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Ignition System for Solid Rocket Motors

Technology Focus focuses on the technological developments in the organisation covering the products, processes and technologies.

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From the Desk of Editor-in-Chief

Dear Friends...

What a great time to share my thoughts with you all. 2020, the unique number of a centenary, inception of a unique decade with lots of hopes, dreams and goals with a passion to accomplish and to touch the heights of success in coming years ahead. So wish you all a very happy new year.

New year is a time to take stock of the year gone by and plan for future. I am happy that Technology Focus (TF) is entering 28th year of its publication. Over the years, TF has successfully highlighted the achievements of the DRDO in a proper perspective to its diverse readers including our users, the Services, paramilitary forces, policy makers, S&T institutions, our partners both in academic as well as in industry, prospective buyers of Make in India defence technologies and above all young budding scientist, our students. The credit for its popularity goes to coordinated efforts of DESIDOC, various DRDO laboratories and honest readership.

In 2019, TF covered areas like Composite Structures; Avalanche Hazard Mitigation in Western & Central Himalayas; Multi-Role Combat Vehicles and Systems; Certification of Aircraft Brake Pads & Batteries; Protection Technologies for Soldiers; and Artillery Rocket Systems. The work carried out by DRDO in these areas is phenomenal and a number of technologies developed by the organisation under these have been inducted into the Services.

Besides regular print and online versions, the TF now also available as video magazines. I thank various DRDO laboratories for their wholehearted support for on-location shooting of these magazines.

I also thank large number of readers who have requested for printed copies. I call them all to kindly visit our link (https://drdo.gov.in/technology-focus) on DRDO website.

At the end, I hope that DRDO laboratories would keep providing their valued contributions in 2020 also. I, on behalf of Editorial Team, thank all the contributors, DRDO community, and our valued readers and wish them very best wishes for 2020.

Happy Reading..!!

Dr Alka Suri
Director, DESIDOC

From the Desk of Guest Editor

High Energy Materials Research Laboratory (HEMRL) has been a pioneering institution in the development of the entire spectrum of high energy materials required for defence forces. Its charter of duty includes basic and applied research on high energy materials. As a part of basic research, HEMRL is responsible for identifying, synthesising and characterising the high energy molecules for scaling-up of the promising ones to pilot plant level for use in systems. The laboratory is carrying out applied research for the development of solid rocket propellants, warhead fillings, pyro-cartridges and flare, gun propellant systems, tank and aircraft protection systems, etc.

The development of solid rocket propellants for rockets and missiles has gradually evolved over the past few decades with advances in the understanding of energetic molecules, high strength and lightweight materials, technology and software tools for simulation and modelling. In line with global trends, HEMRL has strived hard to develop and offer high-energy propellants for the development of rockets and missiles. Starting with the development of EDB/CDB propellants in the 1960s, which delivered specific impulse only up to about 190 seconds, HEMRL is presently working on the propellants that deliver specific impulse of around 260 seconds with a target of 270 seconds in next 5 years.

Initially HEMRL was involved in development of gunpowder-based igniters for the double-base propellants. It later took on developments of igniters in the 1980s, with the launch of the Integrated Guided Missiles Development Programme (IGMDP). The missiles envisaged under IGMDP required higher energy propellants and thus the conventional double-base propellants were replaced by high-energy propellants. Accordingly, advanced ignition technology was concurrently developed, making use of high heat containing (high calorimetric value) Boron/Magnesium and Potassium Nitrate-based igniter compositions packed in suitably designed canisters of Aluminum alloys/steel. As these igniters were highly energetic to match the increased energy of the propellants, innovative safety methods were also developed and introduced. Simultaneously, design evaluation methodologies such as stand-alone igniter qualification method, etc. were also developed. During the late 1990s, work on case-bonded propellant technology was initiated demanding critical & stringent ignition systems with advanced features, viz., smaller size and improved efficiency per unit weight of the system. Today, HEMRL is delivering ignition systems for motors of all the strategic and tactical programmes successfully.

HEMRL has also proven its excellence in developing newer and challenging technologies such as Aft End Ignition, Throat-based Ignition, Through Air Initiation, Through Bulkhead Initiation, etc.

This issue of Technology Focus brings out an introduction to the ignition technology and HEMRL's contributions towards advancement in the field of energetic molecules, materials and technology leading to the development of igniters for all indigenous rockets and missiles – both tactical and strategic systems.

KPS Murthy
Outstanding Scientist & Director
HEMRL

Ignition System for Solid Rocket Motors

High Energy Materials Research Laboratory (HEMRL) is one the leading laboratory under the Armament cluster of Defence Research & Development Organisation (DRDO) and has been entrusted with the task of basic and applied research and development in the area of high-energy materials (propellants, explosives, pyrotechnics and allied chemistry). Under this mandate, HEMRL conducts R&D in synthesis and characterization of high-energy materials, development of propellants, high explosives, pyrotechnics, polymer materials, liners/insulators and other allied materials.

This issue of *Technology Focus* is highlighting HEMRL's contributions towards advancement in the field of energetic molecules, materials and technology leading to the development of igniters for all indigenous rockets and missiles-both tactical and strategic systems of India.

Solid Rocket Motors (SRMs) require an efficient ignition system to start its functioning. A separate ignition system, called igniter, is assembled in the rocket motor to achieve the task. Igniters for SRMs are basically of two types, viz., Pyrogen igniters used for large rocket motors of ballistic missiles, and Pyrotechnic Igniters used for small rocket motors.

The propulsive force of a solid propellant motor is derived from the combustion of solid propellant at high temperature and pressure. The igniter induces the combustion reaction in a controlled and predictable manner by generating heat flux in the form of hot, dense gases that rapidly ignite the propellant surface. The igniter also contributes towards the generation of a certain minimum pressure inside the motor that is adequate for stable and sustained combustion of the propellant.

