may be candidate as a next generation green propellant. In Europe there is little experience in handling NOFB. In the study in to a European NOFB, executed by TNO (NL), NAMMO Westcott (UK) and Bradford Engineering (NL), an NOFB composition was selected based on a clear set of requirements. The handling issues associated with this propellant were evaluated, combustion tests with liquid NOFB were executed and the impact on system level was addressed.

As a result of the study, ethanol-blended with Nitrous Oxide was found to be an attractive propellant for in space propulsion. Within the study a successful engine firing test campaign was conducted with this blend of ethanol and nitrous oxide as a liquid monopropellant. The engine tests proofed that high performance and high combustion efficiency can be obtained with the selected propellant. On system level, the use of ethanol and nitrous oxide blended at the maximal miscible mixture ratio identified, will save mass for monopropellant systems and is therefore attractive, however, a solution for a reliable, simple and small igniter for the NOFB needs to be addressed. To be attractive as a replacement for bipropellant, a blend nearer to stoichiometry is required.

TNO report**TNO 2018 R10640****European Fuel Blend Development**

Lange Kleiweg 137
2288 GJ Rijswijk
P.O. Box 45
2280 AA Rijswijk
The Netherlands

www.tno.nl

T +31 88 866 80 00
F +31 88 866 69 49

Date	8 June 2018
Author(s)	A.E.H.J. Mayer (TNO) I. Waugh (NAMMO Westcott) M. Poucet (Bradford Engineering)
Number of pages	51
Sponsor	ESA Technical officer: F. Valencia Bel ARTES representative: N. Arcis
Project name	European Fuel Blend Development
Project number	060.19610

**EUROPEAN SPACE AGENCY
CONTRACT REPORT**

The work described in this report was done under ESA contract.
Responsibility for the contents resides in the author or organisation that
prepared it.

The copyright in this document is vested in TNO. This document may only be reproduced in whole or in part, or stored in a retrieval system, or transmitted in any form, or by any means electronic, mechanical, photocopying or otherwise, either with the prior permission of TNO or in accordance with the terms of ESTEC Contract no 4000113544/15/NL/AD

Contents

Nomenclature	3
1 Introduction	5
2 Propellant definition	6
2.1 Requirements	6
2.2 Potential fuels	7
2.3 Trade-off	8
2.4 Properties of the pre-mixed propellants.....	11
3 Propellant handling study	13
3.1 Stability and miscibility.....	13
3.2 Handling and safety procedures.....	16
3.3 Material stability and compatibility	18
4 Testing of the European Fuel Blend	21
4.1 Test set-up.....	21
4.2 Results of the firing tests	27
5 System impact	32
5.1 Power Subsystem.....	33
5.2 Thermal Subsystem.....	37
5.3 Mechanical Subsystem.....	37
5.4 Auxiliary Propulsion System	39
5.5 Identification of Development Effort Needed to Implement a EUFB Subsystem	40
5.6 System Impact.....	45
6 Lessons learned	46
7 Conclusions	48
8 References	49
9 Signature	51

Nomenclature

Abbreviations

ADN	Ammonium Di Nitramide	NBR	Nitrile Butadiene Rubber
ALASA	Airborne Launch Assist Space Access	NHNE	Homogeneous Non-Equilibrium
ARTES	Advanced Research in Telecommunications Systems	NOFB	Nitrous Oxide Fuel Blend
CEA	Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications	NTO	Nitrous Tetroxide
COPV	Composite Overwrapped Pressure Vessel	OF	Oxidiser to Fuel ratio
CR	Chloroprene Rubber	P&ID	Piping and Instrumentation Diagram
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.	PMD	Propellant Managing Device
ER	equivalence ratio	POM	PolyOxyMethylene
ESA	European Space Agency	PP	PolyPropylene
EUFB	European Fuel Blend	PPS	PolyPhenylene Sulfide
FEA	Finite Element Analysis	PS	Propulsion System
FKM	Viton / Fluorocarbon	PT	Pressure Transducer
GHS	Globally Harmonized System of Classification and Labelling of Chemicals	PVC	PolyVinyl Chloride
HAN	HydroxylAmmonium Nitrate	RCT	Reaction Control Thruster
HEM	homogeneous equilibrium	REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
HNF	Hydrazinium NitroFormate	SPI	single phase incompressible
IIR	Isobutylene Isoprene Rubber	TCS	Thermal Control System
LC50	Lethal Concentration, the concentration required to kill half the members of a tested population after a specified test duration	TMLV	Torque Motor Latch Valves
LD50	Lethal Dose, the dose required to kill half the members of a tested population after a specified test duration	TNO	the Netherlands Organisation for applied scientific research
MEOP	Maximal Expected Operational Pressure	TRL	Technology Readiness
MIE	Minimum Ignition Energy		
MMH	Monomethyl-Hydrazine		
MoE	Measures of Effectiveness		
MSDS	Material Safety Data Sheet		
NAMMO	Nordic Ammunition Company		

Symbols

ρ	Density in kg/m ³
η	efficiency
γ	Ratio of specific heats
ΔV	Velocity change budget
$\dot{m}$	mass flow rate
A	Area in m ²
c	specific heat at constant pressure
c*	Characteristic velocity in m/s
C _d	Discharge coefficient
g ₀	Earth gravity constant (9.81 m/s ²)
H	Enthalpy in kJ/mol
I _{sp}	Specific impulse in s
m	mass in kg
M	Mach number
M	Molar Mass in kg/kmol

M_0	Initial Mass in kg
P	Pressure in bar
q	heat
T	Temperature in Kelvin
V	Volume in m^3

Subscripts

Δt	firing time
0	initial
0	stagnation condition
atm	atmospheric
ave	average
Bi-prop	Bi-propellant
c	combustion chamber
Conv.	Conventional propulsion system
Cr	condition at critical point
e	nozzle exit

end	end of data set
eoc	end of combustion chamber
Ethanol	Ethanol
f	final
hl	heat loss
ig	Auto ignition
inj	injector
Mono-prop	Mono-propellant
N2O	Nitrous Oxide
NOFB	Nitrous Oxide Fuel Blend
pmx	Premix chamber
start	start of data set
t	throat
theor	theoretical value
TOT	total
vap	vapour

1 Introduction

Monopropellants composed of nitrous oxide and a fuel are not new. Already during World War II the Germans studied blends of nitrous oxide and fuels as propellant for propulsion systems [1]. With the availability of hydrazine in the early 60's the research on monopropellants for in space propulsion came to a halt. Today, the use of chemicals imposing a significant health risk are regulated or banned by means of legislation such as the 'Registration, Evaluation, Authorisation and Restriction of Chemicals' (REACH) legislation in Europe [2]. Because hydrazine and its derivatives as Monomethyl-Hydrazine (MMH) are chemicals with significant health risks, the availability of these classical propellants for space propulsion is uncertain. Because of this, the NOFB propellants are re-emerging and may be candidates for a next generation monopropellant.

Nitrous Oxide Fuel Blends are so called pre-mixed propellants, a special class of liquid monopropellants in which an oxidizer and a fuel are blended and stored in a single propellant tank. In contrast to other well-known pre-mixed propellants (e.g. ADN, HNF or HAN based monopropellants), the NOFB constituents have relatively high vapour pressures (typically between 1 and 75 bar). This offers the potential for a simple feed system arrangement, since the propellant is 'self-pressurizing'. Because NOFB contains both an oxidizer and a fuel, its performance (i.e. specific impulse) is comparable to that of bipropellants. A summary of the main advantages and disadvantages of NOFB propellants is given in Table 1.

Table 1: NOFB pro's and con's.

NOFB advantages:	NOFB disadvantages:
• High gravimetric specific impulse • Simple feed system arrangement • Self-pressurizing • Low freezing point • Non-toxic and non-carcinogenic	• High combustion temperature • Possible flammable vapours in propellant tank • Low density at practical storage temperatures • Igniter required

In Europe little experience is available with these type of propellants. In Germany the DLR is studying the potential of NOFB within a national programme [3, 4, 5, 6] and has been conducting experiments with ethylene as fuel. A blend of oxidizer and fuel is potentially very hazardous because some of the propellant in the storage tank will be in the vapour phase. Also the liquid propellant may gasify in the propulsion system due to local pressure drops (valve operation, filters etc.). If the fuel is not selected carefully, the vapour may be a highly flammable, near stoichiometric mixture which may impose a significant risk for an explosive failure of the propulsion system. That this is a real threat was experienced by DARPA and Boeing within the Airborne Launch Assist Space Access (ALASA) project [7] at two firing trials of an engine using a propellant blend of nitrous oxide and acetylene where the propellant exploded. These failures contributed to the cancellation of the ALASA project [8, 9].

To improve on the European knowhow on NOFB propellants for satellite propulsion systems, ESA initiated a study [10] within the Advanced Research in Telecommunications Systems (ARTES) program to gain experience in this field. The study was awarded to TNO (the Netherlands) with NAMMO Westcott (United Kingdom) and Bradford Engineering (the Netherlands) as subcontractors. This report presents the main results of this study by addressing the fuel selection, fuel trade-off, safety and handling, engine firing trials (text by AEL and NAMMO Westcott) and system impact evaluation (text by Bradford Engineering).

2 Propellant definition

The applied fuel selection strategy included the definition of requirements and a trade-off in which propellant candidates were ranked on how well the requirements were met. The set of requirements must be satisfied by any fuel in order to be a potential fuel for NOFB. The fuels compliant to the requirements were ranked by a trade-off. Fuels for which compliancy with the requirements is unknown at this point, have been provisionally included in the trade-off. In that case, compliancy should still be verified in the future, either by analysis or experimentation.

The activities within this chapter were performed by TNO.

2.1 Requirements

The requirements were defined in consultation with the European Space Agency (ESA) and are presented in Table 2.

To evaluate the performance requirements on gravimetric (req. 8) and volumetric specific impulse (req. 9) the 'Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications' (CEA) was used [11]. With the CEA software combustion was simulated assuming the following evaluation point:

- Chemical equilibrium
- Chamber pressure of 10 bar
- Propellant temperature of 273K
- Nozzle expansion ratio of 60.

To be a viable replacement for hydrazine the NOFB should have a specific impulse that is at least as high as that of hydrazine, which is 240 s at the specified evaluation point. Also the volumetric specific impulse should be at least as high as that of hydrazine, which is 249,000 kg.s.m⁻³ at the specified evaluation point.

Table 2: NOFB fuel requirements

Requirement
1. The acute toxicity of the fuel shall be in toxicity hazard category III or higher, according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).
2. The fuel shall have no carcinogenic, mutagenic and/or reprotoxic hazard classification, according to the GHS.
3. The autoignition temperature of the fuel in air shall be > 400K
4. The fuel shall be miscible with nitrous oxide at temperatures between 273K and the critical temperature of the propellant
5. The fuel shall not undergo explosive decomposition when subjected to pressures below 72 bar and temperatures below 309K
6. The sensitivity to impact of the pre-mixed propellant subjected to a Julius-Peters fall hammer test [12], shall be less than 1 J
7. The pre-mixed propellant shall have a decomposition rate of less than 0.2% per year
8. The gravimetric specific impulse of the pre-mixed propellant shall be >240 s.
9. The volumetric specific impulse of the pre-mixed propellant shall be > 249,000 kg.s.m ⁻³ .
10. The vapour pressure of the pre-mixed propellant shall be >15 bar at temperatures between 273 K and the critical temperature of the mixture.

The requirements with respect to health hazards make use of the classification of chemicals according to the 'Globally Harmonized System of Classification and Labelling of Chemicals' (GHS).

The GHS acute toxicity classification of hydrazine is 'category II'. The requirement (req. 1) with respect to acute toxicity requires that the potential fuel is at least an order of magnitude less toxic than hydrazine. According to the GHS this requires a fuel in category III or higher. To be acceptable as a non-toxic and non-carcinogenic alternative to hydrazine, the fuel should not be classified as posing a carcinogenic hazard as well (req. 2).

With respect to safety, to avoid spontaneous ignition of the propellant vapour, the autoignition temperature of the propellant should be well above the maximum temperature that can be reached inside the propellant tanks. This temperature was assessed to be 333K. Applying a safety factor of 1.2, gives a requirement (req. 3) for the minimum autoignition temperature of 400K.

Also, the fuel should be relatively impact insensitive in order to withstand mechanical shocks encountered during handling (safety) and launch. For the requirement (req. 6) this is quantified by means of a Julius-Peters fall hammer test [12], and a limiting value for the impact sensitivity of less than 1 J.

In order to successfully blend the fuel with nitrous oxide and use the resulting propellant on a satellite platform, the fuel must be stable with nitrous oxide at the maximum expected operating pressure and temperature (req. 5). The maximum operational pressure and temperature are taken to be the critical pressure and temperature of nitrous oxide. Also the propellant should be chemically stable in time, such that it can be at least 15 years in space without an unacceptable loss of performance or pressure rise in the propellant tanks (req. 7). ESA typically specifies a value of 0.2% per year as being an acceptable decomposition rate.

Besides stability, the fuel must also be miscible with nitrous oxide at temperatures typical for large satellite platforms, which is assumed to be between 273 K and 333 K (req. 4). In case of an NOFB propellant, the maximum operational temperature is limited by the critical temperature of the propellant.

To make use of the self-pressurizing capability of NOFB, the vapour pressure should not drop below 15 bar (req. 10), which is equal to a typical chamber pressure of 10 bar plus a typical 35% pressure drop over the injector.

2.2 Potential fuels

An initial list of potentially attractive fuels was established by a review of open literature. In our study we extended this list to include some additional smaller hydrocarbons as well as ammonia and some alcohols. The resulting list of candidate fuels is shown in Table 3.

In Table 3 also the available data with respect to the requirements are summarized. The requirement on the autoignition temperature of mixtures of nitrous oxide and different fuels is applied to the autoignition temperature of the fuel in air because data of the actual blends are not available.

The propellant physical properties were taken from the NIST on line database [13]. The vapour pressure of the blend at a stoichiometric mixture ratio were calculated using the vapour pressure of the pure constituents and using Raoult's law of ideal mixtures [14], except for acetylene.

The reason for this is that no saturation data for pure acetylene could be found in open literature, which was needed to apply Raoult's law. Therefore, a more detailed analysis was performed for this mixture using the ASPEN software package [15]

Table 3: NOFB candidate fuels.

Fuel	T _{Cr} K	P _{Cr} bar	req. 1	req. 2	req. 3	req. 4	req. 5	req. 6	req. 7	req. 8	req. 9	req. 10
			GHS tox.	GHS car.	T _{ig} K	Mis.	Exp. Dec.	Imp. Sen. J	Dec. rate %	Isp s	ρIsp g.s.m ⁻³	P _{vap} bar
Ethane (C ₂ H ₆)	309.6	71.6	5	NO	745	YES	NO	?	?	337	275	30.2
Ethylene (C ₂ H ₄)	305.3	48.7	5	NO	723	YES	NO	?	?	342	268	32.4
Acetylene (C ₂ H ₂)	282.5	50.0	4	NO	578	YES	YES	?	?	351	?	30.8
Propane (C ₃ H ₈)	308.3	61.4	4	NO	723	YES	NO	?	?	336	286	28.7
Propene (C ₃ H ₆)	369.8	42.5	3	NO	728	?	?	?	?	339	289	28.6
Propyne (C ₃ H ₄)	365.6	46.6	?	NO	NA	?	?	?	?	334	292	28.0
Butane (C ₄ H ₁₀)	402.4	56.3	5	NO	561	?	?	?	?	336	291	29.0
Ammonia (NH ₃)	425.1	38.0	3	NO	771	?	?	?	?	327	273	20.6
Methanol (CH ₃ O)	405.4	113.0	5	NO	658	?	?	?	?	323	287	23.3
Ethanol (C ₂ H ₆ O)	512.6	81.0	5	NO	636	YES	NO	?	?	331	295	26.8

■ Compliant
 ■ Compliancy unknown
 ■ Not compliant

Miscibility (requirement 5) and explosive decomposition (requirement 6) were evaluated by means of open literature of NOFB propellant studies [16, 17, 18, 19, 20, 6].

The toxicity GHS classification is based on the LC50 or LD50 (depending on the most likely method of exposure) values published by Linde Gas Benelux [21] in their MSDS of hydrocarbon gases and ammonia. For methanol and ethanol MSDS's as published by ScienceLab.com [22] were used to access the toxicity. None of the fuels in Table 3 are referred to as carcinogenic. For none of the fuels impact sensitivity and decomposition rate data were found in the open literature when blended with nitrous oxide.

