TRIBHUVAN UNIVERSITY
Institute Of Engineering
Pulchowk Campus
Department Of Mechanical And Aerospace Engineering

INTERNSHIP REPORT ON:

TESTS FOR ASSESSING PROPELLANTS PROPERTIES

PRAJIT DHAKAL
SUGAM LAMSAL

SUPERVISOR:

PROF. NAGENDRA KUMAR
PROPELLANT RESEARCH LAB (PRL)
DEPARTMENT OF AEROSPACE ENGINEERING, IIT BOMBAY

भारतीय प्रौद्योगिकी संस्थान मुंबई
Indian Institute of Technology Bombay

A REPORT TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE BACHELOR'S DEGREE IN AEROSPACE ENGINEERING

ACADEMIC YEAR 2024

ABSTRACT

This report provides the outcomes of our internship at the Propellant Research Laboratory(PRL) at the Department of Aerospace Engineering, IIT Bombay, which provided hands-on experience in testing and analyzing solid propellants. The primary objective was to familiarize ourselves and gain practical exposure to the advanced laboratory environment and standard propellant testing methods. Key tasks included performing the Constant Volume(CV) test to analyze pressure character and combustion behavior, the Crawford Bomb test to assess burn time and thermal stability, and the Quench Bomb for determination of depressurization pressure and study the binder melting character of different propellants. Additionally, we assisted in preparing solid fuel grains and in some Hybrid Rocket Motor tests. This internship enhanced our understanding of propellant performance evaluation and combustion characteristics.

Keywords: *Control Volume Test, Crawford Bomb Test, Quench Bomb Test, Depressurization, Burn time*

ACKNOWLEDGMENT

We would like to express our sincere gratitude to the **Propellant Research Laboratory(PRL)** at the **Department of Aerospace Engineering, IIT Bombay**, and **Prof. Nagendra Kumar** for providing us with the opportunity to undertake this internship and gain valuable hands-on experience in propellant research and testing.

We extend our deepest appreciation to the research scholars **Mr. Deepak Govindaraj, Mr. Sachin Sonage, Mr. Yashwant KM,** and **Mrs. Harpreet Kaur** whose guidance and expertise were helpful for us in understanding the intricacies of solid propellant combustion and performance evaluation. Their insightful discussions and constant support greatly enhanced our learning experience.

Our gratitude also extends to esteemed personnel from diverse Professional backgrounds **Mr. Kiran Kandel, Mr. Baikunth Kaushik, Mr. Prashant R, Mr. Anubhav** and **Mr. Ashutosh Sarawgi** who were pursuing a master's degree at the Department of Aerospace Engineering, IIT Bombay, Their expertise, exposure, and support were significant for us in understanding experimental setups and methodologies. Furthermore, we would also like to thank **Mr. Chetan Patil** for helping us in the manufacturing works and supporting us in the new work environment.
We would also like to extend our heartfelt appreciation to **Prof. Sudip Bhattrai** and **Asst. Prof. Kamal Darlami** whose efforts in facilitating this internship made this experience possible. Their coordination and support in arranging this opportunity played a crucial role in our learning journey.

Lastly, We would like to thank our peers and fellow interns for their cooperation and teamwork throughout this internship. This experience has significantly contributed to our technical knowledge and practical skills in propulsion research, and we deeply appreciate everyone who played a role in making this internship a rewarding experience.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CMDB	Composite-Modified Double-Base
RP	Rocket Propellant
HTPB	Hydroxyl-Terminated Polybutadiene
CV	Control Volume
PC	Personal Computer
GG	Gas Generating
DOA	Dioctyl Adipate
TDI	Toluene Diisocyanate
IDPI	Imidodiphosphorimidate
GP	Gun Propellant
SEM	Scanning Electron Microscope

CHAPTER ONE:
INTRODUCTION

1.1 Background

Propellants are chemical substances that are used to produce thrust or propulsion for various systems or devices through chemical reactions. It has become a fundamental part of many industries like defense, space exploration, aviation, etc. They are mainly used in rocket propulsion, missiles, firearms, and also in the operation of heavy machines in industries. Based on the composition and manufacturing of the propellant, it can be of different types each giving distinct thrust and propulsion properties. According to the purpose and use, its composition is fixed and its entire process from manufacturing to operating is set. For this, extensive research on the nature of propellant and its properties is needed to be carried out. Hence, the research of propellant for various applications has grown into a complex and vast field with different industries researching the propellant suitable for distinct purposes. It is a growing field and one of the most important fields of the aerospace industry as Eco-friendly fuel and green propulsion is the major step for the aerospace milestone.

1.2 Organization Profile

The Propellant Research Lab at the Department of Aerospace Engineering, IIT Bombay is one of the facilities which is dedicated to understanding the propellant nature and properties for different purposes and its development. This lab is supervised and in direct control of Prof. Nagendra Kumar, who is an esteemed faculty of the Aerospace Department. PRL hosts a dedicated research group with expertise in the experimental and theoretical study of solid, liquid, and hybrid propellants, focusing on combustion dynamics, ignition characteristics, and performance optimization. Primary research domains in the lab include the study of high-energy propellants, combustion instability, and controlled detonation, for mainly solid and hybrid propellants utilizing advanced characteristic techniques such as IR measurement for temperature measurement, pressure transducer analysis, and SEM observations. The lab receives significant support from the Defence Research and Development Organisation (DRDO) in the form of research grants and collaborative projects, further strengthening its role in national defense research.

The lab supports a broad group of researchers working as project staff in high-end research, PhD and master's students working on combustion modeling and experimentation of propellants for different applications, undergraduate students involved in the project related to propellant, and undergraduate interns gaining hands-on experience in propellant characterization. It has excellent equipment for the preparation and analysis of propellants along with ballistic and performance evaluation. It provides an ideal platform for students and researchers to engage in various projects related to propulsion and propellants. Some of the important projects going on in the lab are the formation of an electrically Controlled Solid Propellant as a thesis for PhD students and a final-year project for undergraduate students, research for controlling the combustion of solid propellant by depressurization as a thesis for PhD students and Project Staff, Modification and manufacturing of the solid propellant for application like airbag technology, increase of muzzle velocity and so on.

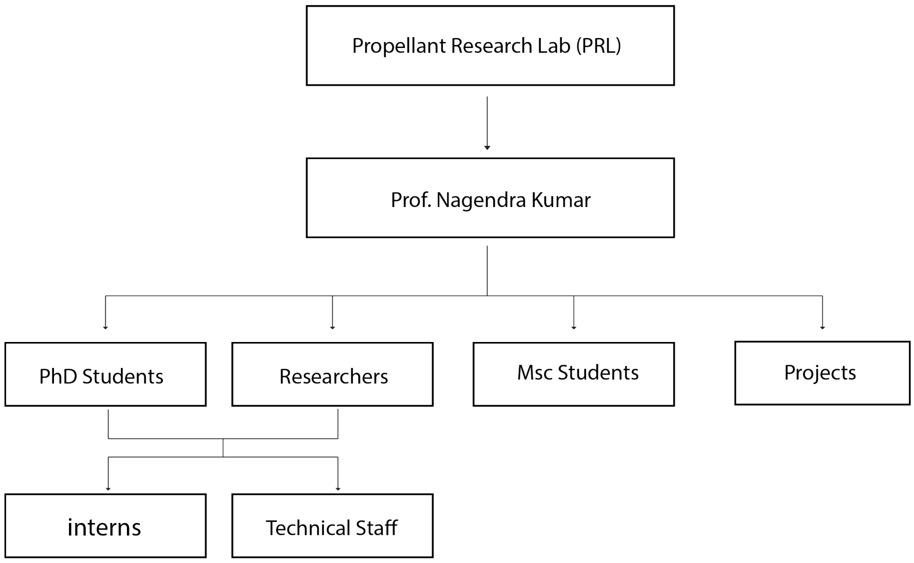


Figure 1.1: Organization structure.

1.3 Objective

The main objective of this internship program was to familiarize ourselves with the Propellant Research Lab environment and learn about the different experiments carried out for the performance testing of the propellant. Furthermore, it was also a part of our program to assist in the lab for testing of the propellant and get hands-on experience in propellant testing.

1.4 Scope of the work

The works we were involved in are as follows:

1. Performing Constant Volume test to determine the maximum pressure of different propellants
2. Performing Crawford Bomb test to asses the burn-time and thermal stability of various propellants
3. Testing Quench Bomb setup for controlling the burning of solid propellant
4. Preparation of the solid propellant grain to be used in hybrid motor.

CHAPTER TWO:
THEORETICAL BACKGROUND

2.1 Propellants

Propellants are substances (gas, liquid, or solid) that undergo chemical decomposition or rapid combustion to produce thrust. Usually, propellants are explosive materials made up of high-explosive compositions that are combusted to produce the required propulsion effect and thrust. Propellants are used in vehicles, particularly rockets, jet engines, and certain experimental propulsion systems, by ejecting mass backward to generate thrust in the opposite direction, as Newton's Third Law of Motion describes. It is mainly used for artillery, firearms, and rocket propulsion.

2.1.1 Types of Propellant

Propellants can be categorized into many types based on the different parameters. But mainly they are divided based on chemical composition, physical state, and applications. These are briefly discussed below:

1. Based on Chemical Composition:
   Propellants are mainly of 4 based on the composition used. They are listed below:

   - Chemical Propellants:
     Chemical substances that undergo chemical change typically undergo combustion to produce gases with high pressure and temperature. These gases expand through a nozzle or drive a mechanism, producing thrust. Propellers are widely used in every field, including rocket propulsion, firearms, and artillery.
   - Electrical Propellants
     These propellants are used to produce thrust using high-intensity electric or magnetic fields. Propellants are passed through high-intensity electric or magnetic fields that further accelerate the propellants to create a propelling effect. They produce a minimal amount of thrust and high specific impulse. Due to this, it is mainly used in space applications for purposes like orientation correction, orbit correction, etc.
   - Nuclear Propellants
     Nuclear propellants are chemical substances that produce high heat through fusion or fission. This heat is then used to produce thrust. This propulsion method is not used in commercial industries, and the concept is being developed.
   - Hybrid Propellant
     These are mixtures of two or more propellants that produce thrust. They can be a combination of chemical and electrical propellants, nuclear and electrical propellants, or chemical and nuclear propellants. Normally, chemical propellant combinations with other propellants are tested and used in some areas, and the combination of atomic propellants is still being developed.

