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A liquid propulsion panorama

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Abstract

Liquid-propellant rocket engines are widely used all over the world, thanks to their high performances, in particular high thrust-to-weight ratio. The present paper presents a general panorama of liquid propulsion as a contribution of the IAF Advanced Propulsion Prospective Group.

After a brief history of its past development in the different parts of the world, the current status of liquid propulsion, the currently observed trends, the possible areas of future improvement and a summarized road map of future developments are presented. The road map includes a summary of the liquid propulsion status presented in the "Year in review 2007" of Aerospace America.

Although liquid propulsion is often seen as a mature technology with few areas of potential improvement, the requirements of an active commercial market and a renewed interest for space exploration has led to the development of a family of new engines, with more design margins, simpler to use and to produce associated with a wide variety of thrust and life requirements.

1. Introduction

In 1898, a Russian schoolteacher, Konstantin Tsiolkovsky [Fig. 1]—(1857–1935), proposed the idea of space exploration by rocket. In a report he published in 1903, Tsiolkovsky suggested the use of liquid propellants for rockets in order to achieve greater range.

Early in the 20th century, an American, Robert H. Goddard (1882–1945), conducted practical experiments in rocketry. While working on solid-propellant rockets, Goddard became convinced that a rocket could be propelled better by liquid fuel. No one had ever built a successful liquid-propellant rocket before. It was a much more difficult task than building solid-propellant

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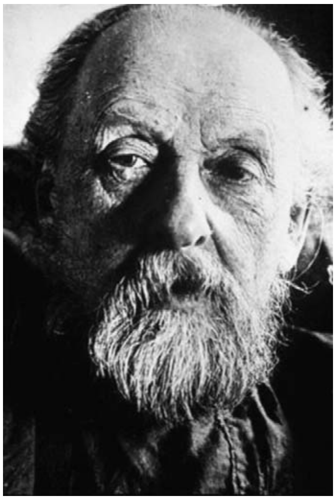

Fig. 1. Konstantin Tsolkiovski.

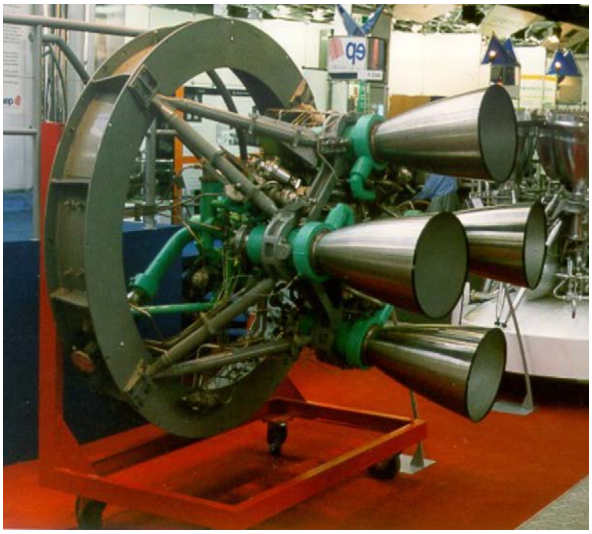

Fig. 2. HM4 engine (*source*: C. Rothmund, Snecma).

rockets. Fuel and oxygen tanks, turbines, and combustion chambers would be needed. In spite of the difficulties, Goddard achieved the first successful flight with a liquid-propellant rocket on March 16, 1926. Fuelled by liquid oxygen and gasoline, the rocket flew for only 2.5 s.

Goddard's gasoline rocket was the forerunner of a whole new era in rocket flight.

Nowadays, liquid propulsion relying on storable, LOX based or cryogenic propellants is a mature field and a core technology for most launchers in service.

2. History

2.1. LOX/hydrocarbons

LOX fed and turbopump fed engines were already tested before WW II. The first large thrust LOX/alcohol engine was flight tested on the A4 in 1942. The chamber pressure was still moderate and the development of large thrust engines was hampered by low frequency hydraulic instabilities or high frequency combustion instabilities in the case of storable and LOX–kerosene engines.