General requirements of an Igniter are:

◊ The temperature of the propellant surface should be raised above its auto-ignition temperature

◊ Motor chamber pressure should be raised above a threshold pressure requirement for stable burning of a propellant

◊ Ignition delay (time delay from application of an electrical pulse to the point when 10 per cent of motor peak pressure is achieved), should be within specified limits

◊ The rate of pressure rise, dp/dt, in the motor chamber during ignition transient should not be unduly high leading to undesirable peaks or shock loads. On the other hand, it should not be too low to cause instability, hang-fires, etc., and

◊ The igniter should satisfy the functional, environmental and shelf-life/storage requirements

PYROTECHNIC IGNITERS

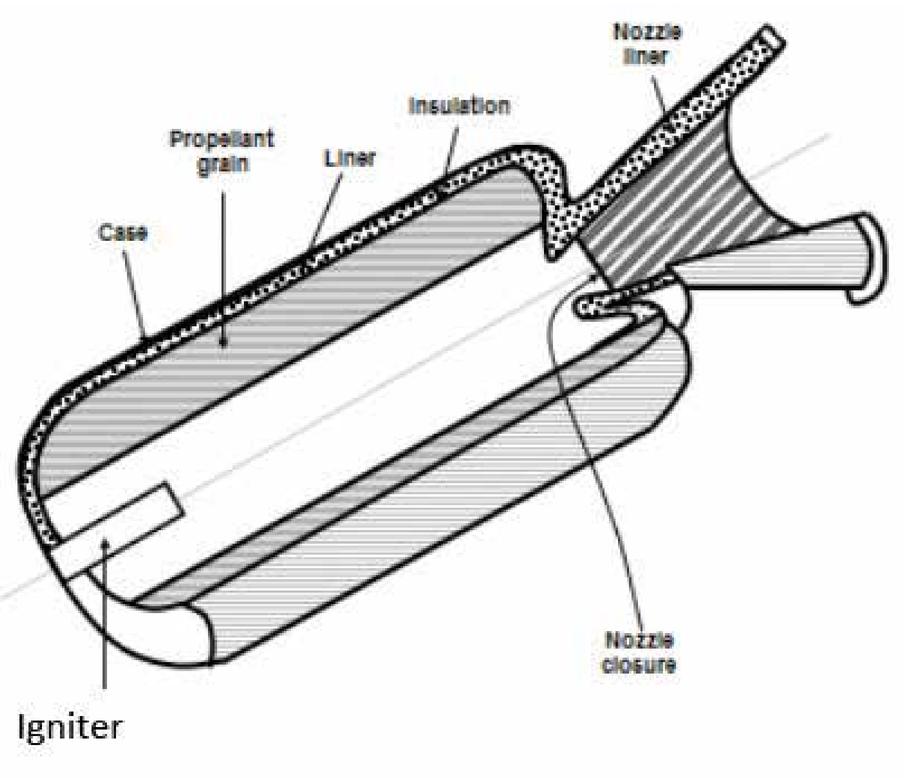
Pyrotechnic igniters are defined as igniters using pyrotechnic composition or energetic propellant like chemical formulations (usually in granule and/or small pellet form to give large burning surface area and short burn time) as a heat producing material.

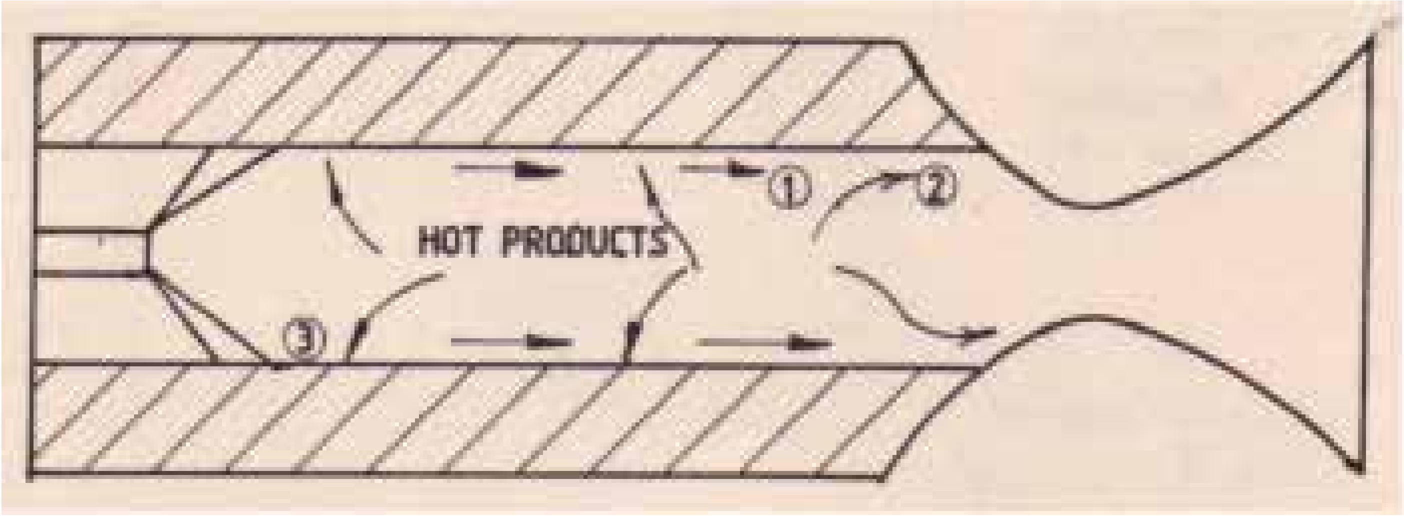
The constituents of igniter charge are : fuel, oxidizer, binder mainly and curing agent and other additives in some cases. Powdered Al, B, Mg are used as fuel. KNO_3, $KClO_3$, $KClO_4$, NH_4ClO_4, NH_4NO_3 are generally used as oxidizers. Plastizedethyl cellulose is used as a binder which reduces sensitivity.