2. Based on Physical State:
   Since every matter generally exists in 3 states i.e. solid, liquid, and gas, propellants are also divided according to their physical state during use. They are:

- Solid propellants:
  Those propellants that are in the solid state until combustion are known as solid propellants. It is the mixture of fuel and oxidizer that is cast into a certain shape to fit into the rocket motor. These propellants are mostly used in military missiles, sounding rockets, space launch vehicles, and fireworks due to their simple working mechanism, storability, and portability. This propellant is ignited by using an igniter and burned to produce highly pressurized gases which are expanded through a nozzle to generate thrust. They are further divided into 4 types based on the chemical composition and the dominant components used. They are:
  - Single base propellant
    It is a type of solid propellant that is made using large amounts of nitrocellulose and can act both as fuel and oxidizer. It is commonly used in small arms ammunition, artillery shells, and low-thrust rocket systems. Since it is of a single composition, it is highly stable but has low energy output compared to other propellants.
  - Double base propellant
    It is a type of propellant that contains a high amount of nitrocellulose and nitroglycerin. It has a higher energy output than that of single-base propellant due to the addition of nitroglycerin. It is mostly used in large-caliber ammunition, rockets, and missiles. It has a high-performance character and relatively simple formation but is less stable and more prone to degradation.
  - Composite propellant
    It is the propellant which is made of oxidizers like, ammonium perchlorate or potassium nitrate and fuels like powdered aluminum or polymers separately mixed with a binder to maintain the shape. Since it has a separate oxidizer and fuel, it has a high specific impulse and is broadly used in modern rockets, missiles, and space launch vehicles. It has the advantage of high output energy, controllable burn rates, and performance but is complex to manufacture.
  - Composite-Modified Double-Base (CMDB) Propellants
    It is a hybrid of the double-base propellant with composite materials like aluminum powder or ammonium perchlorate. It has higher performance than double base propellant due to the addition of composite and is hence used in high-performance rockets and missiles but is complex to manufacture.
- Liquid Propellants:
  These propellants are stored and used in liquid form to produce thrust. They are particularly used in rockets and spacecraft. It has fuel like liquid hydrogen, RP-1, or hydrazine and oxidizer like liquid oxygen or nitrogen tetroxide, placed in separate tanks. While using these to produce thrust, the fuel and oxidizer are pumped and pressurized into the combustion chamber where they are mixed and ignited to produce high-temperature and pressure gas. These are then expanded to produce thrust. They can be controlled using the amount of fuels and oxidizer supplied to make the required thrust or stop or again start the ignition but have complex controlling mechanisms.
- Gas Propellants:
  These are the propellants that are in a gaseous state. These propellants are not changed chemically or combusted for thrust, but rather stored in pressurized tanks and released through a nozzle to produce thrust for a short time. It has high specific impulse and normally inert gases due to which they are used in applications like satellite attitude control and orientation control.

- Hybrid propellant:
  Hybrid Propellant is the combination of solid and liquid propellant, where fuel is stored and used in solid form and oxidizer is in liquid or gaseous form. Here, a separate tank is used to store an oxidizer and is passed to the combustion chamber to react with solid fuel. Their reaction will create host gases which will be expanded through a nozzle to produce thrust. Since fuel and oxidizer are separated, it is safer than that of solid and liquid propellants. Commonly used fuel and oxidizers are Hydroxyl-Terminated Polybutadiene (HTPB) or Paraffin wax, and liquid oxygen or nitrous oxide. It is versatile and allows control of thrust during operation, offering advantages. However, they offer lower performance than that of bipropellant liquid systems, and careful engineering is needed for required combustion efficiency. So, they are generally used for experimental rocket motors, suborbital vehicles, etc.

3. Based on Applications: Based on the area of use of propellant, it is mainly divided into 4 types:

   - Gun Propellant
     These are the propellants used in firearms and ammunition to propel projectiles like bullets and shells. They have a high burn rate and are combusted in closed chambers to produce high-pressure gas which propels the projectiles forward with high velocity. Nitrocellulose-based compositions are used due to their clean burning nature, consistent performance, and smokeless powder.
   - Gas Generating Propellant
     These are the propellants that are designed to produce large amounts of gases due to chemical decomposition or controlled combustion. They are mostly used in technologies like airbags, emergency seat ejectors, or rapid inflatable devices. Sodium azide-based propellants are mainly used for this purpose.
   - Rocket Propellant
     These are the ones that are used for rocket propulsion. This includes liquid and solid propellants mainly due to their high energy output and low specific impulse. High-speed gases which are the product of controlled combustion of fuel and oxidizer are ejected from the nozzle for expansion which produces thrust. This can also be used in some missiles.
   - Spacecraft Propellant
     These are the propellants that are made to work in the vacuum environment of space. These are mostly electric employment which gives a high specific impulse for a long time. These are mostly used in ion thrusters.

2.2 Constant Volume Test

A constant volume test refers to the testing of a propellant sample in a constant volume environment. This is the method used to test the ballistic properties of the propellant using the pressure-time and temperature-time relationship. Here, a small sample of propellant is burned in a constant volume vessel and pressure time and temperature time relation are monitored to determine the performance of the propellant.

2.2.1 Working

Here small sample of propellant is used as a test sample which is placed inside a constant volume vessel. This vessel has ports where the pressure sensor and temperature sensor are connected for pressure and temperature reading with time. It also has another port for mounting the cartridge which contains the propellant sample. This cartridge is connected to the igniter. This igniter contains gun powder which is ignited through the Nichrome wire. The quantity of the igniter mass depends upon the pressure response obtained during the complete burning of the propellant. It is first tested and taken as a standard quantity. When current is passed, it heats the Nichrome wire and ignites the igniter. This provides heat for the combustion of the propellant. When propellant is burned, it produces gas which is enclosed into a constant volume vessel. This makes the pressure and temperature rise which is recorded using pressure and temperature sensor. The plot is then analyzed and required data can be taken to determine burn rate and propellant properties.

2.2.2 Purpose

It is used for the following works:

1. To determine the pressure-time and temperature-time relationship of the propellant
2. To determine the maximum pressure and temperature attained using the propellant
3. To determine the stable temperature for the burning of the propellant
4. To find the ballistic quality and burning performance of the propellant

2.3 Crawford Bomb Test

The time taken for the propellant to burn completely is called burn time and the rate at which it burns is called burn rate. This is the method used for calculating the burn rate of a propellant. It is also called the strand burner test. When a propellant is burned in a closed and controlled environment, it produces a change in pressure and temperature, since the volume of the test vessel is constant. Then from the change of pressure and temperature with time we can determine the burn rate of the propellant. It is done in a pressurized environment to test the starting and stable combustion of the propellant and at different temperatures to determine the temperature sensitivity of the propellant.

$$r = ap^n \tag{2.1}$$

where,
r is burnrate of propellant,
p is chamber pressure,
a and n is the coefficient and pressure index.
When this test is done by increasing the temperature of the chamber, the temperature sensitivity of the propellant is determined.
The change in propellant burn rate is due to the change in pressure and temperature of the chamber. When the chamber pressure is increased, it increases the mass and heat transfer from an unburned surface to a burned surface, this increases the burn rate. Also, an increase in pressure ensures faster reaction between chemical components and leads to higher reactant concentrations. This increases the burn rate with an increase in chamber pressure. The empirical formula above gives the nature of propellant burning and its relation to the change in pressure. The pressure index determines the sensitivity of propellant burning to pressure change and its burning nature. A higher pressure index means a stronger sensitivity to pressure changes. In addition, a higher pressure index value means progressive burning and a faster burn rate increases with pressure. A moderate value of the pressure index means neutral burning and a relatively stable burn rate increase. A lower or negative value of the pressure

index means regressive burning and burn rate decrease or slow increase with pressure (uncommon). Similarly, increasing the chamber temperature increases the energy of the condensed phase of the chemical leading to faster decomposition. Also, it decreases the viscosity of the propellant and increases the vapor pressure of the decomposed pressure. This leads to a higher burn rate and high production of chamber pressure after burning. This study is done to find the temperature relation to the propellant and also the limit chamber temperature for stable burning of propellant.

2.3.1 Working

It consists of a closed vessel of constant volume where a port for pressure and temperature sensors is made. This is used for recording the pressure and temperature change in the closed environment. It is kept at a certain pressure using a compressor. A small sample of propellant is taken which has a regular shape and dimension is known. This is then put into the test vessel using a part that is holding the propellant. The propellant is then burned from one end. When the combustion occurs, the temperature and pressure inside a vessel increase which is recorded by the sensors. This pressure-time plot and temperature-time plot are then used to calculate the burn time of the propellant. Then from the known dimension of the propellant sample, we can determine the burn rate using a simple formula of velocity, i.e.

$$Velocity(v) = \frac{Distance(d)}{Time(t)}$$

which gives

$$Burnrate(r) = \frac{Length of Propellant(l)}{Burntime of Propellant(t)}$$

This data is then fitted into the above empirical relation 2.1.

2.3.2 Purpose

This test is mainly used for the following purposes:

1. To calculate the burn rate of the propellant
2. To test the temperature sensitivity of the propellant
3. To characterize and check the quality of propellant

2.4 Quenching Test

Quenching of solid propellant is the process of stopping the combustion by changing the combustion environment. This generally occurs in solid rocket motors affecting their performance and efficiency. It can be done using different mechanisms but one of the effective mechanisms is using the rapid depressurization of the chamber. To study the result of this phenomenon, the test is done in different burning environments in the lab to determine the threshold of operation.

Solid propellant is made using a certain amount of binder materials to give them a desired shape. Due to this reason, the amount of binder used also influences the burn rate and other performance of the propellant mainly the decomposition of a binder. So the melting properties of the propellant and also a binder are important parameters for the study. This can be done by using the quench bomb test. The binder acts as a structural matrix and additional fuel component in the propellant. The melting of the binder material affects the burn rate and quality burning of the propellant. If the binder melting is higher, it increases the thermal decomposition between the propellant layers and also increases the

mass diffusion. Since it controls the heat transfer between the layers, it also affects the surface burning of the propellant and how combustion proceeds at varying times.
Since higher melting of binder means higher heat transfer across the propellant surface due to thermal decomposition, this is not the case. A binder has higher thermal conductivity when it is in a molten state than in a solid state. But when the binder melts, it forms a thin layer of molten binder before evaporating from the surface. This creates a barrier for heat transfer and delays the temperature change and flame propagation across the propellant surface. Furthermore, other parameters like pressure or energy release and quality of combustion are also factors that are affected by the melting of the binder. So this is an important part of the selection for the propellant of desired performance.

2.4.1 Working

A propellant is placed in a closed vessel which has the ports for transducers and pressure inlet. The vessel is pressurized to the test condition. The propellant is placed inside a vessel and then ignited using the Nichrome wire. When propellant starts burning, after some time, depressurization is done for the chamber, which then affects the stable burning environment and stops the burning. This depressurization is normally done intentionally using a time relay that after a certain time of start of propellant burning will trigger the depressurization.

