Introduction

India is one among the few nations having capability to build satellites, launch vehicles and launch them from its own soil [1-5]. Our Space Transportation Systems (STS) fleet consist of PSLV and GSLV which are currently operational and meets the demand of launches of all the Remote Sensing spacecrafts and communications spacecrafts of GSAT class. India has the capability to define and develop spacecraft systems for communication (INSAT), remote sensing (IRS) and scientific applications (Chandrayaan-1). Space based applications through remote sensing have been serving many areas such as natural resource mapping, disaster management and surveillance. The INSATs are the backbone of the Tele-communication and Television networks in India. Novel applications such as tele-medicine, tele-education has been introduced through these spacecrafts for the benefit of the common man [6-9]. The vision of the founding fathers of the Indian Space Programme has been accomplished fully [1-3]. The vision was to apply the advanced technology of space for solving the problems of the common man and benefit the society at large [10-14]. Now ISRO is treading on a new path with a second cycle of vision. Having established this end-end capability in the space segment, it is important to sustain and enrich the capabilities through the development of cost effective Space transportation systems, Advanced spacecrafts, Contributions in basic science, interplanetary exploration and human presence in space.

The Space Transportation System (STS) is the backbone of the Space segment. The Rocket propulsion technology has remained very closely guarded, due to its duel use nature. It is one of the difficult technologies to be mastered in terms of acquisition of expertise and investments required for infrastructure development. The capability to place our satellites using our vehicles gives us an immense strategic edge and at the same time significant cost effectiveness. The goal of ISRO is to sustain this advantage of mastery over the launch vehicle development in a cost effective manner and extend its wings to the other areas of Space Transportation Systems such as re-usable launch vehicles and Human Space Transportation.

Evolution of Launch Vehicles and Operationalisation of PSLV and GSLV

The development of the rockets in India started in the early 60s at TERLS, Thumba with the launching of small sounding rockets [15]. The development of a Spacecraft Launch Vehicle was the logical route to be followed. The SLV-3 was the learning ground of the new technologies that later paved way for the development of PSLV and GSLV [16-17]. SLV-3 was based on an indigenously developed all solid propulsion technology, with a capability to place a spacecraft of about 40 kg mass in a Low Earth Orbit (LEO) of about 400 km. In addition to the propulsion systems, host of other technologies got developed in the process and new facilities were established.

The Augmented Satellite Launch Vehicle (ASLV) was an SLV-3 derived vehicle with a payload capability of about 150 kg [18-19]. ASLV further advanced the knowledge base of launch vehicle design through the introduction of strap-on technology, bulbous fairing, Closed Loop Guidance (CLG) system, Strap-down Inertial Navigation System [19] etc. The first two launches of ASLV failed to achieve the mission and the analysis of the failure gave valuable inputs to the future developments for PSLV especially in the areas of atmospheric flight dynamics, structural design, control systems design and control transfer algorithm between stages.

The SLV-3 and ASLV (Fig.1) were the learning phase in the Launch Vehicle development. They were not to become the operational launch vehicles. However, the design methodologies, simulation and validation methods, facility elements etc. were established in smaller scale during this programme.

The PSLV (Fig.2) design started during the development phase of the ASLV [18-19]. This vehicle was the designed as the operational launcher for the remote sens-
ing spacecrafts of India, which were being launched through procured launches. Host of propulsion [20] and other technologies were developed during the PSLV programme. The biggest ever solid motor, S125 (later upgraded to S139) and the necessary infrastructure for the production were established. The liquid propulsion second stage was an acquired technology through the collaborative development programme with SEP, France. The third stage solid motor with composite casing was developed which is one of the best solid motor in terms of the performance. The upper stage was using an indigenous liquid engine based on earth storable propulsion technology. Host of other technologies were developed in the area of Control Systems, Avionics, Inertial Systems [21], Mechanisms and Pyros, Simulation and Testing. The first flight of PSLV could not achieve its mission objectives, but it identified certain system weaknesses which were corrected in the subsequent mission. PSLV so far scored thirteen consecutive successful missions.