In ignition of solid rocket motors, a series of events takes place in a tightly timed sequence starting with:

- ◊ Application of an electric pulse
- ◊ Initiation of first fire element (squib or pyro-cartridge)
- ◊ Generation of flash/flamelet
- ◊ Amplification of flash by primer
- ◊ Build up of flash to a strong flame by main igniter charge

Hence, a comprehensive understanding of functioning of the igniter is essential. Pyrotechnic igniters are broadly classified based on their position and operation. The details of the different igniters are:





NOZZLE CAP BASED IGNITER

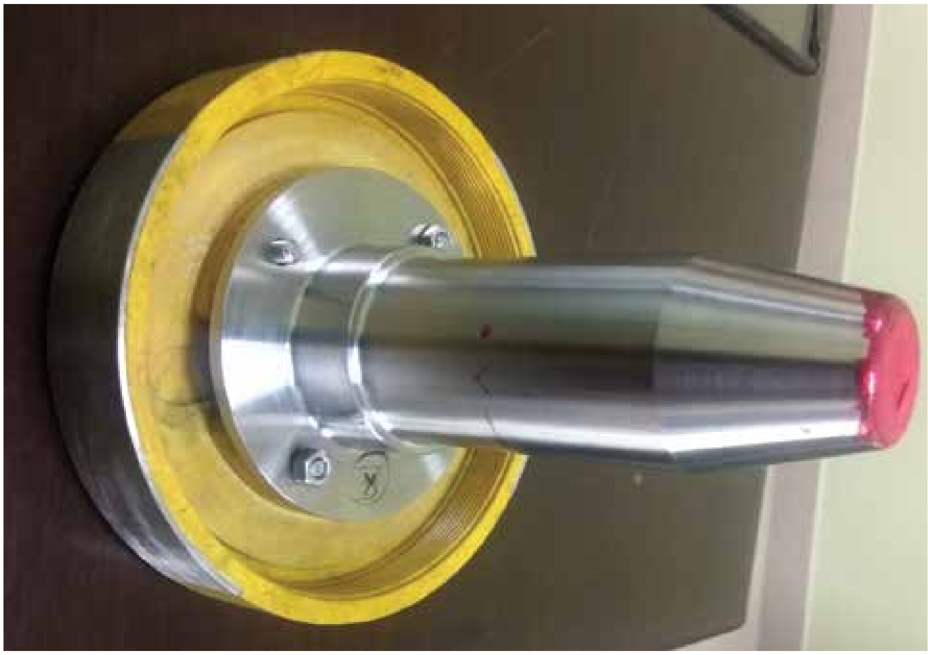
Nozzle cap-based igniters have been developed for compact rocket motors. In propulsion systems, positioning of igniter at the head-end is difficult due to space constraints, provision of electrical connections, etc. It is also desirable to have an ejectable ignition system in such cases to avoid carrying any dead weight during the flight and to avoid high transient pressure peaks.

Design Features

- ◊ Igniter is mounted on an ejectable nozzle cap
- ◊ Nozzle cap also gives provision for electrical connection
- ◊ Nozzle cap ensures sealing of gases generated by the igniter
- ◊ Nozzle cap-based igniter produces a hot gas jet which travels through the throat and ignites the propellant surface

Operational Features

Metallic circular sectors serving the purpose of contact points for electrical connections are embedded in the nozzle cap. A specially designed metallic plunger serves as second electrical contact. The igniter is initiated using squibs that get the electrical power supply through these contact points. Squibs initiate the primer charge that in turn initiates the main charge. Gases formed due to the burning of the charge mass are directed towards the propellant surface using a torch type configuration. Generally, Stainless steel is selected for canister whereas primer assembly is of high strength aluminum alloy. The cap is made of glass-filled phenol-formaldehyde composite material. $BKNO_3$ pellets are used as igniter charge.



Cap-based ignition system assembly

Nozzle cap-based igniters are very useful in complicated rocket motors where igniters can not be mounted at any other location. As it is at the nozzle end, propellant loading at the head end can be improved. This ejectable type of igniter doesn't have any weight penalty on the system during its flight. These igniters are generally deployed in tactical missiles and rockets.

Cap based igniter testing in rockets

THROAT-BASED IGNITER

Throat-based igniters are also useful for compact rocket motors where space at nozzle divergent end cannot be used for configuring nozzle cap-based igniter due to length or diameter constraint, and therefore igniter is mounted on the throat of the motor. The material of construction is chosen to give appropriate ejection pressure and ensure smooth ejection of igniter through the throat without damaging it.

Throat-based igniter with nozzle

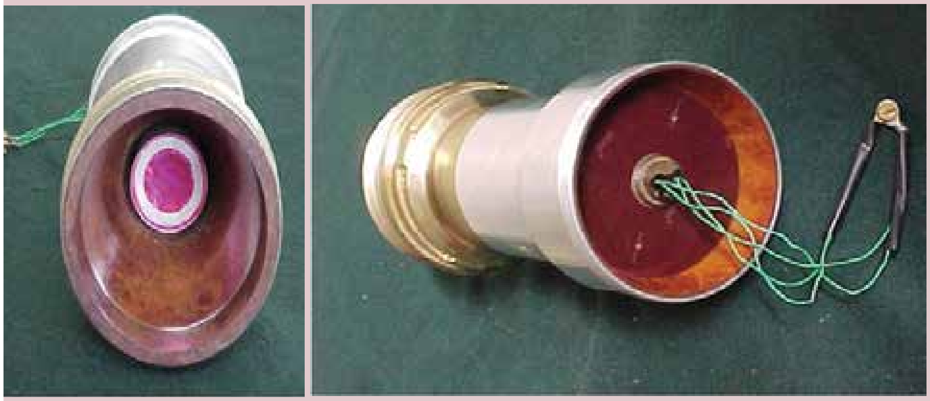
Design Features

- ◊ Igniter is of ejectable type
- ◊ Igniter hardware ensures sealing of gases at the throat using a seal
- ◊ Charge mass consists of gunpowder, $BKNO_3$ granules and pellets, each one for its different purpose
- ◊ O-Ring seating at the neck of the igniter provides sealing at the throat