2.5 Fuel Grain

Those propellants that are in a solid state during the use are referred to as solid propellants. It is a mixture of fuel and oxidizer. But hybrid propellant is a combination where fuel is used in a solid state and oxidizer is used in a liquid state. In both cases, a solid cylindrical mass needs to be prepared for use. These cylindrical masses of fuel or a mixture of fuel and oxidizer that are used as solid and hybrid propellant are known as propellant grain. In hybrid rocket motors, it is the mass of fuel; in the solid state. Generally, paraffin wax or Hydroxyl-terminated polybutadiene (HTPB) is used in hybrid rocket motors for fuel. So these are mixed with other chemicals to prepare a solid mass of fuel. The composition of the fuel to other components like binders, and caring agents is based on the performance given by the propellant which is taken from the already tested composition or found after some tests and trials.
While preparing the fuel grain, great care should be taken as each process will degrade the fuel performance. First, the composition should be taken with great care and a precise weighing machine so that the required performance of the propellant is obtained. The mixing of compositions should be done uniformly. This is to ensure a proper mixture of the components taken and also to reduce the formation of air bubbles. The formation of air bubbles is one of the main problems and components that greatly reduce the performance of the fuel grain. When an air bubble is formed inside the grain, it traps a small amount of oxygen into it. When the grain is used for combustion, Then the oxygen inside the air bubbles will induce rigorous burning. Also, the ratio of oxidizer to fuel will change. If a large number of bubbles are formed it will significantly affect the combustion of the feel and affect the performance. Due to this, air-bubble formation is reduced while preparing the fuel grain. But we cannot mix the chemicals and mixture without the formation of air bubbles. We can only minimize the number of air bubble formations with uniform mixing. The mixed composition is then placed inside an oven at a certain temperature for some time. This will then burst the air bubble that is at the surface of the mixture due to its expansion. Then the mixture is placed in a vacuum chamber which will help to take out the air bubbles inside the mixture on the surface. Then again the mixture is placed inside an oven to remove air bubbles. This process is repeated several times until all the air bubbles inside the grain are removed. Then the grain is placed inside the mold. The internal surface of the mold is

covered by silicon grease so that it will be easier to remove the grain from the mold. Then the mixture is poured into the mold slowly so that there will not be the formation of air bubbles inside the grain. After this, the grain is placed inside an oven at a fixed temperature for 10 to 12 hours for curing and solidifying.

CHAPTER THREE:
EXPERIMENTAL SETUP

During our internship, we tested different propellants for their performance and ballistic characteristics. We worked on the control volume test, Crawford test, and quench bomb testing of the propellant for its pressure-time and temperature-time nature.

3.1 Control Volume Test

This test was done to find the amount of gas generated and the maximum pressure attained from the propellant in the fixed-volume vessel.

3.1.1 Components:

- Pressure Vessel
- Pressure Transducer
- Temperature Sensor
- Igniter
- Data Acquisition System

3.1.2 Propellant and Composition

Gun Propellant	
GP1	GP2
Nitro Cellulose-97%	Nitro Cellulose-87%
Potassium Nitrate-2%	Potassium Nitrate-1%
Charcol-0.3%	Charcol-1%
-	5-Aminotetrazole-11.7%

Table 3.1: Gun Propellants and their Composition

Gas Propellant	
GG1	GG2
Strontium Nitrate-15%	Strontium Nitrate-15%
Sodium Azide-60%	Sodium Azide-50%
Liquified Silicone Rubber-25%	Liquified Silicone Rubber-25%
-	5-Aminotetrazole-10%

Table 3.2: Gas Generating Propellants and their Composition

3.1.3 Setup Description

This setup contains a cylindrical vessel of fixed volume. Here ports were provided for connecting the pressure transducers and temperature sensor. For pressure sensing, a piezoelectric pressure transducer was used. A temperature sensor was used to measure the temperature inside and outside of the vessel. For this k type and t type thermocouple was used. The pressure vessel is made airtight in these connections. The top part of the vessel is made to connect the cartridge which contains the propellant sample. The cartridge is further connected to the igniter for the control volume testing. An ignitor is a small hollow cylindrical part from where 2 electrodes are taken out. The inside of the electrodes are connected by the nichrome wire for providing the ignition. Then after placing the gunpowder, it is sealed tightly in the pressure vessel. The pressure transducer and temperature sensor are connected to the data acquisition device which is further connected to the computer. This is then monitored using the signal express software interface in the pc.

3.1.4 Working

First, the nichrome wire is connected to the ignitor. Then the continuity of 2 electrodes is tested to confirm if the connection is established. After the connection is confirmed a certain amount of gunpower is added in the ignitor. For the gas-generating propellant, we used 0.3gm ignitor mass and for the gun propellant, we used 0.5 igniter mass. Then it is sealed using a small piece of paper and araldite so that the gunpowder will not spill inside the cartridge. Propellant is placed inside the cartridge and then the ignitor is connected to the cartridge. It is sealed tightly with the help of Teflon tape. The cartridge is connected is connected to the pressure vessel. After ensuring that all the ports and connections are airtight, the electrode from the ignitor is connected to positive and negative connections to provide the current. This connection is controlled using a switch. When the switch is closed, the current is passed through the nichrome wire connection inside an ignitor due to which the nichrome wire generates heat. This will ignite the gunpowder in the ignitor. This further provides the heat for combusting the propellant inside a cartridge. When the propellant is burned, it produces gas and since the volume is constant, pressure and temperature inside the vessel increases. This is monitored and recorded in the PC with the help of a data acquisition device and a pressure and temperature sensor connected. Then the pressure and temperature time behavior of the propellant is analyzed to get the expected results.

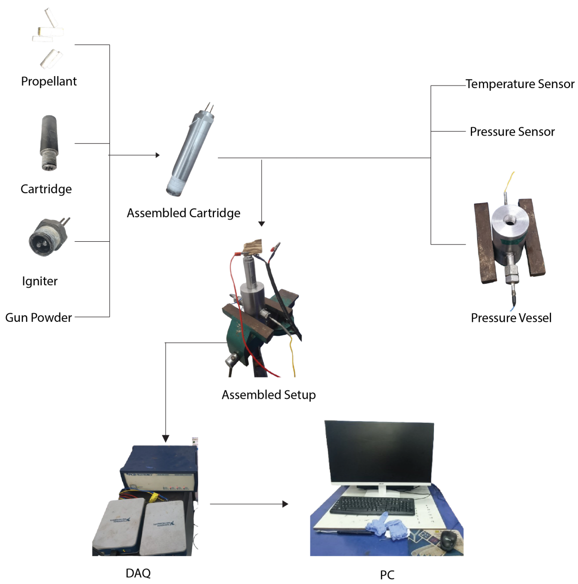


Figure 3.1: Working of CV Test Setup.

3.2 Crawford Bomb

This test was done to find the burn rate of the propellant. This test is also called as strand burner test.

3.2.1 Components:

- Pressure Chamber
- Pressure Transducer
- Temperature Sensor
- 3 slot electrode Igniter
- Data Acquisition System
- Pressurization unit

3.2.2 Propellant and Composition

Gas Generating Propellant		Solid Propellant	
GG1	GG2	tp110	slurry
Strontium Nitrate-15%	Strontium Nitrate-15%	Ammonium PerChlorate (84)	Ammonium PerChlorate (84)
Sodium Azide-60%	Sodium Azide-50%	HTPB Binder (16)	HTPB Binder (16)
Liquified Silicone Rubber-25%	Liquified Silicone Rubber-25%	DOA Plasticiser and TDI curing agent(5.4)	no curing agent
-	5-Aminotetrazole-10%	-	-

Table 3.3: Propellants and their Composition for Crawford Bomb Test

3.2.3 Setup Description

This setup contains a cylindrical vessel of fixed volume. Ports were made for connecting the pressure transducers, temperature sensor, pressure inlet, and pressure outlet. For sensing pressure, a piezoelectric pressure transducer was used. Since only one chamber temperature was needed to be observed, only one thermocouple was used for measuring the temperature. The pressure vessel is made airtight in these connections. The top part of the vessel is made to connect the platform which contains the propellant sample. The platform contains 4 electrodes with one main in the middle and 3 around the middle electrode. A nichrome wire is connected in one of each electrode connecting to the ground. All electrodes are given different connections, and the triggering for combustion is given through the switch. The pressure transducer and temperature sensor are connected to the data acquisition device to monitor and record the pressure and temperature readings using the PC.

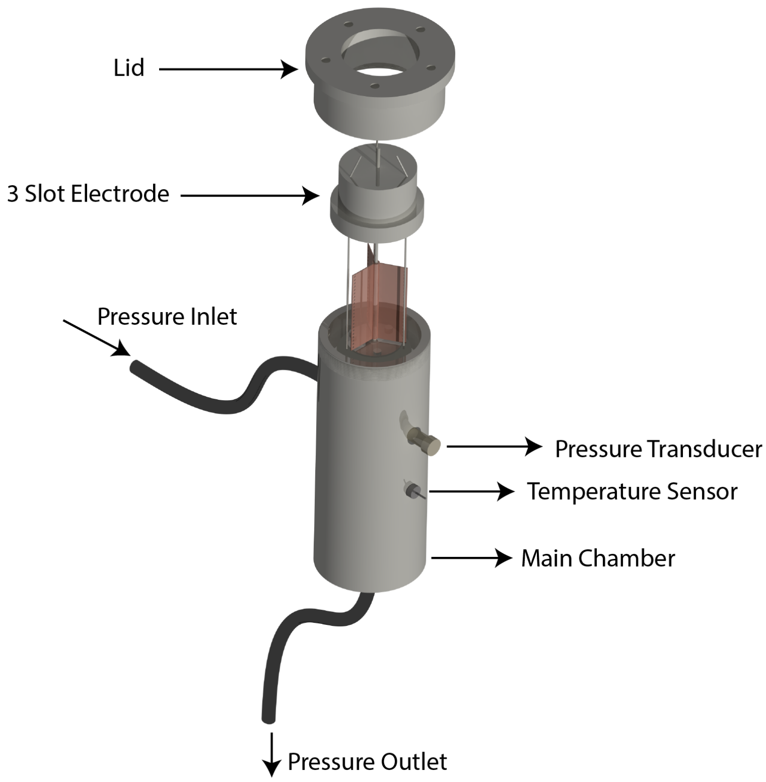


Figure 3.2: CAD Model of Crawford Bomb Setup.

3.2.4 Working

First, the sample of the propellant is shaped into a known dimension and shape. Normally they are of rectangular or cylindrical shape whose dimension is known. Then it is placed on the platform. While setting the propellant, Small amount of silica grease is placed around the propellant so that it will induce uniform burning. Also small amount of silica gel is placed in the platform where propellant is to be placed. This is to ensure that the propellant does not stick to the platform after burning. The propellant is placed in the platform. A nichrome wire is then set up touching the upper surface of the propellant where the combustion should start. Here small drop of device is placed to ensure that the upper surface ignites uniformly at the same time. Then it is placed inside the pressure vessel. The lid is then tightened to make the chamber airtight. Since the testing for the burn rate is done in different chamber pressures, chamber pressure is taken and set up using the pressurized tank and pressure regulator. Nitrogen gas is used for the pressurization. Here pressure reading is shown on the digital monitor as well as on PC using the data acquisition device. The middle electrode is connected to the ground and the other 3 are connected with 3 positive connections through the switch. When the chamber is pressurized to the required pressure, a power supply is given. First main power switch connecting the ground is closed and then one at a time other switch is closed igniting the propellant in the respective position. They are ignited by the heat produced from passing the current in the nichrome wire. Then the pressure time and temperature time behavior are recorded in the signal express software interface for data analysis.

