Cryogenic Engine Realisation - Challenges Overcome

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Abstract
The indigenous capability of building technically complex and most efficient cryogenic engines demanded harnessing techno-managerial expertise across the country and development of specialized processes and technologies. ISRO has successfully developed and demonstrated this most complex technology by enormous intellectual excavation of multi-disciplinary expertise across its own centers and outside, understanding & handling wide range of materials, mastering difficult & innovative production processes and overcoming many technological challenges during realization. This paper attempts to bring out the onerous effort it took to1realize this technical marvel.

1. Introduction

The Cryogenic Rocket EngineusingLiquidHydrogen (LH2) and LiquidOxygen (LOX) as propellantsproduces the highest performance in terms of specific impulse amongst the chemical propulsion systems. Theyreduce the system weight for upper stage because of the propulsive efficiency and help increase the payloadwhich translates intoeconomicbenefits. But they are complex due to the intricate design, specialised fabrication requirements and high thermal protection required for the cryopropellants. The engine system comprises of ThrustChamber, Turbopump, Injector Head Assembly, GasGenerator and Nozzle Divergent Assembly. Cryogenicenginesemploywide range of materials, needhighheat flux management, have high RPM turbo machinery and handlelowtemperaturepropellants. They are all welded, built-up structures and hence a defectat the final stages of realisation forces the entireassembly to berejected. ISRO has takenenormous efforts to develop and demonstratethistechnology for the past 2 decadeswithstrategiccreativeapproach to design and analysis, selection of materials, specialisedmachining and joining technologies, intricatetooling and fixtures, complicatedassembly of subsystems, compliance to highquality standards, elaboratetestingatsubsystems and integratedlevels and observance of strict quality control and safetynorms. This technicalpaper deals with the complexities of the system and the challenges overcomeduring the realisation of cryogenicengines by ISRO. Figures 1 & 2 show the Cryogenicengines for CryogenicUpper Stage CUS (For GSLV Mk2) and CE20 (For GSLV Mk3)developed by ISRO.

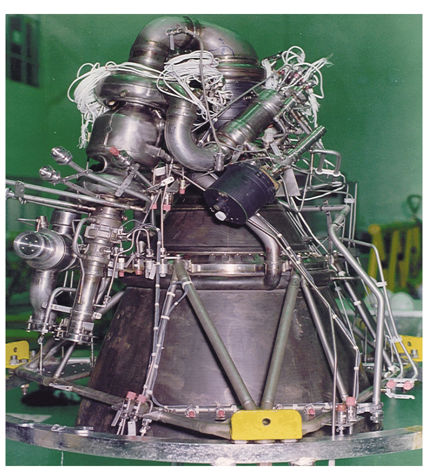

Figure.1 CUS Engine

Figure.2 CE20 Thrustchamber

2. Materials

The choice of material for cryogenic application has to be very meticulously done. The behavior of materials at cryogenic temperatures primarily depends on the lattice structure. As the temperature goes down, generally the tensile strength increases and ductility decreases. For low temperature applications, FCC structured materials are preferred as they have more number of active slip planes to ensure the required ductility at very low temperature. Figure 3 shows the materials used in Cryogenic stage. As material science technology is developing fast pace, quest for higher, stronger and cryo compatible materials is ever increasing**.**