Operational Features

Throat-based igniter is squib-based ignition system. The squib wires are taken out from the back of the igniter and is held tight at the divergent using a tapered disc butting the divergen to nozzle end. Electrically initiated squib ignites the granules, gunpowder and the pellets. Due to the pressure effect of gunpowder, burning pellets are discharged from the canister into the main combustion chamber. This ignites the propellant surface initiating sustainable ignition. Once adequate pressure is developed inside the chamber, the igniter is ejected from the throat by deforming the collar at which it was held at the throat. To ensure smooth ejection of igniter through the throat, soft material like aluminium is selected as a material of construction for igniter canister.

Throat-based igniters of this composition become very essential in high L/D motors where simultaneous ignition at the head end and nozzle end has to be assured. Similar to nozzle cap based type, this configuration also helps in increased propellant loading and simplified interfaces at the head end. These igniters are generally useful for solid propellant motors of long length.



Throat-based igniter fitted inside nozzle
(Throat view & Divergent view)

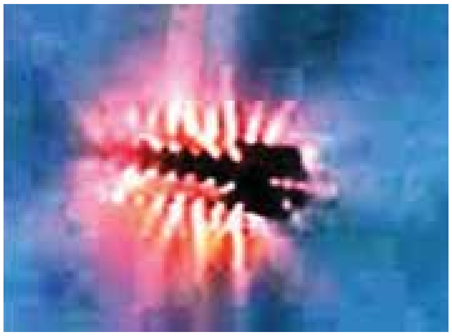
RETAINABLE IGNITER

In many cases, igniters that can withstand the full burn duration of the rocket motor without getting ejected or thrown out are preferred. These igniters are called as retainable igniters. Thermal severity throughout the burn duration is the main concern in protecting these igniter types. Hence the metallic canister, made of Maraging Steel, etc., containing igniter composition, is provided with adequate insulation of carbon phenolic or similar material. These igniters are generally mounted at the head end and in few cases at nozzle end also.

Generally, retainable igniters are initiated using pyro-cartridges. As the deployment of pyro-cartridge can be at the end of all assemblies, it is preferred from the safety point of view during storage, transport and testing of bigger missiles. Compared to squibs, pyro-cartridges are robust in design.

Design Features

- Pyro-cartridge based initiation
- Igniter canister is having outside thermal protection
- Thermal insulation to remain intact during 15-25s of burning duration



Standalone testing of retainable igniter

Retainable igniters

Operational Features

Pyro-cartridges are used to initiate the igniter charge mass. The charge mass, that is in the form of pellets, burns and produces gases, that emanate from the multiple flash holes. The igniter functions only up to 50 ms maximum whereas once the rocket motor starts, the igniter has to withstand high temperature and motor pressure externally. The insulating material protects the internal metal canister even after charring and mechanical erosion.

The retainable igniters are required in long duration motors where ejection of igniter is not possible. During the complete burn duration of the motor, the igniter sustains the severe thermal environment. Generally these igniters are positioned at head end of the motor.

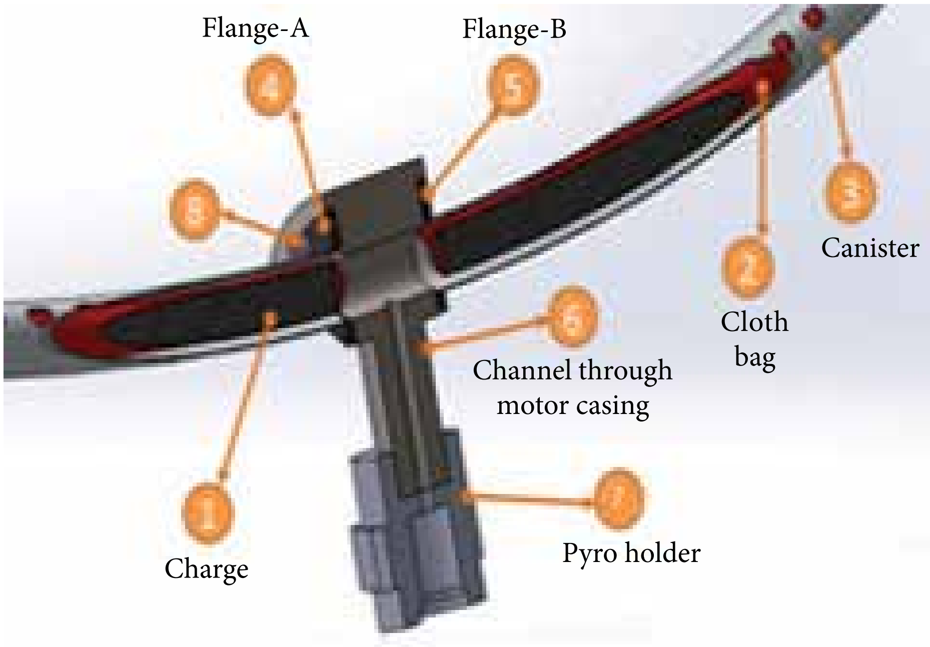
CONTINUOUS MULTIPOINT INITIATION IGNITER

HEMRL has developed igniter for Toroidal motor. The motor has a unique toroidal shape with mean diameter of about 2 meters and 8 equi-distant nozzles. The motor has composite propellant with 11 pairs of total 22 ports.