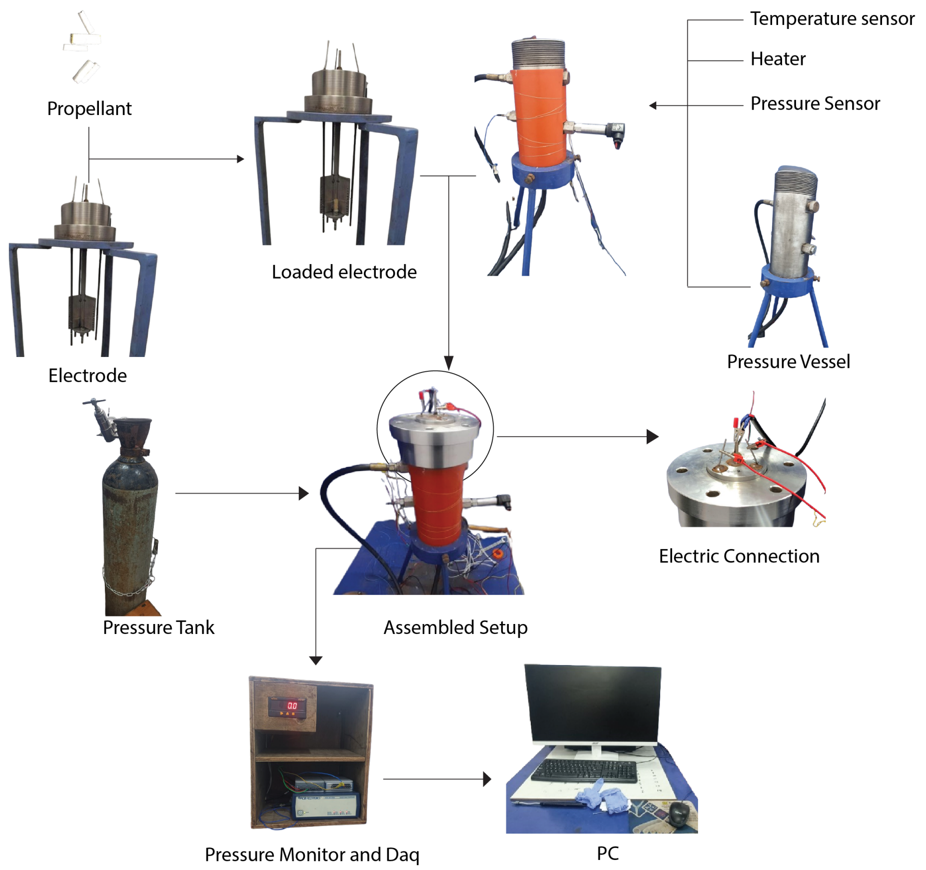


Figure 3.3: Working of Crawford Bomb Setup.

3.3 Quench Bomb

This test was done to stop the burning of the solid propellant. It uses the rapid depressurization of the chamber for controlling the burning of the solid propellant.

3.3.1 Components:

- Pressure Chamber
- Pressurization unit
- Ignitor
- Rubber gasket
- Myler sheet
- Triggering switch

3.3.2 Propellant and Composition

Solid Propellant	
tp11	slurry
Ammonium PerChlorate (84)	Ammonium PerChlorate (84)
HTPB Binder (16)	HTPB Binder (16)
DOA Plasticiser and TDI curing agent(5.4)	no curing agent

Table 3.4: Propellants and their Composition for Quench Bomb Test

3.3.3 Setup Description

This setup contains a cylindrical vessel of fixed volume. Ports were made for connecting the pressure transducers, temperature sensor, pressure inlet, and pressure outlet. Since the pressure and temperature time relation was not important for the ongoing experiment, sensors were not connected in the setup. The upper and lower surfaces of the vessel were made open to connect the upper lid and lower lid. The lower lid is the igniter with 2 electrodes coming out of it and a small clipper placed in the middle for fixing the propellant. The upper section contains a different layer of material for the depressurization mechanism. The order was placed to make the depressurization effective and easier. Myler sheet was placed at the base over which the rubber gasket was stacked. Over them, 2 myler sheets, one rubber gasket, a circular plate, and an upper lid were placed in order. The circular lid contains a smaller hole in the middle than the upper lid, facilitating effective quenching. A small nichrome wire is taken out from the inside of the vessel to facilitate the depressurization time for quenching. This wire is connected to the electrode sticking out from the sides of the chamber. Connections are made between the igniting electrodes and another electrode which are connected to a triggering relay. This triggering relay is connected to a single switch. A pressure regulator is connected to the pressurized tank to provide steady pressure in the chamber.

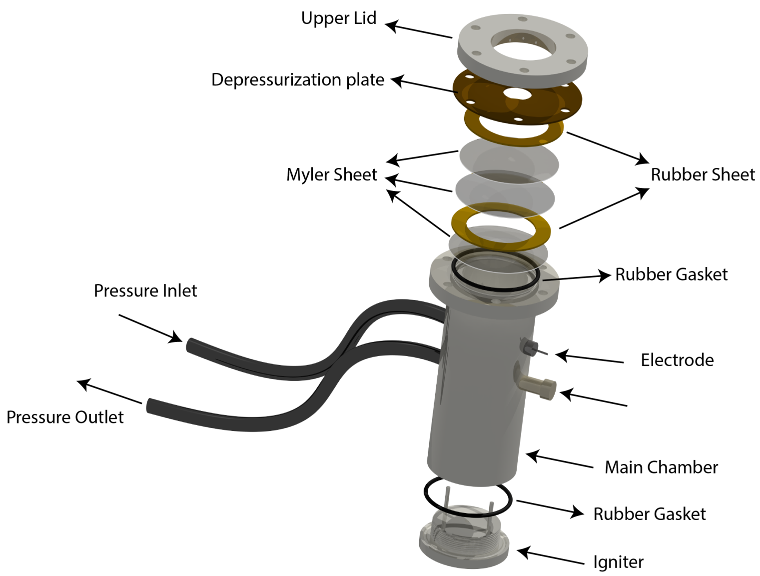


Figure 3.4: CAD Model of Quench Bomb Setup.

3.3.4 Working

First, the propellant sample is shaped into a known dimension and shape. Normally they are of rectangular or cylindrical shape whose dimension is known. Also thin layer of silica gel is placed around the propellant. This is to ensure that the propellant burns uniformly along the length. Then it is fixed the lower lid. Then nichrome wire is set up between two electrodes with the upper surface of the propellant touching the nichrome wire. A nichrome wire is then set up touching the upper surface of the propellant where the combustion should start. While setting the propellant, a Small drop of fevicole is placed on the upper surface of the propellant to start uniform burning. Then it is placed inside the pressure vessel using the threaded locking mechanism. The lid is then tightened to make the chamber airtight. Then myler sheet, rubber gasket, and circular plate are placed on the upper section of the pressure vessel and are made airtight using an upper lid tighten with a screw. Both the upper and; lower lids have small rubber to prevent air leaks. Then the electrodes are connected using respective wires. This is then connected to the triggering switch with a time relay. After the connection is ensured, the chamber is pressurized to the required amount of pressure. When chamber pressure is set to the required pressure, it is left to settle for some time and then propellant is ignited. This is controlled using the relay switch so that after some seconds the depressurization of the propellant is done and the propellant stops burning. Then the quenched propellant is taken out for the study.

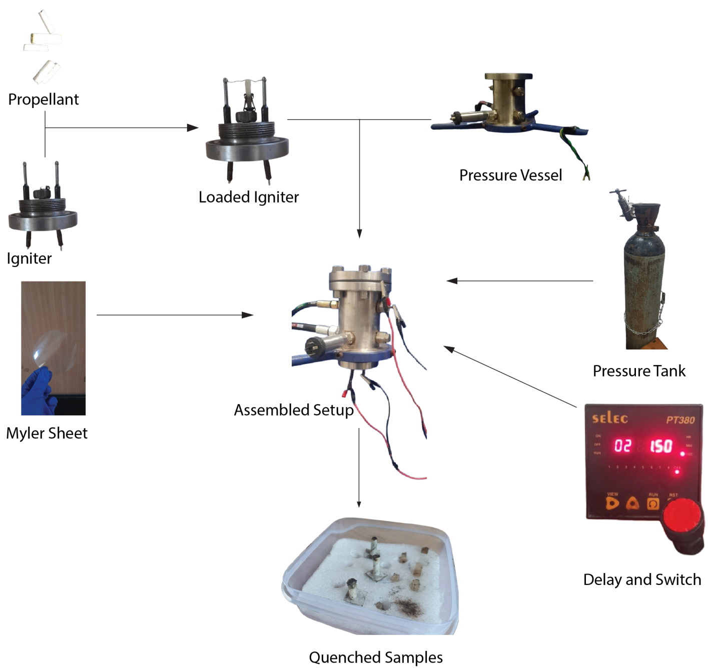


Figure 3.5: Working of Quench Bomb Setup.

3.4 Fuel Grain Preparation

Solid fuel grain that is to be used in hybrid motor firing was prepared. The grain that was prepared was the HTPB fuel grain so the setup and components mentioned are those which were used for HTPB fuel grain.

3.4.1 Components:

- Mold
- Magnetic Stirrer
- Oven
- Vaccum Chamber

3.4.2 Propellant and Composition

Components	Percentage by Weight
HTPB	94.8(%)
IDPi	5.2(%)

Table 3.5: Composition of the Chemical used for Fuel Grain Preperation

.

3.4.3 Setup Description

This setup contains a cylindrical mold for giving the shape to the fuel grain. The cylinder mold is then connected to the base with another part, which creates the required posts in the fuel grain. This connection is secured to be airtight. A magnetic stirrer is used to stir the mixture of the fuel grain uniformly. The oven is used to treat the fuel and remove the air bubbles on the surface. A vacuum chamber is used for removing the air bubble from the fuel mixture which may be formed during the mixing process. Then the fuel grain is cured using the oven.

3.4.4 Working

First, the composition of fuel is decided and mixed according to the required compositions by weight in a clean beaker. Then, it is mixed uniformly using a magnetic stirrer for 10 minutes at a uniform speed. If the speed is not favorable it will form an air bubble inside the mixture which causes low quality of fuel grain. Then, after uniform mixing of the components, the mixture is placed inside an oven for 10 to 15 minutes. This is done to ensure that the airbubble in the surface of the mixture is removed because the air expands and bursting at high temperature. Then it is placed inside a vacuum chamber for 1 hour. This will remove the air bubbles inside the mixture by bringing it towards the surface. In between 20 minutes, the mixture is taken out from the vacuum Chamber and again placed inside the oven to remove the air bubble on the surface. This process is repeated until all the air bubble is removed from the fuel mixture. After this, it is placed inside a mold to give the fuel grain a desired shape. Inside of the mold surface is covered with a silicon gel. This will make the removal of fuel grain from the mold easier. Then fuel mixture is slowly and steadily placed inside a mold ensuring there is no formation air bubble during the molding process. After the mold is filled, it is then placed inside an oven to be cured for almost 24 hours. Then the fuel grain is removed from the mold as it will be ready to be used.