The GSLV (Fig.3) was developed for achieving the indigenous capability to place a communication satellite using and Indian launch vehicle. The GSLV relied on the technology heritage of PSLV. The new Cryogenic propulsion stage was procured form Russia, which was later developed in-house. It also used liquid strap-on motors for the first time. The very first mission of GSLV was successful [19-23], and placed a 1900 kg spacecraft in the Geosynchronous Transfer Orbit, proving the maturity in the design and development of Launch Vehicle technology.

**Development of GSLV Mk-III**

Commensurate with the growing launch requirements, the next vehicle under development is the GSLV-Mk-III (LVM3) [24] (Fig.4), which is having a capability to place a 4 ton spacecraft in the GTO. With this development, all the communication spacecrafts could be launched through our own launchers. The cost of launching per kg of the spacecraft is brought down by 50% compared to the present launch vehicles.

LVM3 is a three stage vehicle using bigger solid motors with 200 ton propellant loading and a cryogenic upper stage with 25 ton propellant loading and a new engine with 20 ton thrust. The development of the vehicle systems are in the advanced stage and testing of vehicle systems have commenced. It is expected that the first flight of LVM3 will take place in the last quarter of 2010.

**Improvements in Present STS**

PSLV and GSLV are the operational launch vehicles of ISRO. PSLV is a very rugged and versatile launch vehicle, which has demonstrated the capability in carrying out a variety of missions. In PSLV-D2, the payload was 856 kg, which was progressively enhanced to the present level of 1600 kg through a systematic improvement programme involving optimized upper stage design with composite structures, performance improvement for the upper stage solid motor, enhancement of propellant loading in the booster (S139) and strap-ons (PSOM-XL) and increase in propellant loading in second stage (PL-40) and in the fourth stage (L2.5). The PSLV has carried out variety of missions such as GTO mission of Kalpana-1 in PSLV-C4, small satellite missions in PSL-C2 and C3, large inclination planar missions in PSLV-C8 and C9, and multiple spacecraft missions [25] in PSLV-C10, dual launch of two main spacecrafts in PSLV-C7 and C8. In the last mission of PSLV-C11, Indias first Moon Mission, Chandrayaan-1 was launched weighing 1380 kg in a highly elliptical orbit with 22600 km perigee.

The GSLV is capable of launching a spacecraft of 2200 kg in the GTO. With the indigenous Cryogenic upper stage, the payload capability will be further enhanced to 2500 kg. A propulsion module for payload assistance is also being developed for variety of other missions. Fig.5 shows the improvements in the payload capability and the reduction in the launch cost per kg of spacecraft mass to orbit.

**Focus on the Specific Technologies**

Launch vehicle design is a multi-disciplinary technology and integration of these technologies and their interactions at system level is the key. The Space Transportation System development is built around this mastery to engineer and integrate various types of these technologies. A review of few of these areas is made highlighting the developments.

**Aerodynamics, Mission and Vehicle Design**

Aerodynamic characteristics and loads are the primary input for the design of any Aerospace Vehicle. From dependence on analytical, empirical and experimental methods, now there is an increasing shift towards the use of CFD for generating design data. Indigenous capability has been achieved in the CFD area required for the launch vehicles and re-entry vehicles. The PARAS software tool is used along with the results from the wind tunnels.
established in ISRO and other National Laboratories. The availability of low cost computer clusters coupled with large parallel computing capability enables high fidelity aerodynamic study of large number of configurations at the preliminary design stage itself. This is followed by experimental studies which focus on high quality data generation for the finalized design. Keeping in mind the future hypersonic reentry missions of ISRO, a hypersonic wind-tunnel facility of 1m test section capable of simulating flows up to Mach Number 12 is being built at VSSC. A beginning has been made to use CFD in formal Multi-disciplinary Design Optimization (MDO) of re-entry vehicles employing CFD based Artificial Neural Network (ANN) models. In future, such high fidelity aerodynamic configuration optimization will be of routine nature.