Based on the requirements, only acetylene is not compliant to at least one of the requirements presented in Table 2 and is discarded as viable NOFB fuel for the remainder of the study.

2.3 Trade-off

The propellants that are compliant to the requirements were evaluated on their effectiveness in meeting the requirements; for this Measures of Effectiveness (MoE) were defined. The MoE's as used for this study are summarized in Table 4. The rationale behind the choice of MoE's is discussed in the following.

The specific impulse is one of the most important engine performance parameters, the higher the specific impulse of an NOFB, the higher the engine performance. For the trade-off, the higher the specific impulse, the higher a fuel will score on this criterion.

The volumetric impulse is also an important engine performance parameter. The volumetric impulse is the multiplication of propellant density and specific impulse. The specific impulse is already defined as an MoE, the second MoE is then the liquid density of the propellant. The higher the saturated liquid density of an NOFB, the higher the volumetric specific impulse resulting in a more compact propulsion system.

Table 4: Measures of Effectiveness.

MoE
1. Gravimetric specific impulse
2. Saturated liquid density
3. Reduced vapour pressure
4. Vapour phase composition at bubble point
5. Risk of not satisfying the requirements
6. Minimum ignition energy
7. Autoignition temperature
8. Combustion temperature

The reduced vapour pressure is defined as the ratio between the mixture vapour pressure at the bubble point and the critical pressure of the mixture. A high reduced vapour pressure means that the propellant is close to the critical point and that the propellant will go completely in the gaseous phase when only a small amount of liquid propellant has been drawn from the propellant tank. From a performance point of view, it would be favourable if a fuel has a low reduced vapour pressure when mixed with nitrous oxide.

When an NOFB mixture is in equilibrium, the liquid and vapour phase will have different compositions, which depend on the vapour pressure of the components and the overall composition of the mixture. Vapour mixtures near stoichiometry are less safe to handle due to the explosion hazards; for this the equivalence ratio (ER) of the NOFB vapour is adopted as MoE.

Table 5: Utility function characteristics per MoE.

MoE	Utility function characteristics	Ranking
Gravimetric specific impulse	Lower limit: Isp Hydrazine (240 s) Upper limit: Highest of blends	10.0 (22.7%)
Saturated liquid density	Lower limit: Lowest of blends Upper limit: Highest of blends	9.0 (20.5%)
Reduced vapour pressure	Lower limit: Highest of blends Upper limit: Lowest of blends	7.5 (17.0%)
Vapour phase composition at bubble point	Lower limit: ER = 1 Upper limit: ER = 0.1 and 10	7.0 (15.9%)
Risk of not satisfying the requirements	Lower limit: Five or more uncertainties Upper limit: No uncertainties	5.0 (11.4%)
Minimum ignition energy	Lower limit: MIE = 500 mJ Upper limit: MIE = 0 mJ and 1 J	3.0 (6.8%)
Autoignition temperature	Lower limit: $T_{ig} = 400$ K Upper limit: $T_{ig} = 800$ K	1.5 (3.4%)
Combustion temperature	Lower limit: $T_c = 2900$ K Upper limit: $T_c = 3400$ K	1.0 (2.3%)

Also, from a safety point of view, it would be favourable to have a fuel with a Minimum Ignition Energy (MIE) as high as possible. This minimizes the risk of an explosion due to static discharge during handling and transportation. However, from a performance point of view, one would like to have a fuel with a MIE as low as possible such that a simple (spark plug) igniter can be used to ignite the propellant. The optimum MIE has

been selected to be 500mJ, which is the lower boundary for compliancy with EU directive 2014/28/EU [12].

Both, from a safety and performance point of view, it is favourable to have an autoignition temperature (T_{ig}) that is as high as possible. A high T_{ig} reduces the risk of a spontaneous explosion of the propellant when stored or operated at high temperatures. Furthermore, a propellant with a high T_{ig} is more suitable for use as a coolant in a regenerative, cooled engine.

NOFB propellants are associated with high combustion temperatures. To cope with these high temperatures, active engine cooling and/or the use of exotic combustion chamber materials is required. For this it is favourable to have a fuel with a low combustion temperature when mixed with nitrous oxide.

In order to rank the candidate fuels on their MoE data objectively, a so-called 'utility function' has been defined for each criterion. The utility functions define the relationship between the actual value of a certain MoE and the corresponding trade-off score, which is a number from 0 to 10. Two examples of a utility function are shown in Figure 1.

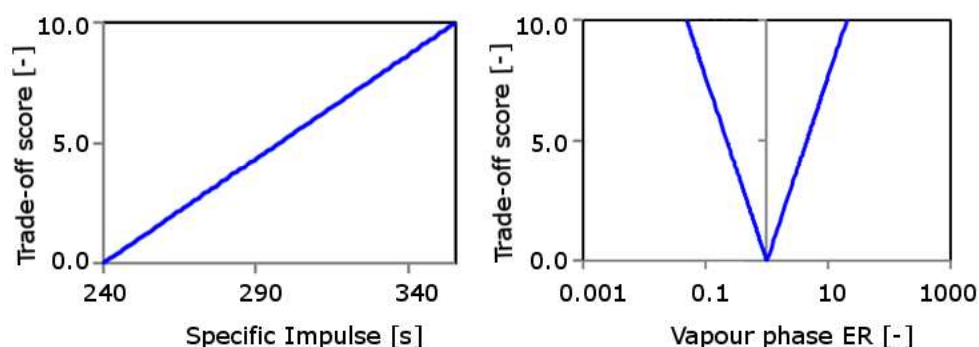


Figure 1: Examples of the utility functions of specific impulse and vapour phase equivalence ratio.

The ranking of the importance of each MoE is a very subjective matter. In Table 5 the utility functions, its characteristics and the assigned ranking values as used in this study are presented. The ranking values were established in close cooperation with ESA. The ranking values are converted into a percentage of the total of the ranking values and presented in the table between brackets.

For each MoE the data was collected and the ranking score based on the utility functions was calculated and multiplied by the relative weight factor (W) as specified in Table 5 to obtain the final trade-off score. The final trade-off scores are presented in Table 6.

Based on the trade-off results in Table 6, ethanol has been selected as the baseline fuel with a total trade-off value of 798. This fuel scores especially well on volumetric specific impulse and vapour phase composition (i.e. safety).

Within the remainder of this report the fuel blend of ethanol / nitrous oxide will be referred to as European Fuel Blend (EUFB).

Table 6: Final trade-off scores. Between brackets the actual value of a criterion is given

Trade-off criterion	Ethane SxW	Ethylene SxW	Propane SxW	Propene SxW	Propyne SxW	Butane SxW	Ammonia SxW	Methanol SxW	Ethanol SxW
Gravimetric specific impulse [s]	(337)191	(342)200	(336)189	(339)191	(334)184	(336)189	(327)170	(323)164	(331)180
Saturated liquid density [kg m ⁻³]	(816)61	(784)6	(852)123	(853)125	(875)162	(867)147	(836)94	(882)182	(392)190
Reduced vapour pressure (P _{vap} /P _{Cr})	(0.62)36	(0.65)22	(0.68)10	(0.61)39	(0.50)87	(0.76)0	(0.31)167	(0.33)159	(0.42)121
Vapour phase composition at bubble point (ER)	(0.73)17	(1.28)9	(0.15)103	(0.19)90	(0.08)135	(0.03)159	(0.15)103	(0.0)159	(0.0)159
Risk of not satisfying the requirements	(3)114	(2)114	(2)114	(4)39	(5)0	(4)39	(4)39	(4)39	(2)114
Minimum ignition energy [mJ]	(0.24)0	(0.07)0	(0.25)0	(0.28)0	(0.28)0	(0.25)0	(628)51	0.143)0	(0.40)0
Autoignition temperature [K]	(745)29	(723)27	(723)27	(728)28	?	(561)14	(771)31	(658)22	(636)20
Combustion temperature [K]	(3170)10	(3263)6	(3178)10	(3235)8	(3331)3	(3182)10	(2945)21	(2974)20	(3093)14
Total (absolute score)	458	384	576	520	571	558	676	745	798

2.4 Properties of the pre-mixed propellants

The main physical and thermodynamic properties of a stoichiometric mixture of nitrous oxide and ethanol (EUFB) are summarized in Table 7.

Table 7: Main physical and thermodynamic properties (theoretical values) of a stoichiometric EUFB.

Properties at 273K	N ₂ O/ Ethanol
Stoichiometric OF ratio [-]	5.73
Saturated liquid density [kg m ⁻³] ¹	892
Critical pressure [bar] ²	63.0
Critical temperature [K] ³	309.6
Vapour pressure at bubble point [bar]	26.75
Vapour phase equivalence ratio at bubble point [-]	0.0005

In Figure 2 the P-xy diagram of the ethanol - nitrous oxide blends are presented. In this figure, for every ethanol – nitrous oxide blend the bubble and dew point are given.

¹ The saturated liquid density of the blended propellant is assumed to be the weighted average of its components.

² The critical temperature of the blended propellant is assumed to be equal to the critical temperature of the pure oxidizer or the pure fuel, whichever is the lowest.

³ The critical pressure of the mixture is assumed to be equal to the critical pressure of the pure oxidizer or the pure fuel, whichever is the lowest.

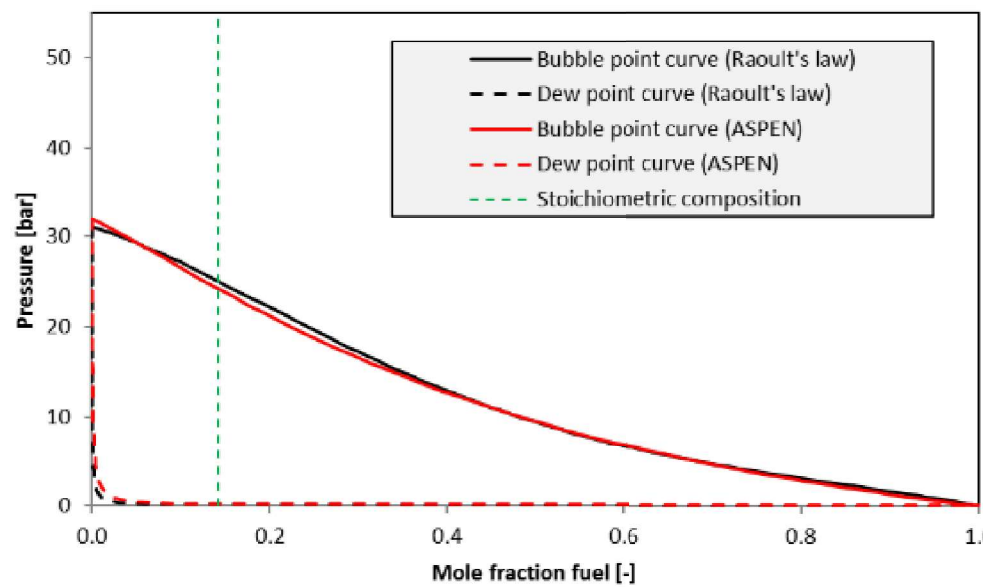


Figure 2: P-xy diagram of the ethanol - nitrous oxide blends at 273 K.

The presented data are theoretical values at a temperature of 273K. Furthermore, the calculation results using Raoult's law or the more accurate ASPEN calculations are presented. For these blends Raoult's law is a very good approximation of bubble point and dew point.

3 Propellant handling study

This chapter will discuss the main activities and results of the propellant handling study. The activities within this chapter were executed by TNO.

3.1 Stability and miscibility

In open literature no information was found about mixing ethanol safely with nitrous oxide (requirements 4 and 5). In order to investigate whether the NOFB is chemically stable (i.e. that it does not decompose or explode when the constituents come into contact with each other) and is homogeneously miscible, mixing trials were performed.

An existing test apparatus was modified for these mixing trials. The constituents of the EUFB were remotely added at ambient temperature and a pressure of approximately 50 bar. This pressure is slightly above the vapour pressure of nitrous oxide at room temperature, which ensures that both the nitrous oxide and the fuel are in the liquid phase when mixed together.

The test apparatus consist of a buffer vessel, shown in Figure 3, which is a stainless steel pressure vessel that can be filled with liquid nitrous and can be pressurized with nitrogen gas up to 100 bar.

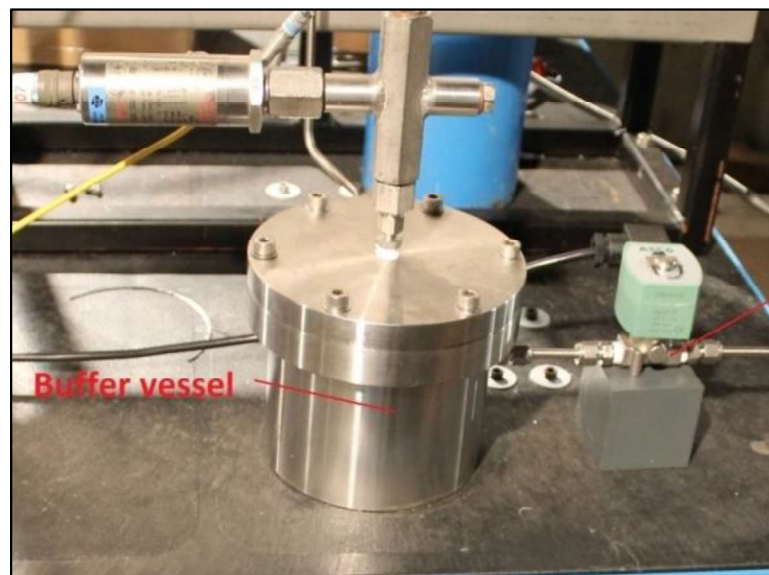


Figure 3: Buffer vessel in the mixing trial setup.

In the setup a test tube (Figure 4) is installed. This test tube is a specially designed glass tube that contains the actual propellant mixture during a test and can withstand pressures up to 55 bar.

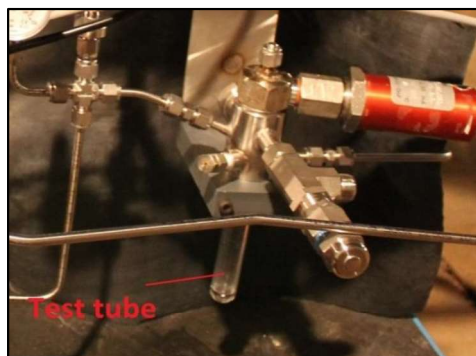


Figure 4: Test tube in the mixing trial setup



Figure 5: Fluid distribution system.

The fluid distribution system is an arrangement of tubes, valves and other flow control components that are used to control different fluid flows inside the test apparatus. The fluid distribution system has 8 electrically actuated valves and one manually operated needle valve. The electrical valves can be opened and closed remotely.

Mixing trials have been performed with a near stoichiometric mixture of nitrous oxide and ethanol ($ER \approx 1.02-1.25$). First the test tube was filled with 2 ml ethanol and installed in the test setup (Figure 6, A). When the first nitrous oxide is added to the ethanol, the components seem to mix well (Figure 6, B). However, after the total volume in the test tube reached approximately 6.5 mL, the liquid column separated into two layers (Figure 6, C). When more nitrous oxide was added, the volume of the top layer increased while the volume of the bottom layer remained constant at 6.5 mL (Figure 6, D). When the target amount of nitrous oxide was added (i.e. when the total volume in the test tube reached 10 mL), the bottom layer still occupied a volume of 6.5 mL and the top layer occupied a volume of 3.5 mL (Figure 6, E).

