

# Development of a Cost-Effective 1.5kN Liquid-Fueled Rocket Propulsion System

Jason Y. Chen <sup>\*1</sup>

<sup>1</sup>*Founder, Project Caelus 501(c)(3)*

(Initial revision 06 August, 2019; received 02 February, 2020)

This is an example of the abstract. Mit der CNN.com Europe Edition verfügt der TV-Sender CNN über eine umfassende Webseite, die im Minutentakt rund um die Uhr aktualisierte Weltnachrichten aus einer europäischen Perspektive auf den Bildschirm bringt. Wichtige, globale Ereignisse, geordnet in den Rubriken breaking news, current news headlines oder in depth, werden mit Hilfe von Video- und Audioclips, Bildern, Karten, Profilen, Zeitachsen und Tatsachenberichten fundiert dargestellt. Die Nachrichten stützen sich auf die Expertenanalysen der CNN Korrespondenten. Die Berichte verweisen auf andere relevante CNN Reportagen und zu Meldungen anderer Websites. Zusätzlich besteht die Möglichkeit, Videos anzufordern und mittels einer Suchfunktion Zugriff auf bereits gesendete Berichte und gesonderte Themenbereiche, die seit 1995 bearbeitet wurden, zu erhalten.

## 1 Nomenclature

Symbols		Acronyms	
$\epsilon$	= Expansion ratio	$CEA$	= Chemical equilibrium with applications
$\gamma$	= Ratio of specific heats	$COTS$	= Commercial off-the-shelf
$\rho$	= Density	$DAQ$	= Data acquisition & control
$C^*$	= Characteristic velocity	$FOD$	= Foreign object debris
$C_d$	= Discharge coefficient	$GLOW$	= Gross lift-off weight
$C_v$	= Valve flow coefficient	$P\&ID$	= Plumbing and instrumentation diagram
$f_d$	= Friction factor	$PT$	= Pressure transducer
$F_t$	= Thrust	$TC$	= Thermocouple
$g_0$	= Acceleration due to gravity	$SF$	= Safety factor
$I_{sp}$	= Specific impulse	$VDC$	= Direct current voltage
$O/F$	= Oxidizer-to-fuel ratio		
$Q$	= Volumetric flow rate		

## 2 Initial System Characterization

The following section outlines the characterization and design process for Aphlex 1B, our second-generation bi-propellant liquid rocket engine, set to fly on our 30 kg launch vehicle, Callisto 1. Project Caelus's unique position as a 501(c)(3) non-profit organization consisting entirely of high school students has laid the foundation for a design approach fully committed to cost-effectiveness, simplicity, and reliability, given certain mission constraints and objectives as discussed below.

### 2.1 Objectives

The Callisto 1 system is set to the following objectives:

1. Reach an altitude of 1500 m ( $\approx$  5000 ft).

---

<sup>\*</sup>contact@projectcaelus.org, jay.chen135@gmail.com

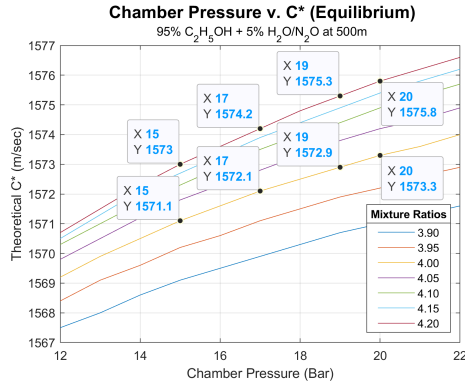


Figure 1: Theoretical C\* efficiency vs chamber pressure and numerous mixture ratios.

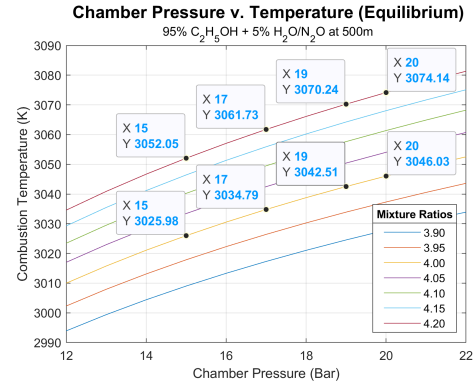


Figure 2: Combustion temperature vs chamber pressure and numerous mixture ratios.