Igniter scheme consist of 8 arc-shaped Aluminium cylindrical tubes of 0.5 mm thickness connected to each other by a T-shaped adaptor to form a circular ring of about 2 meter diameter which matches exactly with PCD of propellant ports. The Aluminum tubes are filled with total 384 g of BKNO3 composition.

Design Features

- ◊ Simultaneously initiated from multiple points using pyro-cartridges
- ◊ Igniter is torroidal in shape
- ◊ Total igniter is divided in to multiple segments from convenient fabrication and assembly point of view but functionally it's a continuous igniter
- ◊ Canister material is consumable as it is located at nozzle end



Ignition train

Igniter hardware

Open testing of igniter

Operational Features

- Initiator located at pyro holder is initiated by electric source
- Pyro flash travels through an annular channel in a motor casing and gets diverted in two opposite directions to initiate two igniter segments
- This is one interface likewise there are multiple interfaces equi-spaced along the circumference

Such igniters are useful for simultaneous ignition of multiple ports placed over large PCD. They are also useful for high free volume motor (upto 100 L) and used where high redundancy for initiator is required

Through Bulk Head Igniter

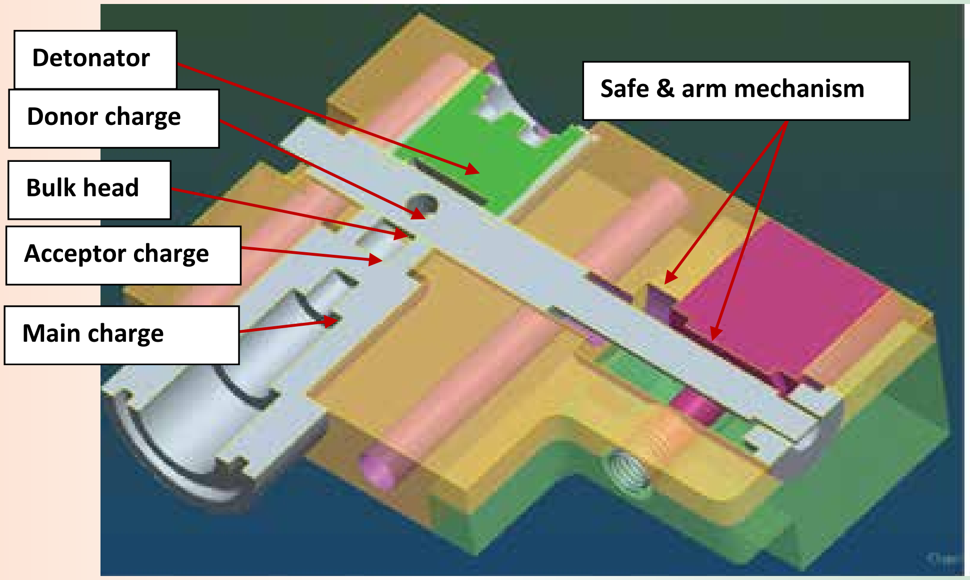
Through Bulk Head Initiation (TBI) is a novel method of initiating solid rocket igniters. This method eliminates some of the safety problems associated with initiation by electro explosive devices. In this method, a detonation shock wave is transmitted from a donor charge through a solid metal interface to an acceptor charge that initiates the deflagration of pyrotechnic composition. The metal interface, or Bulk Head, normally an integral part of the initiator body, remains intact and thus retains the integrity of the seal.

Design Features

- Detonation-based initiation using detonator
- Safe & arm mechanism mechanically isolates the initiator and main charge
- Simple mechanical arrangement with minimum working parts & easily adaptable for placement outside the motor case

Operational Features

- The energy source that provides the stimulus for the initiation ignition process is 24 V DC batteries



Through Bulk Head Igniter: Sectional View

- The electric pulse initiates detonator
- Detonator initiates donor charge in confined volume to generate a shock
- This shock further travels in channelized path through a solid metal interface (Bulk head)
- Shock wave is transmitted from a donor charge through a solid metal interface (Bulk Head) to an acceptor charge
- Acceptor charge further initiates the deflagration of the main charge
- Safe and arm mechanism prevents the unintended activation of the main charge before arming, but allows activation thereafter upon receipt of the appropriate stimuli

TBH is useful for all tactical & strategic missiles and can be used with confined detonating fuses to provide simultaneous ignition of multiple motors.

THROUGH AIR INITIATION IGNITER

This typical design of Through Air Initiation Igniter (TAII) is useful when mission requirements add constraints on the location of initiation system resulting in aerial interconnectivity between initiator and igniter.

Design Features

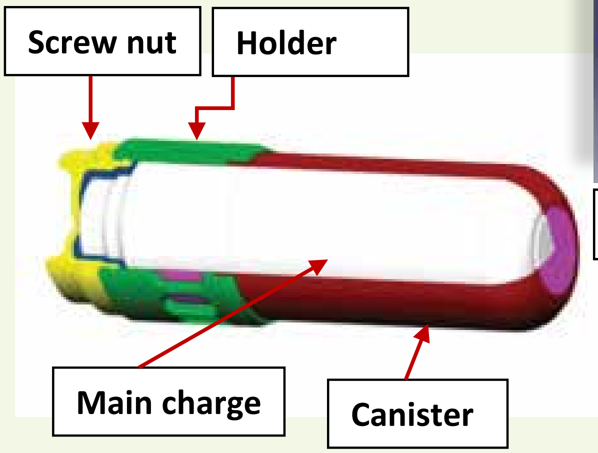
- Pyro-cartridge base initiation
- Generally located at the interface of two motors
- Pyro-cartridge flash travels through the air to initiate the main charge
- Weaken portion at the igniter base of igniter (Holder) provides entry to the pyro flash
- Special material is required to make holder as it acts as a weak portion as well as insulator

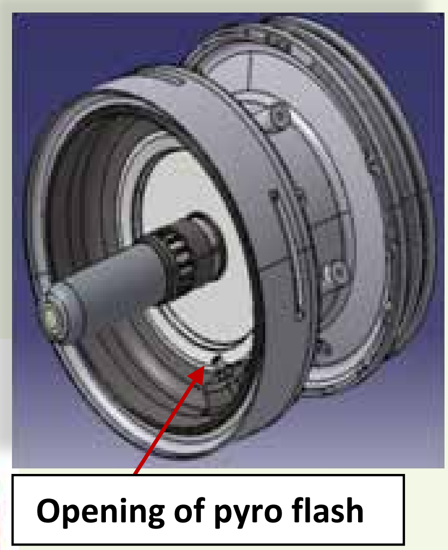
Sectional views of igniter with components are shown in the Figure.