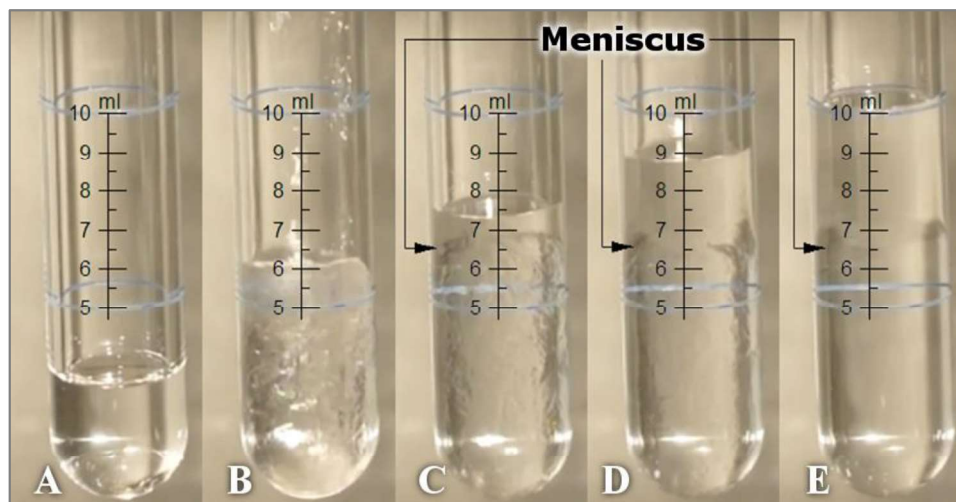


Figure 6: Nitrous oxide is added to the ethanol. At a total volume of approximately 6.5 mL, the mixture separates into two layers and a meniscus appears.

While performing the mixing trials it was found that with the test apparatus it was impossible to avoid small leaks, because the apparatus was never designed for these type of tests. For the mixing trials and stability tests, the small leaks had the advantage that slowly the gas on top of the liquid was evacuated from the setup (Figure 7, F-J) and with this, the total liquid volume decreased slowly over time.

The meniscus that separated the two layers faded away and eventually disappeared when the total liquid volume had dropped to approximately 8.5 mL (Figure 7, I).

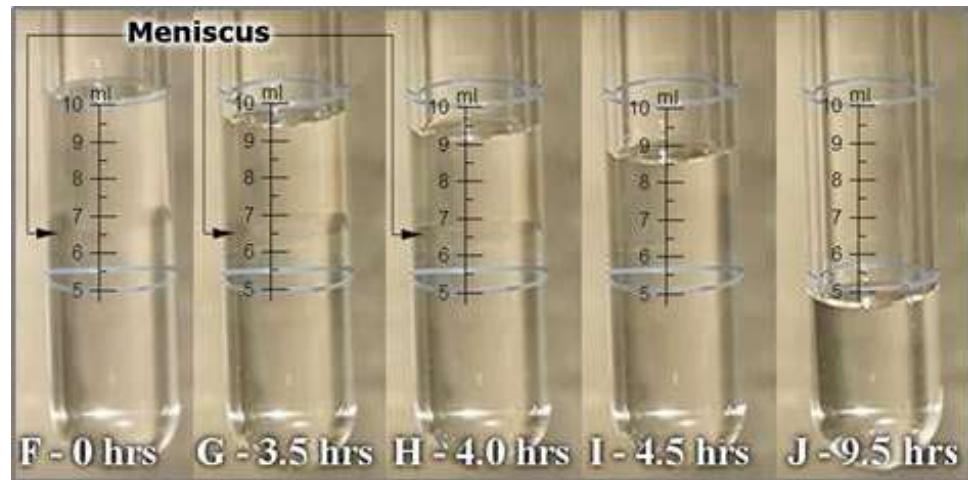


Figure 7: Evolution of the mixture during a time period of 9.5 hrs (J)

Since the bottom layer must per definition have a higher density than the top layer, the mixture was most likely at a temperature at which the density of ethanol is higher than the density of nitrous oxide (otherwise, the nitrous oxide layer would be on the bottom). Figure 8 shows the density of ethanol (at 50 bar) and saturated nitrous oxide as a function of temperature.

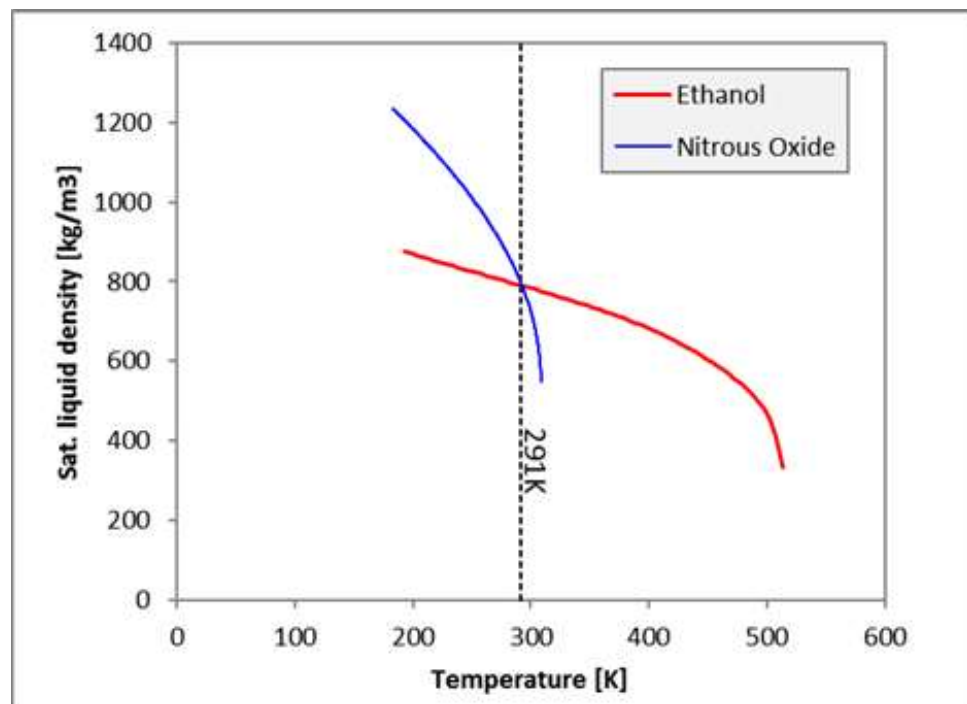


Figure 8: Liquid density of ethanol [23] and nitrous oxide [13], as a function of temperature.

As can be seen, the density of nitrous oxide drops below that of ethanol when the temperature is above 291 K. Although the liquid temperature was not measured, it is plausible that the liquid temperature was above 291 K, which would explain that the nitrous oxide layer was formed on the top. Another possibility is that the liquid was in

fact colder than 291 K, but that the interaction between the ethanol and nitrous oxide results in a mixture with a higher density than the weighted average of its components (as these components form a non-ideal mixture).

Based on the observations, it was concluded that the top layer of the liquid column consisted primarily of nitrous oxide (since its volume increased when additional nitrous oxide was added), whereas the bottom layer consisted of nitrous oxide and ethanol at a volume ratio of approximately 4.5:2 (i.e. a volumetric Oxidizer to Fuel (OF) ratio of 2.25). In the range of mixture compositions that were investigated (volumetric OF ratio ranging from 0 to 4), the ethanol acts as the solvent and the nitrous oxide as the solute (i.e. nitrous oxide dissolves in ethanol, not the other way around). The ethanol appears to have the ability to dissolve more than two times its own volume of nitrous oxide before it becomes saturated.

From the mixing trials it was concluded that ethanol seems to demonstrate good stability when mixed with nitrous oxide at (near) stoichiometric mixture ratios. No bubbles, or other indications of a (decomposition) reaction were observed when the constituents were added together and remained in the test tube over a period of 70 hours.

It was concluded that ethanol and nitrous oxide are not miscible in all proportions. At temperatures around 293K (ambient temperature during the mixing trials), the components seem to be miscible in volumetric OF ratios ranging from 0 up to 3.15. At higher volumetric OF ratios (i.e. at higher nitrous oxide fractions), the excess nitrous oxide forms a separate layer on top of the mixture.

3.2 Handling and safety procedures

This chapter gives an overview of the procedures that must be followed to safely handle and store the potential EUFB constituents during preparation and execution of the hot firing test campaign at NAMMO Westcott. The philosophy for the hot firing test campaign is to feed the oxidizer and fuel to the engine as two separate propellant flows. The two flows are combined just upstream of the injector in a specially designed mixing chamber. The resulting mixed flow is then injected into the engine as a liquid pre-mixed monopropellant.

This philosophy offers a big safety advantage, as there is no need to store and handle a pre-mixed EUFB propellant on site. Only the pure constituents of the EUFB propellant must be handled. Therefore, this chapter focusses the procedures for safely handling the pure EUFB constituents, i.e. nitrous oxide (oxidizer) and ethanol (primary fuel). The information presented in this chapter was taken from the relevant Safety Data Sheets.

3.2.1 Nitrous oxide

3.2.1.1 Precautions for safe handling

- Only experienced and properly instructed persons should handle gases under pressure
- Use only properly specified equipment which is suitable for nitrous oxide, its supply pressure and temperature
- Keep equipment free from oil and grease

- Open valve slowly to avoid pressure shock⁴
- Use only oxygen approved lubricants and sealants
- Use only with equipment cleaned for oxygen service and rated for the pressure⁵
- Refer to supplier's handling instructions
- The substance must be handled in accordance with good industrial hygiene and safety procedures
- Protect containers from physical damage; do not drag, roll, slide or drop
- Do not remove or deface labels provided by the supplier for the identification of the container contents
- When moving containers, even for short distances, use appropriate equipment, such as a trolley, hand truck, fork truck, etc.
- Provide adequate ventilation
- Do not allow back feed into the container
- Avoid suck back of water, acid and alkalis
- Keep container below 50°C in a well ventilated place
- Observe all regulations and local requirements regarding storage of containers
- Do not eat, drink or smoke near a nitrous oxide cylinder
- Store in accordance with local/regional/national/international regulations
- Leave valve protection caps in place until the container has been secured against either a wall or bench or placed in a container stand and is ready for use. Damaged valves should be reported immediately to the supplier.
- Close container valve after each use and when empty, even if still connected to equipment. Never attempt to repair or modify container valves or safety relief devices.
- Replace valve outlet caps or plugs and container caps where supplied as soon as container is disconnected from equipment
- Keep container valve outlets clean and free from contaminants particularly oil and water. If user experiences any difficulty operating container valve discontinue use and contact supplier.
- Never attempt to transfer gases from one container to another. Container valve guards or caps should be in place.
- Contact your gas supplier if in doubt of anything related to the above.

3.2.1.2 *Conditions for safe storage*

- Containers should not be stored in conditions likely to encourage corrosion. Stored containers should be periodically checked for general conditions and leakage.
- Container valve guards or caps should be in place

⁴ The hot firing test setup of NAMMO Westcott will only feature 'slow response' valves in order to avoid pressure shocks.

⁵ To avoid unintended combustion reaction with greases and other chemical residues that can act as a fuel.

- Store containers in location free from fire risk and away from sources of heat and ignition
- Keep away from combustible material. Avoid asphalted locations for storage, transfer and use (ignition risk if spilt)
- Segregate from flammable gases and other flammable materials being stored.
- The use of brass (and other copper alloys) for highly stressed components should be avoided, as this introduces the risk of stress corrosion cracking [24].
- Non-metallic valve/container materials that should be avoided are: PP, POM, PPS, PVC, IIR, NBR, CR, FKM (Viton®) and HC [25].

3.2.2 *Ethanol*

3.2.2.1 *Precautions for safe handling*

- Use only in well-ventilated areas
- Do not drag, slide or roll containers
- Use a suitable hand truck for container movement
- Do not heat container by any means to increase the discharge rate of product from the container
- Use a check valve or trap in the discharge line to prevent hazardous back flow into the container.
- Contact your gas supplier if in doubt of anything related to the above.

3.2.2.2 *Conditions for safe storage*

- Store only in transportation approved container in which it was received and in cool, dry, well ventilated area of non-combustible construction away from all sources of ignition.
- Post “No Smoking or Open Flames” signs
- Avoid all contact with the liquid or vapour
- Close container after each use and when empty

3.3 **Material stability and compatibility**

This paragraph lists the known stability and compatibility issues related to the potential EUFB constituents. As mentioned in the previous chapter, mixing of the fuel and oxidizer components will take place inside the test setup, eliminating the need to store the PMP as a whole. For this reason, only the stability and compatibility issues of the individual constituents will be considered. The information in this chapter was taken from the relevant Safety Data Sheets, as well as from the Cole-Parmer Chemical Compatibility Database [26].

3.3.1 *Nitrous oxide*

3.3.1.1 *Chemical stability*

Stable under normal conditions. At temperatures above 575°C and at atmospheric pressure, nitrous oxide decomposes into nitrogen and oxygen. Pressurised nitrous oxide can also decompose at temperatures equal to or greater than 300°C.

3.3.1.2 Compatibility

May react violently with combustible materials, reducing agents and organic material. Table 8 provides a qualitative assessment of the compatibility between nitrous oxide and various other materials. For the hot firing test campaign at NAMMO Westcott, only materials with an A and B rating are recommended.

Table 8: Chemical compatibility of nitrous oxide with various materials [26].

Material	Compatibility	Material	Compatibility
Aluminium	B-Good	Neoprene	A-Excellent
Brass	B-Good	Nylon	C-Fair
Bronze	D-Severe Effect	Polypropylene	D-Severe Effect
Carbon graphite	C-Fair	Polyurethane	B-Good
Carbon Steel	B-Good	PTFE	A-Excellent
Carpenter 20	B-Good	PVC	A-Excellent
ChemRaz (FFKM)	A-Excellent	PVDF (Kynar®)	D-Severe Effect
Copper	B-Good	Stainless Steel - 304	B-Good
EPDM	A-Excellent	Stainless Steel - 316	B-Good
Fluorocarbon (FKM)	A-Excellent	Tygon®	A-Excellent
Hastelloy-C®	B-Good	Tygon® (E-3603)	A-Excellent
LDPE	C-Fair	Viton®	B-Good
Natural rubber	A-Excellent		

It should be noted that in open literature the compatibility data for nitrous oxide is not unambiguously published and sources can contradict each other. An example is PVC of which the use with nitrous oxide should be avoided according to [25] while [26] states that PVC is 'A-Excellent' compatible with nitrous oxide. It is advised to use only materials with nitrous oxide for which literature is consistent with respect to compatibility. If materials have to be used for which consensus is not unambiguously reported compatibility should be experimentally determined by means of dedicated tests.

3.3.2 Ethanol

3.3.2.1 Chemical stability

Ethanol (or ethyl alcohol) is stable under normal temperatures and pressures.

3.3.2.2 Compatibility

Ethanol is noncorrosive to most metals. The use of lead, aluminium and zinc coated (galvanized) metals should be avoided. Ethanol is incompatible with oxidizers and alkali metals. Table 9 provides a qualitative assessment of the compatibility between ethanol and various other materials.

Table 9: Chemical compatibility of ethanol with various materials

Material	Compatibility	Material	Compatibility
ABS plastic	B ¹ -Good	Kel-F®	A-Excellent
Acetal (Delrin®)	A ¹ -Excellent	LDPE	B-Good
Aluminium	B-Good	Natural rubber	A-Excellent
Brass	A-Excellent	Neoprene	A-Excellent
Bronze	A-Excellent	Noryl®	A ¹ -Excellent
Buna N (Nitrile)	C-Fair	Nylon	A ¹ -Excellent
Carbon graphite	A-Excellent	Polycarbonate	B ² -Good
Carbon Steel	B-Good	Polyetherether Ketone (PEEK)	A-Excellent
Carpenter 20	A-Excellent	Polypropylene	A-Excellent
Cast iron	B-Good	Polyurethane	D-Severe Effect
Ceramic Al ₂ O ₃	A-Excellent	PTFE	A-Excellent
ChemRaz (FFKM)	A-Excellent	PVC	C-Fair
Copper	A-Excellent	Santoprene®	A-Excellent
CPVC	B-Good	Silicone	B-Good
EPDM	A-Excellent	Stainless Steel - 304	A-Excellent
Epoxy	A ² -Excellent	Stainless Steel - 316	A-Excellent
Fluorocarbon (FKM)	B-Good	Titanium	A-Excellent
Hastelloy-C®	A-Excellent	Tygon®	C-Fair
HDPE	A-Excellent	Tygon® (E-3603)	C-Fair
Hypalon®	A-Excellent	Viton®	A-Excellent
Kalrez®	A-Excellent		

¹ Satisfactory to 22 °C.² Satisfactory to 48 °C

4 Testing of the European Fuel Blend

This chapter describes the test rig design for mixing and injecting the EUFB, and presents the results from the hot-firings. The activities within this chapter were executed by NAMMO Westcott and Airborn Engineering Ltd.