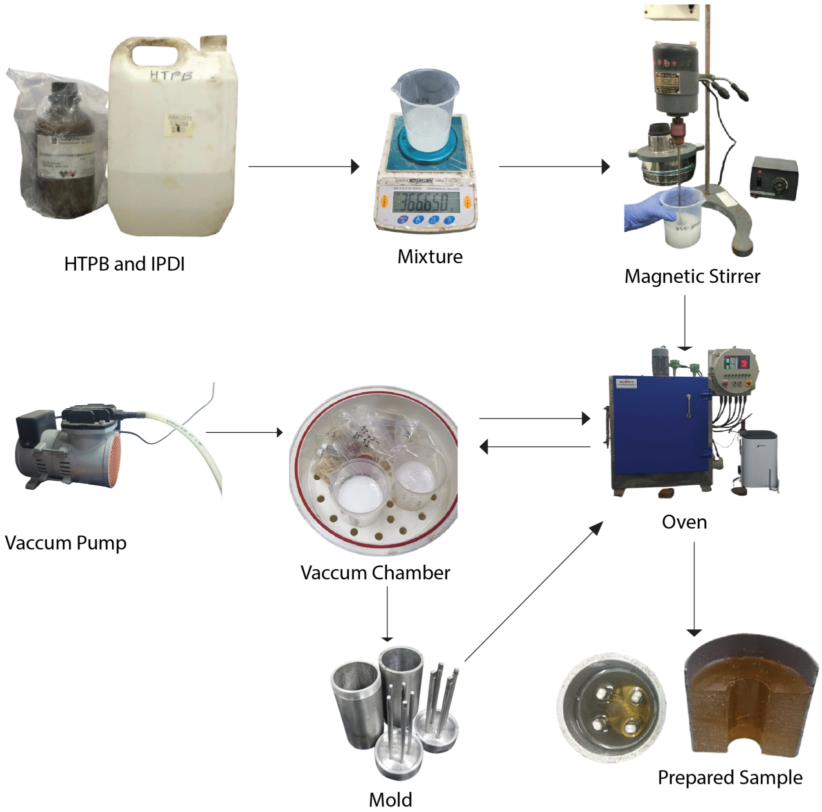


Figure 3.6: Preparing Workflow of Fuel Grain.

CHAPTER FOUR:
RESULTS AND DISCUSSIONS

Different propellants were tested in the lab and matched with theoretical knowledge to verify the results. If the results were deemed to be outside acceptable limits, tests were repeated by changing the related parameters, and the results were verified. If there was a large offset from the required results, propellant compositions were changed to match the needed values.

4.1 Control Volume Test

In this test only the maximum pressure result after the complete burning of propellant was needed. So for the result pressure time graphs were analyzed and monitored the most. Apart from that the temperature of the gas after the complete burning of the propellant was also monitored and recorded. This was later to be used for calculating the volume of the gas produced. Here we needed to have complete and stable burning of the propellant. This would give a steady increase of the pressure with increasing time and reach the maximum value when all propellant is burned. Then the pressure should decrease steadily. If the pressure time character is different from this then the igniter mass is changed, the propellant amount is changed and other components are changed and variation will be recorded until the required pressure time character is obtained.
In theory, after the complete burning of propellant in constant volume the pressure should not decrease and stay at the same value. This is considering the closed volume to be completely adiabatic, i.e. There should not be any heat change through the boundary of the closed volume. But in a real application, heat escapes from the wall of a closed-volume vessel. This decreases the internal temperature and decreases the pressure inside the volume after completely burning a propellant.
Here the gas-generating propellant sample and gun propellant sample were tested and pressure time variations were recorded. First to find the amount of the igniter mass required some tests were done and a pressure time relation was observed. If the variation is like discussed above then that igniter mass was fixed. But if the variation is found different then it was changed. For the gas-generating propellant, the igniter mass was taken at $0.5gm$ initially. This gave 2 rise in pressure of the before decreasing. This was not acceptable and the igniter mass of $0.3gm$ was used. This gave the pressure time graph as required and was used for gas-generating propellant. For the gun propellant $0.5gm$ igniter mass gave the required pressure time relation so $0.5gm$ was used for all gun propellants.

GG1								
Sl. No	**Weight (g)**	$P_{max}(bar)$	T_i**°C (Inner)**	T_f**°C (Inner)**	T_i**°C (Outer)**	T_f**°C (Outer)**	**Igniter Mass(g)**	**Residual Mass (g)**
1	1.08	10.00	24.29	188.8	24.20	25.31	0.5	–
2	1.02	6.91	24.23	157.3	24.32	25.83	0.3	–
3	1.02	6.52	24.94	162.0	24.88	25.12	0.3	–
4	2.00	17.07	25.59	227.0	24.32	25.83	0.3	–
5	2.02	17.54	21.78	207.9	22.32	23.01	0.3	–
6	2.00	16.46	24.94	260.2	23.76	24.19	0.3	–
7	3.00	32.73	24.24	201.8	24.22	24.80	0.3	1.34
8	3.01	26.06	25.53	369.2	24.20	26.16	0.3	0.90
9	3.00	33.82	25.72	300.8	24.48	24.98	0.3	1.36

Table 4.1: Experimental Data for GG1

GG2								
Sl. No	**Weight (g)**	$P_{max}(bar)$	T_i°**C (Inner)**	T_f°**C (Inner)**	T_i°**C (Outer)**	T_f°**C (Outer)**	**Igniter Mass(g)**	**Residual Mass (g)**
1	1.00	9.297	24.16	158.7	24.03	24.43	0.3	0.29
2	1.00	9.481	23.94	145.6	23.51	23.69	0.3	0.34
3	1.01	11.18	23.93	159.9	23.98	23.96	0.3	0.21
4	2.02	23.05	25.13	279.4	24.29	24.34	0.3	0.47
5	2.02	26.51	21.49	244.0	22.72	23.27	0.3	0.45
6	2.03	27.40	24.45	289.9	23.50	24.20	0.3	0.43
7	3.00	30.31	24.90	439.5	24.12	25.87	0.3	0.77
Igniter Leaked								
8	3.00	4.299	24.54	365.8	24.53	27.60	0.3	–
9	3.01	3.313	27.94	391.4	26.80	29.73	0.3	12.00

Table 4.2: Experimental Data for GG2

This test is done for 3 weights for one propellant i.e. $1gm, 2gm, \text{and} 3gm$. When the mass of the propellant increases, the maximum pressure should also increase by the same factor. This is also verified in the data obtained from the test. Also from the test, we can see that the final outer temperature is rising. This is due to the heat loss from the wall. This is also the case for gun propellant whose test results are given below.

GP1										
Sl No	**Weight (g)**	**Loading Density (g/cc)**	**Height (mm)**	**Diameter (mm)**	$P_{max}(bar)$	T_i°**C (Inner)**	T_f°**C (Inner)**	T_i°**C (Outer)**	T_f°**C (Outer)**	**Remarks**
	0.98	–	8.6	9.92	–	–	–	–	–	–
1	0.99	0.007443609	8.48	10	26.28	24.39	437.6	24.76	27.63	–
2	1.02	0.007669173	Not Measured		26.28	26.65	449.5	26.94	29.73	–
3	1.03	0.007744361	8.766	10	26.99	25.01	372.0	25.62	28.46	–
4	2.00	0.015037594	8.526	10	64.95	27.42	561.0	27.17	31.55	–
5	2.00	0.015037594	8.583	10	64.51	27.62	505.2	26.56	30.96	–
6	1.98	0.014887218	8.365	10	61.04	25.71	461.2	25.12	29.52	–
7	2.95	0.022180451	8.55	10	113.1	23.44	520.6	24.94	31.77	–
8	2.91	0.021879699	8.71	9.92	79.78	25.76	647.4	25.73	32.25	–
9	1.04	0.007819549	9.22	9.92	31.16	35.46	377.3	32.18	34.80	abs sensor
10	1.98	0.014887218	8.84	9.93	69.66	31.33	473.9	29.09	33.80	abs sensor
11	2.91	0.021879699	8.6733	9.94	113.3	Problem with the sensor				–
12	2.96	0.022255639	8.76	9.933	116.0	27.85	549.0	27.56	36.17	–

Table 4.3: Experimental Data for GP1

GP2										
Sl No	**Weight (g)**	**Loading Density (g/cc)**	**Height (mm)**	**Diameter (mm)**	$P_{max}(bar)$	T_i°**C (Inner)**	T_f°**C (Inner)**	T_i°**C (Outer)**	T_f°**C (Outer)**	**Remarks**
1	0.98	0.007368421	8.9	10	31.93	28.3	343.3	27.14	28.66	Abs sensor
2	0.96	0.007218045	8.84	10.06	29.73	30.9	330.96	29.53	31.39	Abs sensor
3	0.95	0.007142857	8.7	10	29.28	30.66	328.2	28.54	30.66	Abs sensor
4	1.92	0.01443609	8.6	10.06	68.81	33.47	474.7	31.06	35.82	Abs sensor
5	1.99	0.014962406	8.82	10.02	70.72	33.67	483.1	31.19	36.34	Abs sensor
6	1.98	0.014887218	8.78	10.07	69.62	32.91	428.0	30.59	36.53	Abs sensor
7	2.98	0.022406015	9.06	10.06	136.8	33.52	456.7	29.23	35.23	Abs sensor
8	2.98	0.022406015	8.81	10.1	140.9	33.63	480.7	29.96	37.13	Abs sensor
9	2.98	0.022406015	8.97	1.04	139.7	34.23	483.6	29.73	35.31	Abs sensor

Table 4.4: Experimental Data for GP2

The row highlighted in yellow shows the data that is incorrect or has a high deviation from the required value.
From the above results, we can conclude that the maximum pressure obtained from the gas-generating propellant is lower than that of the gun propellant. This is due to their different composition and purpose for use. The gun propellant modified version of the propellant here was used in the L-70

artillery. This was done to increase the muzzle velocity keeping other parameters the same. Due to this, it needed a higher maximum pressure value during firing. But the purpose of the gs generating propellant is to use in the mechanisms like airbags which do not need a higher maximum pressure value but a stable pressure that could resist the impacts.

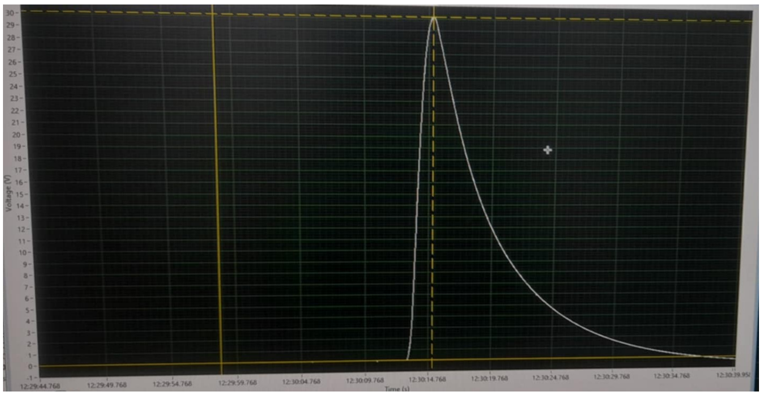


Figure 4.1: Correct Pressure time plot.

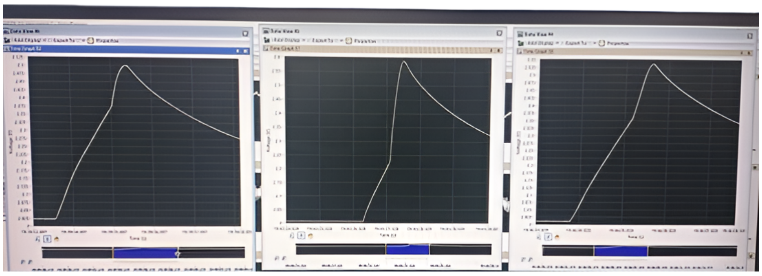


Figure 4.2: Incorrect Pressure Time Plot.