The regenerative cooling of a liquid propellant rocket engine was designed by the German scientist Eugen Saenger in the early 1930s. This discovery proved to be a vital asset for the development of all subsequent high-thrust rocket engines, beginning with that of Von Braun's A-4.

A great deal of work on combustion instabilities was performed in Russia, USA (AEROJET, ROCKETDYNE, CALTECH) and Europe (ONERA and SEP). This contributed to the successful development of the propulsion of well-known launchers, as SOYOUZ (RD 107 and RD 108), TITAN (LR 87), DELTA (RS 27), ATLAS, and ARIANE 1 (VIKING). These engines used the gas generator cycle.

2.2. LOX/liquid hydrogen

Tsiolkovski identified one century ago liquid hydrogen and liquid oxygen as the most promising propellant combination for rocket engines. The first drops of liquid hydrogen were obtained just a few years before in 1905. It took more than 50 years to see the first practical application of this combination to an upper stage (CENTAUR). In the mean time, large thrust engines, operating with storable propellants or with LOX hydrocarbons combinations, were already in use since the 1950s.

In the 1950s, Nuclear Thermal Propulsion was extensively studied in the USA, consequently a better knowledge of hydrogen application for propulsion and of hydrogen based thermodynamic cycles became available. Combined with the development of liquid hydrogen fuelled turbojets, this favoured the start of cryogenic engines, first of all the RL10.

The early sixties showed the development of cryogenic engines in France (HM 4 [Fig. 2]) and in Russia (RD 56 and RD 57).

In Japan, the first cryogenic engine (LE-5) was developed in the 1970s for upper stage application.

2.3. Storable propellants

Storable propellants were initially used during World War 2 on German rocket-plane and early air-launched missile propulsion systems that relied mostly on nitric acid/furalin.

This technology was later taken over by SEPR (France) and applied on their successful SEPR-844 engine that helped power the Mirage 3 interceptors and became the world's only reusable rocket engine used on operational fighters.

In the United States, more powerful storable propellants were developed and used: nitrogen tetroxide, Aerozine 50, UDMH or MMH.

They led to the development of the Titan family of missile propulsion and many spaceflight applications (satellites, space probes and manned vehicles). The Titan I–IV was the workhorse launch vehicle for the Air Force for over 50 years, with LR87 first stage engine and LR91 second stage engine developed by Aerojet.

Storable propellant upper stage and spacecraft engines proved to be highly reliable and are still flown today. The Aerojet Space Shuttle OMS engine has successfully flown over 120 missions and the Delta II upper stage (AJ10-118) engine has successfully flown over 200 flights.

In Europe, storable propellants were used on sounding rockets (VERONIQUE and VESTA), on the DIAMANT launch-vehicle first stage engines VEXIN (nitric acid/turpentine) and VALOIS (N2O4/UDMH). They were also implemented on the French-built second stage ("Coralie") of the EUROPA launch vehicle.

In addition, SEPR initiated the development of a storable propulsion engine (NTO with a fuel consisting of 50% hydrazine and 50% UDMH) for the German-designed third stage ("Astris") of the European launch system "EUROPA".

The storable propellant technology has later on also been applied by EADS Astrium ST to the current Ariane 5 upper stage engine AESTUS with NTO/MMH as propellant combination.

Another well-known representative of the storable propellant family is the VIKING engine [Fig. 3], developed by SEP, which remains one of the most successfully produced rocket engines, with more than 1100 built (ARIANE 1–4). Its uniqueness resides in its regulation system that relied on two regulators. First the main regulation which equalizes the chamber pressure to a reference value by "throttling" the flow to the gas generator, then a "balance regulation" that eliminates the influence of pumps efficiency or in-flight variations of pump inlet pressure on the mixture-ratio. Built under licence as the VIKAS, it is still in use in India (PSLV and GSLV launchers).

Fig. 3. Viking engine (*source*: Snecma).

Storable combinations are still widely used. Cleaner propellant combinations (e. g. nitrous oxide–hydrocarbons) are tested at small scale to identify their potential.