4.1 Test set-up

4.1.1 Test rig

The handling properties of the chosen EUFB are largely unknown. It was therefore considered too dangerous to use a pre-mixed tank of the fuel blend for the hot-firing tests, because of the risk of flashback through the plumbing. It was therefore decided to use a standard bi-propellant setup with two separate feed systems and to mix the propellant in real time in a small volume just before injection into the combustion chamber. Furthermore, it was decided to maintain the propellant in a liquid form up until the point of injection, because there will then be a high degree of flash boiling during injection, and therefore good isolation between the plumbing and the combustion chamber.

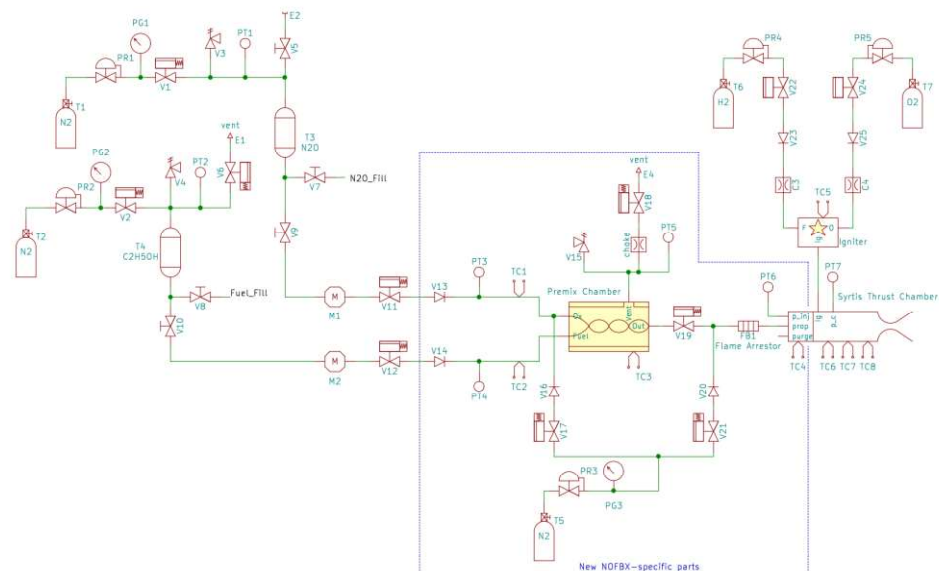


Figure 9: Process and instrumentation diagram (P&ID) for the NOFB test rig.

Figure 9 shows a simplified P&ID for the test rig. Both propellant tanks are pressurised with nitrogen with appropriate valves for pressure relief, isolation, fill and drain. The propellants pass through separate Coriolis mass flow meters before passing into a small premix chamber, before then passing through a run valve and a flashback arrestor made from sintered stainless steel. A nitrogen purge system purges both the premix chamber and the injector gallery immediately after test completion. A hydrogen-oxygen gas torch igniter was used.

4.1.2 Pre-mix chamber

The purpose of the pre-mix chamber is to mix the two propellants in real time, in their liquid state, before they are fed to the engine's injector. This is to avoid any hazards associated with mixing and storage of the fuel blend. The pre-mix chamber must form

a homogenous EUFB liquid, and must have a minimal volume of pre-mixed propellant, although significant in comparison to the injector volume in order to minimise flash boiling when the run valve is opened.

The pre-mix chamber must therefore mix the two liquids efficiently in a small volume. At high Reynolds number, liquid mixing from a jet occurs from turbulent dissipation of structures, commonly either from jet impingement or from vortical rollup at a liquid-liquid shear layer. For the EUFB pre-mix chamber, it is important that there is very little unused volume to minimise stored energy. Unused volume is common for jet impingement injectors, where the jets commonly form only part of the area of a larger face. For the EUFB there is also a large difference in volume flow rate between the two liquids - it is dominated by the nitrous oxide flow. This has two effects: first, it makes distribution of the fuel the priority for mixing, and second, it means that the bulk of the turbulence generation has to come from the larger nitrous oxide flow.

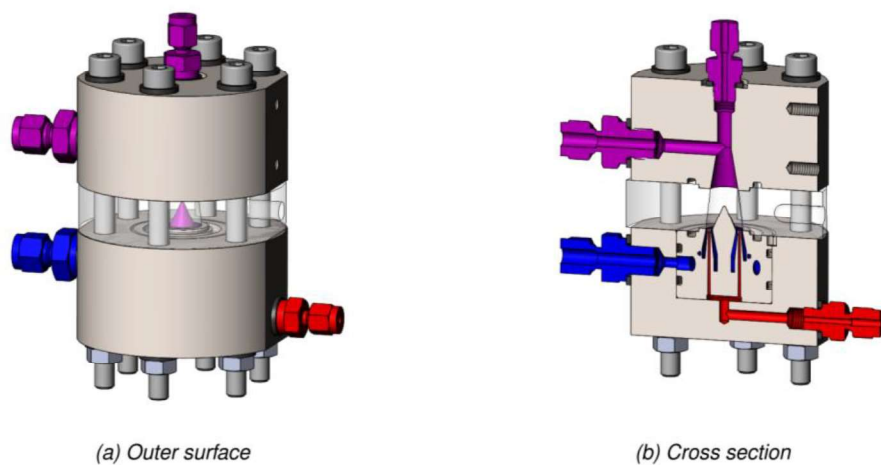


Figure 10: Pre-mix chamber consisting of four machined parts: the additively manufactured injector block and injector housing, the chamber outlet and the chamber spacer (acrylic). The flow paths are colour coded dependent on the fluid: fuel (red), oxidiser (blue), EUFB (purple). There are two outlets, one to the engine (horizontal), and one to a choke which was sized to maintain steady state backpressure during filling (vertical).

The pre-mix chamber was therefore designed to mix the ethanol into the nitrous oxide as homogeneously as possible, whilst minimising the unused chamber volume by using almost the entire injector face. To achieve this, the pre-mix injector:

- 1 Splits the nitrous oxide into two swirling flows.
- 2 Generates a strong shear layer using the two contra-rotating nitrous oxide flows to maximise turbulence.
- 3 Pre-distributes the fuel using plumbing as much as is reasonably practical.
- 4 Injects the small fuel flow rate directly into the nitrous oxide shear layer to maximise its distribution by the turbulence.

Figure 10 and Figure 11 show the geometry of the pre-mix chamber and the additively manufactured pre-mix injector. All parts are made from aluminium except the acrylic chamber spacer.

The pre-mix chamber features a vent connection on the top. This allows gas to be purged from the premix chamber before firing. Furthermore, the vent allows the pre-mix chamber to be filled with fuel blend ahead of the firing. This is achieved by a metering choke fitted into the vent line which gives an equivalent back-pressure to that of the main injector / engine.

The clear acrylic spacer allows verification of the flow phase in the pre-mix chamber and also provides a deliberate failure zone to deal with over-pressure events. The pre-mix chamber injector involves two counterrotating swirling flows of oxidant, each roughly half the mass flow, with the fuel injected in axially through ten 0.5mm holes at the shear layer between the swirling flows. The mixing therefore occurs due to the shear between the $\pm 40\text{m/s}$ counter-rotating flows in the tangential direction, and the shear between the $\sim 40\text{m/s}$ fuel jet and slow moving oxidiser flows in the axial direction. The swirling of the oxidant was achieved through tangential holes into galleries, and the injection of the fuel through small axial holes distributed evenly around the circumference between the two swirling flows. A centre body reduces the chamber volume whilst keeping the shear layers together. A significant pressure drop exists between the individual fuel and oxidiser feeds in order to provide sufficient hydraulic isolation of the feed systems.

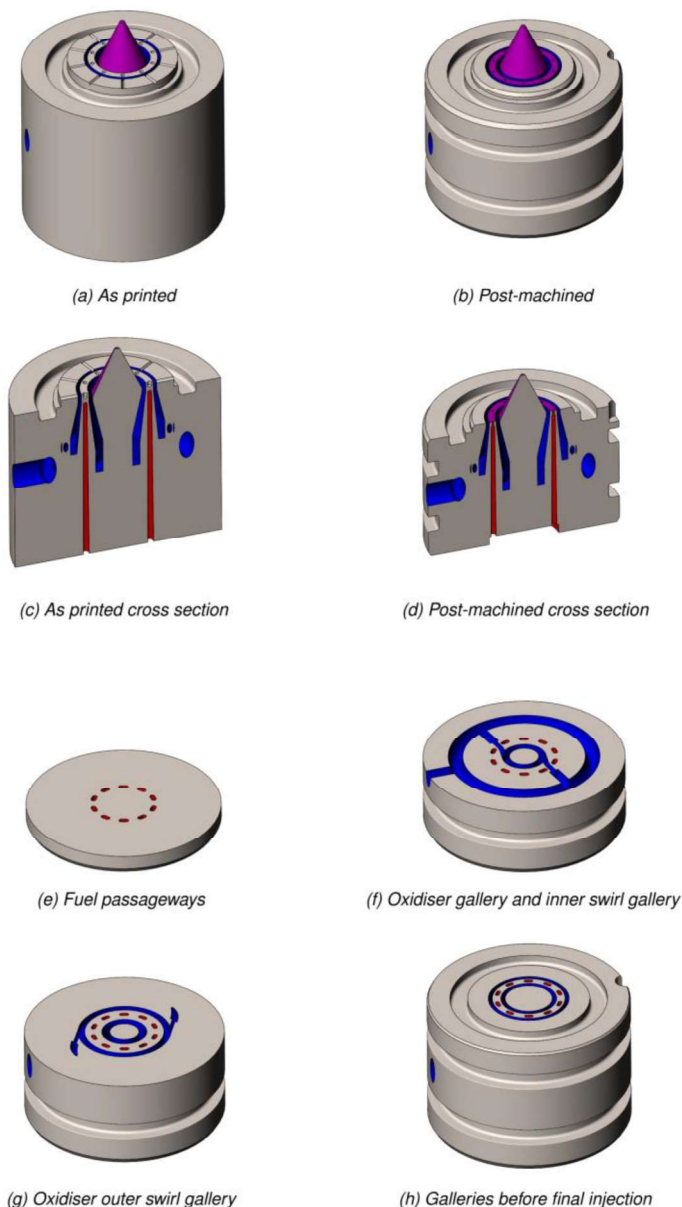


Figure 11: Pre-mix injector block, showing as printed ((a),(c)) and post-machined geometry, including cross sections showing the internal manifolding. The flow paths are colour coded dependent on the fluid: fuel (red), oxidiser (blue), EUFB (purple).

4.1.3 Monopropellant Injector

The injector for the combustion chamber was a simple showerhead because there is no need for mixing within the combustion chamber. The injector has 19 holes. The injector holes are each fed by its own internal pathway of approximately 1.5mm diameter and 50mm long, in order to reduce dribble volume of pre-mixed propellant. There is a high pressure drop across the injector to keep the nitrous oxide in the liquid state in the pre-mix chamber. This means that there will be a significant amount of flash-boiling in the injector orifices. This flash-boiling should help keep the flame front within the combustion chamber.

Nitrous oxide injector flash-boiling is a complicated process, which relies on the pressure drop, heat load from the injector and stay time in the injector orifice. It has been studied in detail in the literature [27] [28] [29].

The nitrous oxide behaves somewhere between two limits: first, where the nitrous oxide remains liquid, which is the single phase incompressible (SPI) limit, and second, where the nitrous oxide remains in equilibrium, expands isentropically and the phases travel at the same velocity, which is the homogeneous equilibrium (HEM) limit. The model proposed by [28], with a correction by [29] and tested by [27] uses a smooth blending between the SPI and HEM extremes, based on the relative bubble growth time and residence time in the injector. This model is known as the Non-Homogeneous Non-Equilibrium (NHNE) model [27], and has been tested extensively for cold flow injection at a range of injector and chamber pressures.

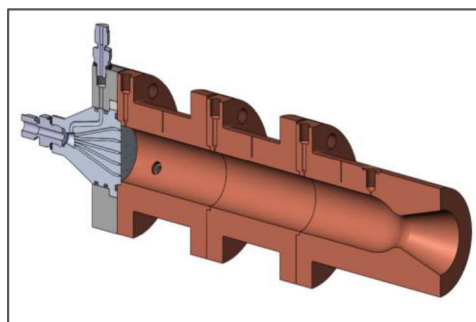


Figure 12: Section of the 3D printed aluminium injector block and copper heat sink combustion chamber as used in the NOFB tests

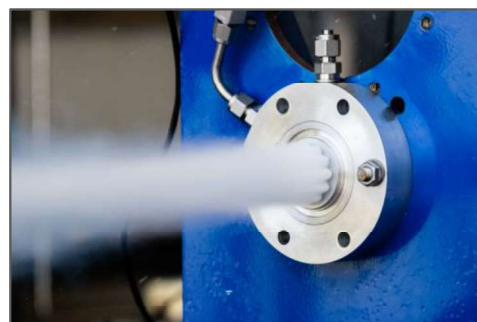


Figure 13: Flash-boiling of the NOFB from the showerhead injector in a cold flow test without combustion chamber.

The NHNE model was used to calculate the injector hole sizes for the showerhead injector. Figure 12 shows the injector block. It was additively manufactured from aluminium and post-machined on the sealing surfaces and drilled on the injector face. Aluminium was used for its relatively high thermal conductivity and because it decomposes nitrous oxide less than copper at high temperature. Because the injector was only used for very short firings, its lower melting temperature was considered sufficient given experience with previous bipropellant injectors. Figure 13 shows the flash-boiling of the fuel blend in cold flow testing without the combustion chamber. The experimental cold flow injector pressure drop results matched well with those predicted by the theoretical NHNE model [27].

4.1.4 Characteristic Velocity

The characteristic velocity, c^* , is often used to categorise the combustion in the chamber, because it is independent of the nozzle geometry. Some calculation steps

are required, however, to accurately compare experimental c^* values, based on static pressure measurements, and theoretical c^* values once heat loss to the combustion chamber is taken into account.

As will be shown in the results section, this heat loss is particularly important for NOFB propellants. The experimental c^* value is calculated as:

$$c^* = \frac{P_{eoc,0} A_t}{\dot{m}_{TOT}} \quad \text{Eq. 1}$$

where the throat area (A_t) is based on a measured diameter of 21.05mm ($A_t = 3.48 \times 10^{-4} \text{ m}^2$). No adjustment of throat area is made for the temperature of the nozzle during hot firing, because this requires significant FEA analysis and thermal measurements and was therefore out of scope of this programme.

The static chamber pressure, p_{eoc} , is measured at the end of the combustion chamber (eoc). The chamber stagnation pressure, $p_{eoc,0}$ can be found from this using the ratio of specific heats, γ_{eoc} , and the chamber Mach number, M_{eoc} , which is a function of the combustion chamber to throat area ratio. Both M_{eoc} and γ_{eoc} are found from CEA [11].

$$P_{eoc,0} = P_{eoc} \left(1 + \frac{\gamma_{eoc}-1}{2} M_{eoc}^2 \right)^{\frac{\gamma_{eoc}}{\gamma_{eoc}-1}} \quad \text{Eq. 2}$$

4.1.5 Heat loss rate

Heat is lost from the combusting gasses to the copper heat sink chamber and the aluminium injector head.

Calculating the heat flux as a function of position in the chamber is a complex problem and for good fidelity requires many thermocouples, or coolant calorimetry, and as such it cannot be done with the current experimental setup.

The average heat loss to the chamber can be calculated, however, by calculating the total enthalpy rise in the chamber components using calorimetry and then dividing by the run time. This average value will be fairly accurate when the chamber pressure remains roughly constant during a test.

The average heat loss rate is therefore given by:

$$q_{hl,ave} = \frac{\sum_i m_i c_i (T_{end} - T_{start})}{\Delta t} \quad \text{Eq. 3}$$

where m_i are the thermal mass values of the aluminium injector and copper chamber sections, Δt is the firing time, T_{end} is the temperature at the end of the dataset when the temperatures have equilibrated (at 30s for the hot firings) and T_{start} is the temperature at the start of the firing. The start and end of the firing, which define Δt , are taken as where the chamber pressure has risen above half of its maximum value. The start time is therefore commonly around 0.4s, rather than 0s, which helps ignore additional heat input from the gas torch igniter. By using half the maximum chamber pressure as the threshold, the firing time takes account of the ramp-up and ramp-down times of the chamber pressure (and therefore ramping of the heat flux to the combustion chamber); this should produce a better 'average' heat loss rate from the calorimetry, because the average assumes that the heat load is constant with time.

