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Feasibility Analysis and Performance Study of a Pulsed Solid Propellant Integrated Propulsion System for Small Satellites

by

Tahir Kanchwala

A thesis submitted to the College of Engineering and Science of
Florida Institute of Technology
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Aerospace Engineering

Melbourne, Florida
December, 2021

We the undersigned committee hereby approve the attached thesis,
"Feasibility Analysis and Performance Study of a Pulsed Solid Propellant Thruster System for Small Satellites."
by
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Abstract

Title: Feasibility Analysis and Performance Study of a Pulsed Solid Propellant Integrated Electric Arc Propulsion System for Small Satellites

Author: Tahir Kanchwala

Advisor: Markus Wilde, Ph.D.

Solid propellant has come a long way since the 13th century when gunpowder was widely used as the go-to means in rocket propulsion. Of course, back then, rockets were not intended to carry humanity out of the atmosphere. Untill the introduction of liquid propellants in the mid-20th century, solid propellants were the foundation. Still, liquid propellants aimed to add more stability and controllability to rocketry and thus were preferred over their solid counterparts.

This thesis seeks to analyze a novel type of propulsive device that aims to eliminate challenges faced by both types of fuels and instead utilize the advantages of both technologies. Solid propellant traditionally offers higher propulsive power and a better thrust-to-weight ratio, especially if the weights of all the additional components are included in the calculation- compared to liquid fuels. However, liquid motors can be turned on and off very quickly, and the combustion itself can be controlled to offer a wide range of propulsive powers and efficiencies. However, liquid fuels require many supplementary parts to make the technology usable. This includes pressurized chambers, anti-sloshing devices, pumps, valves, piping, injectors, etc., to name a few. These parts are often heavy, expensive, and the technology itself is very complex. This thesis proposes a solution that carries the same propulsive efficiency as solid fuel, can produce a range of different thrusts and moments without requiring a vast array of supplementary parts and offers a more extensive range of controllability and stability than both liquid and solid fuels used as they are today.

The proposed thruster shall utilize a pulsed-based electrical ignition system that utilizes solid propellant pellets, featuring a central combustion chamber that opens to five different nozzles—providing high controllability, stability, and propulsive efficiency. This concept is then applied to small satellite technology, providing a more significant deal of propulsion ability into that niche, and opening the market for satellite servicing, orbit manipulation, and debris removal.

This thesis will introduce, analyze, and compare this device to the current state-of-the-art small satellite propulsion technologies. Finally, it will conclude with the need for this technology to exist.

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Acknowledgement

I would like to express extreme gratitude to every single person who enabled me to reach this stage in life.

First and foremost, my grandmother, Batool Kanchwala and my mother, Tasneem Kanchwala, without whom I would not have been here today. My mother for standing by me as a mother and father and supporting me in all aspects of life, and my late grandmother for standing by my side till the final years of my teenage life.

I would like to thank my advisor Dr Markus Wilde for always keeping me motivated and giving me the privilege of bouncing ideas back and forth to come up with creative solutions to various problems. I would like to thank Dr Kish for his support and guidance throughout my graduate career.

Lastly, I would like to thank all my peers, friends and colleges at Florida Institute of Technology who have always looked out for me and made me a better engineer.

Dedication

This thesis is dedicated to my grandmother Batool Hatim Kanchwala whose, love, support and teachings have enabled me to pursue the career of my dreams and complete this research. I would also like to dedicate this thesis to the field of aerospace engineering, which industry has given me a purpose and has motivated me through life.

Chapter 1: Introduction

The objectives of this thesis are to analyze, evaluate and discuss the design of a new pulsed combustion based propulsion device and compare performance parameters of this device to current technologies. Key performance criteria to be evaluated includes the following:

- Size and weight
- Specific impulse
- Operating power
- Total impulse
- Integration capabilities
- Comparison to flight heritage technology

To fully quantity key performance parameters assumptions are made to aid the design process, mission requirements will be set, and flight profiles will be considered. Principally, this thruster will be responsible for fine attitude control, however, may also be able to perform some orbital change maneuvers depending on the amount of propellant carried and the number of thrusters mounted on the satellite.

Overall, the design process follows this procedure:

1. Literature review
2. Definition of control modes
    a. Mission requirements and profiles
3. Definition of environmental constraints
    a. Min/ Max dimensions
    b. Required I_{sp}, Thrust and Mass flow rate
    c. Accuracy requirements
4. Optimization based on quantified constraints
5. Simulation

This thesis will explore points 1 through 5 and present a final prototype design of major components and integration suggestions. A prototype will be built by undergraduate seniors and will be tested based on experimental procedures outlined in final section of this document.

Chapter 2: State of the Art

This section explores various technologies and compares & quantifies their performance parameters to build a basis of what exists today. Comparisons for both chemical and electrical technologies are made as available for small satellite propulsion. Using past performance criteria improvements some requirements are set for the proposed thruster. Table 1 below summarizes technologies explored.

Table 1: Summary of Small Satellite Propulsion Technologies (NASA, 2020)

Technology	Thrust Range	Specific Impulse range [sec]
Chemical Propulsion Technologies		
Hydrazone Monopropellant	$0.25 - 22\ N$	$200 - 235$
Other Mono- and Bipropellants	$10\ mN - 30\ N$	$160 - 310$
Hybrids	$1 - 10\ N$	$215 - 300$
Cold/ Warm Gas	$10\ \mu N - 3N$	$30 - 110$
Solid Motors	$0.3 - 260\ N$	$180 - 280$
Electric Propulsion Technologies		
Electrothermal	$2 - 100\ mN$	$50 - 185$
Electrosprays	$10\ \mu N - 1\ mN$	$250 - 5000$
Gridded Ion	$0.1 - 15\ mN$	$1000 - 3500$
Hall-Effect	$1 - 60\ mN$	$800 - 1900$
Pulsed Plasma and Vacuum Arc Thrusters	$1 - 600\ \mu N$	$500 - 2400$
Ambipolar	$0.25 - 10\ mN$	$500 - 1400$

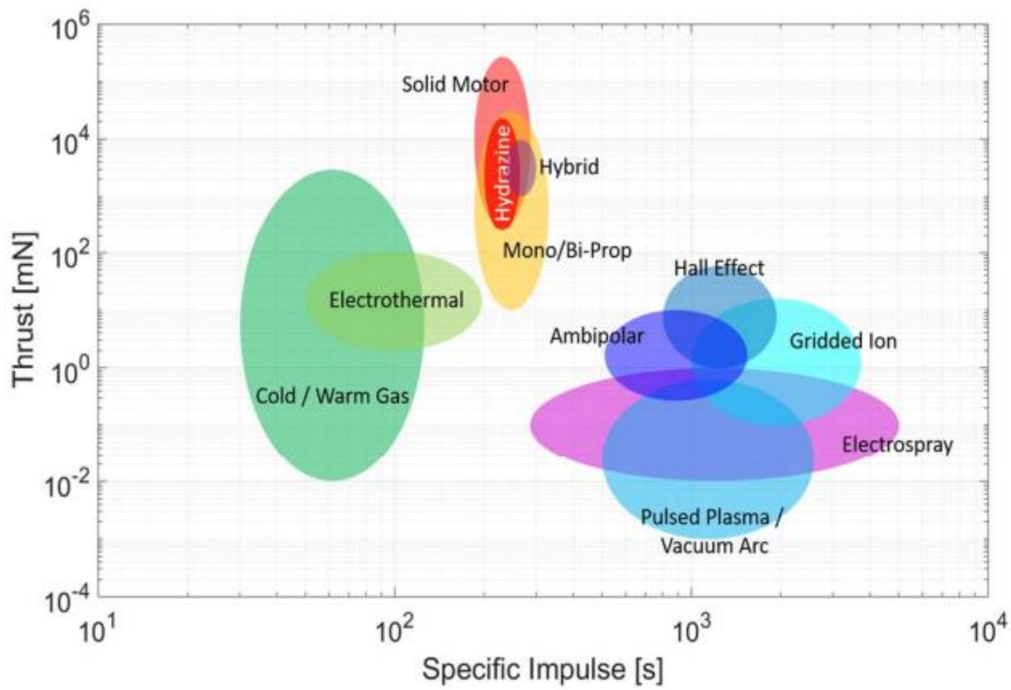


Figure 1:Typical small satellite propulsion trade space (NASA, 2020)

Overall, chemical propulsion technologies have proven to be capable for a variety of mission requirements. These are generally chosen when there is a need for high thrust or rapid maneuvering within the mission. Such propellants include hydrazine-based systems, mono or bi-propellants, hybrid, cold/warm gas systems or solid propellants as depicted in Figure 1 above.

Meanwhile, the application of electric in space propulsion has been limited and only recently some devices have started producing enough thrust to become applicable to the small satellite field. With greater development, there may come a tipping point where these devices are preferred over their chemical counterparts for some specific applications. The electric propulsion type explored in this thesis is the one that generates highest thrust and highest specific impulse, Hall-effect systems. Broadly used in applications which require high impulse and low thrust, such as station keeping. Overall, the difference between theses electric systems and their chemical counterparts lies in the maneuver time. Chemical systems produce thrust in millinewtons all the way to hundreds of kilonewtons, utilizing short maneuver times in magnitudes of milliseconds to seconds with moderate specefic impulse ranging from 100 – 300 seconds. Meanwhile namely Hall-effect propulsion systems produce thrust in millinewtons to newtons, utilizing long maneuver times in magnitudes of hours to even weeks or years with extremely large specific impulse in the magnitude of 1000s of seconds.

Other major technologies not covered include propellant-less technologies that utilize the space environment, such as solar sails, aerodynamic drag, lasers, electrodynamic tethers etc.

Space Chemical Propulsion

Chemical systems are implemented to satisfy high thrust impulsive maneuvers. Applications include attitude changes, docking, debris removal, de-orbit, or orbital change requirements. They operate in the lower specific impulse ranges compared to electrical propulsive technologies, however, have the capability to produce significantly more thrust (magnitudes more). When compared, these also feature much higher thrust to power ratios.

Liquid

Various liquids are in use today for spacecraft propulsion out of which Hydrazine is one of the most common. Mono-propellant hydrazine thrusters utilizes a catalyst to breakdown hydrazine to produce hot gasses. These systems have been used extensively since the early 1960s. Hydrazine however is corrosive and toxic, thus dangerous to use and requires the use of Self Contained Atmospheric Protective Ensemble (SCAPE) suits. As a result, the net cost of hydrazine is high due to the added ground handling.

Due to the toxicity of hydrazine, other mono/bipropellants are sometimes preferred, especially in low-cost situations. Table 2 and

Table 3 summarizes and compares various integrated propulsion systems and thrusters. Where an integrated propulsion system is one which is essentially a plus and play system and contains all the required propellant, controls and electronics, whereas a thruster head is a larger system containing the combustion chamber, exhaust and some piping systems that deliver the propellant, primarily however it is just the nozzle and combustion chamber assembly. A detailed comparison of integrated systems is made in the technology breakdown section, and each product is individually analyzed as these systems most closely match the proposed propulsion system. These tables also characterize the sizing of these systems in units of ‘U’ where one U is defined as a cube of length ten centimeters, subsequently two U is defined as two of these cubes stacked on top of each other and so on.

Additionally liquid thrusters also require the use of redundant valves through the system to prevent leaks. Regardless, these systems have been used in multiple missions especially for larger spacecraft. Systems that used to provide attitude control and correction maneuvers in larger spacecraft have the potential to be implemented as high-thrust maneuvering devices for small satellites. These thrusters have impulses of 200-235 s and can produces thrusts ranging from 1N to 10s of N for small satellite thrusters.

Table 2: Liquid Chemical Propulsion State of the Art Integrated Propulsion Systems

Manufacturer	Product & Reference	Propellent	Thrust	Specific Impulse	Total Impulse	Dry Mass	Envelope	Power	Missions
			[N]	[s]	[kN-s]	[kg]	[U]	W	-
Integrated Propulsion System									
Aerojet Rocketdyne	MPS-120 (Aerojet Rocketdyne, 2021)	Hydrazine	0.25 - 1.0		>2 (2U)	1.2-1.5	1U - 2U		-
Aerojet Rocketdyne	MPS-125 (Aerojet Rocketdyne, 2021)	Hydrazine	0.25 - 1		>7 (4U) >19 (8U)	3.6-5.1	4U - 8U		-
Dawn Aerospace	PM200 (Dawn Aerospace, 2021)	Nitrous Oxide & Propene	0.5	285	0.85	1.01	1U (scalable)	22.5	
NanoAvionics	EPSS C1K (NanoAvionics, 2021)	ADN-blend	1.0 (BoL) 0.22 (EoL)	213	0.4	1	1.3U	0.19 (monitor) 9.6 (preheat) 1.7 (firing)	CubeSat Propulsion EPSS C1
Tethers Unlimited	HYDROS0-C (Tethers Unlimited, 2021)	Water (Electrolysis)	1.1	>310	>2	1.87	190mm x 130mm x 92mm	5-25	Pathfinder Technology Demonstration

Table 3: Liquid Chemical Propulsion State of the Art Thruster Heads

Manufacturer	Product	Propellent	Thrust	Specific Impulse	Total Impulse	Dry Mass	Envelope	Power	Missions
			[N]	[s]	[kN-s]	[kg]	[U]	W	-
Thruster Heads									
Aerojet Rocketdyne	MR-103 (Aerojet Rocketdyne, 2020)	Hydrazine	1	>285	183	0.33-0.37	-	16	Multiple
Aerojet Rocketdyne	MR-111 (Aerojet Rocketdyne, 2020)	Hydrazine	4	202-224	262	0.37	-	16	Multiple
Aerojet Rocketdyne	MR-106 (Aerojet Rocketdyne, 2020)	Hydrazine	22	219-229	561	0.59	-	36	Multiple
Ariane	1N (Ariane Group, 2021)	Hydrazine	1	228-235	135	0.29	-		Multiple
Moog	MONARC-1 (MOOG, 2021)	Hydrazine	1	227.5	111	0.38	-	18	Multiple

Moog	MONARC-5 (MOOG, 2021)	Hydrazine	4.5	226.1	613	0.49	-	18	Multiple
Moog	MONARC-22 (MOOG, 2021)	Hydrazine	22	228-229	533-1173	0.69-0.72	-	30	Multiple
Plasma Processes LLC	100mN Thruster PP3490-B (NASA Jet Propulsion Labratory, 2021)	AF-M315E	0.1-0.17	195-208	-	0.08	-	7.5-10	Lunar Flashlight

Pressurized gas

Cold or warm gas systems are relatively simple and most mature in small spacecraft propulsion; however, they are limited in performance. These systems require no chemical reactions- unlike all other chemical propulsion technologies- instead thrust is produced by expanding propellant often stored as a pressurized gas or a saturated liquid. To increase performance, there are systems which heat up the gas prior to expansion but carry the cost of added power.

Cold gas thrusters are usually used in small buses due to their low cost and complexity, most of these thrusters also use inert gasses which are non-toxic as propellant and thus are beneficial as they do no harm towards other payloads in the event of a malfunction. They are capable to carry out attitude control maneuvers, since they provide very small impulse bits, but very low specific impulse limits this technology to attitude control only.

Table 4 shows the breakdown of the state of the art in cold/ warm gas propulsion devices. Their properties include low Isp and can only produce thrust in magnitudes of mN, this is a significant difference when compared to the liquid propulsion systems.

One unique advantage about these systems is that multiple nozzles can be setup in different directions to utilize and produce thrust or moments in all 6 degrees of motion, such does the GomSpace NanoProp 6DOF, further discussed in the technology breakdown section.

Table 4: Cold and Warm Gas propulsion State of the Art

Manufacturer	Product & Reference	Propellent	Thrust	Specific Impulse	Total Impulse	Dry Mass	Envelope	Power	Missions
			[mN]	[s]	[N-s]	[kg]	[U]	W	-
Integrated Propulsion System									
GomSpace	Nanoprop 6DOF (GOMSpace, 2021)	Butane	1 - 10 (x6)	60 - 110	80	0.77	200 mm x 100 mm x 50 mm	<2	
Lightsey Space Research	BioSentinel Propulsion System (Lightsey, Stevenson, & Sorgenfrei, 2018)	R236fa	40 - 70	40.7	79.8	1.08	200 mm x 100 mm x 40 mm	<4	BioSentinel
Marotta	MicroThruster (Schappell, Scarduffa, Smith, & Solway, 2012)	Nitrogen	0.05 - 2.36 N	70				<1	numerous
Micro Space	POPSAT- HIP 1 (Manzoni & Brama, 2015)	Argon	0.083 - 1.1 (x8)	43					POPSAT-HIP1
UTIAS/SFL	CNAPS (Newman & Zee, 2015)	Sulfur Hexafluoride	12.5 - 40	30	81				CanX-4/CanX-5
VACCO	MiPS Standard Cold Gas (VACCO, 2020)	R236fa	25 (x4)	40	98-489	0.553 - 0.957	0.4 - 1.38 U	12	
VACCO	MarCO-A and -B MiPS (VACCO, 2019)	R236fa	25 (x8)	40	755	3.5	2U	15	MarCO-A & -B

Solid

In the small satellite niche, solid motors are almost exclusively used for high impulse maneuvers such as orbit insertion or rapid de-orbiting maneuvers. Solid propellants generally achieve moderate specific impulse and high thrust magnitudes that are suitable for small satellite applications. Some solid thrusters are electrically controlled as well and operate in the mN thrust range. These are quite special since they can be started and stopped unlike traditional solid propellants which, once ignited, cannot be shut off.

The key consideration for operation is being restartable, however solid motors are generally used for single burn events due to the nature of the propellant. Electric solid systems provide the flexibility but not the thrust. There are a series of devices that configure several small units of solid propellant into a matrix and burn them individually such as the PacSci EMC MAPS rocket motor. However, these configurations are considered unsafe due to the amount of energy stored in the propellants themselves.

This thesis aims to introduce a device similar to the MAPS motor, with added flexibility, redundancy, and safety. Table 5 summarizes the current state of the art in solid propulsion.

Table 5: Solid Propellant Propulsion State of the Art Integrated Propulsion Systems

Manufacturer	Product & Reference	Propellent	Thrust	Specific Impulse	Total Impulse	Dry Mass	Envelope	Power	Missions
			[N]	[s]	[N-s]	[kg]	[U]	W	-
Integrated Propulsion System									
D-Orbit	D-Raise (D-Orbit New Space Solutions, 2021)	-	-	-	-	50-78	-	-	-
D-Orbit	D3 (D-Orbit New Space Solutions)	-	-	-	-	16-257	32 cm x 32 cm x 25 cm to 1100 cm x 500 cm x 1000 cm	-	-
DSSP	CAPS-3 (DSSP, 2021)	HIPEP-501A	0.3	Up to 900 for 12 thrusters	0.125	0.023	0.92 cm x 2.79 cm x 4.2 cm	<2.3	SPINSAT
DSSP	MPM-7 (DSSP, 2021)	HIPEP-H15		200	1.5	<750 g	<0.75 U	200	
PacSci EMC	MAPS (Pacsci EMC, 2021)	-	-	210	-	-	38 cm x 10.5 cm	-	PACSCISA T
PacSci EMC	P-MAPS (Pacsci EMC, 2021)	-	-	-	-	-	-	-	

Table 6: Solid Propellant State of the Art Thruster Heads

Manufacturer	Product & Reference	Propellent	Thrust	Specific Impulse	Total Impulse	Dry Mass	Envelope	Power	Missions
			[N]	[s]	[N-s]	[kg]	[U]	W	-
Thruster Heads									
DSSP	CDM-1 (DSSP, 2021)	AP/HTPB	186.8	235	226.4	0.046	0.64 dia x 0.47 length	<5	-
Industrial Solid Propulsion	ISP 30 Sec Motor (Industrial Solid Propulsion Inc., 2021)	80%Solids HTPB/AP	37	187	996	0.95	5.7 cm	-	-
Northrup Grumman	STAR 4G (Northrup Grumman, 2021)	TP-H-3399	258	258	595	1.49	11.3 cm dia x 13.8 cm length	-	-

Space Electric Propulsion

Space electric propulsion is such that converts electrical energy into kinetic energy, sourcing this electrical energy traditionally from solar arrays but sometimes other power sources such as nuclear reactors. The key technology discussed are hall-effect thrusters due to their high success and thrust quantities in comparison to other electric propulsion (EP) systems.

The Hall-effect thruster (HET) is perhaps the most successful since it has the most flight heritage out of all the other EP systems. These thrusters are a form of ion propulsion and produce thrust be accelerating ionized propellant through an electric field. These thrusters apply a strong magnetic and electric field to the ionize the propellant (traditionally Xenon) and accelerate it through the exit plane and can produce thrust ranging from 2 mN – 55 mN with specific impulse ranging from 800 s – 1600 s, requiring high power in comparison to other systems from 53 W to 1000 W (NASA, 2020).

Table 7 below summarizes the state-of-the-art Hall-Effect propulsion technologies.

Table 7: State of the Art Hall-Effect Thrusters taken from (NASA, 2020)

Manufacturer	Product	Propellent	Thrust	Specific Impulse	Total Impulse	Dry Mass	Envelope	Power	Missions
			[mN]	[s]	[kN-s]	[kg]	[cm^3]	W	-
Integrated Propulsion System									
Exotrail	ExoMG Nano	Xenon	2	800	5	-	-	53	MP6 Demo, ELO3, ELO4
EDB Fakel	SPT-50	Xenon	14	860	126	1.2	1092	220	Canopus-V
SITAEL	HT400	Xenon	27.5	1230	1000	2.77	1330	615	
Safran	PPS-X00	Xenon	43	1530	1000	-	-	650	
NASA JPL	MaSMi	Xenon	55	1920	3000	3.4	1700	1000	

Performance and Technology Breakdown

In this section some thrusters from each chemical technology are analyzed. Their pros and cons are explored based on which a need for a new thruster is presented. Key factors include:

- Size and weight
- Specific Impulse
- Operating power
- ΔV capabilities/ Max thrust capabilities
- Minimum Impulse Bit

Table 8 summarizes the key parameters to be discussed and compared. One of these parameters is the dry and wet mass, of which the dry mass includes only the structure of the system, and the wet mass is the sum of the structure and the propellant. It is evident that the traditional solid propellant thruster can produce maximum thrust, however this thruster has almost no controllability and may only be used to de orbit a satellite if implemented. All other technologies produce comparable thrusts of approximately 200-500 mN and have various advantages and disadvantages over one another. The minimum impulse bit reflects the precision of the burn and reflects the controllability of the spacecraft, whereas total impulse reflects how long could a thruster be used for.

From Table 8 it is evident that a thruster with a small minimum impulse bit, high total impulse, high thrust, and moderate specific impulse would be desirable for implementation on small satellites.