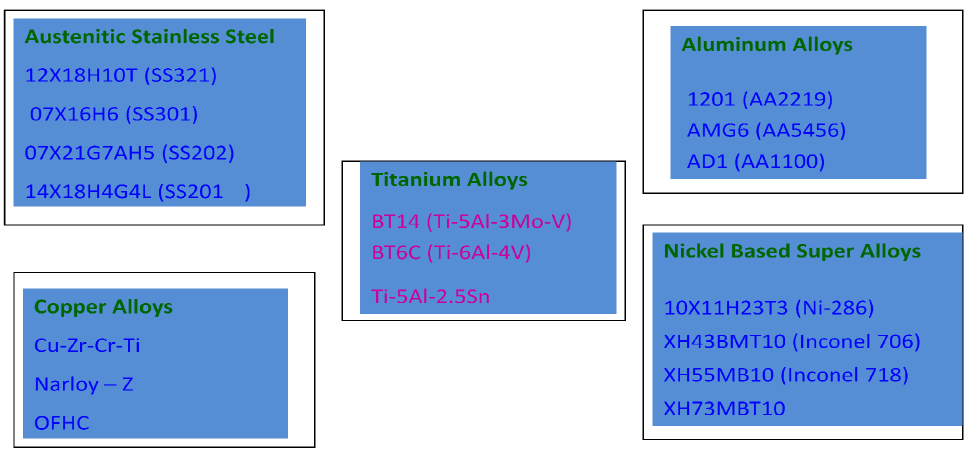

Figure.3 Materials used in Cryogenic Stage

In addition to mechanical and fracture toughness properties, the materials for combustion chamber application should be highly thermally conductive and have the property of fabricatability and compatibility with the propellants. Cryogenic engines are regeneratively cooled and hence combustion chambers are of double walled sandwich configuration. For this application, normally high purity high conductivity copper alloy is preferred to carry the heat flux from the chamber wall to the coolant in the channels. The copper alloy has smaller alloying elements such as chromium, zirconium and titanium to achieve desired properties including hot ductility. The production of this alloy to achieve the specified properties was a challenge overcome successfully. The outer jacket of the copper inner shell is generally with stainless steel 321 shut out to enable the coolant to flow through the passages in between. Realization of this titanium stabilized steel with good mechanical properties was an involved job.

In case of turbo pumps, the material selection is critical. The turbo machinery has the hot turbine zone and very cold pump zones for the respective propellants all connected with the single axis shaft. The turbine side materials need to be compatible for high temperature applications(normally stainless steels and super alloys like high nickel Inconel) and the pump side materials need to be low temperature and propellant compatible like stainless steel 321, aluminium and titanium alloys. We have successfully indigenized about 90% of engine materials through a number of Indian industries. Realizing defect – free investment castings for the turbo pump parts such as turbine exhaust casings, scroll, and inter-stages has been a real technical challenge that needs continuous improvement even now.

As normal elastomers cannot be used for seals, special labyrinth type double layer powder metallurgy rings are used between liquid hydrogen pump and turbine. These need distinct interface between the soft and hard layers and realizing them was quite difficult. About 55 different non-metallic materials have been indigenized by ISRO.. Material characterization at very low service temperatures for mechanical properties even down to 20K, fracture toughness, fatigue and creep studies, thermal and electrical conductivity – all have been done at various laboratories across the country

3. Fabrication

Hardware is the heart of the technology. The complexities of the cryogenic engine demanded newer and newer application oriented custom made fabrication processes. The processes have been conceived to give the hardware greater scope for increasedperformance by ensuring accurate tolerances, surface finish, higher joint strengths and perfect assembly.

The 5- axis helical channel cutting on the inner shell of the combustion chamber, the joining of the inner and outer shells by specialised rotary vacuum brazing process, the development of the chamber from plate through multi-stage forming, heavy duty pressing for nozzle, unconventional electric discharge machining for the turbine rotors, machining of complex inducers, critical Electro Discharge Machine (EDM) micro-hole drilling, very complex sheet metal forming techniques for turbo pump parts, electron beam welding for dissimilar critical joints, electro polishing, vibro-tumbling, specialized coating processes like chromium, nickel, silver coating to improve hardware performance - all these technological challenges to our country's fabrication capability have been successfully overcome after enormous efforts and trials by our engineers. The major welding procedures, standards to be followed, weld and welder qualification, test procedure and acceptance criteria are all well formulated, evolved and followed.

The high heat fluxes experienced in the combustion chamber demands specialized design with regenerative cooling, compatible materials with high thermal conductivity and special fabrication techniques. Cryogenic engines are regeneratively cooled by the fuel which passes through the channels machined on the combustion chamber inner shell and covered by the outer shell before entering the chamber. In the earlier engines, the combustion chambers were made of number of tubes held together in a mandrel and brazed to the adjacent tubes. In order to have structurally stable and thermally effective chambers for higher operating pressures, milled channel configuration was evolved wherein the coolant channels are machined on the inner copper shell. The machining of these channels with helical pattern and varying lead for effective thermal management, calls for a 5 axis CNC machining with 3 rotary axes and 2 translatory axes. This 5 axis simultaneous control is essential in order to machine complex profiles - surfaces formed by 3D straight lines with continuously varying directioncosines. The required amount of width, depth& helixangle of the channels and adjoining ribs are achieved by orienting the cutterposition along carefully calculated co-ordinates which are continuously varying in nature and can be derived either by the use of 3D solid modeling and CAD/CAM software (viz IDEAS, PRO-E, UNIGRAPHICS, CATIA etc.) and the data be processed to suit the machine controls. The surface co-ordinatesare checked in the model itself. The cutter has to remain always perpendicular to the contour. The helix angle varies in the Steering engine. The software generation for the channel contour, programming and the data transfer to the machine were the challenges faced. ISRO have not only demonstrated this critical technology with the help of industry, but also have successfully proven the end milling route for this which has substantially reduced the channel cutting time. Figure 4 shows the 5-axis channel cutting on the machine and channel milled hardware.

