

Study on geosynchronous satellite launch vehicle propellants and combustion mechanism of each stage

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ABSTRACT. GSLV is a “geosynchronous satellite launch vehicle” which aims at launching space objects into GTO- Geosynchronous transfer orbit. This paper provides a brief idea of the chemistry of propellants used in all three stages and strap-on motors of geosynchronous satellite launch vehicles and their combustion mechanism. It includes all series of GSLVs launched till now and a description of criteria for choosing fuel. This paper also includes a brief description on hydrazine which is a basic part of so many propellant combinations. Furthermore, it includes basic reasons which result in unsuccessful ignition especially at cryogenic. It also emphasizes on reasons for modification in fuels over time and advancement in efficiency obtained due to respective modified fuels, further, giving an overview of future ideas in the development of propellants.

1. Introduction

The major key for carrying spacecraft is launching vehicles and selecting a vehicle depends on the type of spacecraft and to orbit in which it is to be transported. One of the launch vehicles developed by the ISRO, which is a space research organization, is the “Geosynchronous satellite launch vehicle”, popularly known as GSLV, used to launch space objects in geosynchronous orbit[1]. GSLV is a fourth-generation launch vehicle that undergoes a three-stage fuel mechanism; the first stage uses fuel in the solid form[2]. Whereas liquid fuel is used in the second stage and the third stage uses cryogenic fuel[3]. There are various factors on which the select ion of launch vehicle type depends like weight, source of energy, calorific value, type of propellant, thrust, response mass, and more[4]. Calorific value is the measure of heat evolved by the complete fuel combustion, so a rocket fuel will be considered good if it is lightweight and gives a high calorific value in less amount of usage[5]. The first geostationary launch vehicle “GSLV-MK-II” successfully launched GSAT-1 into its orbit on April 18, 2001 [6]. After this, many launches took place using GSLV-MK- II but the last mission which was on August 12, 2021, of GSLV-F10/EOS-03, where F10 is the mission sequence and EOS-03 is the earth

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observation satellite, planned to put in GTO orbit, to observe real-time image at frequent interval and to monitor natural disaster, was failed to ignite at cryogenic stage[7]. The official failure report is yet to be published by ISRO but according to officials, GSLV-F10 failed[7] due to a loss of pressure by 50 millibar in the LH2 tank.

Table 1:List of GSLV's respective fuels used[7][13–25]

Title	Launch Date	1ST Stage fuel	Strap-on motors fuel	2nd stage fuel	3rd stage fuel	Remarks		
GSLV- F10/EOS 03	Aug 12,2021	HTPB	UH25*+N2O4		LH2&LOX	Unsuccessful		
GSLV-F11 / GSAT-7A [26]	Dec 19,2018					Successful		
GSLV- F08/GSAT-6A [26]	March 29,2018	Composite solid propellant	Earth storable liquid and composite solid propellant	Earth storable liquid propellant	Cryogenic propellant	Successful		
GSLV-F09 / GSAT-9[26]	May 5,2017					Successful		
GSLV-F05 / INSAT-3DR	Sep 08,2016	HTPB	UH25+N2O4		LH2&LOX	Successful		
GSLV-D6	Aug 27,2015					Successful		
GSLV-D5/GSAT 14[26]	Jan 05/2014					Successful		
GSLV-F06 /GSAT-5P[26]	Dec 25/2010					Unsuccessful		
GSLV D3/GSAT-4	April 15,2010					Unsuccessful		
GSLV F04/INSAT- 4CR	Sep 2,2007					Successful		
GSLV- F02/INSAT- 4C[26]	July 10,2006					Unsuccessful		
GSLV-F01 / EDUSAT(GSAT- 3)	Sep 20,2004					Successful		
GSLV- D2/GSAT-2	May 08,2003					Successful		
GSLV- D1/GSAT-1**	April 18,2001					UDMH+N2O4		Successful

GSLV first stage fuel is Hydroxyl-Terminated Polybutadiene (HTPB) which gives a maximum thrust of 4700kN with a burn time of 100 seconds, four strap on motors that work on Unsymmetrical Dimethyl Hydrazine(UDMH) and Dinitrogen Tetraoxide(N2O4) fuel, this combination is also known as “dirty combination” and fuels are under the category of hypergolic propellants where Nitrogen Tetraoxide used as an oxidizer and UDMH as the fuel[8], giving a maximum thrust of 680kN with burn time 160 seconds[9].