Each of the devices in Table 8 are closely examined further in the section.

Table 8: Key Performance Comparison between Technologies and Propellant types

			[mN]	[s]	[N-s]	[kg]	[kg]	[W]	[mN-s]	
Propellant Type & Manufacturer	**Propellant**	**Product**	**Thrust**	**Specific Impulse**	**Total Impulse**	**Dry Mass**	**Wet Mass**	**Power**	**Minimum Impulse Bit**	**Burn time/ Number of Pulses**
Electric Solid Propellent by DSSP	HIPEP-501A	CAPS-3	300	900	0.125	0.023	0.5	2.3	0.21	2 ms per thruster (250 pulses per thruster)
Traditional Solid Propellant From Northrop Grumman	TP-H-3399	STAR 4G	258000	258	595	0.52	1.5	0	N/A	10.8 s
Liquid Propellant from Dawn Aerospace	Nitrous Oxide & Propene	PM200	500	285	850	1.01	1.42	12	35	-
Liquid propellant from Aerojet Rocketdyne	Hydrazine/ Green Propellant	MPS-120	250-1000	206-217	6000	1.06	1.48	10	4	10,000
Warm Gas from GomSpace	Butane	Nanoprop 6DOF	60	50	65-100	0.682	0.77	2	0.025	-
Cold Gas from VACCO	R236FA	MarCO-A and -B MiPS	200	40	755	3.5	3.5	15	0.5	-
Matrixed Array Solid from PacSci EMC	-	MAPS	-	210	-	-	-	-	-	176

Hydrazine Liquid Propellant: Aerojet Rocketdyne MPS-120

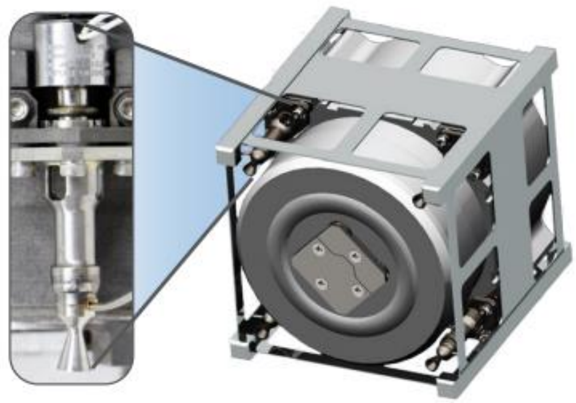


Figure 2: MPS-120-1U Thruster (Aerojet Rocketdyne, 2021)

The Modular Propulsion Device (MPS) series from Aerojet Rocketdyne features multiple CubeSat configurations and is marketed as a high reliability and high delta V propulsion system for small satellites. These systems are designed to be the primary propulsion system and are designed for orbit maintenance, station keeping and reaction control and offer both non-toxic green propellant and traditional hydrazine options. Their thrusters follow designs of 1U (pictured in figure above) to 8U and can provide Delta Vs of 250 to 1200 m/s for a 3kg spacecraft (wet mass) depending on the configuration size and if a piston tank or pump tank system is used. The 1U and 2U systems have an operational temperature range of 5-60 C, take 0.25 Watts per valve, and require 6-8V per valve for operation. On average the system heater takes 10W of power however that is highly dependent on spacecraft mission. The following graph in Figure 3 presents the performance data for these thrusters. The thruster is capable of 10,000 pulses, with a total impulse of > 6000 N-s each and thrust of 0.25-1.25 N. What is especially interesting is the minimum impulse bit of 0.0004 N-s, providing good controllability when desired by the spacecraft.

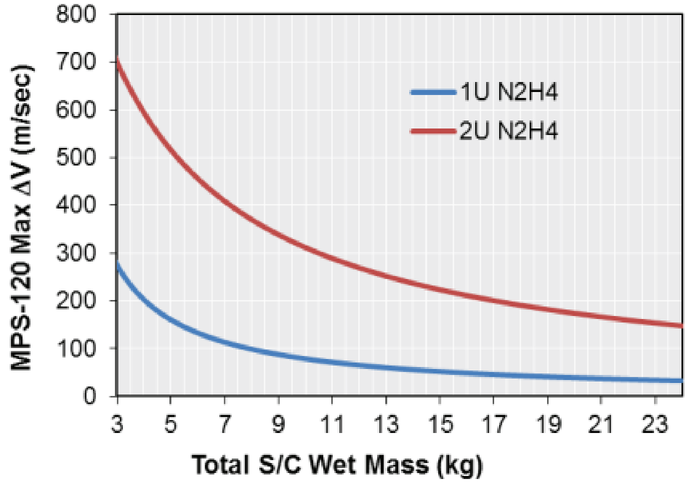


Figure 3: MPS-120 Performance Data Delta V vs Wet Mass of S/C (Dawn Aerospace, 2021)

The overall design is also desirable since the system, or the series of thrusters are made modular thus can be scaled up or down based on mission requirements.

Nitrous Oxide & Propene Liquid Propellant: Dawn Aerospace PM200

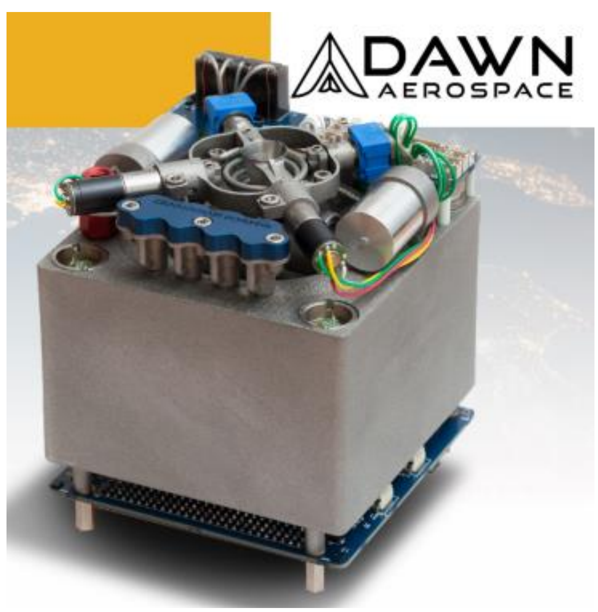


Figure 4: Liquid Propellant thruster PM200 (Dawn Aerospace, 2021)

This liquid propellant thruster offers similar performance to the MPS120 in terms of thrust delivery, however, is less precise in terms of impulse delivery. Instead of 4 different nozzles at each corner it uses a larger nozzle in the middle and has a similar similar size. Its greatest advantage is the total impulse it can deliver and the number of pulses that can be fired that may make is desirable over the MPS-120. In both devices most of the physical volume is taken up by the pressurized chambers that store the propellant.

Warm Gas Propellant: GomSpace Nanoprop 6DoF

This device follows a simplistic design and offers flexibility in terms of attitude control due to the orientation of the MEMS thrusters. It offers an minimum impulse bit (MIB) of 25 micro-Newton seconds and a total impulse of 60-100 Ns. This propulsion system is especially desirable for rendezvous and docking applications due to the small MIB. With 122grams of propellant and a dry mass of 628 grams nominal thrusts of 10 mN can be produced by each thruster with a maximum of 60 mN. The following schematic in Figure 5 shows the simplicity of design of the system. However, like all cold/warm gas systems, thrust and Isp magnitudes are quite small in comparison to all available technology.

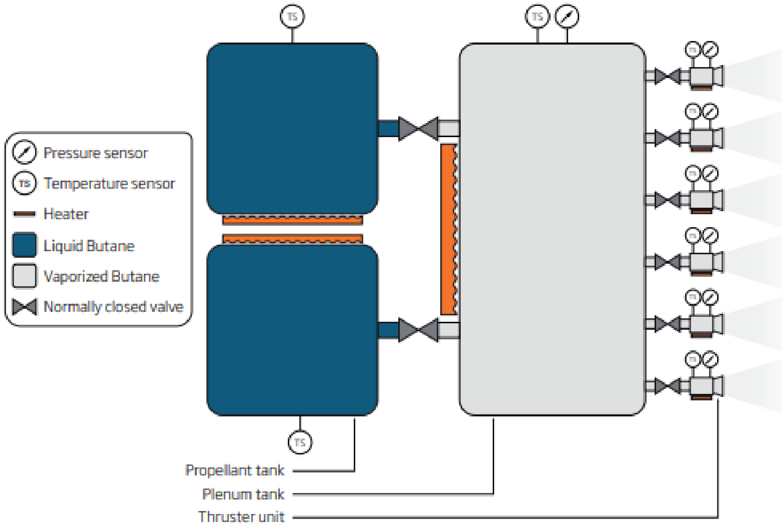


Figure 5: NanoProp 6DoF Schematics (GOMSpace, 2021)

Cold Gas Propellant: VACCO MarCO-A & -B MiPS

This thruster, jointly developed by NASA JPL, is a smart-self-contained propulsion system for use in small satellites primarily in 6U configurations, offers a larger total impulse of 755 N-s with 4 axial and 4 RCS thrusters generating 25 mN of thrust each. However, the drawback of this device is its total wet mass of 3.5 kg, approximately 2 kg higher than the other systems of comparable nature. The schematic in Figure 6 also portrays the simplicity of this device.

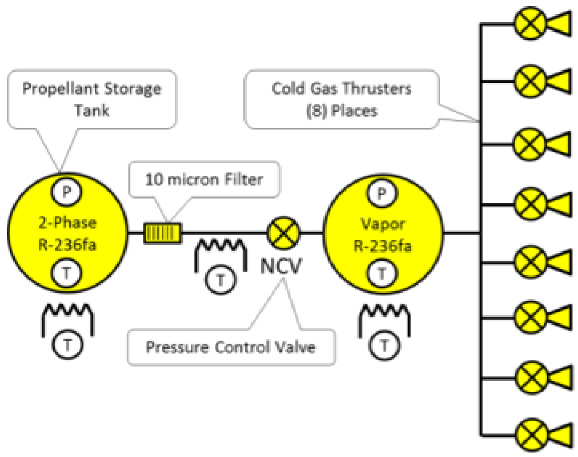


Figure 6: VACCO JPL cold gas thruster schematic (VACCO, 2019)

Electric Solid Propellant: DSSP CAPS-3

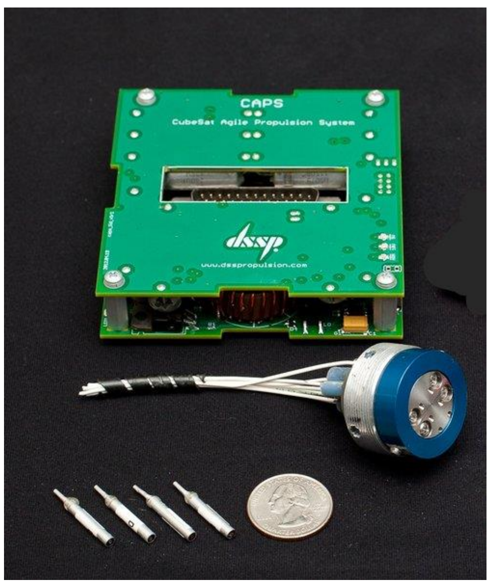


Figure 7: DSSP CAPS-3 Propulsion system (DSSP, 2021)

The CAPS-3 system from DSSP offers unparalleled flexibility, its system is made up of thrusters, the power control unit (PCU) and a wire connector if required. Each PCU can power up to 12 individual thrusters. The thrusters can be placed anywhere on the satellite bus, in any orientation. Depending on the mission multiple units can be used to provide more thrust. Additionally, each thruster can be individually controlled, and a thruster pack (set of 3) can produce 300 mN of thrust or can be fired multiple times, for up to 250 pulses. Each thruster only carries propellant that lasts 2 ms when burned completely to produce maximum thrust. If high thrust burns are required multiple thrusters will be used up while offering no reusability. The thrusters themselves are extremely light weight (7.76 grams each) and multiple can be used. The PCU however is the limiting factor for this device since it can only control up to a maximum of 12 thrusters and weighs 475 grams. If max thrust is required through one axis, a maximum of 1.2 N using all 12 thrusters could be produced, yielding a thrust to mass ratio of $2E-06$. The idea of the proposed device is to overcome this factor while also providing the orientation flexibility, and a larger thrust to mass ratio.

Traditional Solid Propellant: Northrop Grumman STAR 4G

Figure 8: STAR 4G Solid Propellant Motor (Northrup Grumman, 2021)

The STAR 4G motor is an example of a traditional solid propellant motor, truly offering high thrust capability, however this system for single use and cannot be stopped after ignition. Since it is single use and cannot be throttled, it is overall undesirable for the specefic use case presented in this thesis.

Solid Propellant: PacSci EMC P-MAPS

This system is perhaps the most unique and from the above devices and offers the most flexibility within the solid propellant niche. It uses a matrixed array of solid propellant and is developed for use on a 3U- 6U satellite, with a diameter of 38 cm X 10.5 cm length. It is the simplest in terms of integration and is marketed as a *plug and play* device. The matrix array contains 176 individual cartridges of solid propellant which can be fired individually, jointly or in various configurations for attitude correction, desaturation maneuvers or orbital change maneuvers. Has a moderate Isp of 210 s and requires very low power for operation. The schematic below in Figure 9 further breaks down the system. It is unknown however what the nominal thrust levels are, or what the minimum impulse bit is.

Figure 9: PacSci EMC Solid Propulsion System (Pacsci EMC, 2021)

This thesis proposes a thruster that allows for similar flexibility, offers reusability when refueling is available and minimizes the use of pressurized tanks, sprayers or igniters for propellant use or storage. Based on the above devices the objective of this thruster is to be able to produce thrusts in magnitudes of 1 – 10,000 mN, with a moderate Isp between 200 - 300s, and small minimum impulse bit in the magnitude of 10 – 20 ms. The following section addresses the analytical design and the need for such a thruster.

Chapter 3: Analytical Design

Concept Need

The following table outlines the need for development and requirements for the proposed thruster. This table provides a summary for the need of such a propulsion device to exist for small satellites and combines desired qualities of the state of the art into one compact system. The following sections detail the specifics of the system. The largest advantage being reusability, which does not exist for in space propulsion today.

Table 9: Major requirements table for concept propulsion system

Number	Target Quality	Requirement
01	High efficiency in thrust to weight ratio	System to have thrust to weight ratio of 50+
02	Modular flexibility	Modular design for easy installment, scaling and adapting to different mission requirements
03	In space reusability with minimal servicing	Quick release propellant chamber with quick connect cartridge system
04	Easy Integration	Plug and play system for all satellite classes
05	High gain dynamic maneuvering ability	Ability to produce large thrusts for de-orbit maneuvers or quick multiple multi axis maneuvers for docking and rendezvous 150-500 combustion events with 1500+ control events
06	High precision maneuvering with 6 DoF	Control for 6DoF within one dynamic system
07	Low Power and high resiliency	Low power requirements for ease of integration <10 W for operation; <0.1 W for idle storage. Stable propellant for missions with high lifetimes

System Overview

The proposed system follows a relatively simplistic design such as the cold/warm gas devices, however, has the ability to generate more thrust due to its use of solid propellant. A general schematic is shown in Figure 10. The system also operates similar to a liquid propulsion system by the use of a storage chamber, however there is no requirement for a pressurized tank due to the nature of the propellant. The feed system acts in place of a pump which moves propellant through and electrically controlled ignition system.

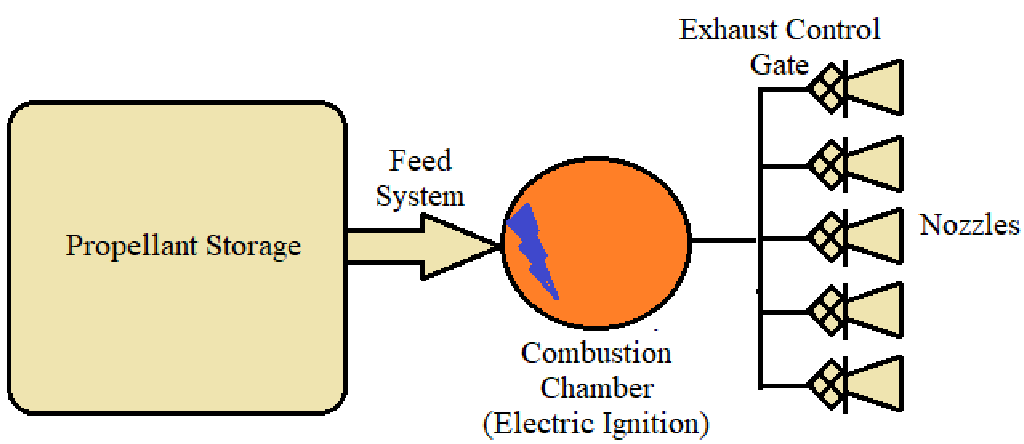


Figure 10: Schematic of Proposed Propulsion System

The uniqueness of this design is in the propellant itself. Unlike traditional solid motors which use cylindrical grains which burn over time, this system uses very small spherical pellets. These pellets are small enough to fully combust via the use of an electric ignition mechanism and pack the same amount of energy per unit volume as traditional solid motors. As a result, this system is able to overcome traditional issues faced with gas, liquid, or solid motor systems. In addition, the five nozzles, on five faces of a cuboid are able to be individually controlled to achieve the desired attitude change, or the desired orbital maneuver.

With the right control algorithm thrusts ranging from mNs to some N value could be produced, while achieving a moderate Isp. This makes the minimum impulse bit, fully dependent on the control system of the exit gates rather than the combustion itself, setting this device apart from all other in production today. A 3D schematic of the device is pictured in Figure 11 which breaks down the entire system.

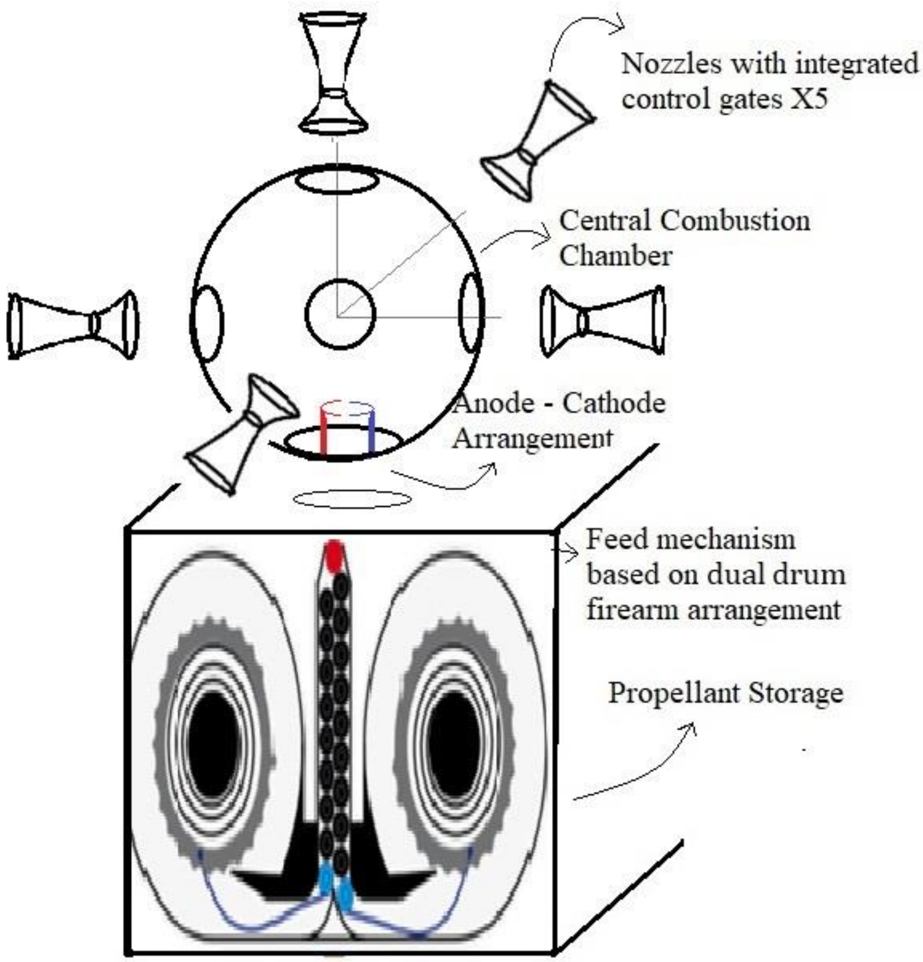


Figure 11: Schematic of proposed propulsion system

In this section the design is developed in more detail and each of the components are further discussed.

Propellant

After careful consideration of multiple traditional propellants, it was found that a new type of propellant would be required for this purpose. The qualities required include: no residue after combustion, electrically ignited using a low power system, thermally stable between extreme temperature variations, combustible in low pressure environments, high energy per unit volume content.

There are multiple classes of solid propellant which must be explored.

- Black powder
- Zinc-Sulphur
- Candy propellants
- Double base propellants
- Composite propellants
- Composite modified double base propellants
- Smokeless propellants
- Electric solid propellants

From these classes some can be disqualified easily due to their inherent properties. Black powder-based propellants leave large amounts of residue, which would make the combustion chamber dysfunctional and may create blockage in the nozzles. However, it is ignited electrically with minimal energy and can be used in vacuum. Zinc-Sulphur based propellants have poor performance and cannot be stored for the large lifetimes required in certain missions. Candy propellants refer to oxidizer plus sugar mixtures, however they generate low Isps and since they are potassium nitrate based (as oxidizer, similar to black powder) they leave behind solid residue.

Double-base propellants are a mixture of two monopropellants with additives for specific use cases. The main ingredients of this class of propellants are Nitrocellulose and Nitroglycerine. These are highly combustible and theoretically leave no solid residue, after complete combustion. The complete combustion reaction for Nitroglycerine follows the following equations, balanced so oxygen from the combustion of Nitroglycerine enables the combustion of Nitrocellulose.

$$18C_3H_5N_3O_9 \rightarrow 54CO_2 + 27N_2 + 45H_2O + \frac{9}{2}O_2$$

Similarly for Nitrocellulose:

$$2C_6H_7N_3O_{11} + \frac{9}{2}O_2 \rightarrow 12CO_s + 3N_2 + 7H_20$$

This class of propellant offers the high energy content and complete no solid residue combustion however is highly explosive and chemically unstable and may self-ignite, proving catastrophic for the mission. (Elbasuney, Fahd, Mostafa, Mostafa, & Sadek, 2018). However, the chemical formulation and the mixture can be stabilized for better performance via the use of the next class of propellants.