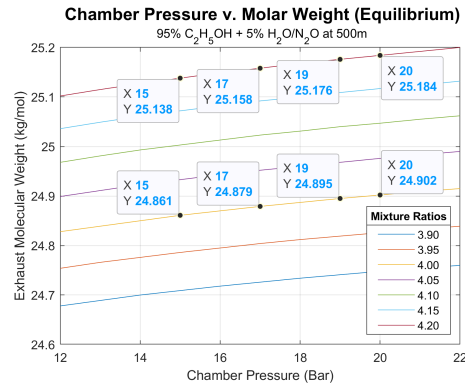


Figure 3: Gas molecular mass vs chamber pressure and numerous mixture ratios.

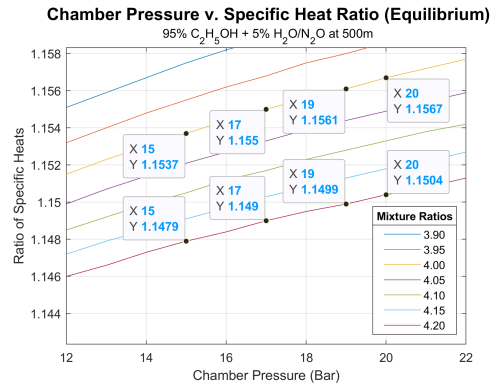


Figure 4: Ratio of specific heats vs chamber pressure and numerous mixture ratios.

2. A *GLOW* of no more than 30 kg ( $\approx 70$  lbsm).
3. A nominal main engine thrust of 1.5 kN ( $\approx 350$  lbf).
4. A chamber pressure in the range of around 15 Bar to 20 Bar ( $\approx 218$  psi to 300 psi)
5. Consume a budget of no more than \$10,000 USD.
6. Utilize 95% ethyl alcohol and nitrous oxide as the propellant combination.

## 2.2 Aphlex 1B

### 2.2.1 Chamber Pressure and Mixture Ratio Selection

The first step is to realize the theoretical maximum performance to be expected from our propellant combination. 95% ethyl alcohol (ethanol) was chosen for its availability, low pricing, and a modest specific impulse. A 95% dilution (by mass) with water was chosen as to lower the expected combustion chamber temperature. This tradeoff sacrifices some  $I_{sp}$  but reduces engineering complexity as regenerative and film cooling circuits may not be required. Industrial nitrous oxide was chosen as the main oxidizer for its self-pressurizing characteristics, non-cryogenic nature as opposed to liquid oxygen, relative ease to obtain, and a modest  $I_{sp}$  with ethanol. Using CEA, an open-source thermodynamics library provided by NASA's Glenn Research Center, critical data describing propellant combustion characteristics could be obtained. Numerical Python scripts were written to iterate through various combustion chamber pressures and mixture ratios and interface with CEA, and MATLAB scripts were used to parse and graph the CEA outputs as shown in Figures 1, 2, 3, and 4. Mixture ratios of 4.0 and 4.2 are labeled at certain chamber pressures. All dependent-variable properties (characteristic velocity  $C^*$ , combustion temperature  $T_c$ , exhaust molar mass  $M$ , and exhaust specific heat ratio  $\gamma$ ) were permuted assuming shifting equilibrium flow and at an operational altitude of 500 m.

A mixture ratio of 4.0 was chosen for Aphlex 1B mainly in the interest of a conservative combustion temperature of around 3026 K and a middle-of-the-line theoretical  $C^*$  of around 1570 m/s, given a chamber pressure of 15 bar. This chamber pressure was chosen to minimize upstream fluid pressures and thus tank weight requirements, while also considering two additional design constraints that were not mentioned above but are nevertheless valid guiding parameters: a fluid flow velocity of less than 6 m/s to avoid water hammer effects [Zucrow Laboratories] and a pressure drop across the injector of around 25% of the designated chamber pressure [Michigan Aeronautical Science Association]. These guidelines further encourage a lower chamber pressure, and thus a conservative value of 15 Bar was chosen.