Operational Features

- An electric pulse initiates pyro-cartridge
- Pyro-cartridge flashes travel through air and impinge on the weak portion of igniter.
- This flash further initiates the deflagration of a main charge

TAII is useful for air-to-air missile with nozzle less booster. Also used in missiles where initiation is possible only from lateral side





SPECIAL PURPOSE MACHINES

AUTOMATIC SIEVE SHAKER

The composition preparation involves sieving of the high energy materials through sieves of various sizes to obtain material of particular particle size and to achieve a uniform mix of fuel and oxidiser. Till recently, the process of sieving the pyrotechnic High Energy Materials (HEMs) was carried out manually. At present, the sieving process is automated to improve safety and eliminate the risk of the manpower involved. An Automatic Vibratory Sieve Shaker is acquired to achieve the above goal. It is remotely operated. By using multiple decks on the machine it is possible to sieve the material through multiple sieves one after another in a single step which reduces the operation time considerably.

STOKE'S OSCILLATING MACHINE

The oxidiser in the composition is a highly hygroscopic material and easily forms lumps. Before using the oxidiser for the formulation, lumps are required to be converted into granules of the desired size. Lump breaking and granulation of the oxidiser is achieved by using an automated machine based on Stoke's Oscillating machine principle. In this machine, the material is passed through sieves of various sizes so as to obtain granular material of particular particle size. The machine can be used for granulation of the composition also which is in the form of semisolid dough after mixing.

Using this Horizontal-axis Oscillating Granulation System one can granulate materials in both dry and wet forms. The system reduces the operation time involved in granulation and increases production efficiency significantly.

VERTICAL PLANETARY MIXER

Earlier preparation of pyrotechnic composition involved dry mixing of fuel and oxidiser. Dry mixing of fuel and oxidiser is a hazardous operation which was required to be replaced with an automatic and remotely operated machine.

HEMRL has developed and demonstrated the wet mixing process for pyrotechnic compositions. In this process, fuel and oxidiser are mixed into the binder solution in the desired quantity in number of installments. The mixing cycle detailing about the time of mixing, rpm of mixing, etc. ,is finalised. The obtained slurry is then granulated and the composition is evaluated for validation of ballistic and mechanical properties.

The Vertical Planetary Mixer is used for mixing the ingredients. The mixing is automatic and remotely operated giving enhanced safety during the operation.

AUTOMATIC GRANULATION MACHINE

Pyrotechnic composition prepared after mixing is in the form of slurry, which can be converted into a soft dough after overnight maturation. Granules of the pyrotechnic composition of desired sizes are to be formed from this dough by the granulation process.

HEMRL uses general process of wet granulation which is based on the principle of continuous breakage of larger particles into smaller particles by application of compressive force against a sieve of suitable size. However, the process of wet granulation necessitates the use of suitably smaller sized lumps as the input material, which is gradually converted into smaller granules. A machine has been designed to accomplish the manual granulation processes using two separate sub-systems, viz., lump making and granulation system.

In lump making, the large mass is converted into smaller lumps by extruding the dough through hydraulically operated piston cylinder mechanism wherein the cylinder is utilized as the mass holder for the pyrotechnic material. The extruded material is cut at regular intervals into smaller lumps.

Granulation system comprises mixing chamber assembly and impeller assembly. The mixer chamber is a hollow cylindrical metallic container in which the pyrotechnic composition is fed. Fixed impellers with rollers made up of conductive Teflon material and brush/wiper are assembled inside the cylinder. The metallic cylinder is provided with sieves of the required sizes.

Impeller assembly is stationary and fixed to the outer machine structure.

The cylindrical metallic container rotates about its own axis powered by a flameproof electric motor via a reduction gearbox. The function of the impeller is to push the explosive material through the sieve so as to achieve the required granule size. In order to vary the pressure applied, the system is designed with provision for varying the gap between rollers and sieving net using a screw thread-nut mechanism.

Granulation is a highly hazardous process. Therefore, the precise control over the granulation process and unmanned operation with highest safety, which was required has been achieved with this system.

AUTOMATED PELLETIZING MACHINE

Pyrotechnic composition is used either in the form of granules or pellets of different sizes. HEMRL has established a remotely operated automated operation which ensures the safety of the working personnel during this hazardous operation.

The machine has a rigid cast iron single piece body. The main shaft is driven by a 2 HP electric motor mounted on the rear of the machine. The drive is through a variable speed pulley (v-belt) with speed reduction ratio of 2:1, furnished with high efficiency worm gear drive. The main shaft is running in bronze bearings.

The automatic and adjustable pressure release system offers positive protection against the use of excessive machine pressure. Machine provides flexibility in adjusting numerous mechanism parts for desirable operation, i.e., Automatic Release Mechanism, Variable Speed Adjustment, Pressure Adjustment, etc.

MODELING AND SIMULATION FACILITY

Combustion of pyrotechnic charge inside igniter canister and the flow of resulting gaseous and solid products inside the rocket motor chamber is a quick transient phenomenon and critical for smooth ignition of solid propellant. The flow of igniter combustion products inside the initial pre-ignited solid propellant port and subsequent transfer of energy to propellant surface by conduction, convection and radiation governs the ignition transient. The information regarding pressure, temperature and the velocity of combustion gases inside the rocket chamber can help in ensuring reliable ignition of propellant and thus aids in the initial stage of the igniter designing.

