The First Steps Towards Self-Reliance in Solid Propellant Rockets

Prof. Rajaram Nagappa

India's standing in solid propellant technology today matches with the best in the world. Some of the largest solid propellant motors in the world power India's launch vehicles. And a still larger solid propellant power plant will power the GSLV Mk III experimental flight later this year. The seeds for this level of achievement and growth of this essentially homegrown technology were sown in the 1960's.

I was always fascinated with aeroplanes and enrolled for Aeronautical Engineering course at the Madras Institute of Technology (MIT). MIT, which was established in 1949, was the only institution in the Country those days to offer a course in Aeronautical Engineering at the Graduate level (the course at the Indian Institute of Science was at the Master's level). MIT was a compact institute with an intake of 100 students every year and the strength of the Aeronautical Engineering course was only 10 per year with the result the faculty-student interaction was rather strong. The added advantage was the Aero faculty boasted of some outstanding teachers, who instilled in us sound theoretical and practical knowledge. The syllabus included a course on rockets and missiles.

The Indian Space Programme came into being with the establishment of Thumba Equatorial Rocket Launching Station (TERLS) and the launch of the first sounding rocket, the US supplied two-stage Nike-Apache on 21 November 1963. Dr Homi Bhabha and Dr Vikram Sarabhai founders of the Indian space programme foresaw the necessity of indigenous capability in the development of sounding rockets followed by capability in the development of satellite launch vehicles. In 1966, the Atomic Energy Commission had approved the establishment of Space Science and Technology Centre (SSTC) for this purpose. I joined SSTC as Senior Technical Assistant in January 1967−I was the thirtieth member in the newly found organisation. The people who had joined ahead of me had specialized in branches of engineering relevant to aerospace and some of them had been trained for brief durations in Japan, in the laboratories of the Institute of Space and Astronautical Science (ISAS). One of the ideas, the propulsion and chemical engineers had picked up was to test the initial designs in a small rocket motor* called the pencil rocket. Back at SSTC, this idea was utilized for the initial development of propellant systems.

* the power plant of a solid propellant rocket is generally referred to as 'motor'

The solid propellant motor has no moving parts. The propellant consists essentially of an oxidiser−ammonium perchlorate commonly used−in a matrix of fuel binder. Quite often metal powder like aluminum is added to increase the propellant density and energetics. The propellant has the consistency of hard rubber (Shore hardness in the region of 70). The burning surface at any given instant of time influences the chamber pressure and thrust produced by the motor. The propellant is therefore, cast with different core shapes like star, wagon wheel, dendrite, fins and slots to provide the desired burn surface regression. The other controlling parameter is the propellant burn rate, in which the ammonium particle size plays an important role.

In SSTC at that time, there was no organized structure; the reorganization into discipline based divisions and groups happened much later. The engineers had taken up development task in their respective areas of interest and consequently, there was some level of duplication. I joined SN Prakash, who was engaged in propellant development and propulsion system design. Propellant formulation was a trial and error approach. Laboratories were yet to be set up and only rudimentary equipment was on hand. The laboratory was an old house inherited when the fisher folk of Thumba were relocated to establish the Rocket Launching Station. Early experiments involved composite propellants comprising Ammonium Perchlorate (AP) in a polyester resin binder. Pestle and mortar was used for hand grinding the AP; a laboratory stirrer powered by a small motor was used for blending the resin and plasticizer; an egg-beater served the purpose of mixing the resin and AP; finally, the thick paste was filled and hand rammed into the rocket chamber in which the central core had been earlier located followed by curing in an oven. Most of the propellant formulations used polyester resin as the binder along with minor quantity of plasticizer. Variations in the percentage composition of the fuel and oxidizer were tried. A few compositions were tried with epoxy resin. If the propellant preparation setup was rudimentary, propellant property measurement and inspection was mostly absent.