### 2.2.2 Nozzle Design

Design Parameters			
Name	Value	Unit	Uncertainty
Propellant (Fuel)	Ethanol ( $C_2H_5OH$ , 95%)	N/A	N/A
Propellant (Oxidizer)	Nitrous oxide ( $N_2O$ )	N/A	N/A
$O/F$ , Oxidizer/fuel ratio	4.0	N/A	$\pm 1\%$
$F_t$ , Nominal thrust	1.50	$kN$	$\pm 0.1\%$
$P_c$ , Chamber static pressure	$1.5 \times 10^6$	$Pa$	$\pm 0.1\%$
$P_e$ , Ambient pressure	$9.5540 \times 10^4$	$Pa$	$\pm 0.1\%$
$T_c$ , Chamber static temperature	3025.98	$K$	$\pm 0.01\%$
$M$ , Exhaust molecular mass	24.861	$kg/mol$	$\pm 0.01\%$
$\gamma$ , Specific heat ratio	1.1537	N/A	$\pm 0.001\%$

Table 1: Summary of exhaust gas properties and fluid parameters.

$$T_3 = 15.04 - 0.00649h \quad (2.1)$$

$$P_3 = \left[ 101.29 \times \left( \frac{T + 273.1}{288.08} \right)^{5.256} \right] \times 1000 \quad (2.2)$$

The nozzle design process followed standard procedures outlined in Rocket Propulsion Elements [CITATION] and open-source NASA documents. The thermodynamic properties of the exhaust gas and other important parameters are summarized and compiled in Table 1. The ambient pressure was calculated using NASA Glenn Research Center's Earth Atmosphere Model for an altitude within the troposphere (less than 11000 meters), as shown in Equations 2.1 and 2.2, where  $T_3$  represents the ambient temperature in Kelvin,  $h$  is the altitude in meters,  $P_3$  is the ambient pressure in Pascals.

Assuming isentropic flow in the supersonic nozzle with choked flow conditions at the throat, an ideal converging-diverging (de Laval) nozzle can be characterized.

## 2.3 Callisto 1

## 2.4 Plumbing System

The following section describes the theoretical process used to dimensionalize the preliminary plumbing framework in preparation for the first static cold flow test. By definition, these calculations are purely speculative and are only used for the initial design process. The purpose of the cold flow test is to verify these parameters, and consequently adjust these parameters to better fit the system requirements.

### 2.4.1 Assumptions

To simplify the rigorous analysis and optimization processes often associated with viscous pipe flow, a couple of assumptions are applied in the following section to both shorten the development timeline and to avoid unnecessarily complex or expensive methods outside of the scope of a high school amateur rocketry program. They are as follows:

1. Flow is driven by both pressure and gravity.
2. Pipe is circular and is of constant cross-sectional area.

3. No swirl, circumferential variation, or entrance effects.
4. No shaft-work or heat-transfer effects.
5. Flow is fully developed (minimal boundary-layer effects).

Design Parameters			
Name	Value	Unit	Uncertainty
$\mu$ , Dynamic viscosity	0.00196	$kg/m \cdot s$	$\pm 0.1\%$
$\rho$ , Density	786	$kg/m^3$	$\pm 1\%$
$L$ , Pipe length	8.0	$m$	$\pm 0.1\%$
$d$ , Pipe diameter	12.7	$mm$	$\pm 0.1\%$
$\dot{m}$ , Mass flow rate	0.9133	$kg/s$	$\pm 0.1\%$
Pipe material	Hard nylon	N/A	N/A
$\epsilon$ , Roughness	1.5 to 40.0	$\mu m$	$\pm 50\%$

Table 2: Summary of exhaust gas properties and fluid parameters.