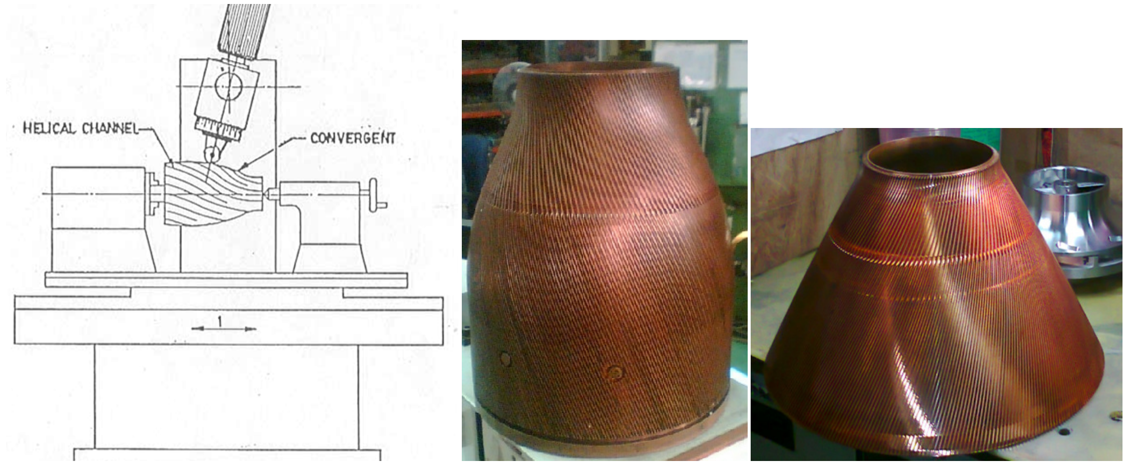

Figure 4 5 – axis channel cutting and channel milled hardware

Rotary vacuum brazing process used for joining the inner and outer shells of the combustion chamber and nozzle is a very complex custom made process, which calls for simultaneous application of temperature, pressure, time, rotation & vacuum in a highly complex facility. Figure 5 shows the multiple parameters at work. The brazing is done normally at elevated temperatures closer to the melting point of parent metal. The braze alloy in foil form is spot welded to the inner surface of the outer shell and then both the inner and outer shells are assembled together for brazing. The technology ie the preparation of the assembly for brazing, finalization of brazing parameters and the brazing cycle, fixtures with flexures, NDT prior and after, acceptance tests such as strength and leak tests – all were evolved after extensive trials and validation. Precisely controlled brazing cycle is necessary to get desired bonding strength, uniformity of brazing and leak tightness.

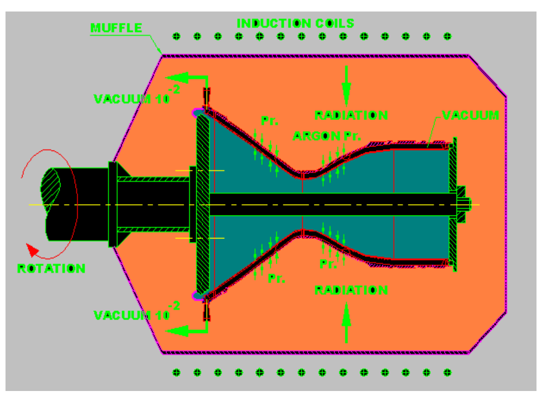

Figure. 5 Multiple parameters at work

The Rotary Vacuum Brazing Facility (RVBF) is a highly complex induction furnace with complex mechanical, electrical, electronic, instrumentation systems to provide precise and simultaneous control of parameters. Figure 6 shows the RVBF.

Figure.6 Rotary Vacuum Brazing Facility

The technology development was systematically done from flat coupon trials, cylindrical specimen and then actual hardware. Many problems were faced during this time with respect to process, material condition, fixtures, facility, temperature measurement etc,. Problems such as cracks forming on the divergent outer shell, sudden stoppage of rotation, blockages in the channels, distortions in nozzles were systematically analyzed, modifications incorporated, trials done and finally the technology got stabilized. Now, RVBF has undergone more than 110 successful heat cycles.