4.1.6 Theoretical characteristic velocity

The theoretical characteristic velocity, c_{theor}^* , is calculated by the CEA program [11] using a multiple pass process. In all cases the finite area combustion model is used, with the experimental combustion chamber area to throat area ratio (3.07). Using the finite area combustion model allows calculation of the combustion chamber Mach

number and ratio of specific heats, and also incorporates the stagnation pressure loss due to acceleration of the gases between the injector (inj) and the end of the combustion chamber whilst under heat addition. This is roughly 2% in this case, and can be expressed as a function of the chamber Mach number using Rayleigh flow assumptions and using integrated Mach equations ([30] with typographical correction).

$$\frac{p_{inj,0}}{p_{eoc,0}} = \frac{1 + \gamma_{eoc} M_{eoc}^2}{(1 + \gamma_{eoc} M_{eoc}^2)^{\frac{\gamma_{eoc}}{\gamma_{eoc}-1}}}$$

Eq. 4

In all cases equilibrium thermodynamics are assumed in the nozzle, because frozen thermodynamics cannot be used simultaneously in CEA with the finite area combustion model. The c_{theor}^* values for equilibrium thermodynamics will be slightly higher than the frozen flow equivalents, with the real nozzle flow somewhere between the two. The input enthalpy of the nitrous oxide is specified to CEA using the enthalpy of formation ($\Delta H_f = +82.05 \text{ kJ/mol}$) plus the enthalpy difference between the injection conditions at chamber pressure and premix chamber temperature and those at standard temperature and pressure. Note that the premix chamber temperature, T_{pmx} , must be used here because there was no thermocouple in the injector flow itself. The calculation method used in this paper extremely similar to that used in [4] for analysing “HyNOx” propellants, although the heat loss rate here is calculated by calorimetry. To avoid confusion, the notation used here is similar to [4]. When calculating the heat-loss adjusted characteristic velocity, $c_{theor,hl}^*$, the input enthalpy of nitrous oxide is therefore specified as:

$$H_{N_2O;hl} = \Delta H_f + (H(p_c, T_{pmx}) - H(10^5, 298; 15)) - \frac{q_{hl,ave} M_{N_2O}}{\dot{m}_{N_2O}}$$

Eq. 5

where the molar mass, $M_{N_2O} = 0.0440123 \text{ kg/mol}$, and mass flow of nitrous oxide, $\dot{m}_{N_2O}$, are used to convert the enthalpy into kJ/mol for the input to CEA. This process therefore removes the heat loss enthalpy from the input oxidiser stream. An equivalent could be done for the fuel stream, and both can be shown to result in the correct enthalpy loss from the combusted gases, but the oxidiser is used here for convenience.

The theoretical characteristic velocity values are therefore calculated in three steps:

- 1 Call CEA with pressure ratio $p_{inj}/p_e = p_{eoc}/p_{atm}$, with exit pressure set to atmospheric, $p_e = p_{atm}$, and H_{N_2O} to obtain the ratio of p_{inj}/p_{eoc} .
- 2 Call CEA again but with the scaled injector pressure $p_{inj}/p_e = p_{inj}/p_{eoc} * p_{eoc}/p_{atm}$. This then matches the static pressure at the end of the combustion chamber to that of the experimental value (technically one should iterate here but the pressure value is close after a single pass). This results in the values for c_{theor}^* , γ_{eoc} and M_{eoc} .
- 3 Call CEA as before but with the heat loss adjusted oxidiser enthalpy, $H_{N_2O,hl}$, to get the value for $c_{theor,hl}^*$.

The combustion efficiency values, η_{c*} , can then be calculated for the standard and for the heat loss adjusted cases.

$$\eta_{c*} = \frac{c^*}{c_{theor}^*}, \quad \eta_{c*,hl} = \frac{c^*}{c_{theor,hl}^*}$$

Eq. 6

This heat loss adjustment will likely be slightly conservative for two reasons. First, because after the firing some heat transfer will occur from the chamber and injector to the surrounding support structure, pipe work and air, and this enthalpy rise is not accounted for by the calorimetry. Second, because some heat will be lost to the cold nitrogen gas purge. It should be noted, however, that some enthalpy from the torch igniter will be erroneously included in the heat loss calculation due to the cross over time between main propellant flow and igniter flow; this would act to reduce the heat loss adjustment.

4.2 Results of the firing tests

Reagent grade ethanol (>99.8%) and technical grade nitrous oxide were used to create a liquid EUFB. The liquid EUFB was hot-fire tested at the desired operating condition (OF 3.18) and two other mixture ratios, one leaner (OF 3.83) and one richer (OF 2.21). Unfortunately, the showerhead injector face was eroded after only a few firings, but some key conclusions can be drawn from the available data, albeit without the statistical certainty from repeated test points.

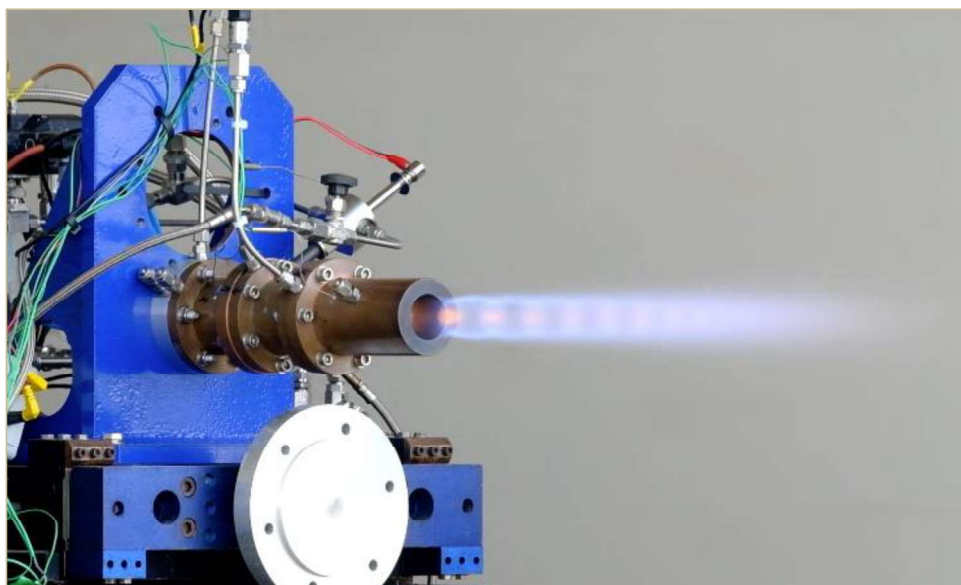


Figure 14: Stable combustion of a liquid nitrous oxide/ethanol fuel blend at mixture ratio 3.85

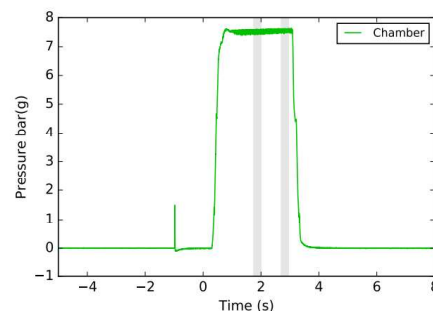
4.2.1 Mixture ratio 3.83

At the leaner condition (OF 3.83) the propellant lit, burned and shutoff smoothly. A minor combustion instability was visible on the chamber pressure trace, at 25Hz with amplitude 0.1bar (1.4% of chamber pressure). No flashback into the injector gallery was seen on shutdown or start-up, which is visible from the smooth injector pressure trace in Fig. 7(b). This suggests that the combination of flash boiling in the injectors, followed by immediate nitrogen purge (visible as the tail Fig. 7(b)) was sufficient for preventing flashback in this test setup. Table 10 shows key time-averaged values for a test at mixture ratio 3.83. The combustion efficiency of the EUFB was 93.4% when no heat losses are taken into account, but this increases to 97.5% when this is corrected for heat lost to the chamber. Given that the heat loss correction is slightly conservative, this suggests that there was almost complete combustion in the chamber, which in turn suggests a fairly homogeneous propellant mixture; the injector

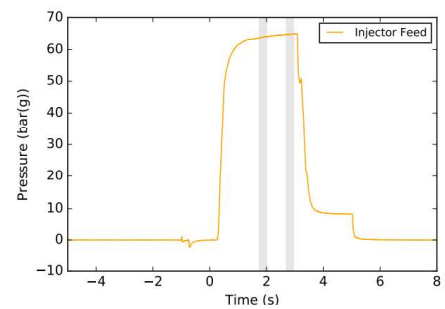
was only a showerhead which has poor mixing between injector flows and therefore could not homogenise the flow if there were large mixture ratio variations between injector elements.

Table 10: Key time-averaged values for mixture ratio 3.83, averaged in the two windows shown in Fig. 7 at times 1.88s and 2.83s. Derived performance values are calculated and compared with theoretical ones calculated with CEA.

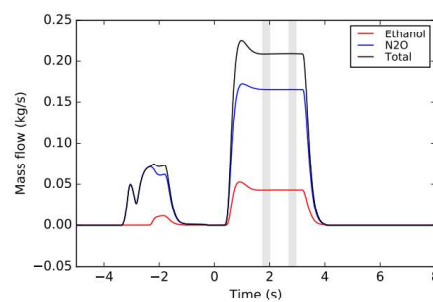
	1.88s	2.83s	
Injector Feed	63.93	64.83	bar(g)
Chamber	7.54	7.57	bar(g)
Ethanol	0.043	0.043	kg/s
N ₂ O	0.166	0.166	kg/s
O/F	3.86	3.83	
Total	0.208	0.209	kg/s
Premix Chamber	18.43	18.27	°C
Injector Face	146.64	164.02	°C
c_{theor}^*	1567.5	1566.8	m/s (CEA)
$c_{theor,hl}^*$	1502.2	1501.0	m/s (CEA)
c^*	1460.5	1463.4	m/s (Derived)
η_{c^*}	93.17	93.40	% (Derived)
$\eta_{c^*,hl}$	97.22	97.49	% (Derived)



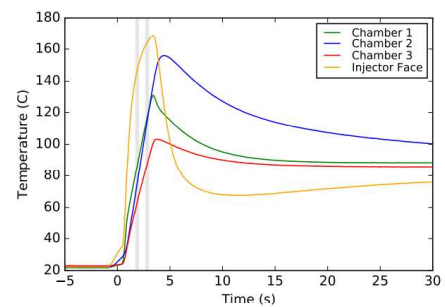
(a) Chamber pressure



(b) Injector pressure



(c) Mass flows



(d) Chamber temperatures

Figure 15: Key traces from the hot firing with liquid NOFB at mixture ratio 3.83. Steady mass flow (c) and chamber pressure (a) are achieved after roughly 1.5s, but the injector pressure increases (b) with the injector face temperature (e). The time averaging windows are shown as vertical grey bars. Note that all graphs have the same time base, apart from the chamber temperatures (in order to show the effect of thermal soak). Time 0s is when the main run valve is commanded to open.

4.2.2 Mixture ratio 2.21

At the richer mixture ratio of 2.21 the propellant lit, but with rough combustion in the chamber and with significant external burning (Figure 16(a)), before the flame blew out shortly after the torch igniter was shut off (Figure 16(b)). Figure 16(c) shows the resulting chamber pressure trace, which has amplitude fluctuations of 1.5bar at roughly 90Hz. Figure 16(d) shows the injector pressure trace, which exhibits amplitude fluctuations of up to 0.6bar at the same frequency. Although the propellant did not burn properly, this firing was nonetheless useful as it may provide an insight into the lower flammability limit of the EUFB, indicating it may be between 2.21 and 3.20, with the caveat that only one data point is available here.

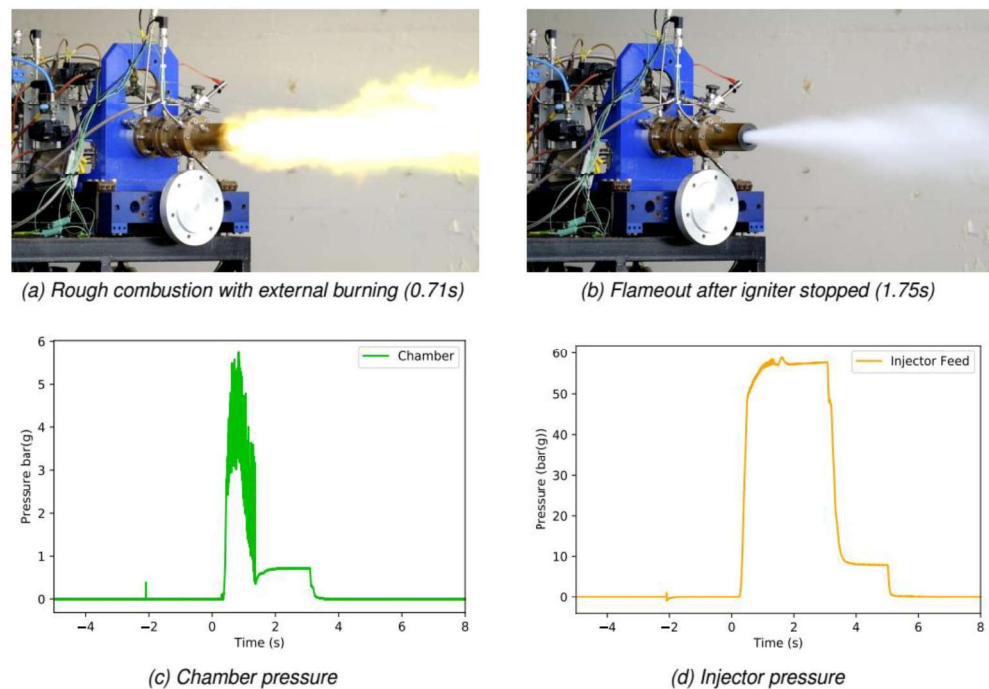


Figure 16: Data from a fuel rich EUFB test (OF 2.21). The propellant lit roughly whilst the igniter was running, with significant external burning (a), but the flame blew out shortly after the torch igniter was shut off (b). The rough combustion is seen from the chamber pressure trace (c), and some oscillation on the feed pressure trace (d).

4.2.3 Mixture ratio 3.20

At the design operating condition (OF 3.20 – target 3.18) the EUFB lit well with smooth combustion. The injector pressure climbed during the test more steeply than at a mixture ratio of 3.83, however, and the injector face temperature rose more quickly. The injector face melted at the very end of the firing, when sparks were noticed coming from the exhaust. Figure 17 shows images from the firing. A colour change in the exhaust can be noticed at 2.35s, and sparks by shutdown at 3.1s. The redline (automatic shut-off threshold) specified for maximum injector face temperature was 250°C. At propellant valve shutdown, the measured injector face temperature was 245°C, so the redline wasn't exceeded, but with thermal soak the temperature reached 272°C.

These measurement values were significantly less than the melting temperature of the injector at ~660°C, suggesting that there was a large thermal gradient between the injector face thermocouple and the injector face and therefore a large heat flux from the combusting propellant. For future propellant testing, the thermocouple

should be mounted closer to the injector face, and either a protective coating applied or water cooling paths printed into the part. Similar injector materials have been used successfully on the same test rig with the propellants in a bipropellant configuration, which shows that the injector heat flux was significantly higher for the pre-mixed EUFB.

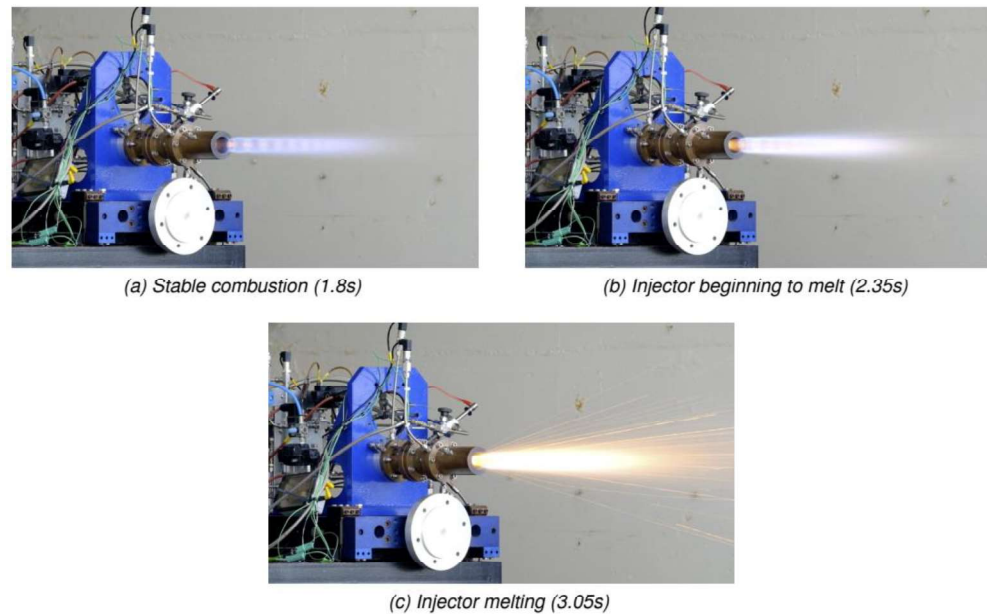


Figure 17: Stable combustion at mixture ratio 3.20, but with melting of the 3D printed aluminium injector face. The melting was first noticed as a colour change of the exhaust in the throat region (b), followed by sparks in the exhaust (c).