HEMRL has developed a numerical model, which can simulate the flow of gases produced due to pyrotechnic igniter inside an inert rocket motor chamber. The model takes into account the flow of gases external as well as internal to the igniter canisters.

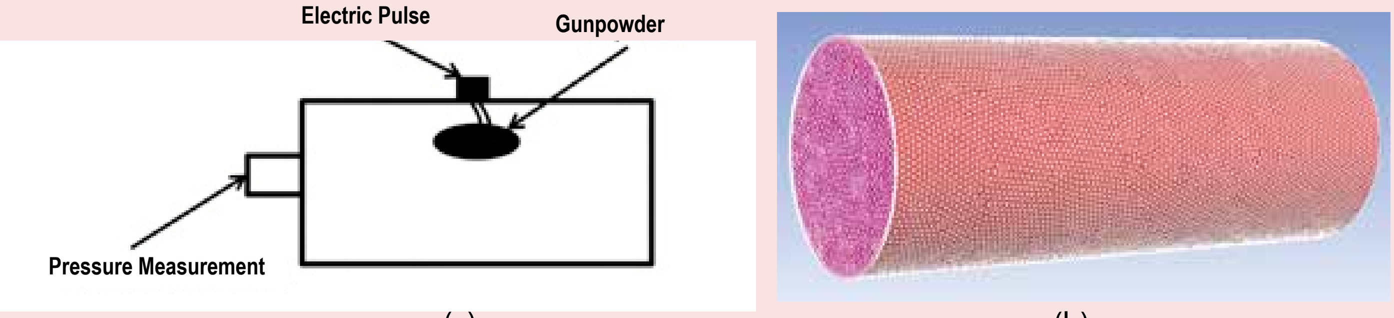
The numerical model is three-dimensional, unsteady, and 2nd Order Implicit with viscosity defined by the standard k-ω model. No-slip condition is assumed at the boundary wall of the motor. Heat loss to the surrounding is neglected, as the burn duration is small. Mass and energy generated by the combustion of a pyrotechnic charge are released inside the igniter canister. The mass generation rate is calculated using a pseudo-average-burn rate approach. The pseudo-average-burn rate approach allows for the prediction of mass generation of charge having regular as well as irregular shapes. The energy release rate is computed by obtaining the product of the mass generated and calorific value of the charge.

Commercially available CFD solver – ANSYS Fluent is utilized for modeling using the in-built User-Defined Function (UDF) utility. Openly available NASA-CEA software is used to compute the required properties of the gaseous mixture. The flow is computed for the entire duration of the burning of charge and profiles for variation of pressure, temperature and velocity inside the motor are obtained.

The model validation is carried out by comparison of predicted and experimental pressure-time profile for Gunpowder composition in granular form having a mean size of 5 mm. The closed vessel and simulated volume inert motor experiments have been carried out in which a fixed quantity of gunpowder is fired and pressure-time data recorded. A very good match is obtained between the experimental and predicted P-t profiles.

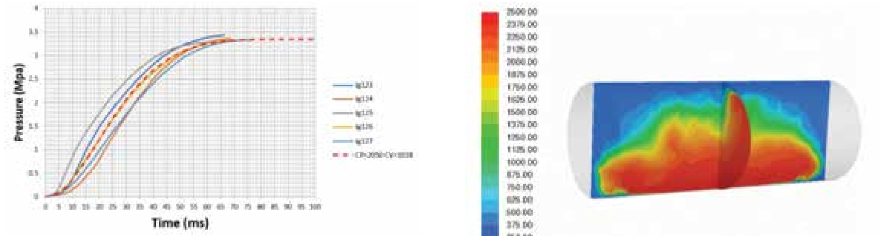
Results

Closed Vessel Test



(a) (b)

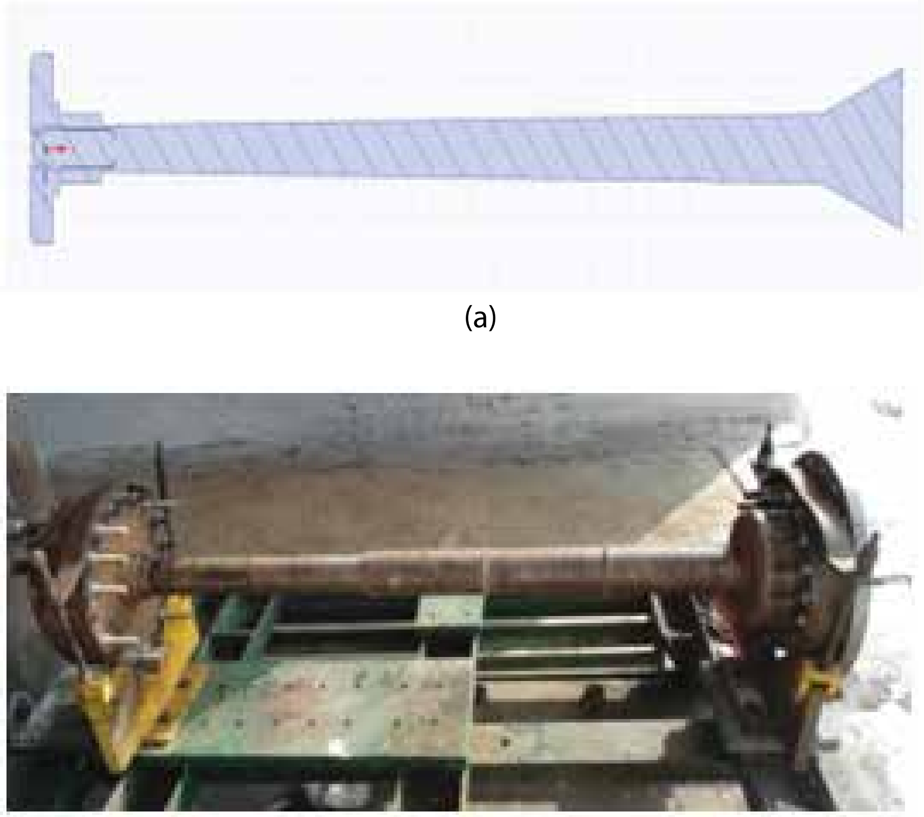
(a) Schematic of Closed Vessel Test Setup
(b) Cylindrical Mesh created for Closed Vessel simulation (700 cc) consisting of 1,99,555 cells