The computational and theoretical capabilities for launch vehicle and other advanced missions have been developed over the years. This capability has been amply demonstrated in the recent missions of ISRO such as Chandrayaan-1 and SRE.

India’s historic entry to the club of countries having reentry technology took place on the 22nd January 2007, when our spacecraft reentry capsule successfully withstood earth reentry and was subsequently recovered back into possession. SRE was intended as a technology demonstrator for reentry and recovery of an orbiting module, providing a platform for long duration microgravity experiments in space and also gain confidence/develop basic technologies required for future missions such as reusable launch vehicles and human space flight missions. Important technology developments attained were in aerothermodynamics, development of lightweight and reusable thermal protection system, navigation, guidance and control, management of communication blackout and recovery support systems.

Solid Propulsion System

Solid propulsion has remained the core technological strength on which launch vehicles were configured. ISRO produces world-class solid motors ranging from very small motors weighing few grams to very large boosters weighing up to 200 tons. The spin motors used in Moon Impact Probe (MIP) has only 6 gm propellant were as the booster of LVM3 has 200 ton propellant loading. The HPS3 motor of PSLV third stage is one the world class with a mass fraction of 0.92 and Isp of 295s. A comparison of the biggest solid motors of the world with S200 motor of LVM3 is made in the Table-1.

<table>
<thead>
<tr>
<th>Table-1 : Comparison of Major World Boosters</th>
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<tr>
<td>Parameters</td>
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<tr>
<td>Mass ratio</td>
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<tr>
<td>Action, s</td>
</tr>
<tr>
<td>Thrust, kN</td>
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<td>Press, ksc</td>
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<td>Isp (vac), s</td>
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The progression of this technology and the present capability is due to the mastery in the following critical technology elements

- Achieving high solid loading of the propellant to the extent of 86%.
- Development of efficient fuel binders like HTPB.
- Development of high strength materials such as Maraging steels and the necessary fabrication expertise.
- Development of case bonding technique instead of free grain charging.
- Improvements in mass ratio up to 86% in large boosters and 92% in upper stage composite motors by reducing the inert and increasing the volumetric loading.
- Development of facilities for production of propellants, propellant processing, testing of motors and predictions.

Capability has been established in terms of software and hardware design for carrying out a wide range of analysis like performance prediction, thermal analysis and thermal protection systems, grain and other structural designs, flex nozzle technology etc. These design have been validated through the data obtained from a number of simulation subscale tests, proof pressure tests, static tests and various flight measurements.

Aluminum composite propellant system with HTPB binder are used in all motors due to its higher specific impulse, better mechanical properties, better castability, and higher safety. However, constant effort is being taken by the R&D group to improve and modify the system through developing better bonding and curing agents, inclusion of high energy oxidizers such as HMX, use of nano-aluminum etc. The production of the ingredients of the propellants has been established in Indian Industries and within ISRO.
**Liquid Propulsion Systems**

The development of the Liquid Propulsion Systems started in the 70s and found its way into the control systems of SLV-3. Today we have a wide range of liquid engines with thrust levels of 1 N to as high as 600 kN. Different types of liquid propulsion systems were developed based on Mono Propellants, Bi-propellants, Hypergolic and non-hypergolic types. The second stage and upper stages of PSLV are earth storable liquid engines which are being produced in the industry. The high performance pressure fed-engines of the upper stages and spacecraft engines are the products of in-house development.

The Cryogenic Engine Technology has now been mastered with the successful long duration testing of the 9 ton engine to be used for the upcoming GSLV flights. Facilities have been established in the Liquid Propulsion Systems Centre (LPSC) at Mahendragiri facilities for the integration and static testing of the engines and stages.