4.2.4 Heat loss to the chamber

The heat loss correction accounts for 4.1% of the total c^* at mixture ratio 3.83 and 5.8% at mixture ratio 3.20.

This suggests that the heat sink combustion chamber was overly long for the current EUFB tests. For other propellant and injector combinations tested previously on this copper chamber, the heat lost to the combustion chamber walls has been lower, commonly one or two per cent. The increase of heat loss makes physical sense for a pre-mixed propellant and a showerhead injector, because the NOFB propellant requires no “mixing distance” and therefore burns early in the chamber, and because there is no protective boundary layer of unburnt propellant near the chamber walls (such as occurs with coaxial injectors).

The large heat loss correlates well with the experimental data for the “HyNOx” propellant [4]. Those experiments examined the effect of the chamber L^* on the heat lost to a variable length copper heat-sink chamber and therefore the effect on combustion efficiency, and showed that the combustion efficiency drops quickly as a function of L^* . At the L^* value used in the current programme (0.83m), $\eta_{c^*} \sim 0.935$ [8], which is comparable to the 4.1-5.9% loss in the current programme.

4.2.5 Injector flash boiling

The NHNE method predicts that a rise in chamber pressure has smaller effect on the injector pressure, because the injectors are “choked” by the flash-boiling [29]. This was not seen in the hot flow results, however, where the injector pressure actually increases more than the chamber pressure increases.

Figure 15(b) shows that the injector pressure continuously increases during the firing, but the mass flow, chamber pressure and feed temperatures do not. The injector face temperature does continuously increase during the firing, however. The NHNE method is very sensitive to the temperature when close to the saturation line, so if there is any heat flux to the propellant during injection a higher pressure drop is required for any given mass flow.

The effect of injector face temperature on the flash boiling can be shown by comparing the effective discharge area of the injectors (C_dA); the true value measured from water calibration tests is compared with calculated values using the SPI and NHNE methods [29]. There was no temperature sensor in the propellant flow directly before the injector face, so the NOFB temperature is assumed to be at the measured premix chamber temperature for calculating fluid properties. For both the SPI and NHNE methods, the nitrous oxide and ethanol are assumed to act independently, and the calculated C_dA values are added together. In both cases the ethanol is assumed to remain liquid and therefore uses the SPI equation.

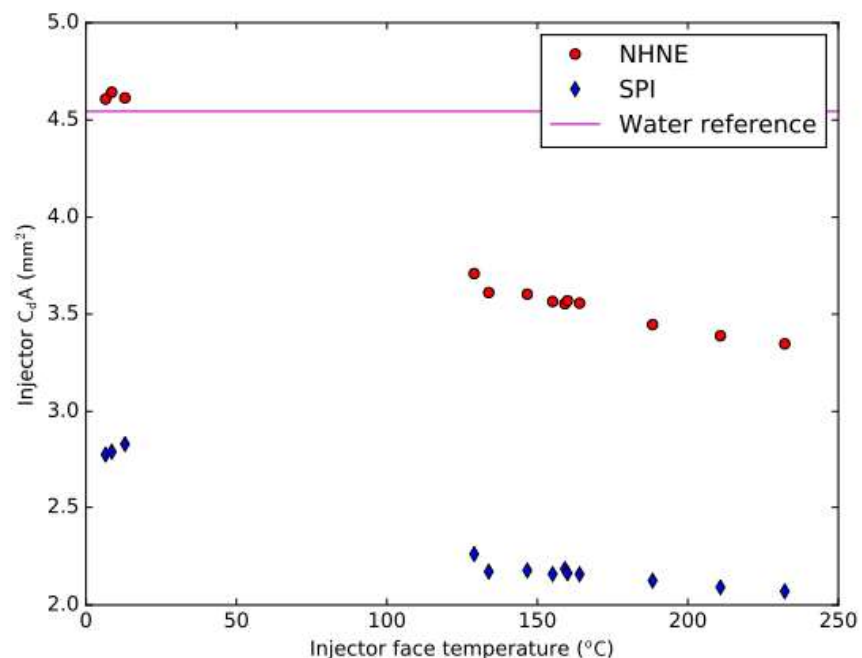


Figure 18: Effective discharge areas for the monopropellant injectors, plotted against the injector face temperature.

Figure 18 shows the estimated effective discharge area of the injectors (C_dA) using time-averaged data, plotted against the injector face temperature. It demonstrates several things. First, that the NHNE equation works well when the injector face is cold, because the calculated C_dA values for all cold values are within 2% of the measured value from water calibration. Second, that the NOFB propellant was definitely flash boiling in the injectors, because the SPI method under predicts the required C_dA at all temperatures. Third, that the injector face temperature has a significant effect on the required C_dA , because the effective discharge area drops with increasing temperature. At 230°C the NHNE method under predicts the C_dA by 25%, with the important caveat that these calculations are using the propellant temperature in the premix chamber, rather than directly before the injector face. Further propellant injection temperature data is therefore required to validate the NHNE method for hot firings ([29] only has cold flows).

5 System impact

Introducing NOFB propellant cannot be addressed in isolation from the overall propulsion system. On system level a new propellant may have a major impact. Moreover, the differences between NOFB and Hydrazine are remarkable. High vapour pressure of NOFB allows the system be self-pressurized, but therefore, it submits the system to high pressures (0-50 bars) and the components must be available to cope the pressures. Drawbacks of NOFB with respect hydrazine are they have a higher combustion temperature and there is a lack of a suitable catalytic bed, and therefore, an ignition system is required.

For engineering a propulsion system the interfaces between the different subsystems must be considered, and must be clearly specified to ensure the subsystems will work together correctly. This chapter summarizes the system impact study results and the activity was executed by Bradford Engineering.

For studying the system impact of a EUFB propulsion system a reference bi-propellant (Configuration A) and reference monopropellant propulsion system (Configuration B) were chosen.

The schematic of the reference bi-propellant propulsion system and its components is depicted in Figure 19.

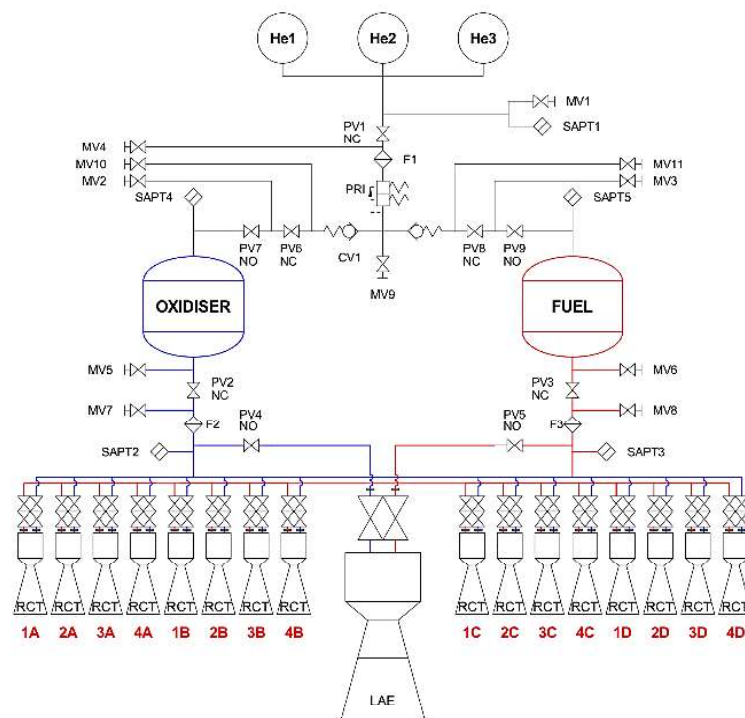


Figure 19: Configuration A: Bi-propellant propulsion system schematic (EuroStar_3000 (EutelSat_W3A) propulsion system.)

The schematic of the reference mono-propellant propulsion system and its components is depicted Figure 20:

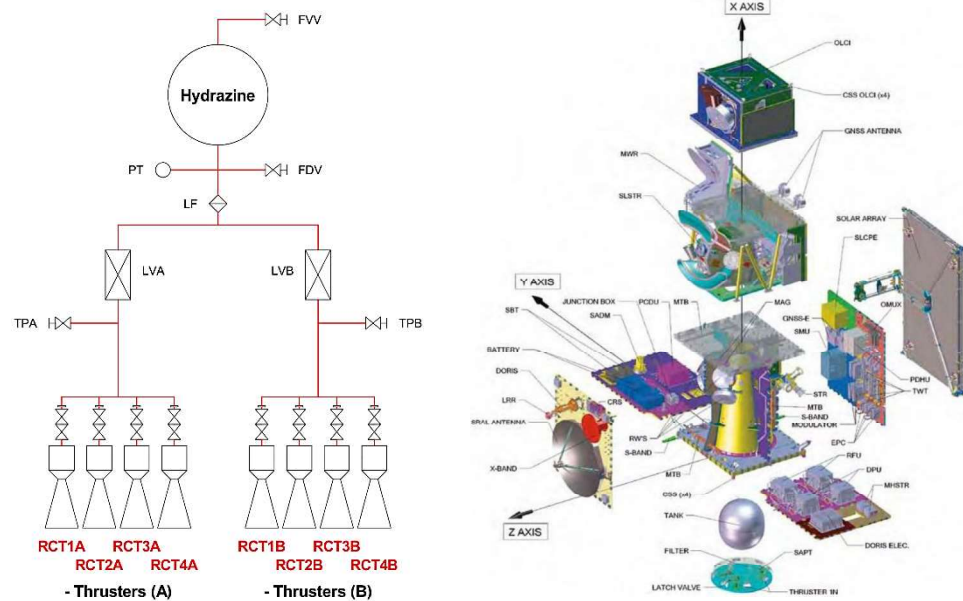


Figure 20: Configuration B: Mono propellant propulsion system schematic (AstroBUS (Sentinel_5P) propulsion system)

This chapter reports on how the inclusion of the EUFB propellant to the propulsion system will impact the subsystems of a Telecommunications spacecraft. In this chapter the impact on the electrical subsystem, the thermal interface, the mechanical and structural subsystems and the required development efforts will be addressed.

5.1 Power Subsystem

The most significant impact in this system is due to the inclusion of an ignition system, however, there are several other differences in the electrical power required by the EUFB propulsion with respect to the conventional hydrazine or hydrazine derivative based propulsion systems.

The power needs for standard continuous operation of the propulsion system are limited to the Thermal Control System (TCS), Pressure Transducers and operation of valves. A detailed design of the TCS is not within the scope of this activity, however to ensure self-pressurizing capability of the propellant, the propellant temperature needs to be controlled by the TCS to ensure a MEOP pressure of about 70 bar and to correct any pressure drop due to temperature excursions during all the mission environments. This will have will have a remarkable impact to the power.

The Pressure Transducers are always powered and will require approximately 0.3 W per Pressure Transducer. For reference configuration A, 5 pressure transducers are assumed resulting in a total power need of 1.5 W. For configuration B, 3 pressure transducers are foreseen resulting in a total power need of 0.9 W. Valves

The Torque Motor Latch Valves (TMLV) require approximately 10 W when cycled in the pre-firing conditions. The controlling spacecraft needs the ability to send a brief square-wave pulse to open or close the two Latch Valves and be able measure resistance of the micro switches that are used to indicate position.

The critical situation for the power budgets estimation is during firing conditions because the latch valves are not using power in this situation the latch valve power consumption is not considered in the power budget.

The following tables show a comparison between the power budgets of EUFB and the current state of the art classical PS.

Table 11: Power Budget comparison between EUFB configuration A and Hydrazine Bi-Prop during firing conditions

Component	# NOFB	# Bi-Prop	EUFB	Bi-Prop
Main 400N Thruster valves	1	1	35 W @24 – 38V (Open) 5 W @10 V (Hold)	35 W @28V (Open) 5 W @10 V (Hold)
RCSs 10N thruster Valves (Isolation Valve)	16 RCTs	16 RCTs	15 W @24-38V (Open) 2 W @10 V (Hold) 32 W – 240 W	15 W @28V (Open) 2 W @5 V (Hold) 32 W – 240 W
PT	5	10	0.3 W each 1.5 W for five (Continuous)	0.3 W each 3 W for five (Continuous)
TMLV ¹⁾	5	9	0	0
Tubing (Internal) Thermal Hardware ²⁾ @ 28 V	#	# x 2	20 W (Cycling)	40 W (Cycling)
Tank Thermal Hardware ²⁾ @ 28 V	#	# x 2	40 W (Cycling)	20 W (Cycling)
Total	-	-	340 W Cycled 1 Main Thruster firing+ 16 RCTs firing @ 28V (Opening firing) 100W Cycled 1 Main Thruster firing+ 16 RCTs firing @ 5V (Holding firing)	340 W Cycled 1 Main Thruster firing+ 16 RCTs firing @ 28V (Opening firing) 100 W Cycled 1 Main Thruster firing+ 16 RCTs firing @ 5V (Holding firing)

Notes:

- 1) TMLV are switched during the pre-firing conditions and only one valve is switched at each time. They are not considered in this comparison table.
- 2) The bi-propellant system has two propellant tanks and a pressurization system. It has a more complex tubing system and for these reasons it is considered to increment twice the power required for the thermal systems in the tubing. For the tanks however the EUFB system needs to increase the temperature to reach the 70 bar in order to fire therefore more power is necessary on the tanks. It is estimated that the power dissipation will therefore be similar with the two systems.

Table 12: Power Budget comparison between EUFB configuration B and Hydrazine Mono-Prop during firing conditions

Component	Number for NOFB	Number for Mono-Prop	EUFB	Mono-Prop
RCSs 1N Valves (Isolation Valve)	8 RCTs firing	8 RCTs firing	8 W @24 -38V (Open) 0.5 W @10 V (Hold) 4 W – 64 W	8 W @28V (Open) 0.5 W @5 V (Hold) 4 W – 64 W
PT	3	3	0.3 W each 0.9 W for three (Continuous)	0.3 W each 0.9 W for three (Continuous)
TMLV ¹⁾	2	2	0	0
Tubing (Internal) Thermal Hardware ²⁾ @ 28 V	#	# x 1.5	20 W (Cycling)	30 W (Cycling)
Tank Thermal Hardware ²⁾ @ 28 V	#	# x 1.5	25 W (Cycling)	15 W (Cycling)
Total	-	-	110 W Cycled 8 RCTs firing @ 28V (Opening firing) 50 W Cycled 8 RCTs firing @ 5V (Holding firing)	110 W Cycled 8 RCTs firing @ 28V (Opening firing) 50 W Cycled 8 RCTs firing @ 5V (Holding firing)

Notes:

1)

TMLV are switched during the pre-firing conditions and only one valve is switched at each time. They are not considered in this comparison table.

From the tables it is observed that the principal differences in the power budgets are due to the TCS. Both type of propellants, EUFB and hydrazine used for bi- and mono-propellants, requires TCS to keep their state in the proper conditions along the feed system. However, it is assumed that both type of systems will require power consumption, but EUFB requires less power in the feed system and more in the tank while during firing only in order to keep the inlet pressure to the thruster brave 50 bar. Instead the TCS of the hydrazine system needs to keep the TCS within the operating temperature of the hydrazine to avoid that it freezes.