4.2 Crawford Bomb Test

This test was done to find the burning rate of the propellant. Here we burn a propellant of known size and dimension at certain chamber conditions. From this, we can get different values of burn rate at different chamber conditions. Then the result is fitted in a parabolic function to get the required value of the pressure index which gives the burning performance of the propellant. In the lab, we did this test for 5 different materials among which 3 were propellants and the other 2 were paraffin and HTPB. These have their individual burn rate value and pressure index.
The propellant or other material in a confined space gives the maximum value of pressure when completely buried. So, we looked at the pressure time relation while testing. For every sample, 3 tests were done for one chamber condition. If the value result of the test was found to be within the required value and following the nature given by the theoretical knowledge, then it was considered to be ok. Tests were done repeatedly until the required value of burn rate was not obtained. Sometimes burnrate value would deviate from the required value. This occurred when the propellant was not completely burned, or the chamber condition was not the same, or the burning was not uniform, and many more reasons. For the slurry propellant, the burn rate would deviate from the required value due to the presence of the air bubble while preparing the sample of the propellant. Also, the materials used for the preparation of the propellant differed in the burn rate value i.e. propellant samples using the paper straw and plastic straw were different due to the variable thickness of the straw and its materials. So, multiple tests were done to verify the result of the burn rate and verified with the theoretical nature.

Sl.no	Pressure	Height (mm)	Burn Time	Burn Rate	Remarks
1	1	19.36			
2	1	18.9	21.52	0.8782	
3	1	19.72			Didn't burn
4	40	22	2.294	9.5902	Didn't burn
5	40	25.1	2.47	10.1619	Didn't burn
6	40	25.16	2.371	10.6116	Didn't burn
7	1 Bar	15.74	12.05	1.3062	grease
8		15.74	5.942	2.6489	no grease
9		15.28	13	1.1754	grease_rubber solution
14-Oct					
1	1 Bar	18	12.5	1.44	
2		17	13.71	1.2399	
3		18.1	15.61	1.1595	
1	10 Bar	19.1	2.56	7.4609	
2		18.84	9.144	2.0604	
3		18	8.564	2.1018	
15-Oct					
1	20 Bar	20.42	9.801	2.083	
2		20.78			not burn
3		19.62			not burn
1	20 Bar	20.6	9.741	2.1148	
2		19			not burn
3		20.52			not burn
1	20 Bar	14	6.329	2.2120	with HTPB bond
2		13.9	7.203	1.9298	
3		14	7.156	1.9564	
1	30 Bar	13.62			not burn
2		15.4	5.382	2.8614	incomplete burn
3		15.7			not burn
1	30 Bar	15.2			not burn
2		15.04			not burn
3		15.6			not burn
1	30 bar	16.2			not burn
2		14.32			not burn
3		15.1			not burn
1	1 Bar	15.84	13.63	1.1621	
2		15.22	12.78	1.1909	
3		15.1	11.4	1.3246	
			Avg	1.2259	
16-Oct					
1	30 Bar	14.72	8.452	1.7416	
2		15			not burn
3		12.2			not burn
1	5 Bar	15.22			not burn
2		15.82			not burn
3		16.2	12.67	1.2786	

1	15 Bar	14.66	6.978	2.1009	
2		14.2	6.602	2.1509	
3		15.22	7.352	2.0702	
			Avg	2.1073	

Table 4.5: Burn rate test data for Gas Generating Propellant

Pressure (Bar)	**Burnrate**
1	1.18
5	1.27
10	2.08
15	2.107
20	2.163

Table 4.6: Pressure vs Average Burnrate Data of Gas Generating Propellant

Pressure	**Width**	**Thickness**	**Length**	**Time**	**Burn Rate**	**Remarks**
2	4.5	4.5	12.6	2.94	4.286	
2	5	4.2	12.2	3.215	3.795	
2	4.6	4.6	11.8	2.406	4.904	
4	4.42	4.92	11.86	2.172	5.460	
4	4.9	4.22	11.88	2.126	5.588	
4	4.32	5	12.36	1.55	7.974	rise is 34 bar
6	3.8	4.54	11	0.686	16.035	
6	5.24	4.82	11.6	0.609	19.048	
6	4.64	4.74	11.12			not fired
6	5	4.7	11.2	0.732	15.301	
4	4.8	4.6	12.3	1.619	7.597	
2	3.9	4.5	11.1	2.84	3.908	
4	5.5	4.76	13.6	2.063	6.592	
8	5.1	5.2	13.18	1.229	10.724	
6.8	4.52	5.28	14.62	1.778	8.223	
8	6.68	4.56	12.4	0.647	19.165	
8	4.3	5.2	11	0.511	21.526	
8	4.5	5.2	13.1			two peaks

Table 4.7: Burnrate for wax

Pressure	**Burn Rate**
2	3.996
4	7.090
6	16.790
8	20.340

Table 4.8: Wax average Burn Rate Data

Pressure	Width	Thickness	Length	Time	Burn Rate	Remarks
2	4.8	4.6	12.4	3.257	3.807	
2	5.8	4.2	13.5	3.828	3.527	
2	5.1	4.8	13.4	0.347	38.617	rise is 15 bar
4	4.9	5	13.2	1.392	9.483	
4	4.5	4.7	12.3	3.406	3.611	2 peaks
4	5.92	5.4	12.3	0.41	30.000	
6	4.1	3.9	11.4	1.577	7.229	
6	4.4	4.8	11.15	0.682	16.349	
6	4.3	4.4	12.8	2.7	4.741	
4	4.35	4.7	11.28	1.77	6.373	
4	4.26	4.34	11.1			failed
4	4.66	4.94	12.86			failed
4	5	5.1	12.4	0.412	30.097	rise to 40 bar
4	4	4.3	13			failed
4	3.9	4.5	12.8			failed
4	4.4	4.2	12.6	1.853	6.800	
4	4.8	4.4	11.7			failed
4	4.5	3.9	12.2	1.996	6.112	
6	5.5	5.9	13.3	0.73	18.219	
6	5.2	4.1	13.5			failed
6	5	4	13	1.793	7.250	
8	3.7	3.9	13.2	0.6405	20.609	rise to 61 bar
8	4.7	4	14.4			failed
8	4.6	5	14.2			failed
6	5	5	12	0.584	20.548	
8	4	4.8	12.5			failed
8	4.9	5.1	12.4			failed
6	3.92	4.88	12.76	1.24	10.290	
6	3.24	4.3	11.7	0.762	15.354	rise to 28.5 bar
6	4.48	3.66	12.26	0.7	17.514	
8	3.24	4.46	11.28	0.727	15.516	rise to 36.74 bar
8	3.4	4.32	10	0.807	12.392	
8	2.96	4.6	11.6	0.62	18.710	
8	4.5	4.9	11.8	0.771	15.305	
6	4.3	3.32	11	0.753	14.608	
8	3.96	5	12.56	0.815	15.411	

Table 4.9: Burrate for HTPB

Pressure	Burn Rate
2	3.660
4	6.450
6	15.437
8	16.235

Table 4.10: HTPB average Burn Rate Data

Sl.no	Pressure	Height	Burn Time	Burnrate	Mass	Volume	Density	Straw Weight
3	70	18.56	1.135	16.3524	0.93	524.5056	1582.4426	0.10
4	70	20.5	1.016	20.1772	0.97	579.33	1449.9508	0.13
5	70	20.12	1.238	16.2520	0.97	568.5912	1512.5102	0.11
6	70	19.8	1.711	11.5722	0.95	559.548	1465.4686	0.13
15	70	20.2	1.118	18.0680	0.98	570.852	1524.0378	0.11
17	70	20.7	1.546	13.3894	1.01	584.982	1538.5089	0.11

Table 4.11: Experimental Data of Slurry Propellant

Sl.no	Pressure	Height	Burn Time	Burnrate	Mass	Temp	Volume	Density	Straw Weight
1	30	15	1.683	8.91266	0.96	25.6	662.34375	1207.83204	0.16
2	30	15	2.031	7.38552	0.93	26.1	662.34375	1192.73414	0.14
3	30	15	1.728	8.68056	1.04	26.4	662.34375	1298.41944	0.18
4	31.3	15	2.074	7.23240	0.95	27.3	662.34375	1192.73414	0.16
5	31.3	15	1.677	8.94454	1.02	27.0	662.34375	1283.32154	0.17
6	31.6	15	1.376	10.90116	0.89	25.1	662.34375	1117.24463	0.15
7	20	15	2.240	6.69643	0.95	29.38	662.34375	1207.83204	0.15
8	20	15	1.565	9.58466	1.15	27.7	662.34375	1479.59424	0.17
9	20	15	1.973	7.60264	1.01	28.8	662.34375	1253.12574	0.18
1	70.9	19.72	1.475	13.36949	0.99	27	557.2872	1561.13401	0.12
2	70.9	20.24	1.624	12.46305	1.01	27	571.9824	1555.99193	0.12
3	70.9	20.1	1.619	12.41507	1.01	27	568.026	1549.22486	0.13
4	60	19.9	1.756	11.33257	0.99	28	562.374	1547.01320	0.12
5	60	20.5	1.792	11.43973	1.03	28	579.33	1570.78004	0.12
6	60	19.66	1.819	10.80814	0.98	28	555.5916	1565.89841	0.11
7	50	19.52	1.858	10.50592	0.95	28	551.6352	1540.87339	0.10
8	50	20.1	1.991	10.09543	0.99	28	568.026	1549.22486	0.11
9	50	19.9	1.961	10.14788	0.99	28	562.374	1547.01320	0.12
10	40	20.1	2.177	9.23289	1.01	28	568.026	1584.43452	0.11
11	40	20.2	2.282	8.85188	1.00	28	570.852	1541.55543	0.12
12	40	20.6	2.243	9.18413	1.01	28	582.156	1545.97737	0.11
13	30	20.2	2.489	8.11571	1.00	28	570.852	1541.55543	0.12
14	30	19.42	2.463	7.88469	0.95	28	548.8092	1567.02912	0.09
15	30	19.7	2.426	8.12036	0.98	28	556.722	1580.68120	0.10
16	20	20.0	2.823	7.08466	1.01		565.2	1556.97098	0.13
17	20	20.6	3.043	6.76964	1.02		582.156	1563.15489	0.11
18	20	20.38	2.949	6.91082	1.01		575.9388	1545.30308	0.12

Table 4.12: Experimental Data of Slurry Propellant(10/24/2024)

Pressure	Burntime
70.9	12.74920558
60	11.19348084
50	10.2497445
40	9.089634003
30	8.040255107
20	6.921704721