Fig. 4. P111 engine (*source*: MBB).

Fig. 5. RD-180 (*source*: PWR).

2.4. Engine cycles

Subsequently to the early era of gas generator engines, the development of very high pressure engines was felt necessary for ascent stages and boosters: high pressure meant more compact engines with better sea level specific impulse.

Practically, this was only possible with a staged combustion engine. Incidentally, the staged combustion provides another advantage: as the turbine exhaust (either oxidiser rich or fuel rich) is gaseous, the main chamber combustion is consequently very stable (gas/liquid combustion).

Early staged combustion work was performed in Germany (MBB P 111 [Fig. 4]) and in Russia. Most Russian engines in use today are relying on this technology: RD 253 and RD 275 for UDMH/NTO, RD 171, RD 180 [Fig. 5], RD 190 for LOX/Kerosene (ZENITH, ATLAS 5, ANGARA).

In the late 1960s the Messerschmitt–Boelkow–Blohm GmbH (MBB) in Ottobrunn (Germany) developed an innovative technology which allowed the design of higher pressure combustion chambers. A copper inner wall with milled cooling channels was associated to a structural nickel jacket, the nickel shell being obtained by electro-deposition over the copper core. This break-through technology for high pressure combustion chambers was applied in the joint MBB/Rocketdyne LOX/LH2 project BORD (1966–1968). Test results showed that adequate LH2 cooling could successfully be obtained at a nominal pressure of 210 bars (3045 psia) and even at pressures as high as 286 bars (4150 psia), the highest known pressure ever achieved for a LOX/LH2 rocket engine.

In Europe, this regenerative cooling technology was used for the HM7 [Fig. 6] on the third stage of the Ariane 1–4 launchers, and later for VULCAIN, AESTUS and VINCI. The Space Shuttle Main Engine (SSME [Fig. 7]), developed by Rocketdyne, was the first staged combustion cryogenic engine used operationally that relied on this technology. The RD 0120 (CADB) and LE 7 (MHI) are the other representatives of this family of engines. In Europe, MBB and SEP studied a staged combustion cryogenic engine of 20 ton thrust for EUROPA 3 upper stage, using the same thrust chamber technology based on nickel electro-deposition, but this development was stopped. This project was also highly

Fig. 6. HM7B engine (*source*: Snecma).

innovative with a single-shaft axially mounted turbopump.

In Japan, this cooling technology was also applied to the open expander engine (LE-5B) in order to enhance the structural and operational margins, thus increasing engine reliability. LE-5B proved its robustness and reliability in actual flights of H-II and H-IIA.

The most recent commercial developments in large cryogenic engines were aimed at providing a high performance level at a reduced cost with an emphasis on robustness: RS 68 in USA, and VULCAIN 2 [Fig. 8] in Europe as well as LE7A in Japan. Based on these criteria, the gas generator cycle was sometimes preferred to the closed cycle (RS68).

The liquid propulsion milestones are summarized in Fig. 9.

3. Current status

The design of a propulsive system involves a compromise between potentially conflicting objectives: reliability, performance, low recurring cost and low development cost.

Fig. 7. SSME engine (*source*: PWR).

Following a focus on performance and the development of technologies which brought engine performances very close to their theoretical specific impulse limit, current developments have placed more emphasis on:

- reliability (reduced failure occurrence);
- cost reduction (both direct—simpler manufacturing processes and reduced parts number—as well as indirect: simplified operation and reduced system complexity) [11,44]; and
- improved endurance and life increase (with indirect benefit on reliability).

The requirement for reliability is becoming increasingly the prime requirement due to:

- the high cost of payloads (especially the scientific and institutional ones) and

- the visibility of a launch failure and the resulting deterioration of the climate of confidence among the actors of the space industry: payload customers, insurers, public authorities.

Fig. 8. Vulcain 2 engine (*source*: Snecma).

The relative weight of performance and cost parameters may vary from a project to another:

- the performance requirement may be essential for upper stage: every additional second of specific impulse results in a significant payload increase;
- the recurring cost parameter is dominant for (expendable) booster engines; and
- the development cost constraint can be very important for a dedicated scientific mission.