Composite propellants are ones generally based on Ammonium-Nitrate (AN) or Ammonium-Perchlorate (AP), generally with some metal fuel and rubbery binder. These are heterogenous mixtures of crystalline oxidizer particles (AP or AN) with hydrocarbon-based fuels like Hydroxyl-terminated polybutadiene (HTPB) , Carboxy-Terminated Polybutadiene (CTPB) and Polybutadiene acrylonitrile (PBAN). At times, aluminum particles are added to the mixture to increase specific impulse. The most common combination is AP-HTPB due to its performance and desired properties. With the addition of aluminum performance is further improved, however a substantial amount of liquid aluminum oxide is left over in the chamber (Chaturvedi & Dave, 2019).

A combination of the two classes exist which start with the nitrocellulose/ nitroglycerin combination with an addition of AP or HMX (Octogen), which further increase performance.

This propellant seems the most viable option for this application, however the burn rates of these propellants are strong functions of pressure and require an ignition charge or an ignitor which can increase chamber pressure for a sustained combustion process for these propellants. For purely electric ignition AP/HTPB mixtures require a large pulse of current, (Lee, 1996) which is not possible for a small spacecraft bus.

HMX however is highly explosive and detonable, with moderate shock which may be a viable ignition mechanism, instead of an electrical system. This however will be determined in future research.

Another possible class of propellants that may be viable is the CL-20 (China Lake compound #20) or chemically known as Hexanitrohexaazaisowurtzitane which has 14% higher energy per unit mass than HMX. There is significant research underway in this class of propellant due to its smokeless, undetectable nature and some research suggest that it could be ignited via laser (McBain, Vuppuluri, Gunduz, Groven, & Son, 2018).

Lastly, perhaps the newest form of solid propellant are electric solid propellants which can be ignited by passing current through them and subsequently can be turned off once there is no current passing through them. These are a family of plastisol propellants whose burn rate/ combustion rate is a function of voltage and are commercially used in the CAPS-3 system by DSSP (Sawka & McPherson, 2013).

Upon discussion with DSSP, there may be a viable solution for a propellant that meets the requirements for this thruster. However, for numerical simulation two cases will be studied, a traditional AP/HTPB propellant pellet with a Boron-Potassium nitrate shell for ignition and a Double-Base propellant with a Boron-potassium nitrate shell. Various mass configurations and their resulting Isps will be reported and then compared to the electrical propellant in use by CAPS-3 system. This could prove a viable system, given some solid residue is accepted in the system.

Figure 12 summarizes the standard propellants mentioned in this thesis and also highlights the region in which electrical solid propellants operate.

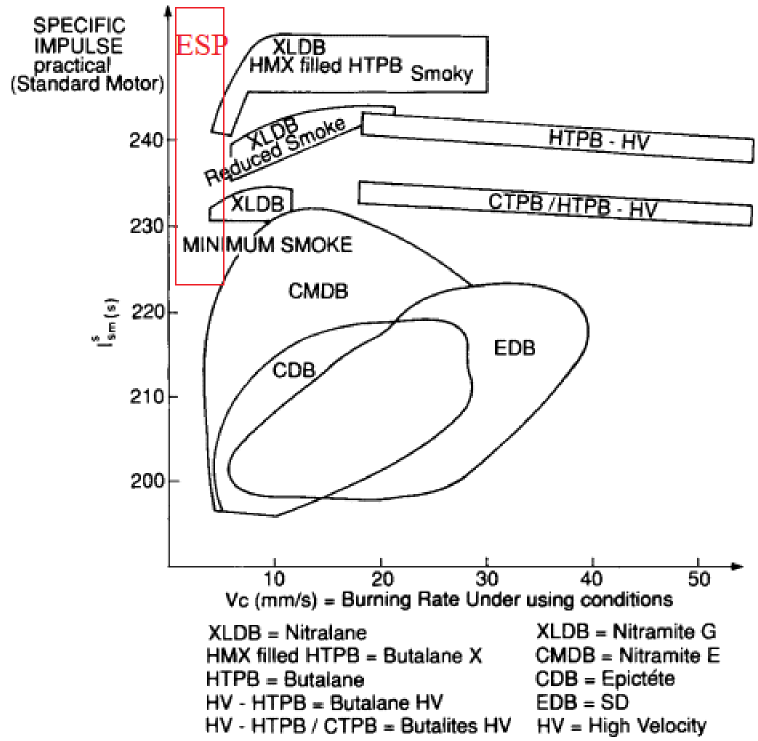


Figure 12: Average propellant class performance from (Davis, 1992) and ESP addition from (Sawka & McPherson, 2013)

Based on performance of ESP, HTPB and EDB propellants, a system design is proposed.

Ignition

Originally, it was proposed that an electric arc may be a viable ignition option that propellant pellets would pass through, from a cathode-anode arrangement. An arc however fundamentally comprises of plasma- hot ionized gasses. However, since the combustion chamber will not be pressurized initially an arc would be difficult to produce. An arc is also a possibility in vacuum but requires more power and especially conductive materials. These materials emit electrons which form the arc between anode and cathode but require greater power.

Instead, the anode and cathode could be made in a ring formation as pictured in Figure 11, whose diameter would match the diameter of the pellets. This would drive current though the solid propellant and force ignition. Further research and experiment are suggested to study what shape pellet would be most efficient with this ignition mechanism.

Alternatively, another means of electric ignition could be through a high-power laser <5W. Laser ignition is a viable option and there is research that suggests that Boron-Potassium Nitrate can be ignited with laser power of 400 mW or above as seen in Figure 13 (Koizumi, et al., 2006). Theoretically, the propellant B-KNO_3 shell could be ignited via laser, which would start the combustion process of the pellet. This heat and pressure buildup inside the chamber from the reaction would cause the AP/HTPB pellet core to ignite and combust after a delay of some milliseconds. The following reactions would take place in sequence. The combustion equations for AP and HTPB is highly complex but the single step equations of each are presented based on a combustion model (Guirao & Williams, 1971).

$$B + KNO_3 \rightarrow KBO_2 + NO$$

$$AP \rightarrow 1.62H_2O + 1.105O_2 + 0.265N_2 + 0.12H_2O + 0.23NO + 0.76HCL + 0.12Cl_2$$

$$HTPB \rightarrow C_2H_4 + light\ hydrocarbon\ species$$

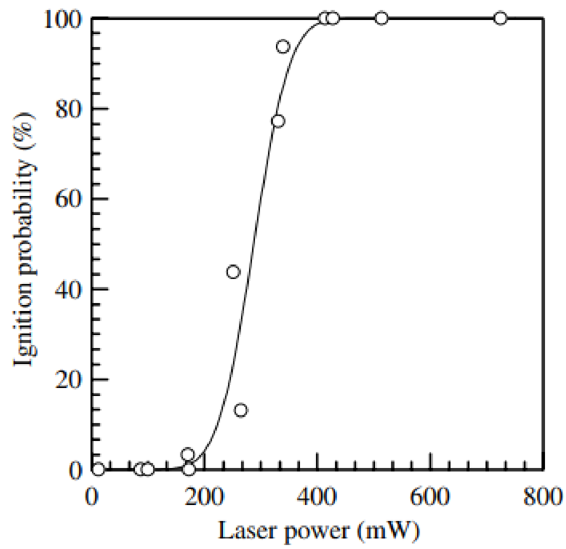


Figure 13: Laser ignition probability of Boron-Potassium Nitrate in vacuum and dependence on laser power (Koizumi, et al., 2006)

Combustion & Expansion

The combustion chamber follows the general geometry as shown in Figure 14, only one nozzle is shown, whereas the same spherical chamber is connected to 5 separate nozzles. For a first level design analysis this single nozzle case is analyzed to determine the appropriate sizes for the combustion chamber and exhaust nozzle.

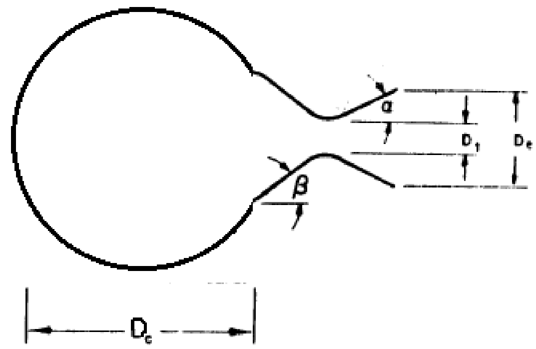


Figure 14: Combustion chamber and nozzle geometry

The nozzle throat area can be determined if the total propellant flow rate is known, and the propellant operating conditions have been determined. Assuming ideal gas and a chocked flow case:

$$A^* = \frac{\dot{m}}{P_t}\sqrt{\frac{RT_t}{\gamma}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

Where R is the gas constant, γ is the ratio of specific heats, T_t is the total temperature of the gasses at nozzle throat, P_t similarly the total pressure at the throat and $\dot{m}$ is the mass flow rate of the gas.

Total temperature at the throat is less than the combustion temperature due to the loss of thermal energy in accelerating the gas to choke conditions thus at the throat:

$$T_t = T_c\left[\frac{1}{1+\frac{\gamma-1}{2}}\right] \tag{2}$$

Similarly

$$P_t = P_c \left[1 + \frac{\gamma - 1}{2}\right]^{-\frac{\gamma}{\gamma-1}} \tag{3}$$

Based on combustion properties of the mentioned propellants, throat conditions can be determined from which throat area can be determined. Optimal areas and ratios are different for each propellant class; thus, this section aims to present a theoretical design approach; based on which final design parameters are determined in the numerical simulation section where specific propellant properties are determined.

An alternate approach for design is to size the chamber based on design constraints and determine the required propellant size to produce those pressures and design an expansion nozzle based on that set pressure. Based on specific research and combustion equations (Scheier, 1960). It was found that a chamber volume of $48\ in^3$ or $786.6\ cm^3$ would result in maximum pressures of $250\ psia\ or\ 17\ atm$ for a pellet of B-KNO_3 weighing 10g (Scheier, 1960), which translates into a combustion chamber $2.25\ in$ or $5.715\ cm$ in radius and a pellet radius of $1.12\ cm$ of pure B-KNO_3 at flame temperatures ranging from 2700 to 3000 K. Since the study only measured ignitor characteristics, thrust was not measured. This result would lead to a larger system than originally planned. However, since the proposed propellant is more energetic, combustion pressures would be higher for the same chamber volume. Based on the parameters in the technical report, a first estimate of the chamber volume is made.

Using 5.715 cm as the radius for the combustion chamber and the corresponding combustion pressure, it is found that a low nozzle expansion ratio of 3, would provide a sea level Isp of 202 s and vacuum Isp 228.8 s, with combustion temperatures of approximately 1700 K, for a 10g propellant pellet containing 70% AP, 10% HTPB and 10% B and 10% KNO_3, however this is not the ideal composition. The ideal composition will be determined in the numerical simulation section.

Since the objective of this thesis is to research into proof of operation this design can be used for prototype testing, however a larger system with larger pellets may not be able to produce lower thrust levels in ranges of mN for attitude control maneuvers and may only be viable for larger dynamic impulse maneuvers. Therefore, objective shall be to encapsulate the entire system within a 1U-2U design space depending on combustion chamber solutions.

Exhaust Control Gates

The exit control gates will contain a valve system that control which nozzle(s) is under operation. The exhaust control will be integrated with the nozzle before the expansion section. A solenoid valve for controlling the exhaust is sought. Common solenoid valves are actuating devices that operate with a voltage input, they are studied and their adaptability to this system is determined.

A solenoid valve contains two fundamental units: an electromagnetic assembly with an actuating plunger or core and a valve with an orifice. A detailed schematic is shown in Figure 15.

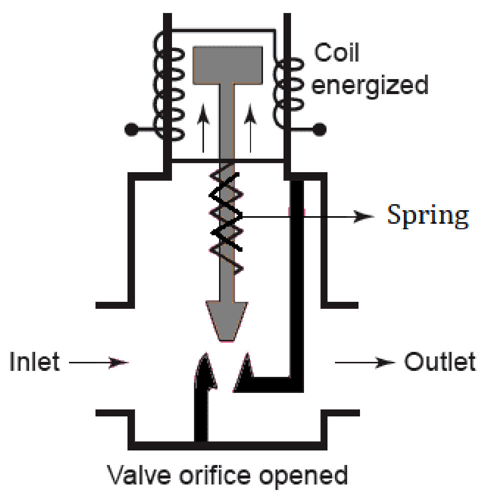


Figure 15: Basic solenoid valve schematic

Table 10 presents to valve systems that may be viable and adapted for this design. Both valves can operate at high pressures and may be adapted for high temperature gasses. The required valve system must have high cycle life, quick response time and a tight seal to prevent leakage, and both these systems meet those specifications. The Nammo system is desirable over the Marotta valve due to its lower mass, smaller footprint, and reasonable operating pressures. The SVS01 valve from Nammo is pictured in Figure 16 and the MV602 is pictured in Figure 17. Generally these values are used in cold gas applications and have temperature ratings of up to 100 C (MV602), however the manufacturers can build custom values on request which may have higher temperature ratings.

Table 10: Viable flow control valves

Manufacturer and Model	**Nammo SVS01**	**Marotta MV602**
Max Operating Pressure	1740 psia	4496 psia
Proof	2610 psia	6744 psia
Burst	4350 psia	11240 psia
Power	~10 W	13 W
Response- Opening	10 ms	10 ms
Response- Closing	10 ms	10 ms
Cycles	300000	N/A
Mass	60 grams	175 grams

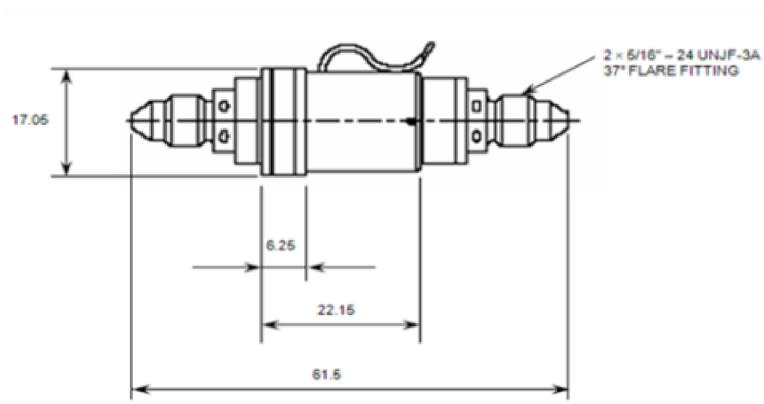


Figure 16: Nammo SVS01 in line solenoid valve (Nammo, 2021)

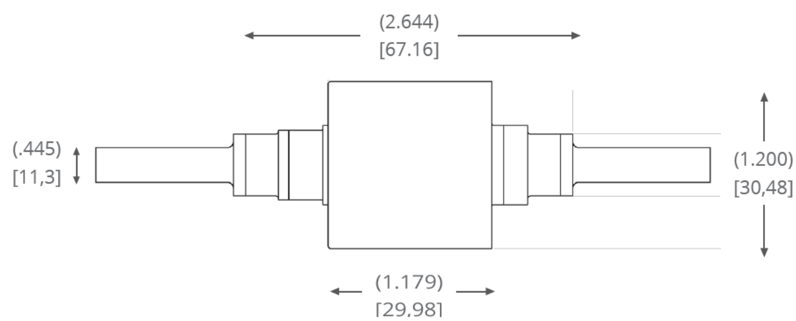


Figure 17: Marotta MV602 in line solenoid valve (Marotta, 2021)

Propellant feed and Storage

The propellent feed mechanism is perhaps the most unique system in the design, it is inspired by a Thompson submachine gun drum magazine and a Lewis gun pan magazine, and operates in the same principle, instead of bullets small explosive solid propellent pellets are loaded. The key difference however in that traditional drum and pan magazines are flat cylinders whereas this system requires a larger helical arrangement similar to that of a Calico magazine. Each system is broken down further in this section.

Drum Magazine

A drum magazine used in the Thompson machine gun operates using a simple spring mechanism. The drum itself contains a coil spring, which is wound up, and the unwinding spring with a spider gear assembly pushes rounds through a spiral path towards an opening at the top of the magazine. However, the operation of a gun magazine requires pellets to be released from the top rather than the center, this key design constraint is taken into consideration when designing the feed system.

Double- Drum Magazine

Similar to the single drum arrangement this double drum arrangement features twin drums with a feed clip that feed a central chamber with rounds one after the other. This type of arrangement has a higher capacity, better weight distribution and is more compact. As a result, this thesis considers a design based on the Beta-C Magazine, designed by Jim Sullivan, and manufactured by the Beta company.

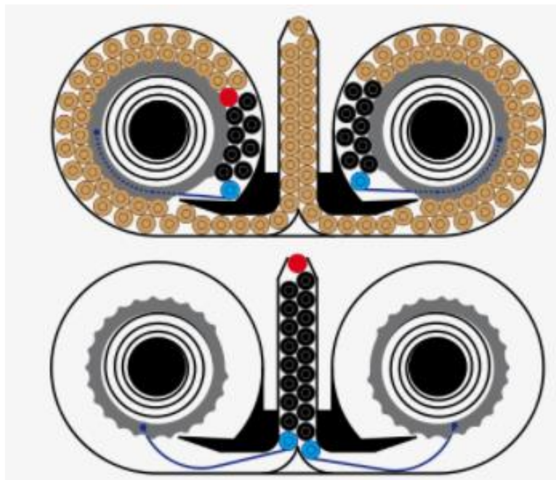


Figure 18: Beta-C Magazine (Beta C-MAG, 2021)

The key difference however that has to follow, the magazine needs to be made helical to utilize more space in 3 dimensions similar that of a Calcio magazine. More research is recommended in this area to adapt the dual magazine arrangement to this thruster.

Modularity and Reusability

The key design consideration behind the use of such a propellant loading device is due to the reusability these magazines offer. They are manufactured to be easily detachable and reattach able. This feature if utilized with some locking mechanism may mean that a multitude of satellites could be reloaded via an easy latch on mechanism and be made to operate. This reusability would prove cost effective especially in satellite swarms where they could be reloaded on board a refueling space station. In addition, magazines similar to this device offer modularity where they could be stacked on top of each other if more propellant is required.

Chapter 4: Numerical Simulation of Propellant

Overview

The successful ignition of the propellant depends on combustion pressure and temperature, especially if an AP/HTPB with a B/KNO_3 igniter shell or a Double-Base pellet with a B/KNO_3 shell is used. As a result, it is important to determine what mass of B/KNO_3 or another igniter may be required to reach critical combustion pressure. Subsequently, from the mass requirement the shell thickness may also be determined.

In the earlier theoretical design section, it was found that a chamber approximately 10 cm in diameter, with 10 g of BKNO_3 (a 2cm pellet) would produce pressures of 250 psia or 17 atm in the chamber (Scheier, 1960), based on which it seems unlikely that a small thickness would be sufficient to ignite the inner propellant core, which would result in incomplete combustion, producing no thrust.

The objective is to highly limit and optimize the use of ignitor due to the solid residue produced from its combustion and ensure complete combustion of the remaining propellent pellet. This is a difficult task since, both ammonium perchlorate and nitrocellulose/ nitroglycerin systems have highly complex combustion mechanisms that propagate only from the surface of the propellant, thus cored propellent is used commercially, which increases the surface area of combustion. Burn rates of both propellant classes are highly dependent on chamber pressure and temperature, ignition of these propellants is a function of the pressure and heat flux into the surface grains, whereas for commonly used igniters it is not.

This result dictates that the combustion chamber be made as small as possible, to produce high enough pressures. It may also be beneficial to core out the propellent pellet, which would increase combustion surface area.

Critical pressures for generally used propellants including an AP/HTPB based, or Nitroglycerine/ Nitrocellulose require higher pressures for self-sustaining combustion. This pressure is called the critical pressure. It can be determined by various methods experimentally or using the Von-Elbe equation (Elbe, 1966):

$$P^{*} = \left[C_1 \frac{2kn}{c\rho b}\right]^{\frac{1}{1-n}} ; C_1 = \frac{A_s}{V}\rho R T_c \,;\, b = \frac{r}{P^n}$$

Where:

$P*$ is the critical pressure (atm),

k is the propellant heat conductivity in (cal/cm-s-K),

n is the propellant exponent,

c is the propellant specific heat of solid (cal/g-K),

ρ is the propellant density (g/cm^3),

A_s is the surface area exposed to igniter combustion products (cm^2),

V is the chamber free volume (cm^3),

R is the propellant gas constant (cm^3-atm/g-K),

T_c is propellant flame temperature (K),

r is the propellant burning rate (cm/s).

This equation is a function of three coefficients C_1, b and exponent n where b describes the relationship between burn rate and chamber pressure via an empirical equation. The coefficient b characterizes the burn rate rate relationship all pressures linearly and the exponent n characterizes the increase in burn rate as pressures get higher and higher, an exponent of 0 would reflect that the energy release of the propellent is independent of the pressure and is always a constant.

$$r = bP^n$$

Whereas C_1 represents a measure of rate of gain of pressure due to propellant combustion and r represents an approximate behavior of the propellant grain. The coefficients b and n depend only on grain temperature.

The mathematical model presented by Von Elbe is experimentally verified, follows a two-step ignition procedure.

First, the cold solid propellant grain is exposed to heat through some medium, such as the deflagration materials from a pyrotechnic igniter such as $BKNO_3$ and thus is preheated to a flash temperature T_S. Second, the igniting medium is replaced by the propellant flame gas as the heat source, which then may develop into a steady-state combustion process, given that the heat flux into the propellant grain during that transient phase is equal or less than the steady state heat flux of combustion of that particular propellant. If the heat flux is equal, then steady state would be established directly after the preheat period. However, if it is not there would be an ignition lag, or a lag between the preheat and sustained combustion.

If, however, the heat flux into the interior of the grain is greater than the steady state at the end of the preheat period then combustion would cease as the surface temperature would drop and the surface flame will not be sustained.

There is one other scenario, for which the critical pressure is a key parameter, this is for the case of combustion instability known as hang fire or chuffing, during which, mathematically the rate of chance of pressure (as measured by coefficient C1) *blows up*. Combustion becomes intermittent as the chamber is filled with hot gasses, but the grain burns intermittently. This occurs especially if the grain configuration is that the surface to volume ratio decreases during the combustion process, i.e., if combustion exposes less burn area than more, pressure decreases to or lower than the critical value and such instability is incurred. This can be avoided by following a design that ensures minimal pressure drop (Elbe, 1966).

Initial and Boundary Conditions

In order to determine critical pressure, the properties of $BKNO_3$ must be determined for a nominal pressure of 1000 psi. Experiments determine the impact of critical pressure for a combustion system (Apinhapat & Pittayaprasertkul, 2014). The following conditions are used to determine the amount of $BKNO_3$ required for successful combustion of propellant;

other igniters are also compared which may prove to be viable options, however for the scope of this thesis only B/KNO3 is studied.