Table 4.13: Slurry Average Burn rate Data

Sl.no	Pressure	Height	Burn Time	Burnrate	Mass	Temp	Volume	Density	Straw Weight
1	70.5	19.82	1.227	16.1532	1.01	70.8	560.1132	1553.2574	0.14
2	70.6	20.00	1.015	19.7044	1.02	70.8	565.2000	1556.9710	0.14
3	70.8	20.00	1.292	15.4799	1.03	70.05	565.2000	1574.6638	0.14
4	70.6	20.00	1.280	15.6250	1.00	70.06	565.2000	1539.2781	0.13
5	70.5	20.10	1.250	16.0800	1.00	70.1	568.0260	1531.6200	0.13
6	70.5	19.36	1.224	15.8170	1.00	70.1	547.1136	1571.8856	0.14
7	59.8	19.76	0.217	91.0599	1.00	70.8	558.4176	1575.8816	0.12
8	59.8	19.90	0.380	52.3684	1.03	70.6	562.3740	1600.3585	0.13
9	59.9	19.62	0.204	96.1765	1.04	70.1	554.4612	1587.1264	0.16
10	50.6	20.40	0.844	24.1706	1.04	70.64	576.5040	1543.7881	0.15
11	50.4	19.76	0.862	22.9234	1.02	70.0	558.4176	1540.0661	0.16
12	50.5	19.98	1.423	14.0408	1.02	69.4	564.6348	1540.8190	0.15
13	40.6	20.00	1.623	12.3229	1.02	70.4	565.2000	1556.9710	0.14
14	40.6	20.28	0.318	63.7736	1.04	70.3	573.1128	1552.9229	0.15
15	40.29	19.92	1.603	12.4267	1.01	70.4	562.9392	1580.9878	0.12
16	30.4	19.52	1.814	10.7607	0.96	70.5	551.6352	1540.8734	0.11
17	30.1	20.10	1.194	16.8342	0.98	70.3	568.0260	1549.2249	0.10
18	30.2	20.20	1.841	10.9723	0.99	70.4	570.8520	1541.5554	0.11
19	20.1	20.26	2.589	7.8254	1.07	70.7	572.5476	1554.4559	0.18
20	20.4	19.62	2.621	7.4857	1.04	70.5	554.4612	1569.0909	0.17
21	20.7	19.62	2.477	7.9209	1.04	70.5	554.4612	1533.0198	0.19
22	50.4	20.10	0.450	44.6667	1.07	70.3	568.0260	1584.4345	0.17
23	50.4	20.36	1.108	18.3755	1.07	70.3	575.3736	1564.2011	0.17
24	50.6	20.46	0.482	42.4481	1.05	70.2	578.1996	1556.5559	0.15
25	50.46	19.90	0.514	38.7160	1.02	70.02	562.3740	1511.4497	0.17
26	51.07	20.22	1.920	10.5312	1.01	70.96	571.4172	1540.0306	0.13
27	51.15	20.36	1.856	10.9698	1.04	70.62	575.3736	1546.8211	0.15
28	50.5	20.38	1.227	16.6096	1.02	69.64	575.9388	1545.3031	0.13

Table 4.14: Experimental Data of Slurry at $70^{\circ} C$

Pressure	Burnrate
70.55	15.72099673
50.5	15.32518796
40.445	12.37477942
30.3	10.86652369
20.4	7.87314362

Table 4.15: Slurry Burn Rate Data at 70° C

Date: 10/11/2024						
Sl.no	**Pressure**	**Height**	**Burn Time**	**Burnrate**	**Temp**	**Remarks**
1	70	18.3	1.209	15.1365	-	
2	70	18.04	1.4	12.8857		
3	70	18.78	1.235	15.2065		
4	70	19.1	1.43	13.3566	28.8	
5	70	19.6	1.532	12.7937	28.8	
6	70	19.4	1.483	13.0816	28.83	
7	60	19.7	1.555	12.6688		
8	60	18.8	1.574	11.9441		
9	60	19.7	1.528	12.8927		
10	50	17.82	1.318	13.5205		
11	50	19	1.611	11.7939		
12	50	20.28	1.725	11.7565		
13	40	20.5	1.96	10.4592		
14	40	20.3	1.77	11.4689		
15	40	20	1.79	11.1732		
16	30	20.4	2.091	9.7561		
17	30	19.1	2.064	9.2539		
18	30	20.2	2.071	9.7537		
19	20	18.34	2.173	8.4399		
20	20	19.62	2.433	8.0641		
21	20	20.5	2.183	9.3907		

Table 4.16: Experimental Data of TP_11 Solid Propellant from 10/11/2024

Date: 10/20/2024						
Sl.no	**Pressure**	**Height**	**Burn Time**	**Burnrate**	**Temp**	**Remarks**
1	50	17	1.415	12.0141	70	
2	50	17	1.227	13.8549	69.3	
3	50	17.2	1.403	12.2594	70.1	
4	40	16.56	1.581	10.4744	70.7	
5	40	17.12	1.623	10.5484	70.7	
6	40	17	1.59	10.6918	70.4	
7	30	16.18	1.719	9.4124	69.7	
8	30	16.08	1.774	9.0643	69.8	
9	30	17.74	1.796	9.8775	70.5	
10	29.5	16.9	1.785	9.4678	69.7	
11	29.6	17.22	1.821	9.4563	70	
12	29.8	17.5	1.038	16.8593	70	Slope change
13	20	16.62	2.015	8.2481	70.4	
14	20	16.48	1.934	8.5212	70.2	
15	20	16.38	1.911	8.5714	70	

Table 4.17: Experimental Data of TP_11 Solid Propellant from 10/20/2024

Pressure	Burnrate
70	13.01203044
60	12.50185731
50	11.85485761
40	10.57152481
30	9.587905228
20	8.631603276

Table 4.18: Burn Rate Data of TP_11 Solid Propellant

Date: 10/18/2024						
Sl.no	**Pressure**	**Height**	**Burn Time**	**Burnrate**	**Temp**	**Remarks**
1	60.6	20.18	2.542	7.938630999	27.4	
2	60	20.2	2.017	10.01487357	27.3	Slope change
3	60.6	19	2.11	9.004739336	27.6	
4	60.7	18.84	1.825	10.32328767	27.9	
5	60.3	15.34	1.562	9.820742638	27.7	
6	60.5	11.9	1.37	8.686131387	27.8	
7	49.8	15.76	1.87	8.427807487	28	
8	50	16.04	1.856	8.642241379	27.9	
9	50.2	18.74	2.223	8.430049483	27.8	
10	40	12.66	1.346	9.40564636	28.2	Slope change
11	40.1	17.16	2.44	7.032786885	28.1	
12	40.2	20.1	2.338	8.597091531	28	Slope change
13	40.2	17.86	2.285	7.81619256	28.5	
14	40.3	17.98	2.42	7.429752066	28.4	
15	40	18.76	2	9.38	28.4	
16	30	10.9	1.542	7.068741894	28.1	
17	30	15.2	1.882	8.076514346	28	
18	30	19.88	2.573	7.726389429	28.2	
19	30.3	19.72	2.865	6.883071553	28.3	
20	30.5	12.7	1.844	6.887201735	28.9	
21	30.6	14.28	1.986	7.190332326	28.8	
22	20	17.16	2.781	6.170442287	28.6	
23	20.3	13.24	2.204	6.007259528	28.4	
24	20.5	16.26	2.621	6.203739031	28.5	
Date: 10/17/2024						
1	70	16	1.621	9.870450339	26.66	
2	70	16.68	2.075	8.038554217	26.6	
3	70	17.56	2.254	7.790594499	26.68	
4	60	15.86	2.943	5.389058784	27.3	Ignition delay

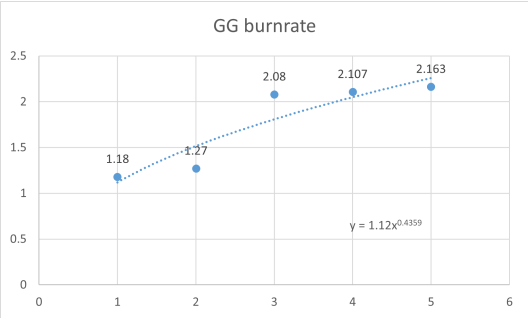
Table 4.19: Experimental Data of TP_11 Propellant with PTHF Binder from 10/18/2024 and 10/17/2024

Date: 10/17/2024						
Sl.no	**Pressure**	**Height**	**Burn Time**	**Burnrate**	**Temp**	**Remarks**
5	60	15.94	1.64	9.719512195	27.4	
6	60	16.08	1.329	12.0993228	27.2	
7	50	16.24	2.267	7.163652404	27.8	
8	50	16	1.897	8.434370058	27.7	
9	50	16.16	1.947	8.299948639	27.6	
Date: 10/21/2024						
1	50	19.1	2.492	7.664526485	67.5	
2	50	19.3	2.475	7.797979798	66.6	
3	50	19.64	2.642	7.433762301	68.5	
4	50	19.32	2.4	8.05	66.8	
5	40	19.9	2.41	8.257261411	66.8	
6	40	19.62	2.47	7.943319838	66.5	
7	40	19	2.4	7.916666667	69.25	
8	40	19.3	2.47	7.813765182	69.8	
9	30	19.32	2.78	6.949640288	69	
10	30	19	2.377	7.993268826	67.2	
11	30	19.2	2.733	7.025246981	68.5	
12	30	19.82	2.746	7.217771304	68	
13	20	19.62	2.801	7.0046412	70	
14	20	19.2	3.078	6.237816764	68	
15	20	19.14	2.703	7.081021088	69	
16	20	19.86	2.927	6.785104202	69	

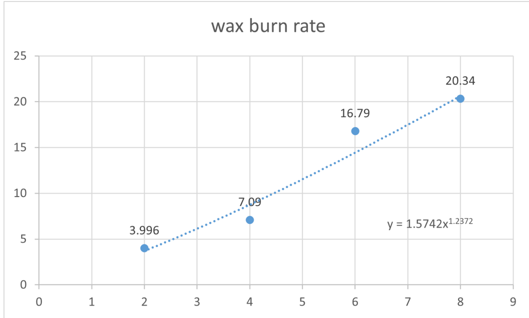
Table 4.20: Experimental Data of TP_11 Propellant with PTHF Binder from 10/17/2024 and 10/21/2024

Pressure	Burnrate
60.5	10.07
50	8.5
40.15	7.816
30.35	7
20.266	6.127

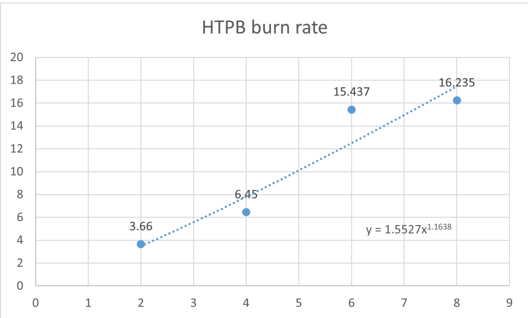
Table 4.21: Burn Rate Data of TP_11 Propellant with PTHF Binder



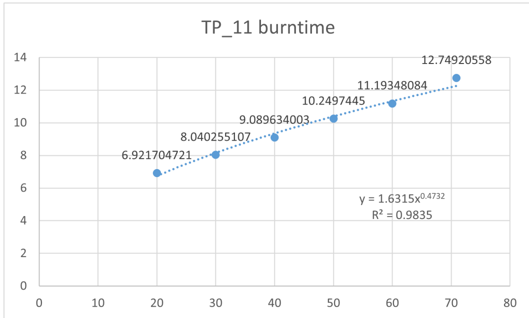
(a) Burnrate progression and Pressure Index of Gas Generating Propellant