Lessons learnt from recent developments have shown that the hierarchy of these design requirements should be clearly expressed at the beginning of a project and maintained along the duration of the project, avoiding shifts from a priority to another.

An increasingly visible trend is the importance of international cooperation [24,32,39].

Numerous projects involve cooperation between companies belonging to multiple countries.

The development of ARIANE is one of the earliest examples of international cooperation, mostly in the frame of Europe.

RD 180 [Fig. 5] engine implementation on ATLAS 5 is another well-known example of this trend.

International cooperation requires solving the following difficulties:

- exchange of large amount of data in compatible formats, especially for CAD models;
- compatibility between different technical standards or norms; and

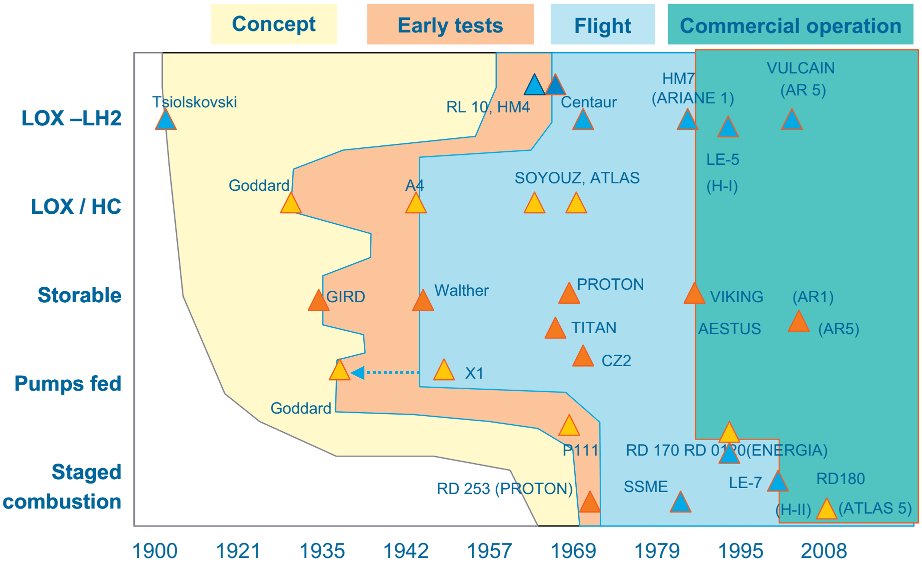

Fig. 9. Liquid propulsion milestones.

Fig. 10. Vinci engine (*source*: Snecma).

- barriers arising from international trade regulations when dealing with sensitive technologies.

Improvements in design (especially with simulation tools) and manufacturing methods, which have transformed the automotive, and aircraft industries in the late 1990s and early 2000s have equally transformed the field of space propulsion.

Numerical simulations and computer-aided design have contributed to significantly shorten development duration by eliminating the trial and error process, which led to long developments in the past.

Recent demonstration engines such as the Vinci [Fig. 10], Ariane 5 upper stage engine, have reached reliable steady state operation in a much smaller number of tests than would have been required in the 1970s or 1980s.

Additionally, increased focus on productivity, reproducibility and environmental concerns has also modified working methods in the space industry as much as in any other industrial sector.

Just as numerical simulation has transformed the development of propulsive systems, miniaturization and new instrumentation technologies have transformed the field of component and engine testing.

The last 10 years have seen the emergence of new type of instrumentation, which helps test engineers in extracting as much information as possible from the tests:

- flush pressure gauge with high bandwidth have helped characterizing fluid excitations of structures which are the source of numerous high cycle fatigue failures in rocket engines;
- laser, optical and magnetic instrumentation have contributed to the knowledge of turbine blade behaviour;
- thermal instrumentation and infra-red camera have led to a more accurate evaluation of heat fluxes;
- etc…

Capitalizing on these new instrumentation technologies, design and test engineers have access to an immediate understanding of the behaviour, reduce the number of tests, and avoid unnecessary design loops induced by wrong corrective actions due to incomplete or faulty interpretation of the physics.