The second stage fuel is UDMH+N₂O₄ giving a maximum thrust of 800kN with a burn time of 150 seconds[10]. The final stage which is known as the “cryogenic stage” works on Liquid Oxygen(LOX) and Liquid Hydrogen(LH₂) giving a maximum thrust of 75kN with a burn time of 720 seconds[11].

Hypergolic fuels combination used at different stages can undergo spontaneous ignition at atmospheric pressure and low pressure, these may result in different reactions causing non-ignition [8] and can also cause inadequate hypergolic reactivity between fuel and oxidant causing burnout or explosions during launch[12]. Various mechanisms have been proposed for the reaction between N₂O₄ and UDMH and the final products found to be formed in it are dimethylnitrosamine, dimethylamine, dimethylhydrazine nitrate, methanol, dimethylformamide, water, nitric oxide, nitrous oxide, nitrogen, carbon dioxide[8]. All of these products can be dangerous if accumulated in the combustion chamber as these products are potentially explosive[8]. A detailed ignition mechanism will be explained ahead in this paper.

This paper describes the detailed chemical mechanism and expected results for different processes of each stage fuel and cross-checking of each product by different spectroscopy methods. It will also give an overview of different expected results over a slight change in condition and which could be the reason for accidental failures.

2. LHRS – Foremost preparation of a launch

Before the launch of any space vehicle, the LHRS stage is the main stage for the hope of a successful launch and it works on hydraulic instrumentation[28]. LHRS is a “Launch Hold and Release System” which hold the vehicle until the computer confirms no anomaly in the strap on’s and releases the command to lift off the launch vehicle by igniting the core motor[29]. At this stage, all the pre-launch testing is completed, and then the countdown to launch starts after considering weather conditions and atmosphere. Strap on motors are ignited in such a manner that the thrust provided by the action of combustion of strap on fuels is greater than the payload of spacecraft to overcome the gravitational force of the earth, therefore, it thrust as the reaction in the opposite direction of ignition flow defines Newton’s third law usage[30].

3. Usage of Hydrazine in rockets and particularly GSLV

Hydrazine (N₂H₄) is the basic key used in nearly all stages of fuel since the first GSLV was launched[31]. Hydrazine has a molecular formula of N₂O₄ and the ignition power of anhydrous hydrazine is very high that it can instantly produce hot gases on reacting with liquid oxidizers[32]. Due to this instant reacting property of hydrazine, it is possible to carry out on and off the system in rockets[32]. Moreover, Hydrazine has the capability to get ignited several times by the same catalyst until its lifetime gets over which provides its another reason to be used in space vehicles[32]. Hydrazine is not found in nature but its synthesis is done in laboratories by the Raschig process by three-step process[33]. The first step-(1) consists of excess ammonia oxidized by Hypochlorite and gives product as Chloramine and hydroxide, then, in the second step-(2) remaining ammonia reacts with Chloroamine and yields as Hydrazine but the rate of this reaction is very high, so, Hydrazine rapidly reacts with chloramine and get converted into unwanted products as shown in third reaction [33].



Hydrazine can be obtained in good yield by increasing the rate of reaction in the second step and at the same time decreasing the rate of reaction in the third step which can be done by carrying out this reaction in presence of aliphatic ketone[34]. By using aliphatic ketone, like Acetone, Ketazine will be formed and it can be hydrolyzed easily forming Hydrazine[34].