Table 11: Properties of various pyrotechnic grain ignitors (Apinhapat & Pittayaprasertkul, 2014)

Properties of Igniter	$BKNO_3$	Al/K_2ClO_4	Mg/Teflon
Burning rate mm/s	43.2	49.9	10.2
Pressure Exponent	0.32	1	0.22
Heating value cal/g	1550	2490	2200

Table 12: Initial and Boundary conditions of propellants

Initial/ Boundary Condition	
Initial temperature of propellant pellet	288 K to 400 K
AP/HTPB Composition	88% AP 12% HTPB
Nitrocellulose/ Nitroglycerine Composition	50% - 50%
Internal radius of propellent pellet	2 mm to 10 mm

Table 13: Properties of propellant from various research and experiment (Hanson-Parr & Parr, 1999; Ward, 1977; Boulkadid, Lefebvre, Jeunieau, & Dejeaifve, 2020; Lengelle, 2002; Dı´rı´kolu & Kalaycioğlu, 2010; Manash & Kumar, 2019; Cai, Thakre, & Yang, 2008)

Properties of propellant	88-12 AP/HTPB	50-50 Nitrocellulose/ Nitroglycerine
Density [g/cm^3] (from Chemical simulator)	1.7106	1.5746
Adiabatic Flame Temperature [K] (from Chemical simulator)	2373	3220
Molar specific heat [cal/mol-K]	11.389	11.585
Heat conductivity through grain [cal/cm-s-K]	0.000822	0.000100
Heat Capacity [cal/g-K]	0.279	0.118
Propellant exponent	0.433	~0.8
Propellant burn coefficient	0.0054	0.0171
Burn rate at 1000psi [cm/s]	0.03331	0.5
Molecular weight of combustion products [kg/kmol]	26.009	27.401
Gas constant of combustion products [J/kg-K]	332.56	303.42

Simulation breakdown and processing

For this system to be useful, complete combustion must be ensured, which means that critical pressures are to be achieved in the combustion chamber prior to exhaust. In order to ensure critical pressures are reached various propellant geometries with different initial conditions are simulated.

The simulation was conducted using ProPEP and MATLAB. ProPEP is a thermochemical software package that can evaluate the performance of solid rocket propellant, it is a chemical equilibrium solver which utilizes the method of minimization of Gibbs free energy to balance chemical equations. It only requires the propellant composition (ignitor or traditional propellant), initial temperature of propellant and nozzle exit pressures for input and outputs a number of performance properties for the selected propellent 'recipe'. Next, MATLAB was used to determine the required critical pressures for the two propellant pellets studied in this thesis, based on which the required ignitor masses, and sizes were determined, results of which are presented in the next section.

The following assumptions were made:

- Complete combustion of propellants following combustion equation
- Ideal gas law
- Adiabatic combustion
- Steady state conditions
- Uniform expansion of gasses in complete chamber volume
- Chemical equilibrium in combustion chamber, which does not shift during expansion
- Uniform burning of propellant grain over entire exposed surface of combustion

Figure 19 presents a screenshot of the ProPEP software used.

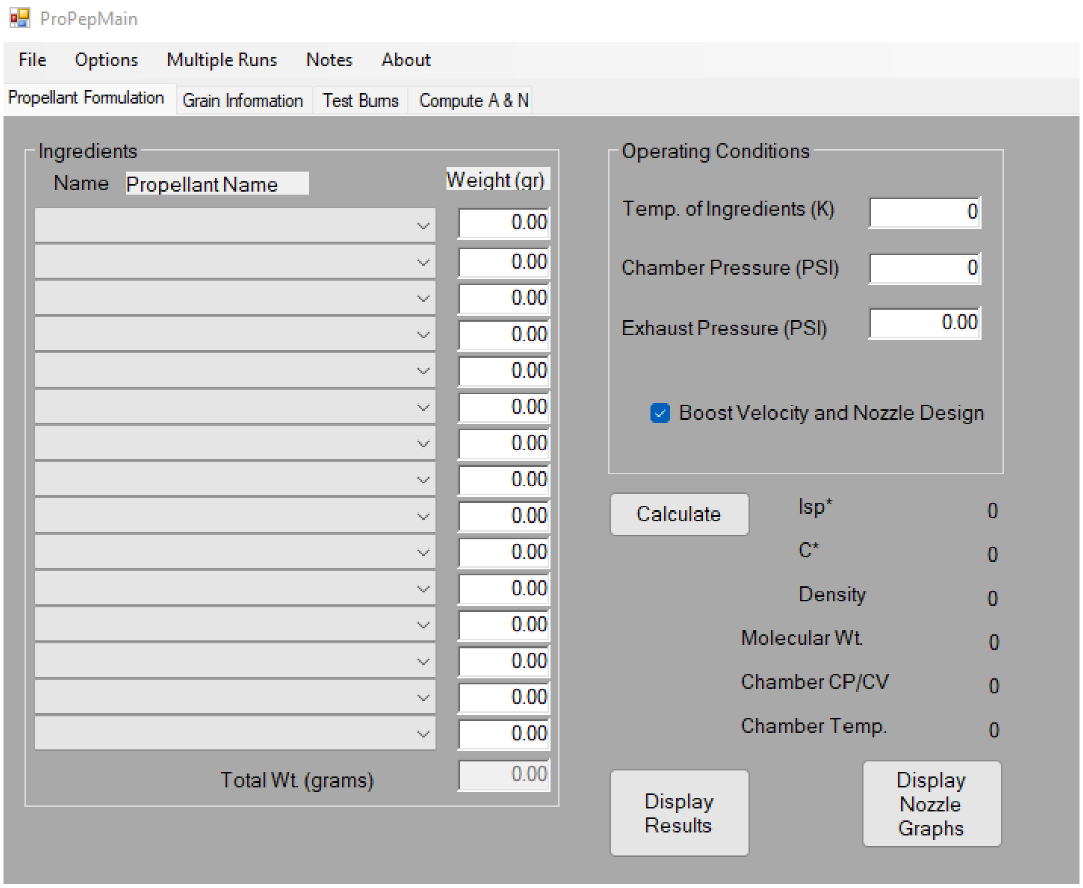


Figure 19: ProPEP software

Simulation Results

Based on the parameters listed in Table 13, critical pressures for both propellants were determined as a function of the combustion chamber radius and propellant burn area which is a function of the core radius of the propellent pellet. A lower critical pressure would be a design benefit, suggesting a smaller pellet should be used, even with larger chambers. Figure 20 suggests that the composite AP/HTPB propellent pellet may be a better option to sustain combustion since it has an overall, lower pressure requirement.

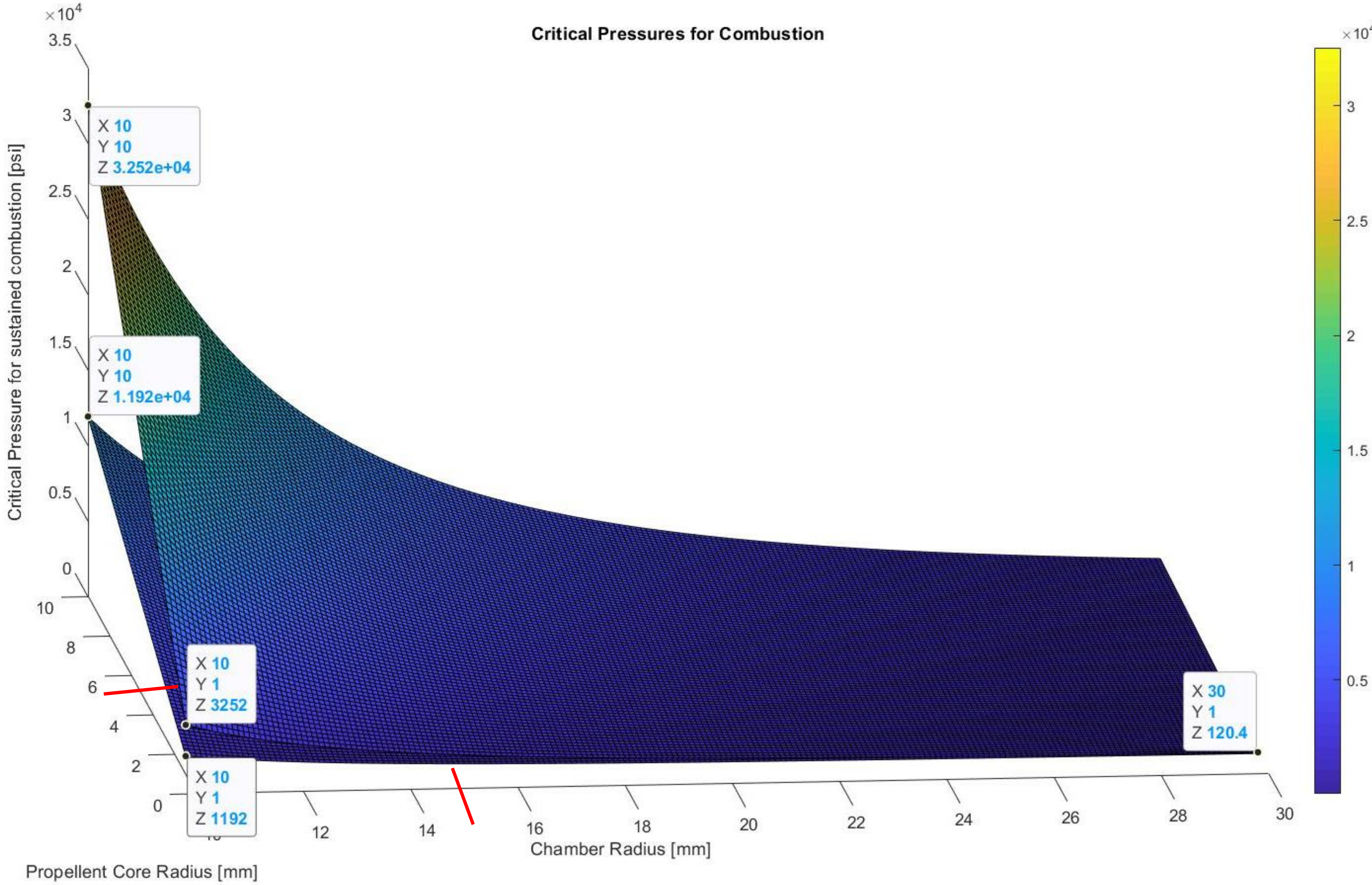


Figure 20: Critical Pressures for Complete Combustion where top surface is Nitrocellulose/ Nitroglycerine and bottom surface is AP/HTPB

Next, to achieve this critical pressure the number of moles of B/KNO_3 is determined using properties determined from ProPEP (as seen in the appendix) and ideal gas law. The initial temperature for the $BKNO_3$ shell was varied from 288K to 395K and it was found that resulting combustion temperatures ranged from 2698 K to 6000 K (reported in appendix). Based on this result it was determined that some propellant heating mechanism would greatly improve propulsion performance, and overall mass requirement.

Figure 21, Figure 23 and Figure 23 summarize the pellet sizing for the system. There is a tradeoff between electrical heating of propellent pellets and required mass and size, there is also a tradeoff between chamber volume and propellent pellet radius. From the surface plots it is evident that none of the corner points optimize all the required conditions. Thus, a conservative approach should be implemented, and a middle ground design should be selected for the system. This thesis proposes a chamber radius of 15 mm, with a $BKNO_3$ AP/HTPB propellant pellet, measuring no more than 5mm in radius. This combination would require the propellant to be preheated. This approach is suggested since it puts the system within 1U-2U of design space, while leaving enough space for propellant feed and storage mechanism and minimizing solid residue in the chamber.

This result implements some changes in the proposed design; however, it also highlights the importance of the right propellant and how the whole system is dependent on that selection.

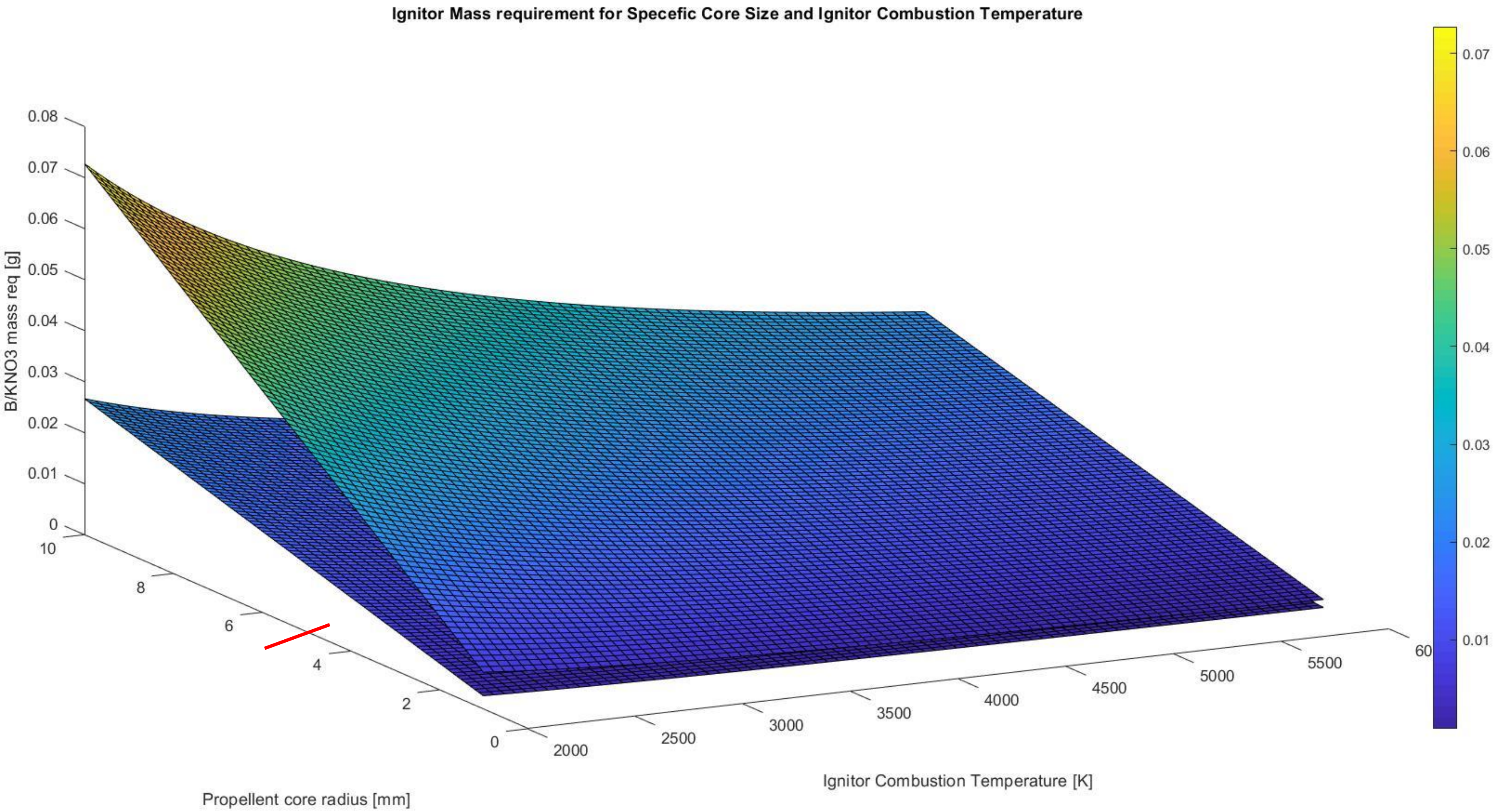


Figure 21: Ignitor Mass Requirement based on Core Size and Ignitor Combustion Temperature where top surface is Nitrocellulose/ Nitroglycerine and bottom surface is AP/HTPB

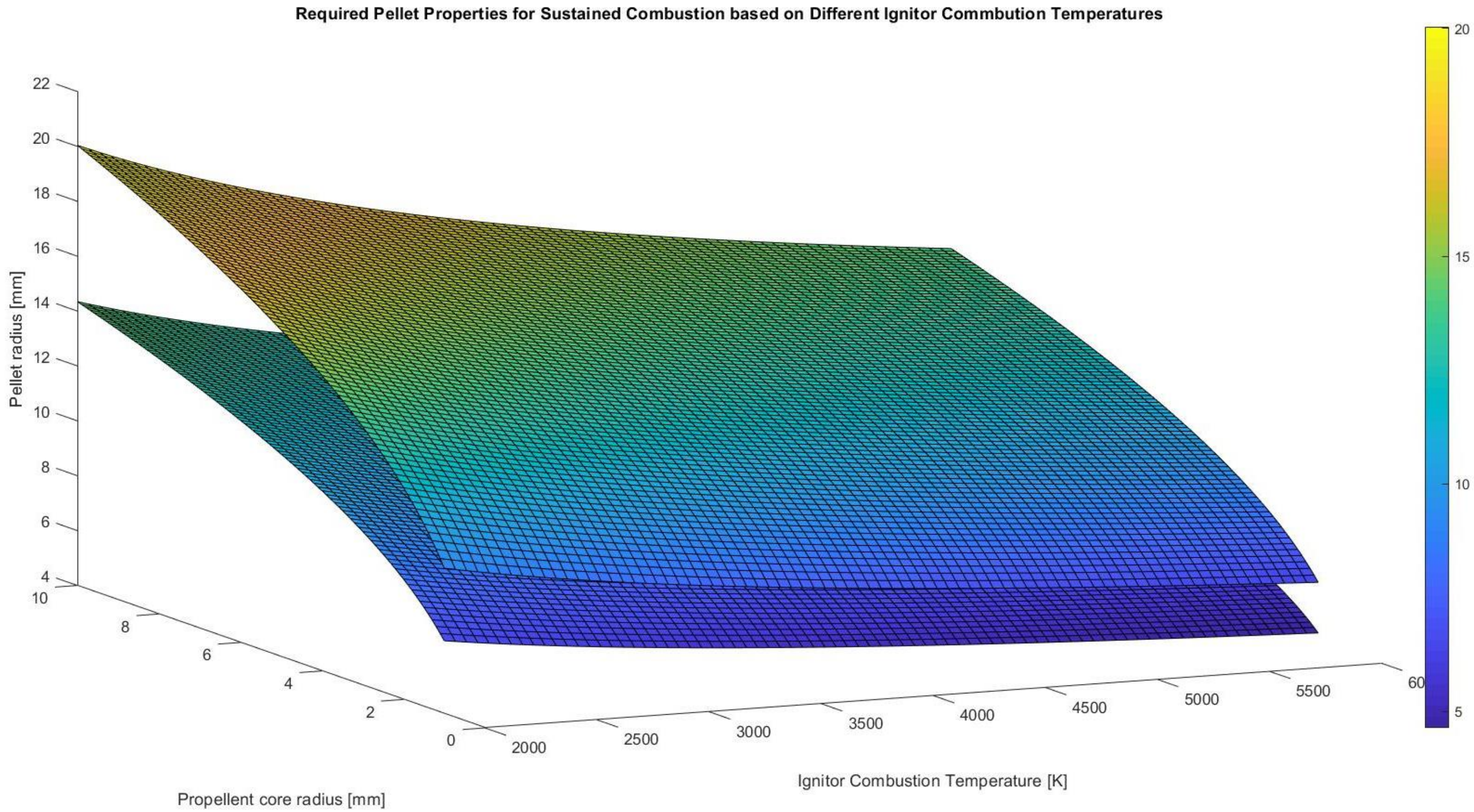
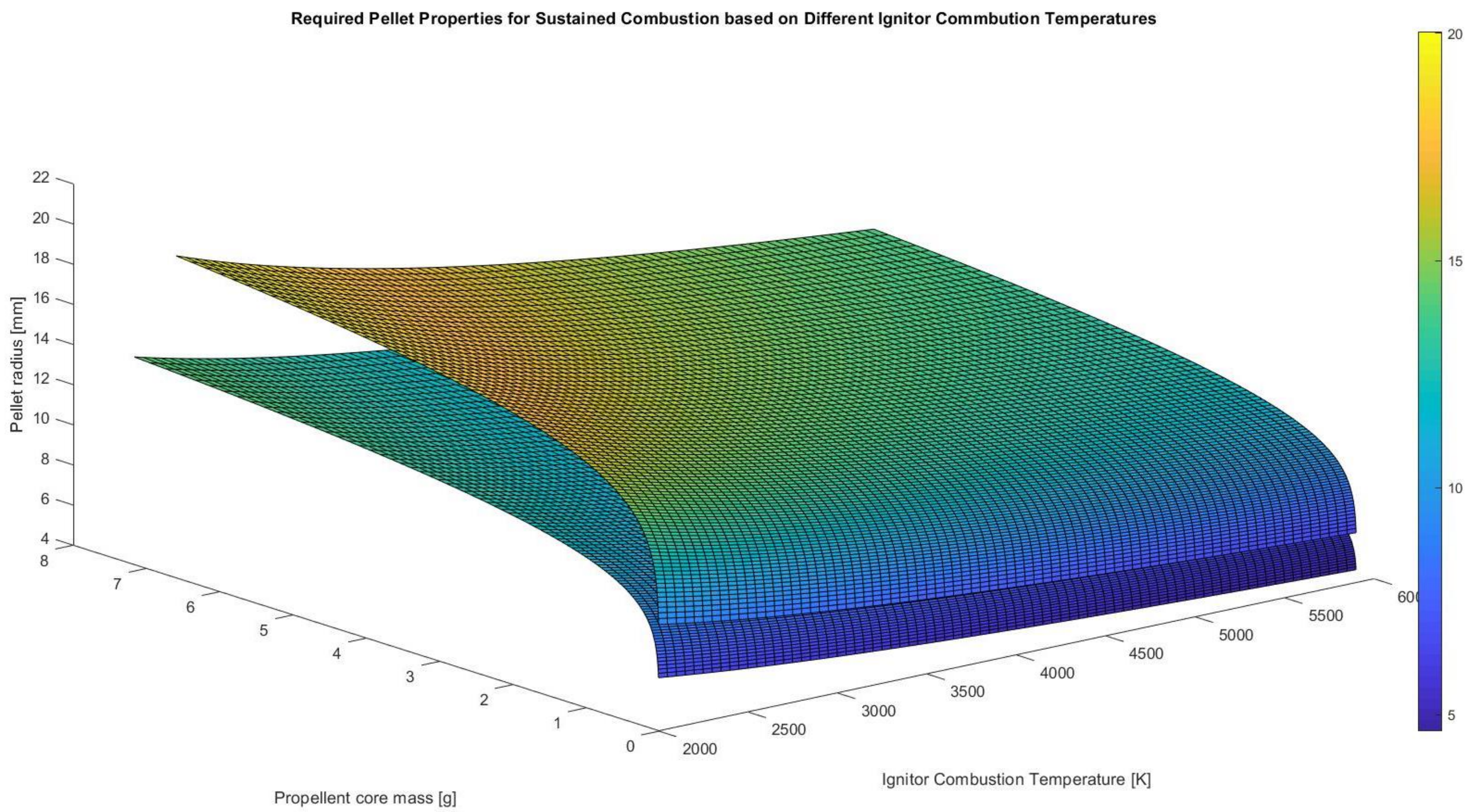


Figure 22: Required Pellet Properties
where top surface is Nitrocellulose/ Nitroglycerine and bottom surface is AP/HTPB



Required Pellet Properties for Sustained Combustion based on Different Ignitor Commbution Temperatures
Pellet radius [mm]
22
20
18
16
14
12
10
8
6
4
Propellent core mass [g]
8
7
6
5
4
3
2
1
0
Ignitor Combustion Temperature [K]
2000
2500
3000
3500
4000
4500
5000
5500
20
15
10
5

Based on the conservative approach selected from the surface plots reported earlier, it is evident that there will be a mixture of gasses present in the combustion chamber. Using ProPEP and the resulting propellent mass compositions an ideal nozzle expansion ratio is determined from the simulation to be approximately 28.99, producing an Isp of 312.9 seconds, a lower expansion ratio of 5 would result in an Isp of 271.5 seconds and a nominal thrust of 3.2 N.