The design and the realization of the multi element coaxial injectors is another area of challenge. The design is complex since the oxidizer is in liquid phase and fuel is in gaseous phase. There are 109 co-axial injector elements with 61 centrifugal (for oxidizer) and 48 jet (for fuel) injectors for CUS. The drilling of these injector holes call for special electro erosion micro-drilling technique with stringent tolerance specifications. The development of chamber shell from a plate through multistage forming to ensure the required properties with intermittent annealing is a critical activity. Heavy duty double action pressing required for the realization of the nozzles to ensure close matching of the inner shell and CNC profile turning for the convergent and divergent is yet another difficult process. The complex sheet metal forming techniques are to be done with strict tolerances. The divergent inner shell is 2.1mm thick with 1.5mm deep channels thereby having the backup wall thickness of 0.6mm and the outer shell is only 0.6mm. Ensuring the required tolerance and avoiding ovality is of paramount importance. This divergent having straight channels employs hydro copying technique where the job itself becomes the copying master of the contour. Figure 7 shows the nozzle after pressing and channel milling. Electron Beam welding is employed for joining the divergent copper inner shell with the interfacing nickel ring and also at throat to join thin convergent and divergent copper inner shells. All these have been successfully proven.

Figure.7 CE20 Nozzle after pressing and CUS channel milled nozzle

The gas generators are also regeneratively cooled having inner and outer shells made of stainless steel 321. The coolant channels which are straight are milled on the inner channel. CUS engine GG handles the entire hydrogen as it runs on Staged combustion cycle and hence the channels are wider and deeper (8mm). CE20 engine runs on GG cycle and hence the GG handles only a portion of hydrogen leading to channels narrow (1.5mm) and shallow (2mm). Rotary vacuum brazing of CE20 GG initially had channel blockages which have been overcome by suitable layout of the foils. The injector head realization is similar to the main chamber injector head though the numbers of elements are much less. The steering engine of CUS also has two shelled construction (integral inner shell) demanding channel milling with variable helix angle and rotary vacuum brazing with the outer shell.

Liquid hydrogen being a low density fluid requires very high speed multi-stage pumps to develop the required delivery pressures. The very high speed calls for meticulous design and fabrication of complex shaped hardware within the stipulated tolerances. CUS turbo pump has a single turbine running both LH2 and LOX pumps on a single axis shaft whereas CE20 has separate LH2 and LOX turbo pumps. Turbo pump system has such complicated elements as inducers configured with variable lead and blades with thick root and thin tip, closed type turbine rotor having integral outer ring, impellers, nozzle block having specially cut vanes for directing hot gases, bearings and seals for speeds as high as 45000 RPM, the power transmitting shaft with three co-axial pieces connected by gear type coupling with high thermal gradient.

Inducers with conical base demands the 5-axis CNC milling and special CAM operated EDM process is used to cut the complex blade profile in turbine rotor and nozzle block. Special rotary cams and templates are used to simulate multi-axes movements of the electrodes in order to have access into the cavities. The development and setting up of cams/templates requires high skill. Alternatively, the possibility of machining such rotor blades on modern CNC EDM machines with planetary electrode motion is being explored. The complex sheet metal forming techniques are to be done with strict tolerances. Newer processes like vibrotumbling for the turbo pump elements remove unevenness, burrs and provide lustrous finish to the parts. Electro polishing and special coatings like chromium, Nickel, Silver, Copper etc. improve the hardware performance. Complex shaped castings are used for turbine exhaust casings, scroll (volute) and interstages. As good quality investment castings are not available, there have been rejections after machining and during the pressure test. In fact, in the absence of castings for CE20 exhaust casing (inconel), machined and welded casings were used for the initial hardware. Figure 8 shows the machining of inducers and Figure 9 shows the EDM of closed type turbine rotors.