**Materials and Structures**

Indigenous development of ultra high strength grade Maraging steel, with yield strength as high as 1800 MPa, enabled the realization of world-class solid booster casings for our launch vehicles. Processing of Electro Slag Refined (ESR) grade high strength low alloy (HSLA) 15CDV6 steel plates and rings and mastering of their welding and heat treatment technologies is another critical development.

Development of new material for lighter, stronger and stiffer metallic alloys, e.g. Al-Li alloys, high temperature Ti-alloys such as Half Alloy square tubes for inter-stages and high specific strength Beta titanium alloy for pressurized gas bottles are important developments. A variety of austenitic and semi-austenitic stainless steels, super alloys, copper-zirconium alloy, refractory metal Columbium based alloy, powder metallurgy products such as Nozzle Throat Inserts, bi-layered copper-tin seal rings and silver-graphite composite brush blocks, bimetallic adaptors based on alloys of stainless steel and aluminium alloy were also developed. Maturing of composite technology has provided high strength/stiffness low weight structures such as the Kevlar/Carbon fibre motor cases, nozzle back-ups, CFRP heat shield, inter stages and payload adaptors has improved its payload capability.

A range of developments in special chemicals were undertaken such as special propellants, special thermal paints, adhesives, rubber elements, potting compounds, primers, optical films, and thermal screens for cryo inter-stages. Expertise in high temperature materials such as Carbon-Carbon, CMC, SiC, Silicide, Zirconia coatings are also attaining maturity.

Establishment of a world-class Cast House at BALCO to produce highest quality billets and Ring Rolling Mill at M/s Bay Forge, Chennai to process rings upto 5m diameter are the noteworthy milestones in the establishment of indigenous capability within the country.

Investments are being made to develop expertise in hot structures, Shape Memory Alloys and Metallic TPS for light, thermal barrier coatings and efficient structures.

Another critical thrust area is Nano materials, which involves developing CNT based Metal Matrix Composite structures, Functionally Graded Materials, CMC, Nano Polymers and Smart Materials and the thrust areas for the future.

**Avionics, Navigation Guidance and Control Systems**

The avionics systems for the launch vehicles are mainly the Navigation, Guidance and Control (NGC) systems, telemetry and tele-command systems and power systems. These systems have been developed indigenously and used in all the ISRO missions successfully. The design capability exists within ISRO and the production is through industry. In the inertial sensor area indigenous capability has been achieved with ISRO sensors being used in all the spacecraft and launch vehicle missions. The accuracy of the spacecraft injections achieved speaks of the quality of the inertial sensors.

Guidance System controls the translational dynamics while the Digital Auto Pilot (DAP) controls the rotational dynamics. Navigation has the vital role of measuring the translational and rotational states of the vehicle. The acceleration and rates are integrated to compute the Euler angles, velocity vector and position vector. Closed Loop Guidance (CLG) system generates optimum steering commands based on the states measured by navigation. After the development of algorithms like E guidance, FE Guidance and VG guidance schemes, a Unified Guidance scheme which is a single algorithm that can be configured for different vehicles and missions is being developed.
The control actuation systems and their power plants are the back bone of the NGC system. They follow the commands and steers the vehicle through the required trajectory. Various types of control systems in vogue for launch vehicles have been developed and used in all the programmes. Starting with small control thrusters based on mono propellants to gimbal control systems for all the liquid engines have been developed. For LVM3, the large flex seal control system for the solid motor with electro hydraulic actuation systems having 30 ton force is one of latest development.