The rocket chamber was a thick mild steel tube of 50 mm diameter designed with a large factor of safety. It was closed at the fore and aft ends by flange with openings for placing the igniter and nozzle block respectively. The assembly was held together with four tie rods with a notch in the centre. These motors were referred to as Rohini 00 motors or RH00 for short. (Dr Sarabhai had chosen to name the indigenous development programme as Rohini rockets—in fact the engineers in SSTC were referred to as Rohini Engineers). The idea of using a heavy walled tube was from considerations of a) withstanding pressure excursions beyond the design pressure and b) refurbishment and reuse of the hardware. The notch in the tie rod was designed to fail if abnormal pressure excursions occurred. This was a handy pressure relief system as in the initial days of development there were many cases of overpressure and failure. The motor is schematically shown in figure 1.

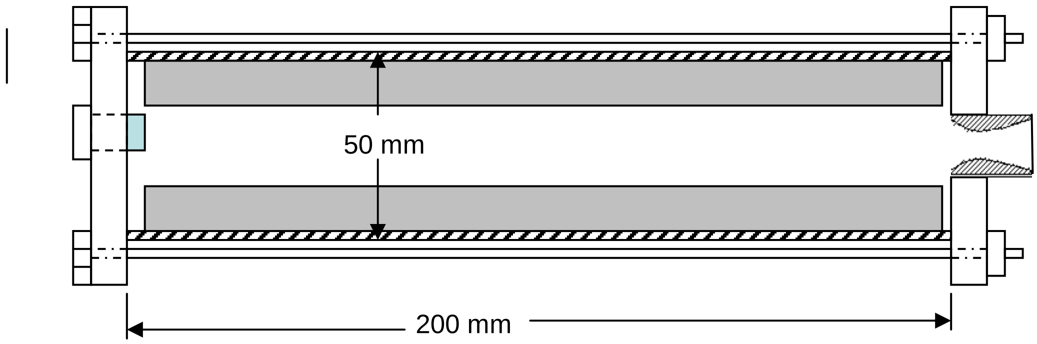

Figure 1: RH-00 Motor

A number of trials had to be done before a propellant grain without visible surface cracks could be obtained. Buried cracks and debonds went unnoticed. Visual examination was the only technique and internal cracks were obviously not always visible to the eye. A strand burner had been designed and fabricated and was used to measure the burning rate of the propellant samples. The igniter was characterized by doing a closed bomb test. For this the setup was taken to the NASA supplied DOVAP trailer for recording the pressure transient.

A small test stand had been put in place at Veli hill. I used to carry the assembled RH-00 motor, a 12-volt lead-acid battery, an igniter tester and the firing console in a jeep to Veli hill every time the motor had to be tested. The approach road to the test stand was not motorable and the motor and the test paraphernalia had to be carried by hand for the last 200 m. The precautions taken were to earth the rocket motor on the test stand, keep the igniter wires shorted till the final connection was made and keep a safe distance from the motor while it was tested. The manual filling of the propellant into the chamber resulted in blowholes and gaps. This in addition to the cracks not visible to the naked eye resulted in quite a few explosions during the static tests. There were instances of non-ignition as well as hang fire. The latter was quite unpredictable—as one was not sure, if the grain would ignite after some time or not. In such an event, a healthy waiting period of 30 minutes was observed before approaching the test article. In addition to these precautions, the humid weather of Trivandrum was perhaps helpful in preventing buildup of static charge or we were plain lucky—during this period, there were no accidents.

The hardware though simple took some effort to fabricate. Inhouse fabrication facilities were just coming up and Trivandrum did not boast of any major industrial support infrastructure. The Industrial Estate in the Pappanamcode locality had some workshops and the fabrication of the hardware was carried out there. This demanded conservation and reuse of hardware. The notched tie rods came in handy for pressure release in many cases. It was the aft-end flange with the nozzle which used to be ejected away either due to overpressure or due to the bolts giving away and would get lost in the dense bushes in the neighbourhood of the test stand. An ingenious method of retrieving the flange and the nozzle assembly was adopted by drilling an extra hole in the flange. A nylon rope was threaded into this hole and knotted. The other end of the rope was anchored to a coconut tree. The ejected nozzle after the test was hauled in, inspected and reused.