Comparison to State of the Art

This table summarizes the comparison between the proposed thruster and its performance parameters based on simulation to current state of the art technology which was presented in the technology breakdown section. An improvement in thrust and Isp is observed when compared to all the other systems.

Table 14: Comparison to state-of-the-art technology

		[mN]	[W]	[s]	
Propellant Type & Manufacturer	**Propellant**	**Thrust**	**Power**	**Specific Impulse**	**Burn time/ Number of Pulses**
Electric Solid Propellent by DSSP	HIPEP-501A	300	2.3	900	2 ms per thruster (250 pulses per thruster)
Traditional Solid Propellant From Northrop Grumman	TP-H-3399	258000	0	258	10.8 s
Liquid Propellant from Dawn Aerospace	Nitrous Oxide & Propene	500	12	285	-
Liquid propellant from Aerojet Rocketdyne	Hydrazine / Green Propellant	250-1000	10	206-217	10,000
Warm Gas from GomSpace	Butane	60	2	50	-
Cold Gas from VACCO	R236FA	200	15	40	-
Matrixed Array Solid from PacSci EMC	-	-	-	210	176
PROPOSED THRUSTER	**AP/HTPB $BKNO_3$**	**3200 (variable)**	**10 W (No heater) Up to 1000 W with large heater**	**271.5**	**Each pulse can be 10 - 15 ms long based on control valve, large number of pulses available ~200-300**

Simulation Justification

This simulation analysis uses a widely used chemical solver that has been in use since the last century. It also considers the fundamental thrust equations for characterizing performance. Overall, the simulation provides enough evidence for a device of this type to be functional, given ignition characteristics can be determined of the propellant to be used. This process can also be implemented on multiple other types of propellants which could even prove to be better options for such a device. What has become most evident is that a device like this thruster is plausible, within the design/ build constraints and competes well with industry as seen in the comparison to the state of the art. Producing more thrust which can be throttled, for minimal power requirements and by using readily available propellants. This means a device like this could be used to perform highly dynamic, yet precise maneuvers that may be required by any small/cube sat.

The next chapter will briefly discuss some techniques that could be used to test the theoretical predictions from the simulation model.

Chapter 5: Testing Methodologies

Parameters to be measured

Various combustion parameters need to be measured independently to determine the accuracy of the model. This starts with the propellent, in terms of measurement of all the defined properties in Table 11, Table 12 and Table 13.

Once those parameters are measured and validated a series of physical combustions experiments must be made to document the time history of adiabatic flame temperatures, combustion pressures, mass flow rates and thrust using various nozzle expansion ratios. Each of those parameters should be iterated with propellant mass, geometry, and composition, to verify is the BKNO3 shell (~0.04 grams) of ignitor is sufficient to ignite the propellant core and to sustain the combustion, till no more product is remaining. It should also be verified that minimal solid residue is produced by the combustion reaction.

All these tests need to be done first in a regular atmospheric environment and then in a vacuum chamber, to understand the pressure dependence on combustion.

Moreover, ignition characteristics of Boron Potassium nitrate need to be investigated, these techniques include both methods mentioned in this thesis, electric ignition using anode and cathode arrangements and via a high-powered laser. It is especially important to conduct these tests in vacuum.

There must also be an experiment on the connection between the initial propellant pellet temperature to the combustion temperatures that are resulted from the reaction.

Simulation Validation

The simulation shall be validated if all the measured temperatures and pressures fall within 5% of the simulated parameters. If these match than the mass flow rate and thrust produced by the specific propellant size and expansion ratio must conform to the predicted values.

Chapter 6: Future Work and Recommendations

There are multiple areas of research that directly follow this thesis. First of which is further research in different propellant configurations and further research in propellants which have high energy density, clean combustion (i.e. do not leave any residue), low dependability on pressures (i.e. small pressure exponent), high burn rates and easily combustible electrically or via laser. SEPs (Solid Electric Propellant) that are in use today address some these requirements and thus are more efficient systems in comparison to the other technologies available.

After general research in propellant class and ignition techniques, manufacturability is a large area of future work for this project. The integration of all the subsystems and the control algorithm for ‘nozzles mixing’ to conduct dynamic maneuvers in 6 degrees of freedom. Another large area of future work is the propellant feed system and the design of the double spiral magazine that would feel solid propellant pellets to the ignition mechanism, along with the reusability and modularity factor. Essential to design is to make that feed system modular (i.e. stackable), and reusable by ensuring that the feed magazine can be easily removed and replaced, perhaps by a quick latching mechanism similar to type used in firearms today.

Once controls and feed systems are completed then the full system can be integrated and tested and if successful deployed to be used in future missions. The key aspect of such missions would be to provide debris removal services, from the highly dynamic maneuvers possible from this device, it would be easy to latch onto a current object and perform de-orbit or grave-yard orbit burns, to take that debris out of harm’s way. An iteration of this also has the potential to be used in missiles and antisatellite missile systems, to be able to accurately perform position control maneuvers.

Chapter 7: Summary and Conclusions

This thesis conducted a feasibility and performance study on a pulsed solid propellent integrated propulsion device and found that a device that meets the defined characteristic is completely within the reach of reality. Upon comparing some performance estimates derived from computational data it was found that such a device would be highly competitive and the first of its class. The development of this device was to perform highly dynamic maneuvers in space, while utilizing 6 degrees of freedom, to perform a number of missions. From numerical and theoretical analysis, it was found that a device with a pulsed solid propellent based on small propellant pellets would have the potential to bring positive improvements for small satellite propulsion technology. It is recommended that further work and time be dedicated to this research, so it yields a fruitful outcome of a revolutionary new thruster that solves the greatest propulsion problems faced today.

Requiring no pressurized fuel tanks, complex pumps or values, high wet mass to energy ratios and the ability to produce a range of different thrusts for fine tune control and for high impulse maneuvers.

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Appendix 1: ProPEP Output for $BKNO_3$

---288K--									
Code	WEIGHT	D-H	DENS	COMPOSITION					
0	BORON	(AMORPHOUS)	0.15	37	0.0856	1	B	1	K
0	POTASSIUM	NITRATE	0.85	-1167	0.0767	1	N	3	O
THE	PROPELLANT	DENSITY	IS	0.07792	LB/CU-IN	OR	2.1567	GM/CC	
THE	TOTAL	PROPELLANT	WEIGHT	IS	1	GRAMS			
NUMBER	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENTS
	0.013863	B							
	0.008407	N							
	0.025221	O							
	0.008407	K							
***************************CHAMBER RESULTS FOLLOW **									
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
	2698	4397	68.02	1000	-1.29	1.41	1.1292	0.015	4398.488

SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	17.532	17.332
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.015	0		
	8.41E-03	KBO2	4.18E-03	N2	2.62E-03	B2O3	1.57E-04	BO2	
	5.22E-05	O2	3.81E-05	NO	2.93E-05	B2O3*	4.39E-06	BO	
	3.90E-06	O	7.66E-07	K	4.65E-07	B2O2	4.32E-08	KO	
	2.63E-08	NO2							
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	64.538		
***************************EXHAUST RESULTS FOLLOW **									
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
	2075	3275	1	14.7	-1.58	1.41	1.1127	0.014	71.111
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	16.627	17.845
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.014	0.001		
	8.41E-03	KBO2	4.20E-03	N2	1.40E-03	B2O3*	1.30E-03	B2O3	
	8.87E-05	O2	5.77E-05	BO2	1.48E-05	NO	1.30E-06	O	

	2.54E-07	BO	2.54E-07	BO					
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	64.663		
*PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE****	
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M
155.4	1.1298	2534	39.35	3044.6	10.28	335.1	0.09465	1661	
159.5	1.0818	2640	40.03	3135	117.8	11.04	344	0.09746	2075
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA	LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	40.034	4055.4	2640	60.4	593	117.8	1155	116.4	1153
2	13.345	1351.8	2524	103.8	1018	142	1393	139.2	1379
3	5.46	553.1	2433	127.1	1246	150.5	1476	146.2	1449
4	3.736	378.4	2395	135.3	1327	156.7	1537	151	1496
5	2.779	281.5	2330	141.4	1387	161.3	1582	154.1	1527
6	2.185	221.4	2268	146.1	1432	164.8	1616	156.2	1548
7	1.788	181.2	2217	149.7	1468	167.7	1644	157.6	1562
8	1.506	152.5	2174	152.8	1498	170	1667	158.5	1571
9	1.296	131.2	2137	155.3	1523	172	1687	159.1	1576
10	1.133	114.8	2105	157.5	1545	173.7	1704	159.4	1579
11	1.005	101.8	2076	159.4	1563	175.3	1719	159.5	1580
12	0.901	91.2	2050	161.1	1580	176.6	1732	159.4	1579

13	0.815	82.5	2027	162.7	1595	177.9	1744	159.2	1577
14	0.743	75.2	2006	164.1	1609	179	1755	158.9	1574
15	0.682	69.1	1986	165.3	1621	180	1765	158.5	1570
16	0.629	63.7	1968	166.5	1633	180.9	1774	158	1565
17	0.584	59.1	1952	167.6	1643	181.8	1783	157.4	1560
18	0.544	55.1	1936	168.6	1653	182.6	1791	156.8	1553
19	0.509	51.5	1922	169.5	1662	183.3	1798	156.1	1547
20	0.478	48.4	1908	170.4	1671	184.1	1805	155.4	1539
21	0.45	45.6	1895	171.2	1679	184.7	1811	154.6	1532
22	0.425	43	1883	172	1686	185.3	1818	153.8	1524
23	0.402	40.8	1871	172.7	1693	185.9	1823	153	1516
24	0.382	38.7	1860	173.4	1700	186.5	1829	152.1	1507
25	0.363	36.8	1849	174	1706	187	1834	151.2	1498
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
26	0.346	35.1	1839	174.6	1713	187.5	1839	150.3	1489
27	0.331	33.5	1830	175.2	1718	188	1844	149.3	1479
28	0.316	32.1	1821	175.8	1724	188.5	1848	148.4	1470
29	0.303	30.7	1812	176.3	1729	188.9	1853	147.4	1460
30	0.291	29.5	1803	176.9	1734	189.4	1857	146.4	1450
31	0.28	28.3	1795	177.3	1739	189.8	1861	145.4	1440
32	0.269	27.2	1787	177.8	1744	190.2	1865	144.3	1430
33	0.259	26.2	1780	178.3	1748	190.5	1868	143.3	1419

34	0.25	25.3	1772	178.7	1753	190.9	1872	142.2	1409
35	0.241	24.4	1765	179.2	1757	191.2	1875	141.1	1398
36	0.233	23.6	1758	179.6	1761	191.6	1879	140	1387
37	0.226	22.9	1752	180	1765	191.9	1882	138.9	1376
38	0.218	22.1	1745	180.3	1769	192.2	1885	137.8	1365
39	0.212	21.4	1739	180.7	1772	192.5	1888	136.7	1354
40	0.205	20.8	1733	181.1	1776	192.8	1891	135.5	1343
41	0.199	20.2	1727	181.4	1779	193.1	1894	134.4	1331
42	0.194	19.6	1722	181.8	1782	193.4	1897	133.3	1320
43	0.188	19.1	1716	182.1	1786	193.7	1899	132.1	1309
44	0.183	18.5	1711	182.4	1789	194	1902	130.9	1297
45	0.178	18	1705	182.7	1792	194.2	1904	129.8	1285
46	0.173	17.6	1700	183	1795	194.5	1907	128.6	1274
47	0.169	17.1	1695	183.3	1798	194.7	1909	127.4	1262
48	0.165	16.7	1690	183.6	1801	194.9	1912	126.2	1250
49	0.161	16.3	1686	183.9	1803	195.2	1914	125	1238
50	0.157	15.9	1681	184.2	1806	195.4	1916	123.8	1226
51	0.153	15.5	1677	184.4	1809	195.6	1918	122.6	1214
52	0.15	15.2	1672	184.7	1811	195.8	1920	121.4	1202
53	0.146	14.8	1668	184.9	1814	196.1	1923	120.1	1190
54	0.143	14.5	1663	185.2	1816	196.3	1925	118.9	1178
55	0.14	14.2	1659	185.4	1818	196.5	1927	117.7	1166
56	0.137	13.9	1655	185.7	1821	196.7	1929	116.4	1154
57	0.134	13.6	1651	185.9	1823	196.9	1930	115.2	1141
58	0.131	13.3	1647	186.1	1825	197	1932	114	1129

59	0.129	13	1644	186.4	1827	197.2	1934	112.7	1117
60	0.126	12.8	1640	186.6	1830	197.4	1936	111.5	1104
61	0.124	12.5	1636	186.8	1832	197.6	1938	110.2	1092
62	0.121	12.3	1632	187	1834	197.8	1939	109	1079
63	0.119	12	1629	187.2	1836	197.9	1941	107.7	1067
64	0.117	11.8	1625	187.4	1838	198.1	1943	106.4	1054
65	0.115	11.6	1622	187.6	1840	198.3	1944	105.2	1042
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.112	11.4	1619	187.8	1842	198.4	1946	103.9	1029
67	0.11	11.2	1615	188	1844	198.6	1947	102.6	1017
68	0.109	11	1612	188.2	1845	198.8	1949	101.4	1004
69	0.107	10.8	1609	188.4	1847	198.9	1951	100.1	991
70	0.105	10.6	1606	188.5	1849	199.1	1952	98.8	979
71	0.103	10.4	1603	188.7	1851	199.2	1953	97.5	966
72	0.101	10.3	1600	188.9	1852	199.4	1955	96.2	953
73	0.1	10.1	1597	189.1	1854	199.5	1956	94.9	940
74	0.098	9.9	1594	189.2	1856	199.6	1958	93.6	928
75	0.097	9.8	1591	189.4	1857	199.8	1959	92.4	915
76	0.095	9.6	1588	189.6	1859	199.9	1960	91.1	902
77	0.094	9.5	1585	189.7	1861	200.1	1962	89.8	889
78	0.092	9.3	1582	189.9	1862	200.2	1963	88.5	876
79	0.091	9.2	1580	190	1864	200.3	1964	87.2	863

80	0.089	9.1	1577	190.2	1865	200.4	1966	85.9	850
81	0.088	8.9	1574	190.4	1867	200.6	1967	84.5	838
82	0.087	8.8	1572	190.5	1868	200.7	1968	83.2	825
83	0.086	8.7	1569	190.6	1870	200.8	1969	81.9	812
84	0.084	8.5	1567	190.8	1871	200.9	1970	80.6	799
85	0.083	8.4	1564	190.9	1872	201.1	1972	79.3	786
86	0.082	8.3	1562	191.1	1874	201.2	1973	78	773
87	0.081	8.2	1559	191.2	1875	201.3	1974	76.7	760
88	0.08	8.1	1557	191.4	1876	201.4	1975	75.4	747
89	0.079	8	1554	191.5	1878	201.5	1976	74	733
90	0.078	7.9	1552	191.6	1879	201.6	1977	72.7	720
91	0.077	7.8	1550	191.8	1880	201.7	1978	71.4	707
92	0.076	7.7	1547	191.9	1882	201.9	1979	70.1	694
93	0.075	7.6	1545	192	1883	202	1981	68.8	681
94	0.074	7.5	1543	192.1	1884	202.1	1982	67.4	668
95	0.073	7.4	1541	192.3	1885	202.2	1983	66.1	655
96	0.072	7.3	1539	192.4	1887	202.3	1984	64.8	642
97	0.071	7.2	1536	192.5	1888	202.4	1985	63.4	628
98	0.07	7.1	1534	192.6	1889	202.5	1986	62.1	615
99	0.069	7	1532	192.7	1890	202.6	1987	60.8	602
100	0.069	6.9	1530	192.9	1891	202.7	1988	59.4	589

---300K---------------------------------------										
	Code	WEIGHT	D-H	DENS	COMPOSITION					
	0	BORON	(AMORPHOUS)	0.15	37	0.0856	1	B	1	K
	0	POTASSIUM	NITRATE	0.85	-1167	0.0767	1	N	3	O
THE	PROPELLANT	DENSITY	IS	0.07792	LB/CU-IN	OR	2.1567	GM/CC		
THE	TOTAL	PROPELLANT	WEIGHT	IS	1	GRAMS				
#	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENT	
	0.013863	B								
	0.008407	N								
	0.025221	O								
	0.008407	K								
***************************CHAMBER RESULTS FOLLOW ***										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	3709	6217	68.02	1000	-0.93	1.53	1.1392	0.016	4206.712	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	16.91	16.265	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.016	0			
	8.34E-03	KBO2	4.15E-03	N2	2.09E-03	B2O3	6.78E-04	BO2		
	5.87E-04	BO	9.73E-05	NO	7.79E-05	O	6.64E-05	K		
	4.40E-05	B2O2	3.87E-05	O2	2.48E-06	KO	5.61E-07	N		

	2.83E-08	NO2	2.70E-08	B	2.41E-08	N2O	1.64E-08	B2O		
	1.09E-08	BN								
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	61.841			
	**************************EXHAUST RESULTS FOLLOW **									
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	2491	4024	1	14.7	-1.33	1.53	1.13	0.016	64.343	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	17.439	17.271	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.016	0			
	8.40E-03	KBO2	4.19E-03	N2	2.59E-03	B2O3	2.53E-04	BO2		
	3.88E-05	O2	2.47E-05	BO	2.35E-05	NO	1.07E-05	O		
	5.42E-06	K	5.42E-06	K	5.42E-06	K				
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	64.345			

*****PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE**********	
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M
185.2	1.1371	3471	39.25	3644	10.11	399.3	0.11328	2230	
188.4	1.1065	3552	39.68	3702.8	140.5	10.5	406.2	0.11511	2491

EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	39.645	4016.1	3552	73.4	720	140.5	1378	138.8	1375
2	13.215	1338.7	3253	124.6	1222	169.3	1660	165.9	1644
3	5.19	525.7	2988	152.9	1499	179.2	1757	174.1	1725
4	3.498	354.4	2860	162.7	1596	186.4	1828	179.6	1779
5	2.598	263.2	2768	169.5	1662	191.5	1878	183	1813
6	2.047	207.3	2696	174.6	1712	195.4	1916	185.2	1835
7	1.676	169.8	2637	178.7	1752	198.5	1947	186.7	1849
8	1.413	143.1	2588	182	1785	201.1	1972	187.6	1858
9	1.216	123.2	2545	184.8	1812	203.3	1994	188.1	1863
10	1.064	107.8	2508	187.2	1836	205.2	2013	188.3	1866
11	0.943	95.6	2475	189.4	1857	206.9	2029	188.3	1866
12	0.846	85.7	2445	191.3	1876	208.4	2044	188.1	1864
13	0.765	77.5	2418	193	1892	209.8	2057	187.8	1861
14	0.698	70.7	2393	194.5	1908	211	2070	187.4	1856
15	0.64	64.9	2371	195.9	1921	212.2	2081	186.8	1850
16	0.591	59.9	2350	197.2	1934	213.2	2091	186.1	1844
17	0.548	55.5	2331	198.4	1946	214.2	2100	185.4	1837
18	0.511	51.7	2312	199.5	1957	215.1	2109	184.6	1829
19	0.478	48.4	2295	200.5	1967	215.9	2117	183.8	1820
20	0.449	45.4	2279	201.5	1976	216.7	2125	182.9	1811

21	0.422	42.8	2264	202.4	1985	217.4	2132	181.9	1802
22	0.399	40.4	2250	203.3	1993	218.1	2139	180.9	1792
23	0.378	38.3	2237	204.1	2001	218.8	2145	179.9	1782
24	0.359	36.3	2224	204.8	2009	219.4	2152	178.8	1771
25	0.341	34.6	2212	205.6	2016	220	2157	177.7	1760
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
26	0.325	32.9	2200	206.3	2023	220.6	2163	176.6	1749
27	0.311	31.5	2189	206.9	2029	221.1	2168	175.4	1738
28	0.297	30.1	2178	207.5	2035	221.6	2173	174.2	1726
29	0.285	28.8	2168	208.1	2041	222.1	2178	173	1714
30	0.273	27.7	2158	208.7	2047	222.6	2183	171.8	1702
31	0.262	26.6	2148	209.3	2052	223	2187	170.6	1690
32	0.252	25.6	2139	209.8	2057	223.5	2191	169.3	1677
33	0.243	24.6	2130	210.3	2062	223.9	2195	168	1665
34	0.235	23.8	2122	210.8	2067	224.3	2199	166.8	1652
35	0.226	22.9	2114	211.3	2072	224.7	2203	165.5	1639
36	0.219	22.2	2106	211.7	2076	225	2207	164.1	1626
37	0.212	21.4	2098	212.2	2081	225.4	2210	162.8	1613
38	0.205	20.8	2090	212.6	2085	225.8	2214	161.5	1600
39	0.199	20.1	2083	213	2089	226.1	2217	160.1	1586
40	0.193	19.5	2076	213.4	2093	226.4	2220	158.8	1573
41	0.187	18.9	2069	213.8	2096	226.8	2224	157.4	1559
42	0.182	18.4	2063	214.2	2100	227.1	2227	156	1546