Furthermore, miniaturization, new instrumentation techniques and availability of computing power will boost the use of regulation and health monitoring technologies, thus significantly contributing to performance and reliability of propulsive systems.

An extensive use of “smart” system and health monitoring technique, which will be able to provide the status of propulsive system with increased accuracy and correct its deviations, is likely to be seen in the coming years.

4. Trend for next and future launchers

The requirement of the commercial satellite market, which dictates a regular increase in satellite mass and a stronger than ever demand for reliability, will probably lead to a family of new or improved engines with more design margins, simpler to use and to produce.

The regular rate of mass increase for telecommunication satellites over the past few years can be explained by the restriction of use of geo-stationary positions which induce telecommunication operators to concentrate as much transmitting capability as possible in one single spot.

Additionally, a common goal of all existing commercial launch suppliers is to possess an array of launch vehicles, which enable them to provide a wide variety of launch services. This is obtained by simultaneously operating a fleet of heavy, medium and small launch vehicles as much as by increasing the flexibility of existing launchers, very often through the development of new upper stages offering new features or additional performance such as a restart capability or an increased propellant load.

In order to maintain the quality of their launch service, launch suppliers need to rely on a dedicated and skilled work force which should be ready to deal with any anomaly or solve any production mishap that may endanger their reliability record. Maintaining a research and development effort, starting new developments may help in keeping motivated teams of engineers and technicians which are as much essential in serving today's need as in preparing the future.

At least in Europe, next launchers are foreseen to be improved versions of existing and expendable ones. Improving the upper stage capability is a very efficient way to increase the overall launcher performance (payload), hence the interest of new cryogenic upper stage engines like VINCI [1,23], in Europe [Fig. 10], but also MBXX [32] in the US and Japan and RD0146 [30] in Russia.

The next launcher generation (2020–2025) is less clearly identified. A programme dedicated to the preparation of future launcher, the Future Launchers Preparatory Programme (FLPP), began in Europe in February 2004 and aims at having a Next Generation Launcher (NGL) operational around 2020. The FLPP is focused on developing concepts for various launch vehicle systems together with the technology needed to realize them.

The debate is still open concerning the choice of upper stage propellants: cryogenic, LOX–methane or storable.

In Europe, this trade-off is focused on small and medium launchers, while in Japan all types of launchers are considered.

The interest in using hydrocarbons, especially methane, for rocket propulsion, is mainly driven by the high fuel density, high boiling point, reduced handling constraints, and reduced need for safety precautions relative to hydrogen.

The emergence of very cheap launchers can be noticed, especially for small payloads, but the recent experiences (e.g. FALCON 1) show that it does not seem so easy to simplify too much the engine design (e.g. the go back from radiative to regenerative combustion chamber on Merlin engine) and to reduce very significantly the development process cost, without discovering unforeseen phenomena during the first flights.

Fig. 11. J2X engine (*source*: PWR).

The role of private entrepreneurship in promoting innovative designs combining performance and low costs is still to be demonstrated.

In the US, manned space transportation came back to the forefront with the development of ARES I and V.

In 2006 NASA made significant progress on Ares I and V system development, selecting Boeing to build the upper stage of Ares I and Pratt & Whitney Rocketdyne for design, development and testing of the J-2X engine [Fig. 11] that will power the upper stages of Ares I and V [46]. For the booster of Ares V it is planned to use a version of the RS-68 cryogenic engine currently used on the Delta IV launch vehicle.

Propulsion is also being developed to support the in-space portion of the exploration architecture. Aerojet is developing a pressure-fed engine for the new human transport Orion service module. This engine is based upon the Space Shuttle Orbital Manoeuvring Engine, which uses storable propellants. The plan is to also use this Orion Service Module engine to perform the ascent function on the lunar module using storable propellants, although methane/LOX options are also being considered.