4. Strap-On motors fuel

There are four strap-on motor fuels attached to GSLV which are made up of various ferrous and non-ferrous alloy materials which have a good strength to weight ratio[35]. Each Strap-on work on liquid propellants and all of these are burned at the same time to initialize take-off [36]. The first GSLV-D1 used Unsymmetrical dimethylhydrazine(UDMH) and Dinitrogen tetroxide(N₂O₄) as fuel in strap on motors but then UDMH was replaced by UH25 which is 75% UDMH and 25% Hydrazine hydrate because UDMH in presence of hydrate burns more rapidly and produces more hot gases which will be giving better efficiency. UDMH consists of a nitrogen atom attached to two methyl and one amino group[37]. Various tests were conducted before considering liquid UDMH as a rocket propellant in an N₂O₄ environment which always carried spontaneous reactions resulting in igniting every strap on and producing a thrust to lift off the vehicle[38].UDMH is such that N₂O₄ reacts with the Nitrogen atom only because of the low reactivity of the methyl group, so the attack is just on the nitrogen atom[27]. Strap on motor fuel and second stage propellant are the same.

5. First stage propellant

The first stage gets ignited just after two seconds of igniting the strap on motors[39]. This stage fuel is Hydroxyl-terminated polybutadiene, commonly known as HTPB, have been in use since starting because of its good resistance to degradation when contaminated with water and it remains intact when it is exposed to extremely low temperatures [40]. Propellant use binder and oxidizer where HTPB itself has good binding property and oxidizer used along it is ammonium perchlorate(AP)[41]. Additionally, plasticizer, which is a low viscous organic liquid like Dioctyl adipate or gallium phosphide, is also added to improve the processing property of HTPB and increases thermal energy on oxidation[41]. AP/HTPB is decomposed in parts as: The first part is the mass loss stage which is between 100°C to 430°C, the second part consists of the decomposition of remaining HTPB between 430°C to 630°C and further oxidation of the remaining oxidizer particle falls under the third part[42].

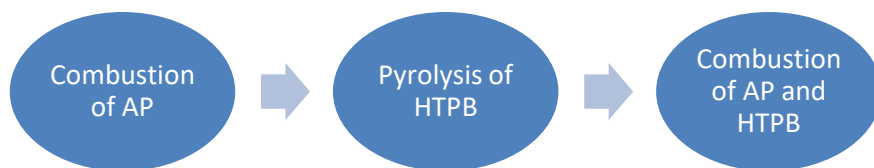
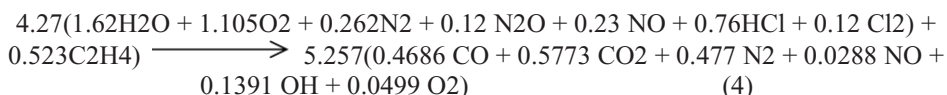


Fig 1 : Binder and fuel are not chemically linked to each other so combustion of AP and HTPB is studied separately first and this flow chart shows a chain of that mechanism[43]

5.1 Combustion of first stage propellant

Ammonium perchlorate(AP) crystal undergoes a phase change and low-temperature decomposition from orthorhombic to cubic at 513°K and produces chlorine, water, nitrogen, oxygen, chlorine dioxide, hydrochloric acid, nitric oxide, nitril chloride[43][44]. Crystal lattice keeps on getting unstable with temperature increment until it melts completely at 830°K, also called high-temperature decomposition, where it undergoes dissociative sublimation and converts into 70% of AP as a thin superficial reaction layer and the other 30 % gets sublimated by proton transfer under endothermic equilibrium with enthalpy of 58±2Kcal/mol and gives product like water, chlorine dioxide, chlorine, oxygen, dinitrogen trioxide, dinitrogen tetraoxide[43][44]. The major problem in the combustion of AP is that the intermediate products formed in condense phase, perchloric acid, and ammonia have solubility differences, due to which the burning rate of AP will drop if pressure is above 136 atm[45]. So to get the maximum burning rate, pressure should be maintained at or below 136 atm in the AP combustion chamber[45]. After combustion of the oxidizer and gets pyrolyzed in two steps where the first step is endothermic depolymerization forming butadiene with 10 to 15% weight loss and in the second stage remaining HTPB gets catalyzed and cross linked[43]. Above 100K/min the first stage dominated and the product found is butadiene. In this chamber, HTPB is exposed to only high temperature so it can't get cross-linked so the majority of the product is butadiene and light hydrocarbon species[43].Hence, two conclusion can be given as:

AP gives H₂+O₂+Cl₂+N₂+N₂O+NO+HCl+ClO₂+NO+N₂O +N₂O₃ +N₂O₄ +NOCl[43] and HTPB gives Butadiene and light hydrocarbons[43].A primary diffusion flame is placed between the chamber of oxidizer and fuel where the pyrolysis product and that of AP get collected to react with each other[45]. Products found from AP dominate in the condensed phase instead of HTPB due to high mass loading and highly reactive sustainable exothermic reaction[45]. So at low pressure, ammonium derivate-perchloric acid reacts with the products formed by pyrolysis of HTBP, which is mainly butadiene and this reaction goes like this [45] :



It was noted that at the end of this reaction propellant was found to be much less viscous with better tensile strength and the ratio was found to be 70:30[46].

6. Second stage propellants

The second stage works on liquid propellant where fuel is UDMH- Unsymmetrical dimethylhydrazine (CH₃)₂NNH₃ and oxidizer is N₂O₄[47]. Due to the toxic property of UDMH, it is harmful to the environment and pollutes the air, so it is replaced by UH₂₅ which is a mixture of 75-25 UDMH and hydrazine, making it less toxic[48]. Various studies were performed to analyze the product formed by the reaction of UDMH –N₂O₄ and it was concluded that the main product given by this reaction is Dimethyldiazene[49]. The mechanism for this reaction was supposed to go by oxidization of UDMH which gives azo compounds as its product which get polymerized to dimethyldiazene and some of the remaining azo compounds get further oxidized to form carbon dioxide, nitrogen, water[49]. One of the most praised applications of this combination of propellants is that it can even work at low temperature with great specific characteristic impulse velocity and it has long

term storage capacity at room temperature[50].UH-25 and N2O4 composition is prepared by first manufacturing nitric oxide gas and then dissolving it with N2O4 [50]. Later two separate chambers are fitted in such a way that in one chamber N2O4 is filled and the second is filled with UH25 fuel respectively, then these two chambers are connected to a third chamber which is known as the combustion chamber, and chamber an outlet is attached to chamber release hot gases produced by combustion to provide thrust and hence allowing ignition of the second stage of GSLV[50].

7. Cryogenic stage propellants

This stage has been the most challenging in GSLV and it works on liquefied LH2 and LOX gases[51]. Combustion of this stage is similar to that of other stages, initially, LH2 and LOX are separately ignited which results in the production of hot gases which get collected to a common chamber, called “bulkhead”, where hot gases react and provide desired thrust[52]. At the cryogenic upper stage, the position of liquefied fuel is not easy to determine due to the low gravity effect and flow pattern changes due to reduced gravity[51][53]. Due to various effects, the study of cryogenic fuel is far beyond just combustion and production of thrust. The propellant used at this stage requires a temperature less than -297°F and chambers used to store propellant should work as a vacuum bottle[54].