For the tests, which performed satisfactorily, the only parameter that could be measured was the burning time using a stopwatch. This was remedied when the instrumentation setup was commissioned in a room adjacent to the test stand. The instrumentation comprised at that time pre-amplifiers and a recorder to record the chamber pressure and rocket motor thrust. Pressure transducers were commercially procured along with a dead weight tester for calibrating the transducer. A load cell, designed inhouse and fabricated in the workshop was used for measurement of thrust. A tensile testing machine was used for calibrating the load cell. As the transducers were available in limited numbers, their deployment was done with great deliberation, after testing a few RH-00 motors without instrumentation and ensuring a level of certainty and repeatability of the stopwatch measured burning time. One can still recall the excitement when the first measurement of pressure and thrust was done. Analysing the data for the exact burn duration, the achieved pressure and thrust provided a level of validation to the design calculations.

RH-75: India’s first indigenous rocket

It was around mid-1967, when Dr. Sarabhai decided that the training and experimentation had provided enough knowledge and should be put to realization of a system. The engineers had shown him some tests and presented their ideas of the laboratory and facility requirements to proceed further with the tasks. Sarabhai decided that two teams would independently build a 75 mm diameter rocket called the Rohini 75−RH75 for short. The rockets built by the two teams were designated as Mk I and Mk II. The exercise, if one may term it so, involved the design and development of the complete rocket systems and its flight test. RH75 would be an unguided rocket; meant for learning; the requirement was it should be able to take off and perform a stable flight; and no payload or performance target was set.

The Mk I team was led by Y Janardana Rao, an aerodynamicist who had worked extensively with NASA prior to joining SSTC; AE Muthunayagam would take care of the propulsion and the mechanical engineering aspects of hardware design and realization. CV Ouseph would work on the propellant development. MC Mathur, also an aerodynamicist, who had worked with Bristol Aerospace in Canada, led the Mk II team. SN Prakash supported him for the propulsion and propellant systems. R Vivekanandan would provide the aerodynamics support to both the teams. Both the teams started off in right earnest chalking a development and rocket realization strategy.

The enunciation of the RH75 development provided opportunity for fresh recruits like me to get involved in the design and development activities. By then I had applied against a post in the Mk I project and had been selected as Engineer SC. Besides me, two more engineers had joined the Mk I propulsion team.

The key element was the propellant and both the teams concentrated on this aspect. This was a slow process as the propellant facilities were still being set up and some facilities had to be shared between both the teams. Also, though computer programme for propellant combustion had been developed, the formulation *per se* was still a trial and error approach and the yield was poor. At this point we came to know that the Cordite Factory at Aravankadu (CFA) in the Nilgiris was producing extruded double base propellant grains, which was 67 mm in diameter. The diameter of the propellant grain was close enough to the design diameter of the RH75 rocket. It was felt engineering the rocket around this grain would save precious time and the Mk I team could chalk up an early success. The propellant could be substituted once the indigenous development came through.

An expedition to Aravankadu indeed confirmed the availability of solventless cordite blocks with the factory designation SU/K. The propellant grain had a seven point star inner geometry and length of 550 mm. The factory had a stipulation of a minimum order quantity that was far in excess of our development requirements. In the absence of an alternative, we ordered nearly a tonne of the propellant. When the batch was ready, we requisitioned a jeep with trailer from the transport section and drove up to Aravankadu to collect the propellant. There were no explosive vans available in SSTC/TERLS complex—even the sounding rockets received from the US and France were unloaded at Cochin port and transported by trucks to Thumba with a pilot escort. Safety features enforced during transport were the speed limit and an earthing chain on the vehicle for grounding any built up charge.