For the descent stage of the lunar exploration architecture NASA has identified pump-fed hydrogen performance levels as being needed. Readiness for this application is being pursued along two fronts: first Pratt & Whitney Rocketdyne is supporting deep throttling demonstrations in the CECE programme [15]; Northrop

Grumman is also pursuing deep throttling technology for LOX/hydrogen propulsion based upon the Pintle injector technology approach.

Meanwhile Space exploration can also rely on robots and automated vehicles.

Europe is focused on automatic planetary exploration. Ascent and landing of heavy robotic payloads will also require the development of new engines.

Space tourism is an emerging field close to space propulsion for launcher in which most work is currently devoted to suborbital flights. Virgin Galactic SPACESHIP 2, the ROCKETPLANE XP and the ongoing EADS ASTRIUM project are the most well-known illustrations of this activity.

Space tourism could also be seen as a way to mature very cheap and reliable propulsion techniques having the potential to drastically reduce the launch cost.

New concepts, like low thrust cryogenic propulsion, may enable to extend the domain of cryogenic propulsion to lower propellant masses and smaller launchers (orbital stage or upper stage of micro launchers with payload below 300 kg) [10,14,17,43].

Fully reusable launchers will probably not be developed in a foreseeable future, but the introduction of reusable boosters (like LFBB: Liquid Fly Back Boosters) could come earlier as a forerunner of full reusability.

Cleaner propellant combinations relative to usual storable propellants (MMH, UDMH, NTO), commonly designated as “green propellants” could come to fruition, provided early demonstration at low thrust level are satisfactory [8,16,21,42].

5. Areas of future improvements

In the mid and long term, areas of future improvements will probably represent a continuation of the objectives, which are already observed in the selection of propulsive solutions for ARES I and V in the US or in ESA Future Launcher Preparatory Programme in Europe.

These main areas of consolidation and improvement are:

- reliability;
- cost reduction which should not be obtained at the expense of reliability;
- availability;
- reduction of development duration; and
- increase of performance considered in term of thrust and specific impulse, and also in term of life duration.

Reliability will remain the number one design criterion in the future. But there will be an increased awareness that achieving the best possible compromise between various objectives as early as possible is essential.

New design tools may help in this task: parametric design methods, sensitivity analysis, probabilistic methods (e.g. for structures).

In the field of car engines and turbojets, while the basic technologies have apparently remain the same over the last 50 years, the reliability and life duration made tremendous progress thanks to use of new material, digital control and regulation. The same evolution could be expected for rocket engines.

New material processes such as metal deposition and new welding technologies will probably allow higher operating temperatures or facilitate the production of complex hydraulic shapes.

The goal of increasing engine life duration-which will be essential in the long term for reusable vehicles—also contributes to increase the reliability level when applied to expandable vehicles.

For commercial launch vehicles, the reduction of launch cost expressed in term of $ per kilogram or lb of payload will remain essential.

For large expandable launch system and infrastructures, this goal can be obtained through a continuous increase in performance, for instance in order to keep the dual launch capability for ARIANE, or by an increased focus on design simplicity.

For instance, in the case of ARIANE or H2, every second of main engine specific impulse brings around 100 kg of additional payload.

Green propellants could contribute to the cost reduction by lowering the direct cost of propellants and reducing the propellant handling cost.

In the long term, the launch cost reduction will be obtained by using partially reusable launchers (FLBB) or totally reusable system.

This future step will probably require a technological rupture in the field of aerospace material with respect to strength to density ratio as well as fatigue and creep capability.

It is difficult to predict when this transition could occur.

6. Roadmap

In this paragraph a distinction is made between a short and mid term future for which a predictable continuation of current programmes can be expected, and a long-term future full of unforeseeable technological ruptures and open to unbridle imagination.

6.1. Short and mid term

6.1.1. USA

The space exploration programme objectives were clearly defined over the 2006–2007 period and the programme is now well on track.

Its main objectives are:

- to safely fly the Shuttle until 2010;
- to develop and fly the crew exploration vehicle before 2014; and
- to return to the Moon no latter than 2020.