Table 13 and provide a summary of telemetry and control need wires for both EUFB system configurations:

Table 13: EUFB Propulsion System Configuration A Telemetry (TLM) and Control Needs (PWR) (TCS excluded)

Item	Qty	# of Wires per Item	Total Wires	Signal Type
Pressure Transducer (PT)	5	4 (2 PWR, 2 TLM)	20	28 Vdc PWR 0.5-5 Vdc TLM
Temperature sensor	5	2 TLM	10	Measured Resistance
Latch Valves	5	11 (4 PWR, 3 TLM, 4 PWR redundant)	55	28 Vdc PWR Analogue +/- 5 Vdc TLM
Thruster	2 (valves)	4 wires (2 wires per coil)	8 wires	24-38 Vdc
Ignition System	2	2 wires	4 wires	100 Vdc

Table 14: EUFB Propulsion System Configuration B Telemetry (TLM) and Control Needs (PWR) (TCS excluded)

Item	Qty	# of Wires per Item	Total Wires	Signal Type
Pressure Transducer (PT)	3	4 (2 PWR, 2 TLM)	12	28 Vdc PWR 0.5-5 Vdc TLM
Temperature sensor	3	2 TLM	6	Measured Resistance
Latch Valves	2	11 (4 PWR, 3 TLM, 4 PWR redundant)	22	28 Vdc PWR Analogue +/- 5 Vdc TLM
Thruster	2 (valves)	4 wires (2 wires per coil)	8 wires	24-38 Vdc
Ignition System	2	2 wires	4 wires	100 Vdc

However, the most remarkable impact of EUFB to Electrical subsystem is due to the necessity of using an ignition system. There is a lack of catalyst bed for EUFB, and therefore, an igniter is required which needs to be developed.

Possibly a (coil-on plug) spark plug or a torch ignition are the best solution for liquid propulsion system. With a coil-on plug spark plug the number of wires is minimized which improves the durability of the ignition system and eliminates the need for separate high voltage wires along their potential for trouble due to electromagnetic interference.

Assuming a coil-on plug spark plug ignition solution, the ignition system requires 100 Vdc for every re-ignition. In general, the thruster will include two igniters (dual) for redundancy in order to increase the reliability of the system.

Depending on the dedicated ignition system for the EUFB engine additional electrical interfacing with the vehicle onboard computer is necessary. Other changes in electrical interfaces are not expected.

5.2 Thermal Subsystem

The function of the thermal subsystem is to maintain the thermal balance inside the spacecraft and, to keep the on-board equipment within operating and storage temperature limits. The following table shows the temperature limits EUFB PS components:

Table 15: Temperature range of EUFB PS components

Item	Acronym	Operating range	Non-operating (storage) range
Propellant Tank	Tank	≥ 42 °C	-40 to +75 °C
Fill & Vent Valves Fill & Drain Valves (Test Port)	F/V F/D (TP)	-35 to +72 °C	
Pressure Transducer	PT	-20 to +70 °C	-40 to +75 °C
Filter	F	-7 to +55 °C	
Latch Valves	LV	+5 to +55 °C	-40 to +75 °C
Isolation Valves	IV	-10 to +55 °C	
Heaters	H	-200 to +200 °C	
Temperature Sensor	T	Up to 200 °C	

NOTE: Temperature range values are extracted from catalogues of each component.

A key driver of EUFB is that the injection pressure of the fuel blend at the engine must be above 50 bars, and therefore, pressure drops along the system due to temperature excursions can result in a required tank pressure well above 70 bars. In order to achieve that, the tank and the feed system shall be thermally decoupled. Accordingly, the TCS shall heat the tank at 315 K.

The combustion temperature of EUFB with ethanol as fuel is comparable to the combustion temperature of classical bi-propellant propulsion systems, which is extremely high compared to the decomposition temperature of monopropellant hydrazine. The TCS must deal with this high temperature in order to keep the temperature inside the spacecraft.

The high combustion temperature of EUFB cannot be managed by radiation alone. If radiation cooling is applied (partly), also a radiation shield should be applied to avoid local heating of the spacecraft. Active cooling should be performed carefully, because of the thermal decomposition and gasification behaviour of the nitrous oxide at elevated temperatures.

The thermal interface for an engine operating with EUFB propellant is challenging and it should be addressed in a further study.

5.3 Mechanical Subsystem

NOFB and hydrazine propellants have different characteristics, especially with hydrazine bi-propellants because EUFB combines their performance characteristics by being a mono-propellant, and consequently, their storage and feed systems must have remarkable differences. Table 16 shows the characteristics of the aforementioned EUFB propellants.

Table 16: Density and specific impulse of the three selected EUFB propellants

Property	N ₂ O/Ethanol
Liquid density [$kg\ m^{-3}$]	892
Ideal Specific impulse [s]	331
Specific impulse [s]	259.1*

* Values from Chapter 4

Moreover, because of the nature of nitrous oxide, EUFB avoids using any pressurization system, and this change on the spacecraft architecture and configuration will let to an impact to the structure sub-system too. Next table show the mechanical interfaces required to incorporate the EUFB propulsion system into telecommunications spacecraft platforms:

Table 17: Mechanical interfaces summary

Component	External Mechanical Interface	Mechanical Interface Connector
Tank	Tank support	1/4" Welding tubes of Stainless Steel 304 or Ti6Al4V
Thrusters	Mounted using 3 off M4/M5 screws	1/4" Welding tubes of Stainless Steel 304 or Ti6Al4V
Flame Arrester	Brackets	1/4" Welding tubes of Stainless Steel 304 or Ti6Al4V
Pressure Relief Valves	Mounting bracket or line mounted using 3 off M4 screws	1/4" Welding tubes of Stainless Steel 304
Pressure Transducer	4 bolts M4	Connector of Stainless Steel 304 or Ti6Al4V
Latch Valves	Brackets	1/4" Welding tubes of Stainless Steel 304 or Ti6Al4V
Service Valves	Mounted using 3 off M4 screws	1/4" Welding tubes of Stainless Steel 304 or Ti6Al4V
Filters	Brackets	1/4" Welding tubes of Stainless Steel 304 or Ti6Al4V

This chapter will show the impact of EUFB propellant to the mechanical and structural sub-system of the spacecraft. The most remarkable impact is regarding the tank volume, and therefore, a more detailed analysis is provided hereunder:

5.3.1 Tank Mechanical Environment

The tank's mechanical interface impact due to EUFB PS is limited, but for the previous reasons, the tank will have a different dimension. This subsection will provide tank volume relations between the EUFB with ethanol as a fuel and hydrazine propellants (NTO/MMH bi-propellant and N₂H₄ mono-propellant).

Considering the reference missions, the initial mass M_0 is unknown and a general $\Delta V = 2000m/s$ for Configuration A and $\Delta V = 850m/s$ for Configuration B is assumed, this subsection will provide the tank volume relations between the EUFB and the systems for a fixed ΔV and the tanks volume relation for a variable ΔV .

Using the Tsiolkovsky rocket equation the mass fractions can be calculated:

$$\Delta v = v_e \cdot \ln \frac{m_0}{m_f} = Isp \cdot g_0 \cdot \ln \frac{m_0}{m_f}$$

Eq. 7

For the EUFB blend with ethanol as a fuel and a mixture ratio of 3.15 the experimentally determined value of the specific impulse (259.1s) is used.

For both configurations the calculated mass fractions are presented in Table 18.

Table 18: Mass fraction required for each propellant

Property	N ₂ O/Ethanol ($m_{Ethanol}$)	NTO/MMH	N ₂ H ₄
Mass fraction (Conf A)	0.54	0.51	-
Mass fraction (Conf B)	0.28	-	0.33

With the mass fraction value provided in Table 18, the tank volume relation between EUFB and the reference configurations are derived, in Table 19 the result is shown.

Table 19: Comparison between the required tank volume of a EUFB propulsion system and the reference propulsion systems

Propellant Volume Relation	Value
$\frac{V_{Ethanol}}{V_{Bi-prop}}$ (configuration A)	1.390
$\frac{V_{Ethanol}}{V_{Mono-prop}}$ (configuration B)	0.969

It can be concluded that the required tank volume of configuration A ($\Delta V = 2000$ m/s) is 1.5 times larger than the current state of the art bipropellant tanks. Alternatively, two tanks may be used, which however is not an optimized solution.

The required tank volume of configuration B ($\Delta V = 850$ m/s) is comparable to that of a hydrazine propulsion system.

Considering configuration A, from a general cross sub-system point of view, EUFB has the advantage of being a more simple system compared to a conventional propulsion system. No separate storage tanks for the fuel and oxidizer is required which makes the structure and the mechanical interface easier than having a separate storage tanks. Having just a single propellant feed system halves the tubing and piping and the spacecraft. Although of having a bigger tank, EUFB will decrease complexity and number of interfaces and as well as saving mass.

Considering configuration B, the volume of the pressurization tanks of the hydrazine systems is not considered in Table 18. Without the need for pressurisation tanks, the total volume and system complexity of a EUFB propulsion system is significantly less than that of a conventional hydrazine system.

5.4 Auxiliary Propulsion System

For reaction control the requirements are very demanding. A typical impulse bit requirement is 100mNs; it is uncertain whether this requirement can be met by a EUFB propulsion system using a dedicated ignition system. If this requirement cannot be met by a EUFB propulsion system then an auxiliary propulsion system is required.

To avoid a dedicated auxiliary propulsion system, the EUFB thrusters may be designed for dual mode operation. When low impulse bit it is required the thruster

may use the gaseous nitrous oxide from the propellant tank. The propulsion system then may act as a cold gas propulsion system or may use catalytic decomposition of the nitrous oxide to operate as a mono-propellant propulsion system.

The same options are applicable for a dedicated auxiliary propulsion system.

5.5 Identification of Development Effort Needed to Implement a EUFB Subsystem

To implement a EUFB propulsion system, preferably, all the components of the current state of the art propulsion system should be made compatible with EUFB. In order to achieve that, the use of titanium for surfaces in contact with the propellant shall be avoided; alternatively these surfaces can be constructed from aluminium or stainless steel (see Chapter 3.3).

For all the propulsion system components a design, development and verification plan is presented in order to reach at least TRL 6 and to demonstrate the technology for a EUFB propulsion system. Depending on the component, there are two possibilities to qualify the components for being used in EUFB PS:

- By means of a Delta qualification if the component is fully qualified for hydrazine systems but the heritage data does not fully encompass the EUFB requirements. In this case, the delta qualification will be done on Qualification Model QM and it will be used to demonstrate the compatibility between the components materials and EUFB and to present new proof that the current product can handle the new requirements.
- By means of a component redesign if the existing components are not compliant to the EUFB propulsion system requirements. In this case an Engineering Model (EM) is required to validate the functional performance requirements and prototyping.

5.5.1 Components

In the following paragraphs an overview is given of the impact on the components in the propellant feed system due to the transition from hydrazine to EUFB propellant.

5.5.1.1 Propellant Tanks

State of the Art Design

Two types of tanks are applicable for a EUFB propulsion systems: PMD or Composite Overwrapped Pressure Vessel (COPV) tanks. For both type of tanks, the wetted surface is made of a metallic liner. The liner is commonly pure titanium or a titanium/aluminium alloy.

PMD tanks made only of pure titanium are already designed to store large volumes of propellant, but they are not suited for the high pressure (70 bar) as used for a EUFB propulsion system.

The COPV tanks are made of titanium/aluminium alloy liner and are overwrapped with carbon fibre composites. This makes these type of tanks suitable for storing propellants at a high pressure, however the current state of the art tanks are only designed to store small volumes of propellant.

The COPV tanks have a significant weight advantage over all-metal tanks, but to design a COPV tank an in depth understanding of the interplay between the

composite overwrap and the inner liner is required. COPV tanks require unique design, manufacturing, and test requirements.

Development Effort

In order to be suitable for use in a EUFB propulsion system, the storage tank shall be fully designed for 70 bar of storage pressure and, in addition, its structure shall be designed to withstand the worst-case satellite accelerations (launch transportation and in-flight operations). The lightest solution to achieve a high storage pressure and sufficient mechanical strength is a COPV tank. These tanks do not exist for large volumes and need to be designed and qualified.

Considering the EUFB self-pressurization nature, gas may be drawn from the storage tank when the tank is almost empty. Ingestion of gaseous EUFB may be a potential hazard and should be avoided. To prevent ingestion of gaseous EUFB, it is proposed to design the tank for a 25% of propellant margin.

Taken in to account reference configurations A and B, the Propellant Managing Device (PMD) inside the tank shall be designed to provide flow rates from either for 175 g/s for the Configuration A or 2.5 g/s for configuration B

5.5.1.2 Flame Arrester

State of the Art Design

The EUFB PS design shall include flame arresters in order to prevent flame flashback. This component shall be designed to allow the flow of liquid EUFB while preventing the flame transmission. Currently only industrial flame arrestors are commercially available and therefore a development effort is required.

Development Effort

Currently there are no potential suppliers of space qualified flame arresters and need to be developed. The flame arrester shall be compliant to the following functional performances:

- The material of the wetted surfaces shall be compatible with Ammonia and Ethane.
- The flame arrester shall be suitable for pressure levels up to 70 bar and the pressure drop shall be:
 - Reference configuration A: less than 200mbar at a flow rate of 130 g/s of EUFB.
 - Reference configuration B: less than 3.8mbar at a flow rate of 2.5 g/s of EUFB.
- The dimensions and mass shall be compliant to the space EUFB propulsion system requirements.
- Mechanical connection shall be ¼" welding tube of Stainless steel connection in order to be compatible with the propulsion system tubing system.
- Subsequently, full qualification shall be performed to reach an adequate TRL Level

5.5.1.3 *Pressure Relief Valve*

State of the Art Design

The EUFB propulsion system shall include a pressure relief valve at the top of the tank in order to limit and control the tank pressure. The purpose of this component is to vent gas from the tank in the event of a significant increase of pressure in the tank.

An example of the current state of the art pressure relief valve is the Nammo UK VRS01 Pressure Relieve Valve (PRV) to control and limit the pressure downstream of the tank in order to protect the sub-system against excess pressures.

Development Effort

The Nammo UK VRS01 pressure relief valve is a space qualified component, both for gaseous and liquid media, and is suitable for the high pressure in a EUFB feed system. For EUFB with Ethanol as fuel the component is assessed to be compatible.

5.5.1.4 *Pressure Transducer*

State of the Art Design

The EUFB propulsion system shall include pressure transducers at the lines of the system in order to monitor and control the pressure. A potential European Supplier, considering the current state of the art, is Bradford Engineering with their mini-Standard Accuracy Pressure Transducer (mini-SAPT) for the pressure monitoring needs. The mini-SAPT is a piezo-resistive principle based, fully qualified pressure gauging component, both for gaseous and liquid media.

Development Effort

Bradford's mini Standard Accuracy Pressure Transducer (mini-SAPT) are suitable for use in EUFB propulsion system. For EUFB with Ethanol as fuel the component is assessed to be compatible.

5.5.1.5 *Latch Valves*

State of the Art Design

The EUFB propulsion system shall include latch valves to start or stop the propellant flow. Latch valves are available up to a pressure level of 310 bar and in material (stainless steel) suitable for EUFB propellant.

Development Effort

Torque motor latch valves (TMLV) as produced by MOOG are suitable to be used in a EUFB propulsion system. For EUFB with Ethanol as fuel the MOOG latch valve is assessed to be compatible.

5.5.1.6 *Service Valves*

State of the Art Design

The EUFB propulsion system shall include service valves (Fill and Drain valve, and Fill and Vent valve) for ground operations. Nammo UK Cheltenham is a European supplier of space qualified service valves suitable for the EUFB PS test ports. The valves do have a pressure range up to 310 bar and can be made of stainless steel.

Development Effort

Nammo's services valves are suitable for use in EUFB propulsion system. For EUFB with Ethanol as fuel the component is assessed to be compatible.

5.5.1.7 Propellant Filters**State of the Art Design**

Filtration protection is implemented upstream of the latch valves to protect the system during priming and operation. A supplier of space qualified propellant filters is SOFRANCE. A stainless steel SOFRANCE propellant filter is used on Ariane 5 ME. Space qualified propellant filters are commercially available, but only at a pressure rating too low for a EUFB propulsion system.

Development Effort

To allow the high pressure of a EUFB propulsion system a redesign of the housing of the filter required. This redesigned filter shall be delta qualified for the use in a EUFB propulsion system.

5.5.2 EUFB Propulsion System Development Effort

The table below is an overview of the various components of a EUFB propulsion system including potential suppliers, TRL for hydrazine and EUFB service and development impact.