For the Project team, speed of accomplishment was as important as a good design. Rather than design and fabricate the rocket casing, a survey was done to see what was readily available in the market. The Indian Aluminum Company (INDAL) was manufacturing extruded seamless aluminum tubes and aluminum rods. It was decided the tubes could be used for the rocket chamber and appropriate machined lengths of the aluminum rods could be used for the fore and aft closures for the chamber with appropriate openings for the nozzle and igniter. A check showed that the wall thickness of the tube was adequate for the design maximum pressure with necessary factor of safety. INDAL agreed to fabricate a die and extrude the tubes to our requirements, but insisted that a minimum order quantity of 1 tonne had to be placed. Orders were placed for Aluminum tubes of 75 mm diameter with wall thickness of 2 mm and aluminum rods of 75 mm diameter. The alloy offered by INDAL was B51SWP, a solution treated and precipitation hardened alloy whose ultimate tensile strength was around 280 MPa.

The rocket motor length was obviously dictated by the propellant grain in this instance. It was felt that a single cordite grain of 550 mm would be too short and to have some meaningful thrust and performance, a longer length was desirable. The engineers at CFA had informed us that the grains could be bonded by applying acetone on the surfaces to be bonded and maintaining slight pressure. Bonding two lengths of the cordite grain to achieve a grain length of 1100 mm was an obvious conclusion. The grain ends were chamfered and bonded to realize the full length grain.

In a solid propellant rocket, the chamber pressure is dependent upon the propellant burning surface area at any given instant of time and the nozzle throat area through which the combustion gases are exhausted. In the RH-75 design, a design issue came to the fore. The nozzle throat had been arrived at to maintain the maximum pressure within the capability of the case material. This resulted in a throat diameter which was larger than the initial port diameter of the grain, which was contrary to normal design practice. My calculation showed that this will lead to overpressure as sonic velocity would be reached at the end of the grain rather than in the nozzle throat. We discussed this but I could not convince the team that the pressure achieved will be beyond the case capability. We went ahead with the first test using a heavy walled mild steel proof motor case. The test result showed overpressure as predicted but did not end with catastrophic result as the proof motor had a large factor of safety. The maximum pressure could not be recorded as the pressure transducer showed a flat value corresponding to the saturation limit of the transducer.

In the discussion following the proof motor test, it was decided that the grain port area had to be increased to a value higher than the throat area to ensure that the sonic velocity occurs in the nozzle throat. The centre port of the grain was a 7-point star. It was noted that the diameter of the outer star point was slightly greater than the throat area and it was decided to enlarge the propellant bore equal to the outer star diameter for a length of 300 mm. The grains were taken to the workshop and radial drilling machine was used to machine off the star lobes and render the port circular for a length of 300 mm.

Thankaiyyan was one of the two machinists in the workshop. A well built person, he found drilling into the cordite grain was like cutting butter and we had to constantly remind him to do the drilling slowly. Even while using the coolant, the grain became quite warm. The other precaution we took, was to carry out the work after the main shift was over. Thinking back, I feel the exercise we did was risky, but the spirit and adventure of accomplishment was so great we just went after the job. We managed to drill the cordite grains without any mishap.

The modified grain was tested in the proof chamber and provided good result. The maximum pressure and thrust as well as the burn time matched with the prediction. With this successful achievement, it was time to take up tests with the flight chamber. The flight chamber construction was quite simple. The aluminum tube formed the chamber. Even at the initial stages of design, we realized the importance of thermal management and sealing gas ingress to undesired areas. This called for ensuring not only good bond between the propellant grain and the casing, but also good sealing at the grain termination points and at the hardware joints. For the RH75 this was achieved essentially through resin systems. The outside diameter of the grain was smeared with polyester resin and then inserted into the tube. Polyester resin was then gravity fed into the annular gap between the grain and the chamber to the point of overflow.

The fore-end closure was fashioned from the aluminum rod and housed the igniter. The aft-end closure also used the aluminum rod of a longer length and housed the nozzle. Both the closures were attached to the chamber with twin rows of screws. Araldite applied to the closures prior to assembly ensured gas tightness of the joints. The nozzle used a graphite block for the throat and some part of the divergent. The remaining part of the divergent was made of mild steel and functioned as a heat sink for the hot gases. For the 2 seconds of burning of the motor, this proved to be adequate. A basket type igniter with a charge of black powder and SR 371 was used to ignite the motor. The rocket motor parts are shown in figure 2.