**Hardware Production and Industry Interface**

The launch vehicle hardware design, development tests and their integration is carried in-house. But the launch vehicle sub-systems are produced in the industry. The motor cases, light alloy structures, engines, avionics packages, propellants chemicals etc come from the industry. The partnership between ISRO and the industry has been a long standing one with mutual benefits. For example the development of the Maraging steel material took place in ISRO, but the large scale production and processing is carried out through MIDHANI and Rourkela steel plants. The productions of the motor cases are from L&T and WIL. The light alloy structures are produced at HAL making use of their expertise in the field of aerospace structure manufacturing. The precision fabrication required for the control systems, component modules for the propulsion systems, pyros and mechanisms are through many of the Indian Industries who have developed the expertise in association with ISRO. The production of Vikas engines and Cryo engines are through a consortium of industries, with the technological support from ISRO. The development of the new Launch Vehicle LVM3 poses new challenges in terms of the size and precision requirements of the hardwares. The first-off hardwares have been successfully produced. Perfecting the fabrication techniques is the key to the successful development of the new C25 upper stage cryogenic engine. Some of the challenges are in the process of five axis milling of the thrust chamber to generate the precision coolant channels, brazing of the outer chamber and welding, production of high quality injector elements that provide consistent performance, machining of turbo pump impellers and casings with complicated profiles and precision.

**Assembly and Integration**

The assembly and integration of the space transportation system involves significant amount of system engineering and planning. The sub-systems are integrated electrically and tested out. The stage level tests are carried out to ascertain the performance before shipping them to the launch site. The methodology and protocols were developed over the years and perfected through the launch vehicle programmes. The facilities are planned for meeting the specific needs of the sub-system and stage integration. The hardware sub-assembly preparation and integration at launch pad are meticulously carried out in an orchestrated manner.

**Future Programmes**

The development of the future Space Transportation Systems is aimed at bringing down the launch cost by half for placing a kg of spacecraft mass in orbit through the expendable launch vehicle technology and by an order less by the reusable technologies. At present the expendable launch vehicles are being continuously upgraded for increased payload capability through by incremental improvements. Larger vehicles are being developed with fewer stages so as to bring down the cost of launching to 50% of the present costs. It is also our target to increase the indigenous contents in the Space Transportation System and efforts are on to fully become self reliant in the area of materials, special components etc.

In the area of launch vehicle technology continual research in advanced propulsion methods is essential for reducing the cost of access to space and for further space exploration. Significant R&D effort is being carried out in the area of semi-cryo propulsion and air-breathing propulsion. On the space exploration front, candidate technologies include ion propulsion, pulse detonation, beamed energy, nuclear propulsion, antimatter propulsion and magnetic levitation launch assist. Air breathing propulsion systems reduces system weight since they do not carry oxidizer.

**Technology Demonstrator for Reusable Launch Vehicle**

Accessing space like air travel with a short turnaround time using a fully reusable single stage vehicle is the dream of the STS developer. A Two Stage To Orbit (TSTO) fully reusable vehicle is a practical solution, that will bring down the cost of the launches by an order. The configuration studies are in progress for a TSTO vehicle. As a precursor to this, a Technology Demonstrator for the Reusable Launch Vehicle (RLV-TD) is being readied for validation of the technologies (Fig.6). RLV-TD is a winged body which has interaction between aerodynam-
ics, structures, propulsion, guidance, control and navigation. The flight path of RLV-TD is similar to that of the first stage of a TSTO vehicle. Typically, RLV-TD lifts off vertically with a 9-ton solid rocket booster to an altitude of 25 km and Mach 6. Further, it coasts to an altitude of 80 km. At this altitude, it starts its return flight at about Mach 6.7 and then reenters traversing supersonic to subsonic flights and lands like a conventional aircraft. To test the air-breathing propulsion module, the vehicle ignites its scramjet engine at Mach 6.0 and flies for 15 seconds.

The vehicle hosts a variety of cutting edge technologies such as Carbon-Carbon / Inconel hot structures, Flight Air Data System (FADS), controlled aerodynamic re-entry, control logic and material development. The RLV-TD would serve as a flying test bed for proving many of the critical technologies.

Air-Breathing Technology Demonstrator

As scramjet engine with supersonic combustion is recognized as the most critical element in Air Breathing Propulsion technology, the current focus is on development and flight testing of a scramjet engine. Under this program, supersonic combustion in ground testing and 3D reacting flow computational simulations have been successfully achieved.