43	0.176	17.9	2056	214.5	2104	227.4	2230	154.6	1532
44	0.172	17.4	2050	214.9	2107	227.7	2233	153.2	1518
45	0.167	16.9	2044	215.2	2111	228	2235	151.8	1504
46	0.163	16.5	2038	215.6	2114	228.2	2238	150.4	1490
47	0.159	16.1	2032	215.9	2117	228.5	2241	149	1476
48	0.155	15.7	2026	216.2	2120	228.8	2243	147.6	1462
49	0.151	15.3	2021	216.5	2123	229	2246	146.1	1448
50	0.147	14.9	2015	216.8	2126	229.3	2248	144.7	1433
51	0.144	14.6	2010	217.1	2129	229.5	2251	143.2	1419
52	0.14	14.2	2005	217.4	2132	229.8	2253	141.8	1405
53	0.137	13.9	2000	217.7	2135	230	2255	140.3	1390
54	0.134	13.6	1995	218	2138	230.2	2258	138.9	1376
55	0.131	13.3	1990	218.2	2140	230.5	2260	137.4	1361
56	0.128	13	1985	218.5	2143	230.7	2262	135.9	1347
57	0.126	12.7	1980	218.8	2145	230.9	2264	134.5	1332
58	0.123	12.5	1976	219	2148	231.1	2266	133	1317
59	0.121	12.2	1971	219.3	2150	231.3	2268	131.5	1303
60	0.118	12	1967	219.5	2153	231.5	2270	130	1288
61	0.116	11.7	1963	219.7	2155	231.7	2272	128.5	1273
62	0.114	11.5	1959	220	2157	231.9	2274	127	1258
63	0.111	11.3	1954	220.2	2159	232.1	2276	125.5	1243
64	0.109	11.1	1950	220.4	2162	232.3	2278	124	1228
65	0.107	10.9	1946	220.7	2164	232.5	2280	122.5	1213
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS

ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.105	10.7	1942	220.9	2166	232.6	2281	121	1198
67	0.104	10.5	1938	221.1	2168	232.8	2283	119.5	1183
68	0.102	10.3	1935	221.3	2170	233	2285	117.9	1168
69	0.1	10.1	1931	221.5	2172	233.2	2286	116.4	1153
70	0.098	10	1927	221.7	2174	233.3	2288	114.9	1138
71	0.097	9.8	1924	221.9	2176	233.5	2290	113.4	1123
72	0.095	9.6	1920	222.1	2178	233.7	2291	111.8	1108
73	0.093	9.5	1917	222.3	2180	233.8	2293	110.3	1093
74	0.092	9.3	1913	222.5	2182	234	2294	108.8	1078
75	0.09	9.2	1910	222.6	2183	234.1	2296	107.2	1062
76	0.089	9	1906	222.8	2185	234.3	2297	105.7	1047
77	0.088	8.9	1903	223	2187	234.4	2299	104.2	1032
78	0.086	8.7	1900	223.2	2189	234.6	2300	102.6	1016
79	0.085	8.6	1897	223.4	2190	234.7	2302	101.1	1001
80	0.084	8.5	1894	223.5	2192	234.9	2303	99.5	986
81	0.083	8.4	1890	223.7	2194	235	2304	98	970
82	0.081	8.2	1887	223.9	2195	235.1	2306	96.4	955
83	0.08	8.1	1884	224	2197	235.3	2307	94.9	940
84	0.079	8	1881	224.2	2198	235.4	2308	93.3	924
85	0.078	7.9	1878	224.3	2200	235.5	2310	91.7	909
86	0.077	7.8	1876	224.5	2201	235.7	2311	90.2	893
87	0.076	7.7	1873	224.7	2203	235.8	2312	88.6	878
88	0.075	7.6	1870	224.8	2204	235.9	2314	87	862
89	0.074	7.5	1867	225	2206	236.1	2315	85.5	847

90	0.073	7.4	1864	225.1	2207	236.2	2316	83.9	831
91	0.072	7.3	1862	225.2	2209	236.3	2317	82.3	816
92	0.071	7.2	1859	225.4	2210	236.4	2318	80.8	800
93	0.07	7.1	1856	225.5	2212	236.5	2320	79.2	785
94	0.069	7	1854	225.7	2213	236.7	2321	77.6	769
95	0.068	6.9	1851	225.8	2214	236.8	2322	76.1	753
96	0.067	6.8	1849	225.9	2216	236.9	2323	74.5	738
97	0.067	6.7	1846	226.1	2217	237	2324	72.9	722
98	0.066	6.7	1844	226.2	2218	237.1	2325	71.3	706
99	0.065	6.6	1841	226.3	2220	237.2	2326	69.7	691
100	0.064	6.5	1839	226.5	2221	237.3	2327	68.2	675

--330K--										
	Code	WEIGHT	D-H	DENS	COMPOSITION					
	0	BORON	(AMORPHOUS)	0.15	37	0.0856	1	B	1	K
	0	POTASSIUM	NITRATE	0.85	-1167	0.0767	1	N	3	O
THE	PROPELLANT	DENSITY	IS	0.07792	LB/CU-IN	OR	2.1567	GM/CC		
THE	TOTAL	PROPELLAN T	WEIGHT	IS	1	GRAMS				
#	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENTS	
	0.013863	B								

	0.008407	N								
	0.025221	O								
	0.008407	K								
***************************CHAMBER RESULTS FOLLOW **										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	4841	8254	68.02	1000	-0.03	1.73	1.1993	0.021	3242.317	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	13.164	11.96	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.021	0			
	6.93E-03	KBO2	4.38E-03	BO	3.96E-03	N2	1.52E-03	O		
	1.46E-03	BO2	1.38E-03	K	4.61E-04	B2O3	4.50E-04	NO		
	2.28E-04	O2	9.02E-05	KO	8.07E-05	B2O2	2.49E-05	N		
	7.35E-06	B	1.32E-06	BN	7.81E-07	K2	7.26E-07	B2O		
	1.80E-07	NO2	1.80E-07	NO2						
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	47.664			
***************************EXHAUST RESULTS FOLLOW ***										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	3425	5706	1	14.7	-0.7	1.73	1.1633	0.019	53.816	

SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	14.582	14.153	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.019	0			
	7.77E-03	KBO2	4.13E-03	N2	2.59E-03	BO	1.40E-03	BO2		
	1.02E-03	B2O3	6.96E-04	O	6.35E-04	K	1.58E-04	O2		
	1.54E-04	NO	3.41E-05	B2O2	5.73E-06	KO	1.34E-06	N		
	1.12E-07	B	1.12E-07	B	1.12E-07	B				
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	53.818			

**********PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE**********	
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M
231.8	1.1908	4419	38.52	4667.3	9.03	499.9	0.1451	2462	
242.1	1.1	4725	39.77	4933.4	182.9	10.08	522.2	0.15337	3425
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	39.723	4024	4724	93.4	916	182.9	1794	180.7	1790

2	13.241	1341.3	4496	158.9	1559	218.6	2144	214.1	2121
3	5.291	536	4314	194.6	1908	230.4	2259	223.6	2215
4	3.603	365	4239	207	2030	239.5	2348	230.4	2283
5	2.695	273	4184	215.6	2114	246	2412	234.7	2325
6	2.134	216.2	4140	222.1	2178	251	2461	237.5	2352
7	1.705	172.8	3939	228.5	2241	255.4	2505	239.6	2374
8	1.4	141.8	3740	233.8	2293	259.1	2540	241	2388
9	1.178	119.4	3576	238.2	2336	262.1	2570	241.8	2395
10	1.012	102.5	3436	241.9	2372	264.7	2595	242.1	2399
11	0.883	89.4	3315	245	2403	266.9	2617	242.1	2398
12	0.78	79	3209	247.8	2430	268.9	2636	241.8	2395
13	0.696	70.5	3115	250.2	2453	270.6	2653	241.3	2390
14	0.627	63.5	3031	252.4	2475	272.1	2669	240.6	2383
15	0.569	57.7	2955	254.3	2494	273.6	2683	239.7	2375
16	0.52	52.7	2886	256.1	2511	274.8	2695	238.8	2365
17	0.478	48.4	2823	257.7	2527	276	2707	237.7	2355
18	0.442	44.7	2765	259.2	2542	277.1	2717	236.5	2343
19	0.41	41.5	2711	260.6	2555	278.1	2727	235.3	2331
20	0.382	38.7	2661	261.8	2567	279	2736	233.9	2318
21	0.357	36.1	2615	263	2579	279.9	2745	232.6	2304
22	0.335	33.9	2571	264.1	2590	280.7	2753	231.1	2290
23	0.315	31.9	2531	265.2	2600	281.5	2760	229.6	2275
24	0.297	30.1	2492	266.1	2610	282.2	2767	228.1	2260
25	0.281	28.4	2456	267	2619	282.9	2774	226.5	2244
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU	VACUU	VACUU	SEA LV	SEA LV

					M	M	M		
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
26	0.266	27	2422	267.9	2627	283.5	2780	224.9	2228
27	0.253	25.6	2389	268.7	2635	284.1	2786	223.3	2212
28	0.241	24.4	2358	269.5	2643	284.7	2792	221.6	2195
29	0.229	23.2	2329	270.3	2650	285.3	2797	219.9	2178
30	0.219	22.2	2301	271	2657	285.8	2803	218.2	2161
31	0.209	21.2	2274	271.7	2664	286.3	2807	216.4	2144
32	0.201	20.3	2249	272.3	2670	286.8	2812	214.6	2126
33	0.192	19.5	2224	272.9	2676	287.2	2817	212.9	2109
34	0.185	18.7	2201	273.5	2682	287.7	2821	211	2091
35	0.178	18	2179	274.1	2688	288.1	2825	209.2	2073
36	0.171	17.3	2157	274.6	2693	288.5	2829	207.4	2054
37	0.165	16.7	2136	275.2	2698	288.9	2833	205.5	2036
38	0.159	16.1	2116	275.7	2703	289.3	2837	203.6	2017
39	0.154	15.6	2097	276.2	2708	289.7	2841	201.8	1999
40	0.148	15	2078	276.6	2713	290	2844	199.9	1980
41	0.144	14.5	2060	277.1	2717	290.4	2847	197.9	1961
42	0.139	14.1	2043	277.5	2722	290.7	2851	196	1942
43	0.135	13.6	2026	278	2726	291	2854	194.1	1923
44	0.131	13.2	2009	278.4	2730	291.3	2857	192.1	1903
45	0.127	12.8	1994	278.8	2734	291.6	2860	190.2	1884
46	0.123	12.5	1978	279.2	2738	291.9	2863	188.2	1865
47	0.119	12.1	1963	279.6	2741	292.2	2865	186.3	1845

48	0.116	11.8	1949	279.9	2745	292.5	2868	184.3	1826
49	0.113	11.4	1935	280.3	2748	292.8	2871	182.3	1806
50	0.11	11.1	1921	280.6	2752	293	2873	180.3	1786
51	0.107	10.8	1908	281	2755	293.3	2876	178.3	1766
52	0.104	10.6	1895	281.3	2758	293.5	2878	176.3	1747
53	0.102	10.3	1882	281.6	2762	293.8	2881	174.3	1727
54	0.099	10	1870	281.9	2765	294	2883	172.3	1707
55	0.097	9.8	1858	282.2	2768	294.2	2885	170.3	1687
56	0.094	9.6	1846	282.5	2771	294.5	2888	168.2	1666
57	0.092	9.3	1835	282.8	2773	294.7	2890	166.2	1646
58	0.09	9.1	1824	283.1	2776	294.9	2892	164.2	1626
59	0.088	8.9	1813	283.4	2779	295.1	2894	162.1	1606
60	0.086	8.7	1802	283.7	2782	295.3	2896	160.1	1586
61	0.084	8.5	1792	283.9	2784	295.5	2898	158	1565
62	0.082	8.4	1782	284.2	2787	295.7	2900	155.9	1545
63	0.081	8.2	1772	284.4	2789	295.9	2902	153.9	1524
64	0.079	8	1762	284.7	2792	296.1	2903	151.8	1504
65	0.077	7.8	1753	284.9	2794	296.3	2905	149.7	1483
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.076	7.7	1743	285.2	2796	296.4	2907	147.7	1463
67	0.074	7.5	1734	285.4	2799	296.6	2909	145.6	1442
68	0.073	7.4	1725	285.6	2801	296.8	2910	143.5	1422

69	0.072	7.2	1717	285.8	2803	297	2912	141.4	1401
70	0.07	7.1	1708	286.1	2805	297.1	2914	139.3	1380
71	0.069	7	1700	286.3	2807	297.3	2915	137.3	1360
72	0.068	6.8	1691	286.5	2809	297.5	2917	135.2	1339
73	0.066	6.7	1683	286.7	2811	297.6	2918	133.1	1318
74	0.065	6.6	1675	286.9	2813	297.8	2920	131	1297
75	0.064	6.5	1667	287.1	2815	297.9	2922	128.9	1277
76	0.063	6.4	1660	287.3	2817	298.1	2923	126.8	1256
77	0.062	6.3	1652	287.5	2819	298.2	2924	124.7	1235
78	0.061	6.2	1645	287.7	2821	298.4	2926	122.5	1214
79	0.06	6.1	1638	287.9	2823	298.5	2927	120.4	1193
80	0.059	6	1630	288	2825	298.6	2929	118.3	1172
81	0.058	5.9	1623	288.2	2826	298.8	2930	116.2	1151
82	0.057	5.8	1617	288.4	2828	298.9	2931	114.1	1130
83	0.056	5.7	1610	288.6	2830	299.1	2933	112	1109
84	0.055	5.6	1603	288.7	2832	299.2	2934	109.8	1088
85	0.054	5.5	1597	288.9	2833	299.3	2935	107.7	1067
86	0.053	5.4	1590	289.1	2835	299.4	2936	105.6	1046
87	0.053	5.3	1584	289.2	2836	299.6	2938	103.4	1025
88	0.052	5.2	1577	289.4	2838	299.7	2939	101.3	1004
89	0.051	5.2	1571	289.6	2840	299.8	2940	99.2	983
90	0.05	5.1	1565	289.7	2841	299.9	2941	97.1	961
91	0.05	5	1559	289.9	2843	300	2942	94.9	940
92	0.049	4.9	1553	290	2844	300.2	2943	92.8	919
93	0.048	4.9	1548	290.2	2846	300.3	2945	90.6	898

94	0.047	4.8	1542	290.3	2847	300.4	2946	88.5	877
95	0.047	4.7	1536	290.5	2848	300.5	2947	86.3	855
96	0.046	4.7	1531	290.6	2850	300.6	2948	84.2	834
97	0.046	4.6	1525	290.8	2851	300.7	2949	82.1	813
98	0.045	4.6	1520	290.9	2853	300.8	2950	79.9	792
99	0.044	4.5	1514	291	2854	300.9	2951	77.8	770
100	0.044	4.4	1509	291.2	2855	301	2952	75.6	749

							1	K	
	Code	WEIGHT	D-H	DENS	COMPOSITION		3	O	
	0	BORON	(AMORPHOUS)	0.15	37	0.0856	1	B	
	0	POTASSIUM	NITRATE	0.85	-1167	0.0767	1	N	
THE	PROPELLANT	DENSITY	IS	0.07792	LB/CU-IN	OR	2.1567	GM/CC	
THE	TOTAL	PROPELLANT	WEIGHT	IS	1	GRAMS			
NUMBER	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENTS
	0.013863	B							
	0.008407	N							
	0.025221	O							
	0.008407	K							
**************************CHAMBER RESULTS FOLLOW ***									

	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
	5409	9277	68.02	1000	0.87	1.91	1.2675	0.027	2521.198
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	10.761	9.416
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.027	0		
	7.82E-03	BO	4.12E-03	O	4.11E-03	KBO2	4.03E-03	K	
	3.81E-03	N2	1.42E-03	BO2	6.76E-04	NO	3.40E-04	O2	
	2.57E-04	KO	1.58E-04	B2O3	9.92E-05	N	6.89E-05	B2O2	
	5.51E-05	B	6.82E-06	BN	3.38E-06	K2	2.20E-06	B2O	
	2.49E-07	NO2	2.49E-07	NO2					
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	37.063		
***************************EXHAUST RESULTS FOLLOW ***									
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
	3762	6312	1	14.7	-0.07	1.91	1.2124	0.023	43.473
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	11.817	11.341
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.023	0		
	5.98E-03	KBO2	5.45E-03	BO	4.06E-03	N2	2.45E-03	O	
	2.41E-03	K	1.62E-03	BO2	3.75E-04	B2O3	3.14E-04	O2	
	2.85E-04	NO	3.25E-05	B2O2	2.58E-05	KO	6.80E-06	N	
	1.12E-06	B	7.69E-08	K2	5.31E-08	B2O	4.40E-08	BN	

	2.33E-08	NO2	1.00E-08	B2	1.00E-08	N2O	1.00E-08	N2O3	
	1.00E-08	N2O4	1.00E-08	N2O5	1.00E-08	O3	1.00E-08	NO3	
	1.00E-08	N3	1.00E-08	B&	1.00E-08	B*	1.00E-08	BN&	
	1.00E-08	B2O3&	1.00E-08	B2O3*	1.00E-08	N2O4&	1.00E-08	N2O4*	
	1.00E-08	K&	1.00E-08	K*	1.00E-08	KO2&	1.00E-08	K2B4O7&	
	1.00E-08	K2B4O7*	1.00E-08	K2B6O10&	1.00E-08	K2B8O13&	1.00E-08	K2B8O13*	
	1.00E-08	K2O&	1.00E-08	K2O2&	1.00E-08	KBO2&	1.00E-08	KBO2*	
	1.00E-08	K&							
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	43.474		

*PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE**	
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M
266.6	1.2596	4788	37.63	5480.1	7.92	574.9	0.17037	2267	
286.3	1.1405	5161	39.2	5714.2	217.5	10.01	617.4	0.17764	3762
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	39.203	3971.2	5161	115.2	1130	217.5	2133	214.9	2129
2	13.068	1323.7	4700	192.8	1891	261.1	2560	255.8	2534
3	4.935	500	4326	236.3	2317	274.9	2696	267.1	2646

4	3.325	336.8	4183	250.6	2457	285.3	2798	274.8	2723
5	2.467	249.9	4078	260.4	2554	292.6	2869	279.6	2769
6	1.941	196.6	3996	267.8	2626	298.2	2924	282.5	2799
7	1.588	160.9	3928	273.7	2684	302.7	2968	284.4	2818
8	1.337	135.4	3871	278.5	2731	306.4	3005	285.6	2829
9	1.149	116.4	3821	282.6	2771	309.6	3036	286.1	2834
10	1.005	101.8	3778	286.1	2806	312.4	3063	286.3	2836
11	0.896	90.7	3766	289.1	2835	314.8	3087	286.1	2834
12	0.81	82	3770	291.6	2860	317	3108	285.6	2830
13	0.738	74.7	3774	293.9	2882	319	3128	285	2823
14	0.677	68.6	3777	296	2903	320.8	3146	284.2	2816
15	0.625	63.3	3780	298	2922	322.5	3162	283.3	2807
16	0.58	58.8	3783	299.8	2940	324.1	3178	282.3	2796
17	0.541	54.8	3786	301.5	2957	325.5	3192	281.1	2785
18	0.506	51.3	3788	303.1	2972	326.9	3206	279.9	2773
19	0.476	48.2	3791	304.6	2987	328.2	3218	278.6	2760
20	0.448	45.4	3793	306	3001	329.4	3230	277.2	2746
21	0.424	42.9	3795	307.3	3014	330.6	3242	275.8	2732
22	0.402	40.7	3797	308.6	3026	331.7	3253	274.3	2717
23	0.382	38.7	3799	309.8	3038	332.7	3263	272.7	2701
24	0.364	36.8	3801	311	3049	333.7	3273	271.1	2685
25	0.347	35.1	3803	312.1	3060	334.7	3282	269.4	2669
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	

26	0.332	33.6	3805	313.1	3070	335.6	3291	267.7	2652
27	0.318	32.2	3807	314.1	3080	336.5	3300	266	2635
28	0.305	30.9	3808	315.1	3090	337.3	3308	264.2	2618
29	0.293	29.6	3810	316	3099	338.2	3316	262.4	2600
30	0.282	28.5	3811	316.9	3108	338.9	3324	260.6	2582
31	0.271	27.5	3813	317.8	3116	339.7	3331	258.8	2563
32	0.261	26.5	3814	318.6	3124	340.4	3338	256.9	2545
33	0.252	25.6	3816	319.4	3132	341.1	3345	255	2526
34	0.244	24.7	3817	320.2	3140	341.8	3352	253.1	2507
35	0.236	23.9	3818	320.9	3147	342.5	3359	251.1	2488
36	0.229	23.2	3820	321.6	3154	343.1	3365	249.1	2468
37	0.222	22.4	3821	322.4	3161	343.8	3371	247.2	2448
38	0.215	21.8	3822	323	3168	344.4	3377	245.1	2428
39	0.209	21.1	3823	323.7	3174	345	3383	243.1	2408
40	0.203	20.5	3824	324.4	3181	345.5	3388	241.1	2388
41	0.197	20	3826	325	3187	346.1	3394	239	2368
42	0.192	19.4	3827	325.6	3193	346.6	3399	237	2347
43	0.187	18.9	3828	326.2	3199	347.2	3404	234.9	2327
44	0.182	18.4	3829	326.8	3205	347.7	3409	232.8	2306
45	0.177	18	3830	327.4	3210	348.2	3414	230.7	2285
46	0.173	17.5	3831	327.9	3216	348.7	3419	228.6	2264
47	0.169	17.1	3832	328.5	3221	349.2	3424	226.4	2243
48	0.165	16.7	3833	329	3226	349.6	3428	224.3	2222
49	0.161	16.3	3834	329.5	3231	350.1	3433	222.2	2201
50	0.157	15.9	3835	330	3236	350.5	3437	220	2179

51	0.154	15.6	3835	330.5	3241	351	3442	217.8	2158
52	0.15	15.2	3836	331	3246	351.4	3446	215.6	2136
53	0.147	14.9	3837	331.5	3251	351.8	3450	213.5	2115
54	0.144	14.6	3838	331.9	3255	352.2	3454	211.3	2093
55	0.141	14.3	3839	332.4	3260	352.7	3458	209.1	2071
56	0.138	14	3840	332.8	3264	353	3462	206.8	2049
57	0.135	13.7	3840	333.3	3268	353.4	3466	204.6	2027
58	0.133	13.5	3841	333.7	3273	353.8	3470	202.4	2005
59	0.13	13.2	3842	334.1	3277	354.2	3473	200.2	1983
60	0.128	12.9	3843	334.6	3281	354.6	3477	197.9	1961
61	0.125	12.7	3844	335	3285	354.9	3481	195.7	1938
62	0.123	12.5	3844	335.4	3289	355.3	3484	193.4	1916
63	0.121	12.2	3845	335.8	3293	355.6	3488	191.2	1894
64	0.119	12	3846	336.1	3296	356	3491	188.9	1871
65	0.117	11.8	3846	336.5	3300	356.3	3494	186.6	1849
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.115	11.6	3847	336.9	3304	356.7	3498	184.3	1826
67	0.113	11.4	3848	337.3	3307	357	3501	182.1	1804
68	0.111	11.2	3848	337.6	3311	357.3	3504	179.8	1781
69	0.109	11	3849	338	3314	357.6	3507	177.5	1758
70	0.107	10.9	3850	338.3	3318	357.9	3510	175.2	1735
71	0.106	10.7	3850	338.7	3321	358.3	3513	172.9	1713
72	0.104	10.5	3851	339	3325	358.6	3516	170.6	1690