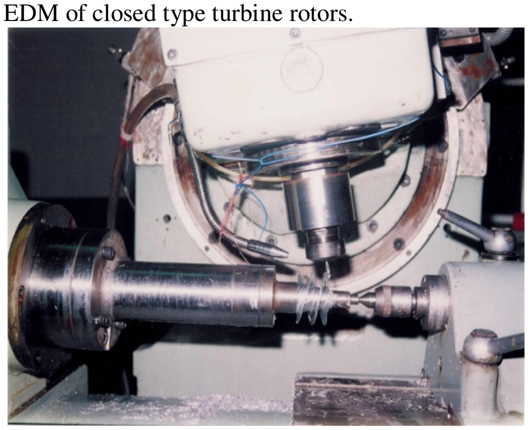

Figure.8 Machining of Inducers

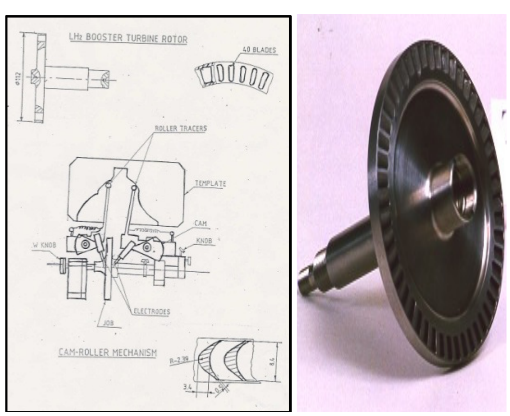

Figure.9 CAM mechanism for turbine rotors

The high speed turbo pump leads to criticality in the selection of bearings and seals. Turbo pump with hot gas at high temperature around 900K for driving the turbine at one end and LH2 at very low temperature around 20K in the other end experiences very high thermal gradient and thermal stresses. This leads to differential expansion of the hardware and affects the running clearance and performance of the system. The alignment of the co-axial 3 pieces shaft with gear couplings is an important factor to be taken care of. The clearances between the shaft and seals at the operating temperatures are extremely important as gripping may lead to abrupt stoppage of the turbo pump system which will shutdown the engine as it happened in the fuel booster turbo pump during GSLV D3 flight. Subsequently, the design has been revisited; all the geometrical tolerances have been restricted to be within 10microns. This has added criticality during realization. The leakage of cryo fluids in the turbopump system could lead to not only performance loss but also its hazards resulting in explosion when the fluids mix under unfavorable condition. Thus, the selection of seals is another complex aspect. High quality leak-proof welding is essential for the booster turbopump assemblies which are kept immersed in the respective propellants in their respective tankages.

4. In-Process Testing

The hardware undergoes various stages of acceptance tests during its realization such as cold flow tests, flow calibration, hydraulic (strength) and pneumatic (leak) tests. The injector elements need to be calibrated for the fuel and oxidizer passages before and after the welding of inner and outer sleeves. The LOX flow rate is 211g/sec for both CUS & CE20 and LH2 side flow rate is 800g/sec for CUS and 320g/sec for CE20. LOX flow is controlled by 1.7mm holes and LH2 side by the EDM slots and swirl passage. Though the elements meet the drawing requirement, initially most of them got rejected during flow calibration. It was difficult to improve the yield and with lot of progressive effort, element realization is now stabilized and the yield better.

The facility for flow calibration of chamber after brazing has been erected in the work centre. The aquarium strength test and pneumatic leak test facilities have also been established in the workcentres. The turbo pumps are cold flow tested for ascertaining their head and efficiency prior to further assembly. Cryogenic engines are all welded in construction and are not reversible by design. Hence, any defect at final stages or failure during acceptance tests lead to the rejection of the entire assembly. That is why the yield on the cryo engines is less. All the processes are refined, the quality control tightened at the workcentres and additional capacity added to improve the yield.

5. Production Management

As high technology domain is involved, prudent ways of utilization of diverse resources and strategies to unearth vital & scarce resources amidst existing restrictions, needed to be well planned. Contingencies had to be factored into the plan in anticipation of unforeseen difficulties. After finalization of hardware requirement, the realization methodology for each subsystem was worked out. Potential Indian industries capable of taking up the critical and challenging hardware realization for the Cryogenic engine, were explored and contracts were signed with industries who have already demonstrated their might for the realization of earth storable engines. The contracts were with consortium partners who shared work among them. The overall management plan had a subcontracting philosophy and a comprehensive quality plan to ensure reliability with maximal utilization of industries. This way, we could utilize the expertise, capability, knowledge, resources, management acumen and strengths of the contractors.

The pre-production activities such as study of fabrication drawings, tooling design, review, approval and realization & prove-out, preparation of process documents, review & approval, carrying out technology development activities, establishing in-process test facilities and proto hardware realization were meticulously done though they were very new unknown technical territories for the industries because of the complexity of the hardware. The crisis response mechanisms during realization should be prompt and appropriate. The problems always needed multi-disciplinary efforts to understand them, assess the various alternatives, conduct sample / sub-scale level experiments, develop the hypothesis, choose the right solution, implement the same, analyze the results and clamp the modifications in place. The collective wisdom of people was always bigger than the problem faced. The realization of Cryo hardware has brought in certain new kind of expertise with in industries that have enhanced their core competence.

6. Conclusion

The emerging trends for improving the performance of Cryogenic engines in areas such as engine cycle, combustion chamber, turbo pumps, nozzles with exotic materials and deployment of advanced fabrication techniques such as laser welding, hot isostatic pressing, friction stir welding, powder metallurgy appear to be promising.This paper has brought out clearly the various techno-managerial challenges faced during the realization of the Cryogenic engines. The Cryogenic engine realization has was really a marvellous experience for ISRO, with participation from Indian industries, other governmental agencies, academic institutions and research centers.