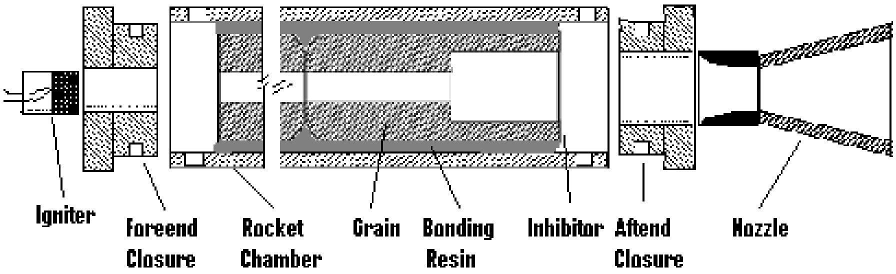

Figure 2: RH-75 assembled motor

The choice of the bonding/filling resin and curator ratio was done with abundant caution. Resin samples were prepared in paper ice cream cups with different resin/curator ratios. The temperature due to the exothermic nature of curing was measured and a ratio where the cure temperature remained below 60° C was chosen. After successful static tests, the motor was integrated with the fin shroud and nosecone. The nose cone was filled with 1 kg of lead−euphemistically called inert payload−to maintain the centre of gravity of the rocket forward and to provide an adequate margin of static stability. The first flight of the motor took place on November 20, 1967 and was tracked by the range radar. The height achieved was 10 km. This was a historic event as this symbolized the first indigenously built rocket to be flown from Indian soil. This would prove to be the stepping stone to further accomplishments in solid rockets. The RH-75 Mk I rocket can be seen in the following picture.

Dr YJ Rao showing the RH-75 flight rocket to Dr. Vikram Sarabhai. The others in the picture are Shri HGS Murthy (extreme left) and Dr AE Muthunayagam (partially hidden by Dr Rao). Shri Murthy was at that time Director, TERLS

The environment at SSTC was informal, competitive and knowledge seeking. Engineers were encouraged to come out with new development ideas and propose technology development projects. New propellant compositions (at a time three agencies were separately conducting propellant formulation trials), different case materials and manufacturing techniques, use of ablative materials and composites all came about during these early years. Experimentation included multi-stage rockets and boosters employing multiple rocket grains. It was a good learning experience, which paved the way in the later years for systematic and organized approach to realizing solid propellant motors for the sounding rockets and launch vehicles.

In the years to follow, I had the privilege of leading the solid propellant rocket team and the team chalked up many significant events. Realization of case bonded motors for the SLV programme was followed by motors with higher energy propellants for the ASLV motors. An improved fourth stage motor with poly aramid (Kevlar) fibre motor case was another achievement. Major technology development in terms of hydroxyl terminated poly butadiene (HTPB) based propellant systems, maraging steel for booster motor case and filament wound Kevlar motor for the third stage, gimbaled nozzle construction for the upper stage were all developed and realized for the motors of the Polar Satellite Launch Vehicle (PSLV). When the PSLV booster with a diameter of 2.8 m and containing 125 tonnes of propellant was static tested in October 1989, it was third largest motor in the world. All elements of the motor were made in house or fabricated/processed by Indian industry. Only few items like fasteners and resin curator, which were not economical to make in view of limited quantity requirements or freely available due to usage in other industries were procured. The present set of solid propellant rocket engineers at the Vikram Sarabhai Space Centre have contributed to further refinements and new systems. They realized and tested in January 2010 a solid motor of 3.2 m diameter and employing 200 tonnes of solid propellant, longer motor segments and employing a submerged gimbaled nozzle for vectoring the thrust for control of the launch vehicle in pitch and yaw directions. With the retirement of the Space Shuttle and Titan IVB solid rocket motors, this motor is next only to the 230 tonnes propellant solid motors used in the Ariane 5 vehicle.

This has truly been a remarkable and satisfying journey.

Note: The development of solid propellant rockets in the Country is brought out in more detail in my recent book "Evolution of Solid Propellant Rockets in India". The book is published by DESIDOC under the DRDO Monographs/Special Publication Series.