73	0.102	10.4	3852	339.4	3328	358.9	3519	168.3	1667
74	0.101	10.2	3852	339.7	3331	359.2	3522	165.9	1644
75	0.099	10.1	3853	340	3334	359.4	3525	163.6	1621
76	0.098	9.9	3853	340.3	3337	359.7	3528	161.3	1598
77	0.096	9.8	3854	340.7	3341	360	3530	159	1575
78	0.095	9.6	3855	341	3344	360.3	3533	156.6	1552
79	0.094	9.5	3855	341.3	3347	360.6	3536	154.3	1529
80	0.092	9.3	3856	341.6	3350	360.8	3538	152	1505
81	0.091	9.2	3856	341.9	3353	361.1	3541	149.6	1482
82	0.09	9.1	3857	342.2	3355	361.4	3544	147.3	1459
83	0.088	9	3857	342.5	3358	361.6	3546	144.9	1436
84	0.087	8.8	3858	342.8	3361	361.9	3549	142.6	1412
85	0.086	8.7	3859	343	3364	362.1	3551	140.2	1389
86	0.085	8.6	3859	343.3	3367	362.4	3554	137.9	1366
87	0.084	8.5	3860	343.6	3369	362.6	3556	135.5	1342
88	0.083	8.4	3860	343.9	3372	362.9	3559	133.1	1319
89	0.082	8.3	3861	344.1	3375	363.1	3561	130.8	1295
90	0.081	8.2	3861	344.4	3377	363.4	3563	128.4	1272
91	0.08	8.1	3862	344.7	3380	363.6	3566	126	1248
92	0.079	8	3862	344.9	3382	363.8	3568	123.6	1225
93	0.078	7.9	3863	345.2	3385	364.1	3570	121.3	1201
94	0.077	7.8	3863	345.4	3388	364.3	3572	118.9	1178
95	0.076	7.7	3864	345.7	3390	364.5	3575	116.5	1154
96	0.075	7.6	3864	345.9	3392	364.8	3577	114.1	1130
97	0.074	7.5	3865	346.2	3395	365	3579	111.7	1107

98	0.073	7.4	3865	346.4	3397	365.2	3581	109.3	1083
99	0.072	7.3	3865	346.7	3400	365.4	3583	106.9	1059
100	0.072	7.3	3866	346.9	3402	365.6	3585	104.5	1036

---390K--										
Code	WEIGHT	D-H	DENS	COMPOSITION						
	0	BORON	(AMORPHOUS)	0.15	37	0.0856	1	B	1	K
	0	POTASSIUM	NITRATE	0.85	-1167	0.0767	1	N	3	O
THE	PROPELLANT	DENSITY	IS	0.07792	LB/CU-IN	OR	2.1567	GM/CC		
THE	TOTAL	PROPELLANT	WEIGHT	IS	1	GRAMS				
NUMBER	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENTS	
	0.013863	B								
	0.008407	N								
	0.025221	O								
	0.008407	K								
***************************CHAMBER RESULTS FOLLOW ***										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	5915	10188	68.02	1000	1.77	2.07	1.3321	0.033	2064.824	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	9.441	7.97	

NUMBER	MOLS	GAS	AND	CONDENSED	=	0.033	0			
	1.08E-02	BO	7.27E-03	O	6.54E-03	K	3.67E-03	N2		
	1.52E-03	KBO2	1.05E-03	BO2	7.62E-04	NO	3.36E-04	KO		
	3.24E-04	O2	2.75E-04	N	2.60E-04	B	4.99E-05	B2O2		
	4.89E-05	B2O3	2.42E-05	BN	5.03E-06	K2	4.74E-06	B2O		
	2.22E-07	NO2	2.22E-07	NO2	2.22E-07	NO2				
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	30.354			
****************************EXHAUST RESULTS FOLLOW **										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	3973	6693	1	14.7	0.55	2.07	1.265	0.028	36.23	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	9.962	9.486	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.028	0			
	8.06E-03	BO	4.61E-03	O	4.50E-03	K	4.01E-03	N2		
	3.86E-03	KBO2	1.53E-03	BO2	3.85E-04	O2	3.65E-04	NO		
	1.77E-04	B2O3	4.69E-05	KO	2.89E-05	B2O2	1.69E-05	N		
	4.36E-06	B	1.86E-07	K2	1.33E-07	BN	1.14E-07	B2O		
	2.74E-08	NO2								
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	36.232			

**PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE**	
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M
296.9	1.3334	5070	36.72	6194.2	6.98	640.2	0.19256	2059	
326.6	1.1223	5755	39.46	6839.1	252.1	9.29	704.2	0.21261	3973
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPUL S
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	39.418	3993.1	5754	128.9	1264	252.1	2472	249	2466
2	13.139	1331	5444	217.3	2131	299.4	2936	293.2	2904
3	5.092	515.8	5189	266.2	2610	313.9	3078	304.5	3017
4	3.447	349.1	5088	282.6	2771	325.7	3194	313.2	3103
5	2.567	260	5013	294	2883	334.1	3276	318.5	3155
6	2.025	205.1	4953	302.6	2968	340.6	3340	321.8	3188
7	1.582	160.2	4614	311.7	3056	346.3	3396	324.4	3214
8	1.272	128.8	4297	319.1	3129	350.9	3441	325.9	3228
9	1.052	106.6	4040	325	3187	354.6	3478	326.5	3234
10	0.89	90.2	3826	329.9	3235	357.8	3508	326.5	3234
11	0.766	77.6	3643	334.1	3276	360.4	3534	326.1	3230
12	0.669	67.8	3486	337.7	3311	362.7	3557	325.2	3222
13	0.591	59.9	3348	340.8	3342	364.8	3577	324.2	3211

14	0.527	53.4	3226	343.5	3369	366.6	3595	322.8	3198
15	0.474	48.1	3116	346	3393	368.2	3611	321.3	3183
16	0.43	43.5	3018	348.2	3414	369.7	3625	319.7	3167
17	0.392	39.7	2928	350.2	3434	371	3638	317.9	3149
18	0.359	36.4	2847	352	3452	372.2	3650	315.9	3130
19	0.331	33.6	2772	353.6	3468	373.3	3661	313.9	3110
20	0.307	31.1	2703	355.2	3483	374.3	3671	311.8	3089
21	0.285	28.9	2639	356.6	3497	375.3	3680	309.7	3068
22	0.266	26.9	2580	357.9	3510	376.2	3689	307.4	3046
23	0.249	25.2	2525	359.1	3522	377	3697	305.1	3023
24	0.233	23.6	2473	360.3	3533	377.8	3705	302.8	3000
25	0.22	22.2	2424	361.4	3544	378.5	3712	300.4	2976
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
26	0.207	21	2379	362.4	3554	379.2	3719	298	2952
27	0.196	19.8	2335	363.3	3563	379.9	3725	295.5	2927
28	0.185	18.8	2295	364.2	3572	380.5	3731	293	2902
29	0.176	17.8	2256	365.1	3580	381.1	3737	290.4	2877
30	0.167	17	2220	365.9	3588	381.6	3742	287.9	2852
31	0.16	16.2	2185	366.7	3596	382.1	3747	285.3	2826
32	0.152	15.4	2152	367.4	3603	382.6	3752	282.6	2800
33	0.145	14.7	2120	368.1	3610	383.1	3757	280	2774
34	0.139	14.1	2090	368.8	3617	383.6	3762	277.3	2747

35	0.133	13.5	2061	369.4	3623	384	3766	274.7	2721
36	0.128	13	2033	370.1	3629	384.4	3770	272	2694
37	0.123	12.4	2007	370.6	3635	384.9	3774	269.2	2667
38	0.118	12	1981	371.2	3640	385.2	3778	266.5	2640
39	0.114	11.5	1957	371.8	3645	385.6	3781	263.7	2613
40	0.11	11.1	1933	372.3	3651	386	3785	261	2585
41	0.106	10.7	1911	372.8	3656	386.3	3788	258.2	2558
42	0.102	10.3	1889	373.3	3660	386.7	3792	255.4	2530
43	0.099	10	1868	373.7	3665	387	3795	252.6	2502
44	0.095	9.7	1847	374.2	3669	387.3	3798	249.8	2475
45	0.092	9.3	1828	374.6	3674	387.6	3801	247	2447
46	0.089	9	1809	375.1	3678	387.9	3804	244.1	2419
47	0.087	8.8	1790	375.5	3682	388.2	3807	241.3	2390
48	0.084	8.5	1772	375.9	3686	388.4	3809	238.5	2362
49	0.081	8.3	1755	376.2	3690	388.7	3812	235.6	2334
50	0.079	8	1738	376.6	3693	389	3814	232.7	2305
51	0.077	7.8	1722	377	3697	389.2	3817	229.9	2277
52	0.075	7.6	1706	377.3	3700	389.5	3819	227	2248
53	0.073	7.4	1691	377.7	3704	389.7	3822	224.1	2220
54	0.071	7.2	1676	378	3707	389.9	3824	221.2	2191
55	0.069	7	1661	378.3	3710	390.2	3826	218.3	2163
56	0.067	6.8	1647	378.6	3713	390.4	3828	215.4	2134
57	0.065	6.6	1633	379	3716	390.6	3830	212.5	2105
58	0.064	6.5	1620	379.3	3719	390.8	3832	209.6	2076
59	0.062	6.3	1607	379.5	3722	391	3834	206.6	2047

60	0.061	6.1	1594	379.8	3725	391.2	3836	203.7	2018
61	0.059	6	1582	380.1	3727	391.4	3838	200.8	1989
62	0.058	5.9	1570	380.4	3730	391.6	3840	197.8	1960
63	0.057	5.7	1558	380.6	3733	391.8	3842	194.9	1931
64	0.055	5.6	1546	380.9	3735	392	3844	192	1902
65	0.054	5.5	1535	381.2	3738	392.1	3845	189	1872
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPUL S
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.053	5.4	1524	381.4	3740	392.3	3847	186.1	1843
67	0.052	5.2	1513	381.6	3743	392.5	3849	183.1	1814
68	0.051	5.1	1503	381.9	3745	392.6	3850	180.1	1785
69	0.05	5	1492	382.1	3747	392.8	3852	177.2	1755
70	0.049	4.9	1482	382.3	3749	393	3853	174.2	1726
71	0.048	4.8	1472	382.6	3752	393.1	3855	171.2	1696
72	0.047	4.7	1463	382.8	3754	393.3	3856	168.3	1667
73	0.046	4.6	1453	383	3756	393.4	3858	165.3	1637
74	0.045	4.5	1444	383.2	3758	393.6	3859	162.3	1608
75	0.044	4.4	1435	383.4	3760	393.7	3861	159.3	1578
76	0.043	4.4	1426	383.6	3762	393.8	3862	156.4	1549
77	0.042	4.3	1417	383.8	3764	394	3863	153.4	1519
78	0.041	4.2	1409	384	3766	394.1	3865	150.4	1490
79	0.041	4.1	1400	384.2	3767	394.2	3866	147.4	1460
80	0.04	4.1	1392	384.4	3769	394.4	3867	144.4	1430

81	0.039	4	1384	384.6	3771	394.5	3869	141.4	1401
82	0.039	3.9	1376	384.7	3773	394.6	3870	138.4	1371
83	0.038	3.8	1368	384.9	3775	394.8	3871	135.4	1341
84	0.037	3.8	1360	385.1	3776	394.9	3872	132.4	1311
85	0.037	3.7	1353	385.3	3778	395	3873	129.4	1282
86	0.036	3.7	1345	385.4	3780	395.1	3875	126.4	1252
87	0.035	3.6	1338	385.6	3781	395.2	3876	123.4	1222
88	0.035	3.5	1331	385.8	3783	395.3	3877	120.4	1192
89	0.034	3.5	1324	385.9	3784	395.5	3878	117.3	1162
90	0.034	3.4	1317	386.1	3786	395.6	3879	114.3	1133
91	0.033	3.4	1310	386.2	3787	395.7	3880	111.3	1103
92	0.033	3.3	1304	386.4	3789	395.8	3881	108.3	1073
93	0.032	3.3	1297	386.5	3790	395.9	3882	105.3	1043
94	0.032	3.2	1290	386.7	3792	396	3883	102.2	1013
95	0.031	3.2	1284	386.8	3793	396.1	3884	99.2	983
96	0.031	3.1	1278	387	3795	396.2	3885	96.2	953
97	0.03	3.1	1272	387.1	3796	396.3	3886	93.2	923
98	0.03	3	1266	387.2	3797	396.4	3887	90.1	893
99	0.029	3	1260	387.4	3799	396.5	3888	87.1	863
100	0.029	2.9	1254	387.5	3800	396.6	3889	84.1	833

--395K--										
Code	WEIGHT	D-H	DENS	COMPOSITION						
	0	BORON	(AMORPHOUS)	0.15	37	0.0856	1	B	1	K
	0	POTASSIUM	NITRATE	0.85	-1167	0.0767	1	N	3	O
THE	PROPELLANT	DENSITY	IS	0.07792	LB/CU-IN	OR	2.1567	GM/CC		
THE	TOTAL	PROPELLANT	WEIGHT	IS	1	GRAMS				
NUMBER	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENTS	
	0.013863	B								
	0.008407	N								
	0.025221	O								
	0.008407	K								
***************************CHAMBER RESULTS FOLLOW **										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	6000	10340	68.02	1000	1.92	2.09	1.3408	0.034	2016.787	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	9.322	7.818	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.034	0			
	1.11E-02	BO	7.75E-03	O	6.83E-03	K	3.65E-03	N2		
	1.24E-03	KBO2	9.74E-04	BO2	7.61E-04	NO	3.34E-04	KO		

	3.27E-04	B	3.19E-04	N	3.10E-04	O2	4.61E-05	B2O2		
	3.92E-05	B2O3	2.93E-05	BN	5.23E-06	B2O	5.04E-06	K2		
	2.10E-07	NO2	2.10E-07	NO2	2.10E-07	NO2				
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	29.648			
***************************EXHAUST RESULTS FOLLOW **										
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V	
	4005	6750	1	14.7	0.65	2.09	1.2738	0.028	35.267	
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	9.721	9.244	
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.028	0			
	8.48E-03	BO	4.99E-03	O	4.84E-03	K	4.01E-03	N2		
	3.51E-03	KBO2	1.50E-03	BO2	3.88E-04	O2	3.74E-04	NO		
	1.56E-04	B2O3	4.97E-05	KO	2.81E-05	B2O2	1.92E-05	N		
	5.31E-06	B	2.04E-07	K2	1.57E-07	BN	1.27E-07	B2O		
	2.75E-08	NO2								
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	35.268			

*PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE***	
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M
303.2	1.3374	5134	36.67	6278.4	6.94	653.9	0.19518	2069	
333.1	1.1223	5834	39.46	6959.9	256.9	9.27	718.4	0.21637	4005
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPUL S
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	39.457	3997	5834	131.4	1289	256.9	2519	253.7	2513
2	13.152	1332.3	5512	221.7	2174	305.3	2994	299	2962
3	5.092	515.8	5248	271.6	2663	320.2	3140	310.6	3077
4	3.447	349.1	5144	288.4	2828	332.2	3258	319.5	3165
5	2.567	260	5066	300	2942	340.8	3342	324.9	3219
6	2.025	205.1	5005	308.8	3028	347.5	3407	328.4	3253
7	1.571	159.2	4626	318.3	3121	353.3	3464	331	3279
8	1.265	128.2	4317	325.7	3194	357.9	3510	332.5	3293
9	1.048	106.2	4065	331.7	3253	361.7	3547	333.1	3299
10	0.887	89.9	3855	336.6	3301	364.8	3578	333	3299
11	0.764	77.4	3677	340.8	3342	367.5	3604	332.6	3294
12	0.668	67.7	3522	344.4	3377	369.9	3627	331.7	3286
13	0.59	59.8	3386	347.5	3408	371.9	3647	330.6	3275
14	0.527	53.4	3265	350.3	3435	373.8	3665	329.2	3262

15	0.474	48	3158	352.8	3459	375.4	3681	327.7	3246
16	0.43	43.5	3060	355	3481	376.9	3696	326	3229
17	0.392	39.7	2972	357	3501	378.2	3709	324.2	3211
18	0.36	36.4	2891	358.9	3519	379.5	3721	322.2	3192
19	0.332	33.6	2817	360.5	3536	380.6	3732	320.2	3172
20	0.307	31.1	2749	362.1	3551	381.6	3742	318	3150
21	0.285	28.9	2686	363.5	3565	382.6	3752	315.8	3129
22	0.266	27	2627	364.9	3578	383.5	3761	313.5	3106
23	0.249	25.2	2572	366.1	3590	384.3	3769	311.2	3083
24	0.234	23.7	2521	367.3	3602	385.1	3777	308.8	3059
25	0.22	22.3	2472	368.4	3612	385.9	3784	306.4	3035
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPUL S
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
26	0.208	21	2427	369.4	3622	386.6	3791	303.9	3010
27	0.196	19.9	2384	370.4	3632	387.2	3797	301.4	2985
28	0.186	18.9	2344	371.3	3641	387.9	3803	298.8	2960
29	0.177	17.9	2305	372.2	3649	388.5	3809	296.2	2935
30	0.168	17	2269	373	3658	389	3815	293.6	2909
31	0.16	16.2	2234	373.8	3665	389.6	3820	291	2882
32	0.153	15.5	2201	374.5	3673	390.1	3825	288.3	2856
33	0.146	14.8	2170	375.2	3680	390.6	3830	285.6	2829
34	0.14	14.2	2139	375.9	3686	391	3834	282.9	2803
35	0.134	13.6	2111	376.6	3693	391.5	3839	280.2	2775

36	0.129	13	2083	377.2	3699	391.9	3843	277.4	2748
37	0.124	12.5	2057	377.8	3705	392.3	3847	274.7	2721
38	0.119	12	2031	378.4	3710	392.7	3851	271.9	2693
39	0.114	11.6	2007	378.9	3716	393.1	3855	269.1	2665
40	0.11	11.2	1983	379.4	3721	393.5	3858	266.3	2638
41	0.106	10.8	1960	380	3726	393.8	3862	263.4	2610
42	0.103	10.4	1939	380.5	3731	394.2	3865	260.6	2581
43	0.099	10	1917	380.9	3735	394.5	3868	257.7	2553
44	0.096	9.7	1897	381.4	3740	394.8	3872	254.9	2525
45	0.093	9.4	1877	381.8	3744	395.1	3875	252	2496
46	0.09	9.1	1858	382.3	3749	395.4	3877	249.1	2468
47	0.087	8.8	1840	382.7	3753	395.7	3880	246.2	2439
48	0.084	8.6	1822	383.1	3757	396	3883	243.3	2411
49	0.082	8.3	1805	383.5	3760	396.3	3886	240.4	2382
50	0.08	8.1	1788	383.9	3764	396.5	3888	237.5	2353
51	0.077	7.8	1772	384.2	3768	396.8	3891	234.6	2324
52	0.075	7.6	1756	384.6	3771	397	3893	231.7	2295
53	0.073	7.4	1740	384.9	3775	397.3	3896	228.7	2266
54	0.071	7.2	1725	385.3	3778	397.5	3898	225.8	2237
55	0.069	7	1711	385.6	3781	397.7	3900	222.8	2207
56	0.068	6.8	1697	385.9	3785	398	3902	219.9	2178
57	0.066	6.7	1683	386.2	3788	398.2	3905	216.9	2149
58	0.064	6.5	1669	386.5	3791	398.4	3907	213.9	2119
59	0.063	6.3	1656	386.8	3793	398.6	3909	211	2090
60	0.061	6.2	1643	387.1	3796	398.8	3911	208	2060

61	0.06	6	1631	387.4	3799	399	3913	205	2031
62	0.058	5.9	1619	387.7	3802	399.2	3915	202	2001
63	0.057	5.8	1607	388	3804	399.4	3916	199	1972
64	0.056	5.6	1595	388.2	3807	399.6	3918	196	1942
65	0.054	5.5	1584	388.5	3810	399.7	3920	193	1912
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMU M	VACUU M	VACUU M	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPUL S
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.053	5.4	1573	388.7	3812	399.9	3922	190	1883
67	0.052	5.3	1562	389	3814	400.1	3923	187	1853
68	0.051	5.2	1551	389.2	3817	400.3	3925	184	1823
69	0.05	5.1	1541	389.5	3819	400.4	3927	181	1793
70	0.049	5	1531	389.7	3821	400.6	3928	178	1763
71	0.048	4.9	1521	389.9	3824	400.7	3930	175	1733
72	0.047	4.8	1511	390.1	3826	400.9	3931	171.9	1703
73	0.046	4.7	1502	390.4	3828	401	3933	168.9	1673
74	0.045	4.6	1492	390.6	3830	401.2	3934	165.9	1643
75	0.044	4.5	1483	390.8	3832	401.3	3936	162.8	1613
76	0.043	4.4	1474	391	3834	401.5	3937	159.8	1583
77	0.043	4.3	1465	391.2	3836	401.6	3938	156.8	1553
78	0.042	4.2	1457	391.4	3838	401.8	3940	153.7	1523
79	0.041	4.2	1448	391.6	3840	401.9	3941	150.7	1493
80	0.04	4.1	1440	391.8	3842	402	3942	147.6	1462
81	0.04	4	1432	392	3844	402.2	3944	144.6	1432

82	0.039	3.9	1424	392.1	3845	402.3	3945	141.5	1402
83	0.038	3.9	1416	392.3	3847	402.4	3946	138.5	1372
84	0.038	3.8	1408	392.5	3849	402.5	3947	135.4	1342
85	0.037	3.7	1400	392.7	3851	402.7	3949	132.4	1311
86	0.036	3.7	1393	392.8	3852	402.8	3950	129.3	1281
87	0.036	3.6	1386	393	3854	402.9	3951	126.2	1251
88	0.035	3.6	1378	393.2	3856	403	3952	123.2	1220
89	0.035	3.5	1371	393.3	3857	403.1	3953	120.1	1190
90	0.034	3.5	1364	393.5	3859	403.2	3954	117	1159
91	0.034	3.4	1357	393.7	3860	403.4	3955	114	1129
92	0.033	3.3	1351	393.8	3862	403.5	3956	110.9	1099
93	0.033	3.3	1344	394	3863	403.6	3958	107.8	1068
94	0.032	3.2	1337	394.1	3865	403.7	3959	104.8	1038
95	0.032	3.2	1331	394.3	3866	403.8	3960	101.7	1007
96	0.031	3.1	1325	394.4	3868	403.9	3961	98.6	977
97	0.031	3.1	1318	394.5	3869	404	3962	95.5	946
98	0.03	3.1	1312	394.7	3870	404.1	3963	92.4	916
99	0.03	3	1306	394.8	3872	404.2	3964	89.4	885
100	0.029	3	1300	395	3873	404.3	3964	86.3	855