Table 20: Technology readiness level

Item	Potential Suppliers	Hydrazine TRL	EUFB TRL	Impact
Propellant Tank (Titanium PMD)	ATK Airbus MT-Aerospace RAFAEL	9	2	High: - Increase of storage pressure (70 bar) - Increase of tank volume - Change of material (aluminum)
Propellant Tank (COPV)	ATK Airbus MT-Aerospace RAFAEL	3	3	Medium: - Increase of storage pressure (70 bar) - Increase of tank volume - PMD - Change of liner material (aluminum)
Thruster	-	9	3	High/Medium: - Performance to be demonstrated - Active cooling required
Igniter	-	-	2	High : - Technology needs to be demonstrated
Flame Arrester	Protego	-	2	High : - Basic technology research and research to prove feasibility - No European supplier for space applications
Pressure Relief Valves	Moog Inc.	9	3	Low : - Redesign for EUFB compatible materials
Pressure Transducer	Bradford Engineering	9	3	Low : - Delta-QM is required to validate is functionality with EUFB
Latch Valves	Moog Inc. Omnidea-RTG VACCO	9	3	Low : - Redesign for EUFB compatible materials - Qualification for EUFB service
Service Valves	MOOG Inc. Nammo UK Omnidea-RTG	9	3	Low: - Redesign for EUFB compatible materials - Qualification for EUFB service
Filter	SOFRANCE VACCO EJAY	9	3	Medium/Low: - Redesign for EUFB compatible materials - Redesign for increased pressure - Qualification for EUFB service.

5.6 System Impact

To address the impact of a NOFB propulsion system on system mass the Tsiolkovsky rocket equation (Eq. 7) was used for comparison of the propellant mass ratio with a conventional propulsion system. Assuming an identical Δv requirement for both systems, the ratio between initial and dry mass of an NOFB system relative to that of a conventional system becomes:

$$\frac{[\Delta v]_{NOFB}}{[\Delta v]_{Conv.}} = \frac{[Isp]_{NOFB}}{[Isp]_{Conv.}} \cdot \frac{\left[\ln \frac{m_0}{m_f} \right]_{NOFB}}{\left[\ln \frac{m_0}{m_f} \right]_{Conv.}} = 1 \leftrightarrow \frac{\left[\frac{m_0}{m_f} \right]_{NOFB}}{\left[\frac{m_0}{m_f} \right]_{Conv.}} = \left(\left[\frac{m_0}{m_f} \right]_{Conv.} \right)^{\left(\frac{1}{\frac{Isp_{NOFB}}{Isp_{Conv.}}} - 1 \right)}$$

Eq. 2

Assuming a certain system with known ratio between initial and dry mass of the spacecraft Figure 21 is constructed. In the figure some data of actual spacecrafts are presented as a reference.

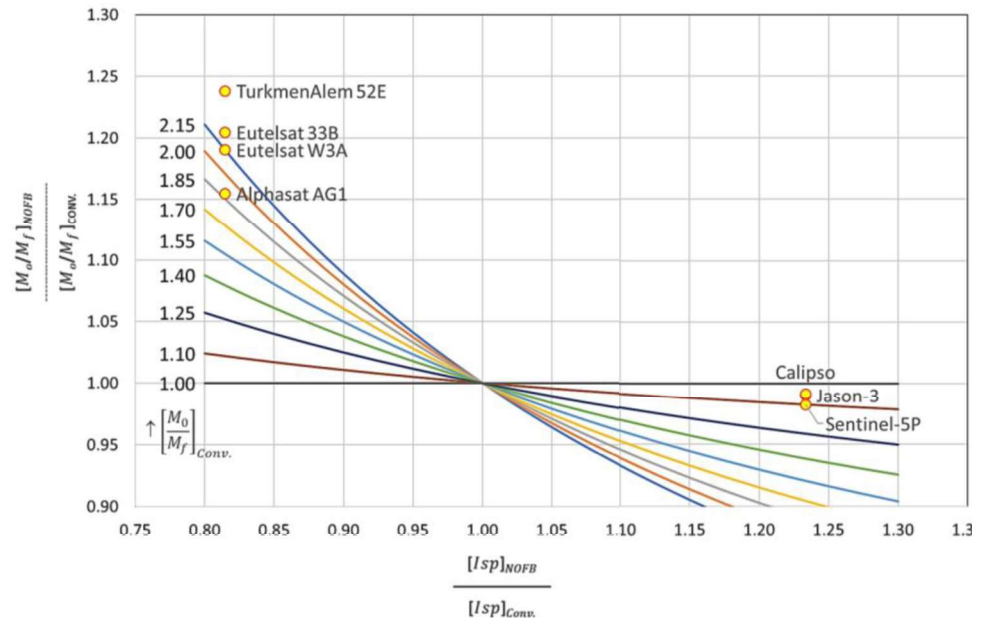


Figure 21: Ratio between initial and dry mass of the spacecraft with respect to a conventional propelled vehicle as a function of the specific impulse ratio.

With respect to conventional hydrazine, the specific impulse of the ethanol-based NOFB is about 20% higher. With respect to a conventional MMH/MON-based propulsion system the ethanol NOFB performs about 20% less. Note that this is a very conservative approach, the mixture ratio of the ethanol-based NOFB is taken as the mixture ratio for which miscibility is proven. When miscibility is optimized, the specific impulse of the blend can be as high as 97% of the of classical bipropellants and 148% of that of hydrazine. Furthermore, in comparison with the bipropellant system, the reduction of mass due to the absence of a pressurising gas system for both the oxidizer and fuel is not accounted for.

For a replacement of hydrazine, the current blend of EUFB is already an attractive propellant that improves the system mass efficiency. For a replacement of the current state-of-the-art bipropellant the current EUFB blend needs further improvement.

6 Lessons learned

During the course of the activity experience was gained in working with an EUFB blend as a propellant for thrusters. Also test hardware was designed, build and tested in a firing test campaign. In this chapter we sum up the lessons learned and the nearby needs which were not addressed in this study but mandatory before continuation with an EUFB engine and testing of such an engine.

From the miscibility assessment it was learned that a dedicated test set-up is required to study the miscibility accurately. For optimal performance the miscibility of ethanol in nitrous oxide must be known over the complete applicable temperature range. The setup as used was not designed for miscibility tests but was altered to do so. Small leaks were experienced which affected the accuracy of the tests. Also the miscibility could not be investigated at the temperature extremes, this data is required for a viable propulsion system design.

It was learned that nitrous oxide is limited miscible in ethanol, resulting in a fuel rich propellant. To improve on performance the miscibility of ethanol and methanol in nitrous oxide may be improved by the adding a proper solvent.

With respect to the firing tests it was learned that the non-existing mixing distance in the combustion chamber requires a design strategy different than that of bipropellant engines. Especially this is true for the propellant injector. It was found that the flame front in the combustion chamber is very close to the injector and that the heat load on the injector is severe. Where a regular bi-propellant engine can use a metal (for example copper alloy or aluminium) as injector material this is only suitable for a EUFB engine with protective measures. These measures may be active cooling of the injector by the propellant or ensuring very high injection velocity to generate enough standoff of the flame front. Possibly selecting a ceramic injector plate is the most secure solution. These design options should be addressed in any follow-on attempt to design a EUFB test engine.

During tests flash back events were never observed however it is uncertain if this was because of the physical parameters of EUFB or by an injector design that prevented effectively a flash back. To understand a flashback event better and to design an injector or flame arrestor such that it is capable to successfully quench a developing flash back event, data on laminar burning velocity and quenching distance is required for the EUFB of interest.

As stated in the report, the compatibility of nitrous oxide with other materials is not well and consistently documented. Literature sources may show contradictory compatibility information. Lessons learned is that when using nitrous oxide, one should be extremely aware about this fact. For nitrous oxide, a clear and consistent compatibility data set should be established.

It is recommended that, for making a final assessment of the feasibility of the EUFB propellant and to improve the design of the test engine, a more detailed investigation into the EUFB physical and chemical properties should be performed. The following activities have been identified to be included in possible future follow-on studies:

1. The miscibility of nitrous oxide in ethanol or visa-versa;
2. The use of solvents to obtain a more optimal (stoichiometric) composition;
3. The bubble point and dew point of EUFB as a function of temperature and mixture composition;
4. The laminar burning velocity as a function of mixture composition and pressure ;
5. The quenching distance as a function of mixture composition and pressure;
6. Generation of a consistent and verified compatibility table of nitrous oxide with common materials as used in space propulsion systems;
7. Design rules for an EUFB injector plate/dome should be established addressing suitable materials and design solutions to avoid too high a heat load on the injector and to avoid or neutralize flash back events.

7 Conclusions

By means of a clear set of requirements and a trade-off ethanol was selected as a fuel for a NOFB which was called the EUropean Fuel Blend EUFB.

For ethanol the stability and miscibility with nitrous oxide was investigated. It was found that the mixture of ethanol and nitrous oxide was chemically stable. No reaction between the components was observed for a period of more than 70 hours. Ethanol was found to be only partially miscible with nitrous oxide, miscibility up to a mixture ratio of 3.15 was proven.

This study successfully hot-fired a EUFB in liquid form, and the resulting combustion was stable (less than 1% pressure oscillation) and with good combustion efficiency (97%) at the desired operating condition of $OF=3.20$. At this operating point the specific impulse was found to be 259 s. Despite the volatile nature of this propellant and unknown characteristics, the test programme was conducted safely with no flashback or detonation events seen. However, the desired number of tests could not be completed because the injector was damaged by unexpectedly high heat flux. The EUFB was shown to have several peculiarities because it is pre-mixed and therefore burns extremely close to the injector face: first, it loses a significant proportion of heat to the chamber walls, second, it has high injector face heat flux, and third, this high injector heat flux leads to more flash-boiling in the injectors. Flashback was not seen with the liquid (pressurised) EUFB showerhead injector and nitrogen purge on shutdown. For more realistic thruster geometries, further work should concentrate on flashback arrestors and injector geometries suitable for EUFB in both the liquid and gaseous phases.

From the system study it is concluded that as a replacement of hydrazine the current blend is already attractive; as a bipropellant replacement a more near-stoichiometric blend is required and for this a study an improvement of the miscibility of ethanol in nitrous oxide is advised.

Further developments in the pressure rating of propellant storage tanks are required because the self-pressurizing EUFB exceeds the pressure rating of the current propulsion tanks. In propulsion components often titanium is used. For EUFB it is unclear whether titanium is compatible with the propellant. By similarity with other oxidizers it is expected that some incompatibility between EUFB and titanium exists. This needs to be investigated or contact between the propellant and titanium needs to be avoided. This will result in a redesign and qualification of feed system components.

An important unknown today is on how to ignite EUFB such that it is competitive with the current catalytic and hypergolic propellants.

The ethanol-based EUFB is an attractive replacement for hydrazine on the short term. On the longer term the ethanol-based NOFB may also be an acceptable replacement for the current MMH/MON propellant.

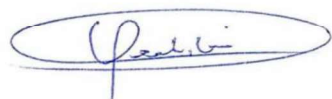
8 References

- [1] J. D. Clark, *Ignition!: An Informal History of Liquid Rocket Propellants*, Rutgers University Press, (1972), p. 18.
- [2] "Regulation(EC) No 1907/2006 of the European parliament and of the Council," 2006.
- [3] L. Werling, N. Perakis, B. Hochheimer, H. Clezki and S. Schlechtriem, "Experimental Investigations based on a Demonstrator Unit to analyze the Combustion Process of a Nitrous Oxide/Ethene Premixed Green Bipropellant," 2015.
- [4] L. Werling, M. Haßler, P. Batz, H. Ciezki and S. Schlechtriem, "Experimental Performance Analysis (c* & c* efficiency) of a Premixed Green Propellant consisting of N₂O and C₂H₄," 2017.
- [5] L. Werling, N. Perakis, S. Müller, A. Hauck, H. Clezki and S. Schlechtriem, "Hot firing of a N₂O/C₂H₄ premixed green propellant: first combustion tests and results," Rome, 2016.
- [6] L. Werling, A. Gernoth and S. Schlechtriem, "Investigation of the Combustion and Ignition Process of a Nitrous Oxide/Ethene Fuel Blend," in *Space Propulsion 2014*, Cologne, Germany, 2014.
- [7] C. Niederstrasser and W. Frick, "Small Launch Vehicles—A 2015 State of the Industry Survey," in *29th annual AIAA/USU Conference on Small Satellites*, 2015.
- [8] "Innovation at DARPA," DARPA, July 2016. [Online]. Available: https://www.darpa.mil/attachments/DARPA_Innovation_2016.pdf. [Accessed 19 03 2018].
- [9] "ALASA Launches on Hold Due to Exploding Fuel," [Online]. Available: <http://www.parabolicarc.com/2015/11/30/alasa-launches-hold-due-exploding-fuel/>. [Accessed 19 03 2018].
- [10] *ARTES 5.1 Statement of Work, European fuel blend development, Date 25/06/2014*, 2014.
- [11] B. McBride and S. Gordon, "Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications; II User's Manual and Program Description," National Aeronautics and Space Administration Lewis Research Center Cleveland, Cleveland, Ohio, 1996.
- [12] "On the harmonisation of the laws of the Member States relating to the making available on the market and supervision of explosives for civil uses (recast)," *DIRECTIVE 2014/28/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL*, no. 2014/28/EU, 2014.
- [13] "Thermophysical properties of fluid systems," 2011. [Online]. Available: <http://webbook.nist.gov/chemistry/fluid/>. [Accessed December 2015].
- [14] L. Theodore, F. Ricci and T. Vanvliet, *Thermodynamics for the Practicing Engineer*, Wiley, 2009.
- [15] *ASPEN_PROPERTIES, v8.8.2. Computer program for thermophysical properties modelling*, Aspen Technology, Inc..

- [16] "Firestart Technologies," [Online]. Available: <http://www.firestar-engineering.com/index.html>. [Accessed 20 3 2018].
- [17] G. Mungas, "Nitrous Oxide Fuel Blend Monopropellants". United States Patent US2009/0133788 A1, 2009.
- [18] G. Mungas, "NOFBX Single stage to orbit mars ascent vehicle," in *Aerospace Conference, IEEE*. 0.1109/AERO.2012.6187299, 2012.
- [19] "Kelly Space & Technology," Kelly Space & Technology, [Online]. Available: <http://www.kellyspace.com/>. [Accessed October 2015].
- [20] M. Kelly, "Nitrous oxide/fuel monopropellants". Worldwide Patent WO2001051433 A1, 2001.
- [21] "Specialty Gases & Specialty Equipment," Linde Gas Benelux, [Online]. Available: http://hiq.linde-gas.com/en/specialty_gases/pure-gas-finder.htm. [Accessed 2016].
- [22] "ScienceLab," [Online]. Available: <http://www.sciencelab.com/msdsList.php>. [Accessed 20 03 2018].
- [23] "DBBST Germany," Dortmund Data Bank, 2018. [Online]. Available: <http://ddbonline.ddbst.de/DIPPR105DensityCalculation/DIPPR105CalculationCGI.exe>. [Accessed 09 04 2018].
- [24] NEN, "NEN-EN-ISO 11114-1: Gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 1: Metallic materials," 2012.
- [25] NEN, "NEN-EN-ISO 11114-2: Gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 2: Non-metallic materials," 2013.
- [26] "Cole-Parmer Chemical Compatibility Database," [Online]. Available: <http://www.coleparmer.com/Chemical-Resistance>.
- [27] Waxman, B., et al., "Mass flow rate and isolation characteristics of injectors for use with self-pressurizing oxidizers in hybrid rockets," in *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, San Jose, CA, 2013.
- [28] J. Dyer et al., "Modeling Feed System Flow Physics for Self-Pressurizing Propellants," in *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Cincinnati, OH, 2007.
- [29] B. Solomon, "Engineering Model to Calculate Mass Flow Rate of a Two-Phase Saturated Fluid Through An Injector Orifice," Utah State University, 2011.
- [30] Deeken, J. et al., "Combustion efficiency of a porous injector during throttling of a LOX/H₂ combustion chamber," *Progress in Propulsion Physics*, vol. 2, 2011.

9 Signature

Rijswijk, July 2018

A handwritten signature in blue ink, enclosed within a blue oval. The signature appears to be 'P. Hendriksen'.

P. Hendriksen
Head of department

TNO

A handwritten signature in blue ink, featuring a large, stylized 'M' and 'A'.

A.E.H.J. Mayer
Author