(a) (b)

(a) Comparison between experimental and predicted pressure time profile inside the closed vessel
(b) Temperature distribution inside the closed vessel at time instant t=5 ms

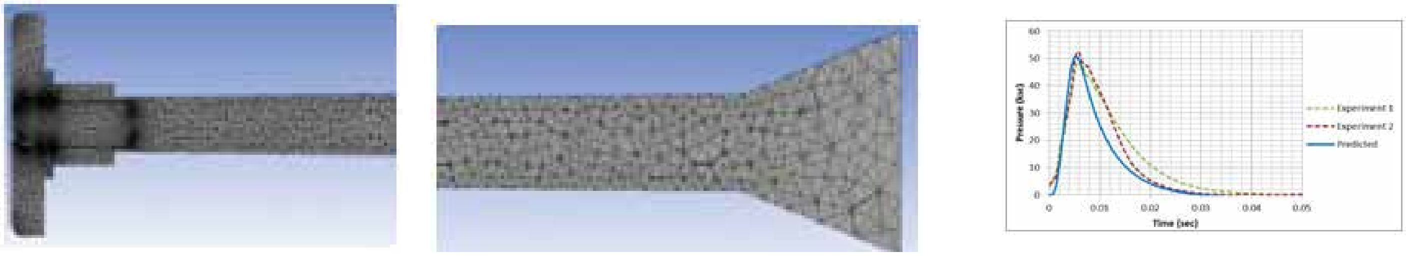
Vented Vessel Test



(a)

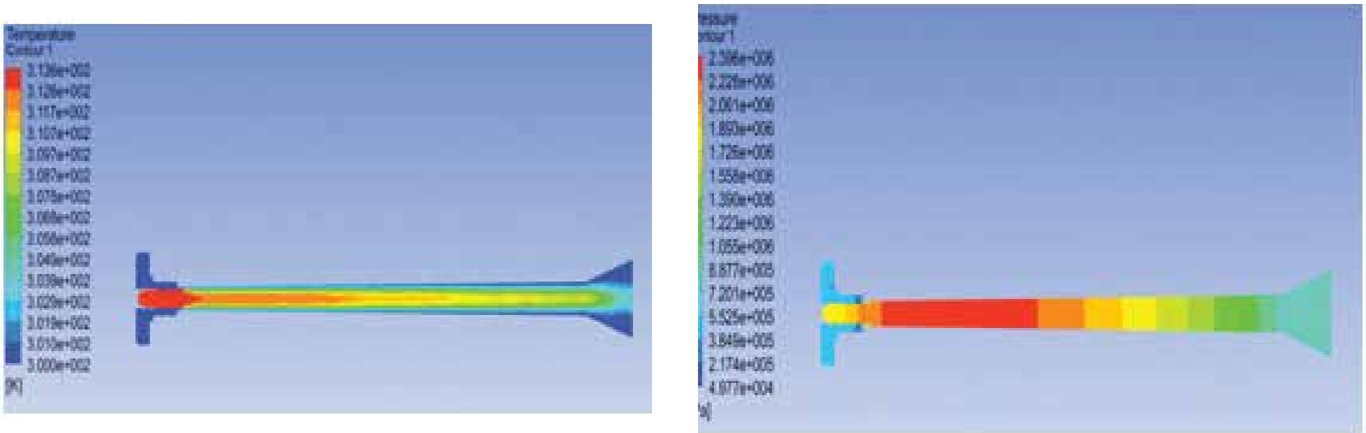
(b)

(a) Schematic of rocket motor and igniter test setup
(b) Experimental test setup for inert motor test



(a) (b)

(a) Mesh generated for rocket motor analysis
(b) Comparison between experimental and predicted pressure time curves for inert motor test



(a) (b)

(a) Temperature contour inside rocket motor after 0.2 ms
(b) Pressure contour inside rocket motor at 1.5 ms

FUTURE WORK

The numerical model for simulating flow of combustion gases of igniting composition can be further developed to take into account pellet dispersion and individual pellet combustion although such model would be highly demanding of the computational power. Hence, a judicious approach and suitable approximations will be needed to be applied while modeling them.

In the present model, the volume occupied by the solid charge is very small compared to the volume of the motor. Hence, to avoid computational complications, the region occupied by the charge is also considered to be part of free volume of motor. The model can be further refined to deduct the volume occupied by the charge for motor-free volume and increase the motor-free volume as the charge regresses.

Also by appending model for solid propellant ignition, combustion and regression to the igniter model, an ignition transient model can be developed.

DESIDOC thanks Dr (Mrs) SD Kakade, Sc 'G', Asso. Director; Mr Shrikant Ghogale, Sc 'F', Group Director; Dr (Mrs) Varsha Bhingarkar, Sc 'E'; Mrs Sukeshni Rawal, Sc 'E'; Mr Vijay Kale, Sc 'D' and Mr Navin Dahiwale, Sc 'D' of High Energy Materials Research Laboratory (HEMRL) for bringing out this issue of Technology Focus.

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I, Alka Suri, hereby declare that the particulars given above are true to my knowledge and belief.

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