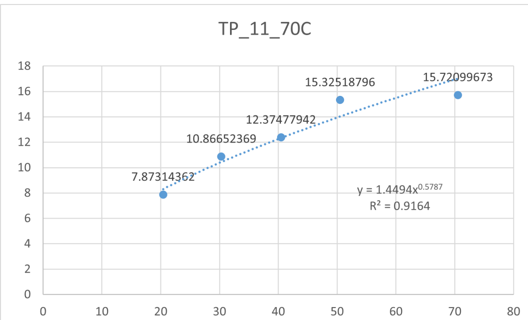
(b) Burnrate progression and Pressure Index of Wax



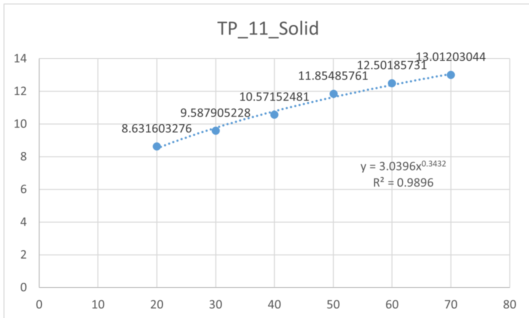
(c) Burnrate progression and Pressure Index of HTPB



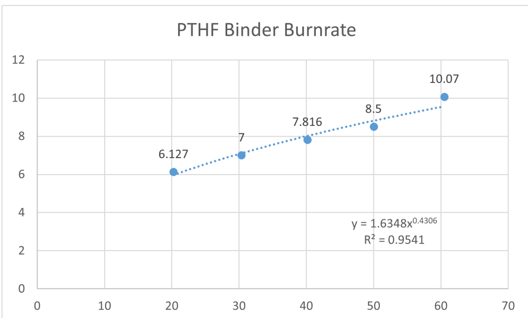
(d) Burnrate progression and Pressure Index of Slurry



(e) Burnrate progression and Pressure Index of Slurry at $70^{\circ}C$



(f) Burnrate progression and Pressure Index of TP_11 solid Propellant

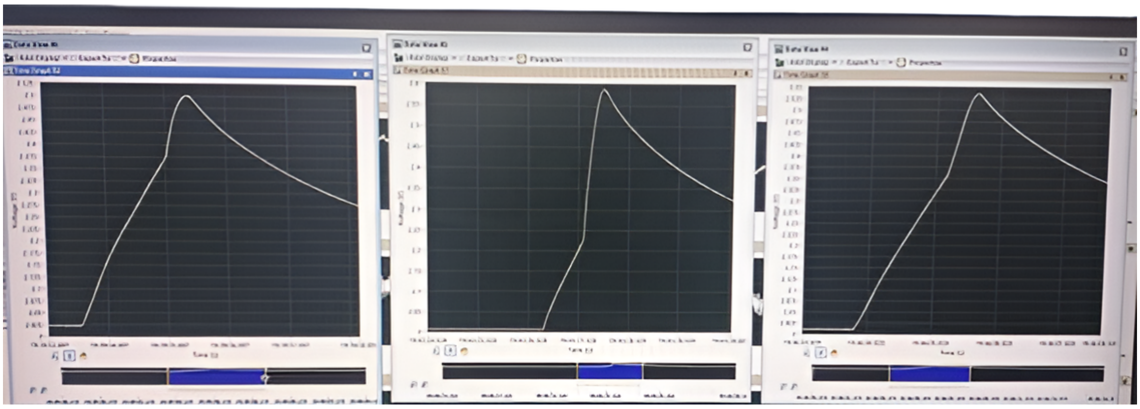


(g) Burnrate progression and Pressure Index of TP_11 solid Propellant

Figure 4.3: Burnrate Curve and Pressure Index of Tested Propellant

.

(a) Unburnt Propellant remaining After Test



(b) Deviated Pressure Time Plot of Slurry Propellant due to Presence of Air Bubble

Figure 4.4: Error Condition Result in Crawford Bomb Test

.

4.3 Quench Bomb Test

This test was done to check for the binder melting properties of the solid propellant TP11 and a slurry propellant. Since only the surface of the quenched propellant was needed, we did not take any pressure or temperature readings during or after the test. Also, the required depressurization pressure value and depressurization area were tested and found for both of the propellants.

Quenching of the solid propellant was relatively very easy. Since it was solid, a known shape was cut into little longer pieces. Then it was placed inside the quench bomb setup and 10 bar pressure was set up. Then it was quenched. After quenching the quenched surface of the propellant was observed. The surface of the propellant needed to be flat as it would be easier to check the binder melt on the surface using the Scanning Electron Microscope (SEM) image. This flat quenched sample was not found at first and many factors were suspected, there was no uniform burning of the propellant, the quenching was not being done at the right chamber pressure and depressurization was not happening correctly. For this, we covered the side surfaces of the propellant using silicon gel and on the igniting surface, we used a drop of the device so that it would give uniform burning in the igniting area. At early tests, 2

layers of Myler sheet and 1 layer of paper were used for the depressurization. During depressurization of the chamber, the depressurization area should be the area of the hole in the depressurization plate. During the early test, this was not the case. So the number of sheets and sheets used were changed and tested for the proper depressurization condition. Afterward, 3 layers of myler sheet produced the desired result so it was used along with a 29mm internal diameter plate for solid propellant and a 26 mm depressurization plate for slurry propellant. And since the environmental condition and propellant shape were not always consistent during initial testings, we needed to test many samples to get a few properly quenched samples.
Quenching of the slurry propellant was relatively much harder than that of the solid propellant. Since it was in a semifluid state, it was difficult to make it fix in the testing igniter and also give the known shape. For this, we used a peer straw and a known diameter. These small pieces of straw were filled and placed in the igniter to be quenched. It shows problems like irregular depressurization area, complete combustion of the propellant, and or irregular quenching. This happened because of certain reasons. For the depressurization area, we used a 26mm internal diameter depressurization plate and 3 Myler sheets. However, the irregular quenching was also due to the thickness of the straws used. Paper straws were then replaced with plastic straws which had smaller thickness. Also, the shape of the propellant was made different which made propellant fixing in the igniter easier. These are shown below. After this, the main problem that arose was the complete combustion of the propellant or ejection of the quenched propellant from the straw during quenching. This was observed as sometimes the whole straw tube would blow up and when the tube was intact, the propellant inside the tube would not remain. For this tests were done by reducing the chamber pressure and found a value for stable quenching of slurry propellant. Hence further tests were done in 10 bar pressure for slurry propellant.

(a) Improperly Quenched Properly

(b) Properly Quenched Propellant

(c) Propellant Samples

Figure 4.5: Observation Result of Quench Bomb Test

.

(a) Improper Depressurization due to incomplete tear of Upper Sheet

(b) Proper Depressurization due to complete tear of Upper Sheet

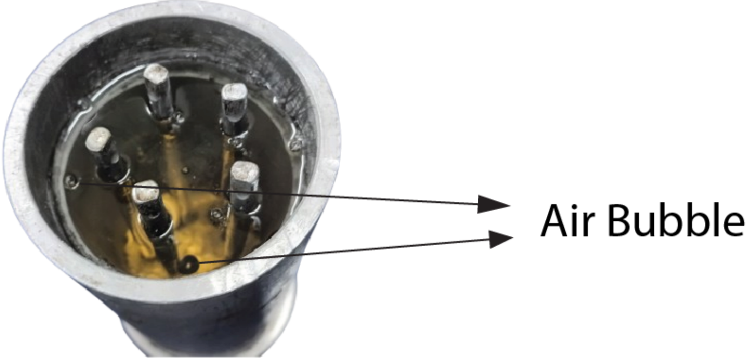
Figure 4.6: Observation Result of Quench Bomb Test

.

4.4 Fuel Grain Preparation

The solid fuel grain prepared was to be used in the hybrid motor testing and some experiments. Two grains of the same size were made simultaneously with different numbers of ports. The composition is already given above which was the standard composition. The weight was taken according to the dimension of the grain needed.

While making the fuel grain the most important thing to be considered is the absence of the air bubble inside it. Since the composition of the grain is initially in the semi-liquid state, it could trap some air bubbles during the mixing of the components. Due to this, the morning performance of the fuel will be affected. Due to this, we need to put the final mixture inside a vacuum chamber to suck out the air bubble towards the surface and then place it in the oven to remove it completely. This was repeated until the solution was free from the air bubble. But while pouring the final mixture in the mold it might catch some air bubbles inside the grain. This happened when we prepared the fuel grain and it can be seen in the picture below. After this, the grain was discarded and another fuel grain was made using the same technique.



(a) Defect in the Fuel Grain due to Air Bubble

(b) Good Quality Fuel Grain

Figure 4.7: Observation During Fuel Grain Prepeation

.

CHAPTER FIVE:
CONCLUSION

During the total duration of the internship, we extensively conducted tests i.e. Control Volume (CV) test, Crawford Bomb Test, and Quench Bomb Test for different propellants. We got to know the practical knowledge of the context as well as practical application. We got hands-on experience with the subject and applied it in some cases. Since these tests were done for different types of propellants, we got to know the behavior of different propellants. Furthermore, we got to apply the test results for the practical application. Apart from the testing of propellant we also made the fuel grain of the hybrid rocket motor. Its burn time behavior was also studied using the Crawford bombing test. Also, we got to observe and help in the hybrid motor firing and scaled version of the L70 artillery. The test data were used for the design of the motor and scaled version of the L70 Artillery. Furthermore, we also observed and helped during the IR testing of different propellants to measure the flame temperature. We created some igniters that can be used for the control volume testing after the used igniters were damaged. Collectively, we participated actively in the propellant testing and research in a propellant research lab, got exposure from esteemed personnel from different professions, learned about the new culture and work environment, and gained practical and hands-on experience during the internship duration.

REFERENCES

1. P. K. Raj and C. Segal, *Hybrid Rocket Propulsion Systems: Advances and Applications*. Springer, 2020.

2. M. J. Chiaverini and K. Kuo, *Fundamentals of Hybrid Rocket Combustion and Propulsion*. Progress in Astronautics and Aeronautics, vol. 218, AIAA, 2007.

3. W. J. M. Rankine, "Hybrid rocket propulsion: An overview of recent research," *Journal of Propulsion and Power*, vol. 28, no. 5, pp. 1034–1045, 2012.

4. A. J. Huzel and D. H. Huang, *Modern Engineering for Rocket Propulsion*. NASA Special Publication, 2016.

5. S. Frolov and A. Fomenko, "Recent advances in solid propellant combustion research," *Combustion, Explosion, and Shock Waves*, vol. 52, no. 3, pp. 239–256, 2016.

6. N. Kubota, *Propellants and Explosives: Thermochemical Aspects of Combustion*, 3rd ed. Wiley-VCH, 2017.

7. R. F. McGuire, "Combustion instability in hybrid and solid rocket motors," *Aerospace Science and Technology*, vol. 10, no. 6, pp. 495–506, 2010.

8. M. Pers, A. D. King, and H. R. Patel, "Experimental and theoretical research on hybrid rocket motors," *Acta Astronautica*, vol. 179, pp. 199–210, 2021.