To demonstrate supersonic combustion in flight, a low cost two-stage flight technology demonstrator (DMRJ-FTD) is conceived. Novel mission profile has been arrived at for the vehicle by which it will dwell on the "Mach number-dynamic pressure" (M-q) window of interest for 5-7 seconds enabling evaluation of the scramjet performance.

Human Spaceflight

The access to space by humans provides immense advantage in terms of the future exploration. There is a renewed interest world over for further human exploration of moon and other planets. Building space stations, establishing base in moon and begin further exploration missions from there are being thought of. To acquire the capability to transport humans to space and bring back safely is challenging task. The present launch vehicles are to be up-rated for human transportation by building adequate safety, reliability and failure detection and abort capability. The studies in this front has been initiated including human rating of the launch vehicles, development of the technology elements for the human space capsule with its constituents of life support systems, environmental control systems, recovery systems etc. It is the new vision of ISRO to acquire this capability of Space Transportation of human beings in the near future. An orchestrated effort with other scientific establishments, industries and ISRO centres has been initiated.

Technology Road Map

ISRO believes in continual improvements in technology, capability and scope driven by necessity. Besides catering to all remote sensing and earth observatory requirements, the vision beckons the space programme beyond mastering the reentry technology to inter-planetary mission, rover to moon and to human space flight. Technology has to be aggressively taken forward; new technology has to be imbibed [28].

To meet the surge in space flights, generation of high fidelity, fast and robust aerodynamic data demands establishing state of the art aerodynamic and aero-thermodynamic test facilities and developing highly accurate and versatile CFD tools. For thermal protection, research is underway for suitable coatings for thermal and radiation protection as well as acoustic and cryogenic insulation. Also micro-meteoroid impact resistant systems are vital for protection from small objects traveling at very high speeds. Studies have been initiated in inflatable space structures, free return trajectories, IP based telemetry tracking and soft lander. Space debris engineering models are being developed for success of these critical missions.

Human spaceflight missions demand unprecedented stress on safety and reliability. Software and hardware implemented fault tolerance, redundancy management, structural health monitoring, crew health monitoring are required to be developed for this purpose. Polymer sciences have to deliver special polymers for space suits, opto electronic polymers and fluoro polymers and chemicals for life support systems, energy management systems such as super capacitors and advanced fuel cells. Moreover for operations while in space, research is to be done for MEMS and NEMS based actuators and robotic manipulators. The futuristic concepts of space habitats demand research in the area of micro-gravity processing, solar welding and also thermal control for long duration missions. And in the times to come, efforts have to be directed towards in-situ synthesis for planetary habitats and material mining.
Conclusions

A brief overview of the developments in the Space Transportation Systems has been brought out in this paper. The achievements in this critical technology area of national importance enabled us to have end to end capability for the space missions without external support. The STS being an integral part of the Space activities have been receiving adequate attention from all quarters. The programmes to improve the payload capability and reduce the cost of the launch vehicle are bearing fruit. The rates of launches of PSLV and GSLV have increased substantially to meet the national goals of space based applications as well as to participate in the commercial launch service market. The infrastructure and the industry capability are being enhanced to meet the increased production and launch requirements. Advanced launch vehicles and concepts are being given adequate attention so that we will not lag behind in this enabling area.

The vision of the forefathers of the space activities in India have been enriched and built up on by the subsequent leaders. This tradition enabled ISRO to have continuity of programmes with adequate focus. The second vision for space has enthused the space community to take up challenges for exploration beyond earth’s orbits and planning is underway to achieve and demonstrate further capabilities.

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References


Fig. 1 SLV-3 and ASLV

Fig. 2 PSLV Configuration

Fig. 3 GSLV Configuration evolution from PSLV

Fig. 4 GSLV MK-III (LVM3) Configuration
Fig. 5 Improvements in payload capability

Fig. 6 RLV Technology Roadmap