Appendix 2: ProPEP outputs for Complete Propellent

Code	WEIGHT	D-H	DENS	COMPOSITION									
0	AMMONIUM	PERCHLORATE	3.52	-601	0.0704	1	CL	4	H	1	N	4	O
0	HTPB	(R-45HT)	0.48	-367	0.0326	200	C	302	H	2	O		
0	BORON	(AMORPHOUS)	0.01	37	0.0856	1	B						
0	POTASSIUM	NITRATE	0.02	-1167	0.0767	1	N	3	O	1	K		

THE	PROPELLANT	DENSITY	IS	0.0619	LB/CU-IN	OR	1.7135	GM/CC		
THE	TOTAL	PROPELLANT	WEIGHT	IS	4.03	GRAMS				
NUMBER	OF	GRAM	ATOMS	OF	EACH	ELEMENT	PRESENT	IN	INGREDIENTS	
	0.172765	H								
	0.000924	B								
	0.035054	C								
	0.030156	N								
	0.120777	O								
	0.029958	CL								
	0.000198	K								

********CHAMBER	RESULTS	FOLLOW	**************						
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
	3908	6575	374.13	5500	0.6	9.83	1.2277	0.164	2277.127
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	10.997	10.714
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.164	0		
	5.57E-02	H2O	2.53E-02	HCl	2.26E-02	CO	1.43E-02	N2	
	1.24E-02	CO2	1.19E-02	H2	8.40E-03	HO	4.28E-03	Cl	
	3.10E-03	H	2.23E-03	O2	1.58E-03	NO	1.23E-03	O	
	6.85E-04	BHO2	1.61E-04	KCl	1.22E-04	BO2	6.68E-05	OCl	
	4.15E-05	Cl2	3.88E-05	HOCl	3.56E-05	HO2	2.94E-05	BO	
	2.79E-05	BOCl	2.34E-05	BHO	1.74E-05	KBO2	1.41E-05	KHO	
	1.12E-05	COCl	5.96E-06	CHO	4.48E-06	BH3O3	4.24E-06	B2O3	
	4.06E-06	NHO	3.17E-06	K	3.15E-06	N	2.33E-06	NO2	
	1.60E-06	NH3	1.51E-06	NH2	1.42E-06	NOCl	1.35E-06	NH	
	6.38E-07	KO	5.41E-07	N2O	5.05E-07	NHO2	4.57E-07	NHO2	
	3.72E-07	BH2O2	3.40E-07	CH2O	2.62E-07	CNH	2.25E-07	CNHO	
	1.89E-07	KH	7.49E-08	BCl	4.43E-08	BCl2	4.32E-08	CNO	
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	24.528		

***********EXHAUST	RESULTS	FOLLOW	******************************						
	T(K)	T(F)	P(ATM)	P(PSI)	ENTHALPY	ENTROPY	CP/CV	GAS	RT/V
	1804	2787	1	14.7	-4.63	9.83	1.2276	0.152	6.576
SPECIFIC	HEAT	(MOLAR)	OF	GAS	AND	TOTAL	=	10.736	10.717
NUMBER	MOLS	GAS	AND	CONDENSED	=	0.152	0		
	6.17E-02	H2O	2.97E-02	HCl	2.22E-02	CO2	1.51E-02	N2	
	1.29E-02	CO	9.36E-03	H2	8.91E-04	BHO2	1.83E-04	KCl	
	3.37E-05	Cl	1.39E-05	H	1.24E-05	KBO2	1.20E-05	BH3O3	
	6.24E-06	HO	1.17E-06	BOCl	9.47E-07	B2O3	3.52E-07	BHO	
	1.94E-07	NO	1.07E-07	BO2	8.44E-08	KHO	7.27E-08	Cl2	
	4.20E-08	K2Cl2							
THE	MOLECULAR	WEIGHT	OF	THE	MIXTURE	IS	26.502		

**********PERFORMANCE:	FROZEN	ON	FIRST	LINE,	SHIFTING	ON	SECOND	LINE**********		
IMPULSE	IS	EX	T*	P*	C*	ISP*	OPT-EX	D-ISP	A*M	EX-T
312.9	1.2447	3482	207.99	5704.1	28.99	536.1	0.03224	1219		
336	1.1344	3708	216.08	6008.4	227.5	35.09	575.7	0.03396	1804	

EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
1	215.83	21863.6	3708	119.8	1175	227.5	2231	227	2249
2	71.943	7287.9	3339	200.9	1970	272.7	2674	271.7	2692
3	27.427	2778.4	3045	246.1	2413	287.2	2816	285.7	2830
4	18.506	1874.7	2933	261.1	2560	298	2923	296	2933
5	13.727	1390.5	2846	271.5	2662	305.8	2998	303.3	3004
6	10.6	1073.8	2721	280.1	2746	311.8	3058	308.8	3059
7	8.548	865.9	2621	286.7	2811	316.6	3104	313.1	3101
8	7.109	720.1	2538	292.1	2864	320.5	3143	316.5	3135
9	6.05	612.9	2468	296.6	2908	323.7	3175	319.3	3163
10	5.243	531.1	2407	300.4	2946	326.6	3202	321.6	3186
11	4.609	466.9	2354	303.7	2978	329	3226	323.5	3205
12	4.1	415.3	2306	306.6	3007	331.2	3248	325.2	3222
13	3.683	373.1	2263	309.2	3033	333.1	3267	326.7	3236
14	3.336	337.9	2225	311.6	3056	334.9	3284	327.9	3248
15	3.043	308.3	2189	313.7	3076	336.5	3300	329	3259
16	2.793	283	2157	315.6	3095	338	3314	330	3269
17	2.578	261.1	2127	317.4	3113	339.3	3327	330.8	3277
18	2.39	242.2	2099	319.1	3129	340.5	3339	331.6	3285
19	2.226	225.5	2073	320.6	3144	341.7	3351	332.2	3291
20	2.081	210.8	2049	322	3158	342.8	3361	332.8	3297
21	1.952	197.7	2026	323.3	3171	343.8	3371	333.3	3302
22	1.836	186	2005	324.6	3183	344.7	3381	333.8	3306

23	1.732	175.5	1985	325.7	3194	345.6	3389	334.1	3310
24	1.638	166	1966	326.8	3205	346.5	3398	334.5	3314
25	1.553	157.3	1947	327.9	3215	347.3	3405	334.8	3317
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
26	1.476	149.5	1930	328.9	3225	348	3413	335.1	3319
27	1.405	142.3	1914	329.8	3234	348.8	3420	335.3	3321
28	1.34	135.7	1898	330.7	3243	349.4	3427	335.5	3323
29	1.28	129.7	1883	331.6	3251	350.1	3433	335.6	3325
30	1.225	124.1	1868	332.4	3259	350.7	3439	335.7	3326
31	1.174	118.9	1855	333.2	3267	351.3	3445	335.8	3327
32	1.127	114.1	1841	333.9	3274	351.9	3451	335.9	3328
33	1.083	109.7	1829	334.6	3281	352.4	3456	336	3328
34	1.041	105.5	1816	335.3	3288	353	3461	336	3329
35	1.003	101.6	1805	336	3295	353.5	3466	336	3329
36	0.967	98	1793	336.6	3301	354	3471	336	3329
37	0.934	94.6	1782	337.2	3307	354.5	3476	336	3328
38	0.902	91.4	1771	337.8	3313	354.9	3480	336	3328
39	0.872	88.4	1761	338.4	3318	355.4	3485	335.9	3327
40	0.844	85.5	1751	338.9	3324	355.8	3489	335.8	3327
41	0.818	82.8	1741	339.5	3329	356.2	3493	335.7	3326
42	0.793	80.3	1732	340	3334	356.6	3497	335.7	3325
43	0.769	77.9	1723	340.5	3339	357	3501	335.5	3324
44	0.747	75.6	1714	341	3344	357.4	3505	335.4	3323

45	0.725	73.5	1705	341.5	3348	357.8	3508	335.3	3321
46	0.705	71.4	1697	341.9	3353	358.1	3512	335.2	3320
47	0.686	69.5	1689	342.4	3357	358.5	3515	335	3319
48	0.668	67.6	1681	342.8	3362	358.8	3518	334.8	3317
49	0.65	65.9	1673	343.2	3366	359.1	3522	334.7	3315
50	0.634	64.2	1666	343.6	3370	359.5	3525	334.5	3314
51	0.618	62.6	1658	344	3374	359.8	3528	334.3	3312
52	0.602	61	1651	344.4	3378	360.1	3531	334.1	3310
53	0.588	59.6	1644	344.8	3381	360.4	3534	333.9	3308
54	0.574	58.1	1637	345.2	3385	360.7	3537	333.7	3306
55	0.561	56.8	1631	345.6	3389	360.9	3539	333.5	3304
56	0.548	55.5	1624	345.9	3392	361.2	3542	333.3	3301
57	0.536	54.3	1618	346.3	3395	361.5	3545	333	3299
58	0.524	53.1	1611	346.6	3399	361.8	3547	332.8	3297
59	0.512	51.9	1605	346.9	3402	362	3550	332.6	3294
60	0.502	50.8	1599	347.2	3405	362.3	3552	332.3	3292
61	0.491	49.7	1593	347.6	3408	362.5	3555	332.1	3290
62	0.481	48.7	1588	347.9	3411	362.8	3557	331.8	3287
63	0.471	47.7	1582	348.2	3414	363	3560	331.6	3284
64	0.462	46.8	1577	348.5	3417	363.2	3562	331.3	3282
65	0.453	45.9	1571	348.8	3420	363.5	3564	331	3279
EXP.	EXIT	EXIT	EXIT	OPTIMUM	OPTIMUM	VACUUM	VACUUM	SEA LV	SEA LV
RATIO	PRESS	PRESS	TEMP	IMPULSE	IMPULSE	IMPULS	IMPULS	IMPULS	IMPULS
ATM	SI	K	SEC	SI	SEC	SI	SEC	SI	
66	0.444	45	1566	349.1	3423	363.7	3566	330.7	3276

67	0.436	44.1	1561	349.3	3426	363.9	3569	330.5	3274
68	0.427	43.3	1555	349.6	3428	364.1	3571	330.2	3271
69	0.42	42.5	1550	349.9	3431	364.3	3573	329.9	3268
70	0.412	41.7	1545	350.2	3434	364.5	3575	329.6	3265
71	0.405	41	1541	350.4	3436	364.7	3577	329.3	3262
72	0.397	40.3	1536	350.7	3439	364.9	3579	329	3259
73	0.39	39.6	1531	350.9	3441	365.1	3581	328.7	3256
74	0.384	38.9	1526	351.2	3444	365.3	3583	328.4	3253
75	0.377	38.2	1522	351.4	3446	365.5	3584	328.1	3250
76	0.371	37.6	1517	351.6	3448	365.7	3586	327.8	3247
77	0.365	37	1513	351.9	3451	365.9	3588	327.5	3244
78	0.359	36.4	1509	352.1	3453	366.1	3590	327.2	3241
79	0.353	35.8	1504	352.3	3455	366.3	3592	326.8	3238
80	0.347	35.2	1500	352.6	3457	366.4	3593	326.5	3234
81	0.342	34.6	1496	352.8	3459	366.6	3595	326.2	3231
82	0.337	34.1	1492	353	3462	366.8	3597	325.8	3228
83	0.332	33.6	1488	353.2	3464	366.9	3598	325.5	3225
84	0.327	33.1	1484	353.4	3466	367.1	3600	325.2	3221
85	0.322	32.6	1480	353.6	3468	367.3	3602	324.8	3218
86	0.317	32.1	1476	353.8	3470	367.4	3603	324.5	3215
87	0.312	31.6	1473	354	3472	367.6	3605	324.2	3211
88	0.308	31.2	1469	354.2	3474	367.7	3606	323.8	3208
89	0.303	30.7	1465	354.4	3476	367.9	3608	323.5	3204
90	0.299	30.3	1462	354.6	3477	368.1	3609	323.1	3201
91	0.295	29.9	1458	354.8	3479	368.2	3611	322.8	3197

92	0.291	29.5	1455	355	3481	368.3	3612	322.4	3194
93	0.287	29.1	1451	355.2	3483	368.5	3613	322.1	3190
94	0.283	28.7	1448	355.4	3485	368.6	3615	321.7	3187
95	0.279	28.3	1444	355.5	3486	368.8	3616	321.4	3183
96	0.276	27.9	1441	355.7	3488	368.9	3618	321	3180
97	0.272	27.6	1438	355.9	3490	369.1	3619	320.6	3176
98	0.268	27.2	1434	356.1	3492	369.2	3620	320.3	3173
99	0.265	26.8	1431	356.2	3493	369.3	3622	319.9	3169
100	0.262	26.5	1428	356.4	3495	369.5	3623	319.5	3165

Appendix 3: MATLAB Script

```
clc
clear all
%% Chemical Properties of Propellant
%Propellant composition

%AP      -    1 CL   4 H    1 N    4 O
%HTPB    -  200 C  302 H    2 O

%Molecular weight (g/mol)
MW_AP =     (1*35.45)+(1*4)+(1*14.01)+(4*16);
MW_HTPB =   (200*12)+(1*302)+(2*16);
MW = 0.88*MW_AP + 0.12*MW_HTPB; %For 1g total
propellant

%% Critical Pressure Calculation vs chamber sizing


r_chamber =   [10:0.1:30];            %mm
radius of chamber
r_core =   [1:0.1:10];                %mm
radius of internal propellant core
A_s =   4*pi.*r_core/100^2;           %cm^2
surface area of internal propellant
V =     4/3*pi*(r_chamber/100).^3;    %cm^3
Volume of chamber in


rho =   1.7106;      %g/cm3      Density of solid
T_c =   2373;        %K          Adiabatic Flame
Temperature
Msh =   11.389;      %cal/mol-K  Molar specefic heat
c =     Msh/MW;      %cal/g-K    Specific heat of
solid
k =     0.000822;    %cal/cm-s-K Heat conductivity
through grain
HC =    0.277;       %cal/g-K    Heat Capacity
```

```
n =      0.433;      %           Propellant exponent
r =      0.0333;     %cm/s       Burn rate at
1000psi
R =      332.56/1000;%J/g-K      Specific Gas
constant
b =      r/((1000*0.068046)^n);      %includes psi
to atm conversion


for i =1:91
    for j =1:201
C1(i,j) = A_s(i)/V(j)*rho*R*T_c;
    end
end


for i =1:91
    for j =1:201
P_star(i,j) = ...                        %atm
Critical pressure
    C1(i,j)*(2*k*n)/(c*rho*b);
    end
end


% figure (1)
% [F,G] = meshgrid(r_chamber,r_core);
% surface (F,G,P_star)
% title ('Critical Pressures for Combustion')
% xlabel('Chamber Radius [mm]')
% ylabel ('Propellent Core Radius [mm]')
% zlabel ('Critical Pressure for sustained
combustion [psi]')



%% Ignitor thickness required

%Ignitor BKNO3
%85% Pottasium Nitrate 15% Bron
```

```
MW_B = 10.81;
MW_KNO3 = (1*39.10)+(1*14.01)+(3*16);
MWi1 =  0.15*MW_B + 0.85*MW_KNO3;

rho_i1 = 2.1567;          %g/cm3    Desnity of
ignitor composition
T_ci1  = 2000:50:5900;            %K
Combustion Temperature
R_i1 = 132.7542/1000;   %J/g-K      Specific Gas
constant

for i =1:91
    for j =1:101
 x(i,j) = ((V(j)/(100^3))*(P_star(i,j)*101325));
    end
end

for i=1:91
    for j=1:79
 nmol(i,j) = x(i)/(8.31*T_ci1(j));
 mass_req(i,j) = nmol(i,j)*MWi1;
 V_req(i,j) = mass_req(i,j)/rho_i1;
 t_req(i,j) = (((V_req(i,j)/((4/3*pi) +
r_core(i)/100^3)).^(1/3)) - r_core(i)/100)*100;
    end
end

for i=1:91
    for j=1:79
r_pellet(i,j) = r_core(i) + t_req(i,j);
    end
end

m_i = rho*4/3*pi*(r_core/10).^3;

% figure (2)
% [X,Y] = meshgrid(T_ci1,r_core);
% surface (X,Y,mass_req)
```

```
% title ('Ignitor Mass requirement for Specefic
Core Size and Ignitor Combustion Temperature')
% xlabel ('Ignitor Combustion Temperature [K]')
% ylabel ('Propellent core radius [mm]')
% zlabel ('B/KNO3 mass req [g]')


% figure (3)
% [L,M] = meshgrid(T_ci1,m_i);
% surface (L,M,r_pellet)
% title ('Required Pellet Properties for Sustained
Combustion based on Different Ignitor Commbution
Temperatures')
% xlabel ('Ignitor Combustion Temperature [K]')
% ylabel ('Propellent core mass [g]')
% zlabel ('Pellet radius [mm]')

%
% figure (4)
% [L,M] = meshgrid(T_ci1,r_core);
% surface (L,M,r_pellet)
% title ('Required Pellet Properties for Sustained
Combustion based on Different Ignitor Commbution
Temperatures')
% xlabel ('Ignitor Combustion Temperature [K]')
% ylabel ('Propellent core radius [mm]')
% zlabel ('Pellet radius [mm]')

%
%
%
%% Thruster Performance

%m_dot = 3.4474e+7*(pi*(5/1000)^2)/(5704*0.3048);
m_dot =
1.7135*4*pi*5/100^2*(b*(5500*0.068046)^n)/1000;
gm = 1.2447;
M_e = 2/(gm-1)*((5000/14.7)^((gm-1)/gm)-1);
a_e = (gm*313.7122*1219)^1/2;
```

```
V_e = M_e*a_e;
Thrust = m_dot*V_e
```

```
clc
clear all

%% Chemical Properties of Propellant
%Propellant composition

%Nitrocellulose   - 755 H  600 C  245 N  990 O
%Nitroglycerine   -   5 H    3 C    3 N    9 O

%Molecular weight (g/mol)
MW_NC =   (755*1)+(600*12)+(245*14.01)+(990*16);
MW_NG =   (5*1)+(3*12)+(3*14.01)+(9*16);
MW = 0.5*MW_NC + 0.5*MW_NG; %For 1g total
propellant

%% Critical Pressure Calculation vs chamber sizing


r_chamber =   [10:0.1:30];       %mm         radius
of chamber
r_core =   [1:0.1:10];                %mm
radius of internal propellant core
A_s =   4*pi.*r_core/100^2;          %cm^2
surface area of internal propellant
V =     4/3*pi*(r_chamber/100).^3;    %cm^3
Volume of chamber in


rho =   1.5746;      %g/cm3      Density of solid
T_c =   3220;        %K          Adiabatic Flame
Temperature
Msh =   11.585;      %cal/mol-K  Molar specefic heat
c =     Msh/MW;      %cal/g-K    Specific heat of
solid
```

```
k =     0.000100;   %cal/cm-s-K Heat conductivity
through grain
HC =    0.118;      %cal/g-K    Heat Capacity
n =     0.8;      %           Propellant exponent
r =     0.5;     %cm/s       Burn rate at 1000psi
R =     303.42/1000;%J/g-K      Specific Gas
constant
b =     r/((1000*0.068046)^n);      %includes psi
to atm conversion

for i =1:91
    for j =1:201
C1(i,j) = A_s(i)/V(j)*rho*R*T_c;
    end
end


for i =1:91
    for j =1:201
P_star(i,j) = ...                   %atm
Critical pressure
    C1(i,j)*(2*k*n)/(c*rho*b);
    end
end


% figure (1)
% [F,G] = meshgrid(r_chamber,r_core);
% surface (F,G,P_star)
% title ('Critical Pressures for Combustion')
% xlabel('Chamber Radius [mm]')
% ylabel ('Propellant Core Radius [mm]')
% zlabel ('Critical Pressure for sustained
combustion [psi]')



%% Ignitor thickness required

%Ignitor BKNO3
```

```
%85% Pottasium Nitrate 15% Bron

%Ignitor BKNO3
%85% Pottasium Nitrate 15% Bron

MW_B = 10.81;
MW_KNO3 = (1*39.10)+(1*14.01)+(3*16);
MWi1 =  0.15*MW_B + 0.85*MW_KNO3;

rho_i1 = 2.1567;          %g/cm3    Desnity of
ignitor composition
T_ci1  = 2000:50:5900;   %K         Combustion
Temperature


for i =1:91
    for j =1:101
 x(i,j) = ((V(j)/(100^3))*(P_star(i,j)*101325));
    end
end

for i=1:91
    for j=1:79
 nmol(i,j) = x(i)/(8.31*T_ci1(j));
 mass_req(i,j) = nmol(i,j)*MWi1;
 V_req(i,j) = mass_req(i,j)/rho_i1;
 t_req(i,j) = (((V_req(i,j)/((4/3*pi) +
r_core(i)/100^3)).^(1/3)) - r_core(i)/100)*100;
    end
end

for i=1:91
    for j=1:79
r_pellet(i,j) = r_core(i) + t_req(i,j);
    end
end

m_i = rho*4/3*pi*(r_core/10).^3;
```

```
% figure (2)
% [X,Y] = meshgrid(T_ci1,r_core);
% surface (X,Y,mass_req)
% title ('Ignitor Mass requirement for Specefic
Core Size and Ignitor Combustion Temperature')
% xlabel ('Ignitor Combustion Temperature [K]')
% ylabel ('Propellent core radius [mm]')
% zlabel ('B/KNO3 mass req [g]')


figure (3)
[L,M] = meshgrid(T_ci1,m_i);
surface (L,M,r_pellet)
title ('Required Pellet Properties for Sustained
Combustion based on Different Ignitor Commbution
Temperatures')
xlabel ('Ignitor Combustion Temperature [K]')
ylabel ('Propellent core mass [g]')
zlabel ('Pellet radius [mm]')


figure (4)
[L,M] = meshgrid(T_ci1,r_core);
surface (L,M,r_pellet)
title ('Required Pellet Properties for Sustained
Combustion based on Different Ignitor Commbution
Temperatures')
xlabel ('Ignitor Combustion Temperature [K]')
ylabel ('Propellent core radius [mm]')
zlabel ('Pellet radius [mm]')
```