After entering space, launch vehicles are highly subjected to heat due to solar radiation and other planetary radiation and it reaches to propellant by the means of radiation transfer or conduction through tank walls and this leads to a rising temperature of the propellant which was supposed to be on low temperature[51]. For saving propellant to boil off it is ensured that additional propellant is loaded in the tank from the desired amount but this was also not enough to carry out cryogenic stage propulsion well so after many studies an approach to low boil-off was carried out by inserting small tubes coupled on the boundary of fuel tank[51]. These small tubes carried cryocoolers which very efficiently transfer heat to the cold sink of space and save propellant to boil off[51]. Another major problem at this stage is due to the entrance of heat by the process of partial vaporization and this causes pressure to drop in tanks[51]. To tackle this challenge, a strategy was developed- by mixing axial jets and spray bars which counters heat produced to drop again and keep desired pressure to not change[51].Hence, this was the region because of which GSLV –F10 failed due to drop in pressure. So, insulation of final stage is always carried out by taking various aspects into consideration which will be explained further.

7.1 Insulation of cryogenic stage propellant and common bulkhead chamber

A plastic material, called ‘polyurethane’, has been finalized after a wide variety of tests for the outer layer and bulkhead tanks[55][56]. These layers have been parted in three different ways where the First layer is the outermost layer and its basic principle is to oppose thermal energy from reaching tanks and erosion[56]. The middle layer works on opposing cryo pumping process and low heat conductivity, furthermore, the lower layer is responsible for providing high tensile strength and the ability to resist different thermal expansion as well as to keep LH2 and LOX at desired temperature and pressure[56]. So, all these layer works combine to successfully carry out the cryogenic stage and if any of these doesn’t work out, inner properties like temperature-pressure changes can result in to boil off internal fuel and certainly unsuccessful ignition of cryogenic fuel[57].

7.2 Present discoveries to use LOX/CH4 instead of LH2/LOX

Though LOX/CH₄ combination is not yet in use, various studies and thoughts have been put down for it. The thought of using CH₄ instead of LH₂ is gaining popularity in rocket sciences due to its easy extraction from LNG and its non-toxicity nature of it[58]. Also, methane has good corrosion resistance and because of the small difference in liquid density of oxygen and methane, only a single shaft design is needed for its tanks[58][59]. In the case of LH₂ and LOX, different methods were needed to implement to avoid fuel boil off or change in pressure and temperature, whereas on the other hand methane itself has good capability to cool the combustion chamber and low soot combustion[59]. Using methane is also cost-effective and it is estimated that it can reduce cost by 45% for the preparation of a launch vehicle[58].

Conclusion

GSLV has been a remarkable invention in the rocket industry. GSLV works in three stages where the first stage works on liquid propellant –HTPB, the second stage works on N₂O₄ as the oxidizer, and UH₂ as fuel but initially UDMH was in use as fuel, and the third stage works on liquefied oxygen and hydrogen[60]. The cryogenic stage still needs development as it has major hindrances like the thermal expansion to fuel tanks due to solar radiation and low gravity[61]. A few discoveries helped to overcome these hindrances like coating tanks with cryocoolers and insulating tanks with three layers of polyurethanes for better tensile strength and to avoid thermal energy to reach fuels inside tanks[62]. With this, an additional amount of fuel is added to tanks for avoiding loss of fuel.

GSLV still needs development for the cryogenic upper stage and various studies are currently going on to make it better and avoid failures. Methane is also in studies to replace hydrogen due to its non-toxic and good capability to itself cool down chambers if thermal energy reaches its surface[63]. A good launch not only includes better chemical and physical studies but also needs to be cost-effective[63]. India completed its Mars mission in 2014 with a commendable less cost and better efficiency approach[64]. So, the incoming mission aims at developing cryogenic stage knowledge to avoid failures like “GSLV-F10” and make the mission cost-effective[65].

India is working to execute another mission with the help of GSLV with modification in cryogenic stage motors[66]. Rocket sciences successfully made use of chemicals like HTPB, UH-25, N₂O₄, LOX, and LH₂ to carry out space missions[67]. HTPB works very well as solid fuel in the first stage providing a good amount of hot gases after combustion and providing maximum thrust[68]. UH-25 works as a fuel with oxidizer N₂O₄ giving good thrust[69]. Several challenges like the concept of reusable hypersonic rockets are still under consideration and it can help to reduce the cost of mission[70].

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