The propulsion options, which were retained to fulfil these objectives, are:

- the J2X, a 1300 kN cryogenic engine [Fig. 11],based on the Saturn era J2 engine and the powerpack of the more recent X-33 aerospike demonstration [46];
- an upgraded version of the RS68; and
- development of the pressure-fed storable engine for the Orion crew vehicle service module, based on the Shuttle orbital manoeuvre engine [45].

In July 2007, NASA announced that the common extensible cryogenic engine demonstrator (CECE) based on Pratt & Whitney Rocketdyne RL10 engine was under development to support future space vehicles, with specific focus for the deep throttling lunar Lander stage [18].

In the Apollo lunar module, the lunar descent engine from TRW was capable of throttling from 10,125 lb down to 1250 lb. It was a pressure fed storable system that has limited performance for the new NASA lunar missions.

The CECE will serve the same purpose. In its demonstrator configuration, it is a 13,800 lb engine fuelled by higher performance liquid oxygen and hydrogen. Its main requirements include the capability to be throttled down to about 10% of maximum thrust.

NASA's Propulsion and Cryogenic Advanced Development (PCAD) programme is investigating the use of liquid oxygen and liquid methane technologies applicable for lunar ascent. Aerojet is currently developing a 5500 lbf pressure-fed LOX/Liquid Methane high performance engine that will be tested in 2009. Aerojet also just completed the successful development and testing of a 100 lbf LOX/Liquid Methane Reaction Control Engine for similar applications.

LOX–methane RCS eliminates the handling of toxic propellants.

At the same time, the consolidation of the existing space launch infrastructure was completed in 2006 with the creation of the United Launch Alliance which combines the Delta launch system (Delta II and IV) and the rival Atlas V system.

Booster propulsion for these US Air Force systems include the RS-68 engine produced by PWR for the Delta vehicle and the RD-180 kerosene booster engine produced by NPO-Energomash in Russia, but supplied for the Atlas vehicle through a Joint Venture with PWR. For the upper stage, both launchers use models of the RL10 hydrogen/oxygen engine. Significant activities to improve these propulsion systems are currently limited to a performance improvement for the RS-68 designated RS-68A.

Aerojet is providing the kerosene-fuelled AJ26, a highly modified version of the Russian NK-33 LOX-rich staged combustion engine, as main propulsion for the first stage of the Orbital Sciences Taurus II launch vehicle, scheduled for first flight in 2010.

Farther term technology readiness for the next generation of Air Force systems is being pursued under the IHPRPT (Integrated High Payoff Rocket Propulsion Technology) programme. During Phase I of IHPRPT, PWR and Aerojet successfully completed demonstration of new hydrogen/oxygen propulsion in a full-flow staged combustion cycle. The recently initiated IHPRPT Phase II activity is focused on the kerosene/oxygen oxygen-rich staged combustion cycle and is being performed by Aerojet.

Meanwhile developments of new engines for space application and spacecraft control were on going. In 2007, a major accomplishment by Aerojet was the successful hot-fire testing of an MR-80 series monopropellant hydrazine engine. This is a Mars Lander derived engine tested as a proof of concept for an Ares roll control engine.

Orbital Technologies (Orbitec) continues its development of the Forward-1 reusable 7500 lbf LOX–liquid propane vortex engine. Forward-1 is a pump fed engine system that uses a regenerative-cooled nozzle and vortex cooling in the chamber.

6.1.2. Europe

6.1.2.1. ESA and the national space agencies (DLR, CNES, ASI, SNSB…). The short-term main goal of ESA and the national space agencies is the consolidation and improvement of ARIANE 5 and the completion of the development of VEGA.

When improvements of Ariane 5 deals mainly with a new cryogenic upper stage with the VINCI oxygen/hydrogen expander engine [Fig. 10], the completion of the development of VEGA deals with the qualification of the AVUM storable 4th stage [7], and the qualification the RACS, monopropellant hydrazine Roll and Attitude Control System [36].

In parallel these agencies are actively promoting and managing research and demonstration programmes aimed at initiating new technologies and upgrading the technology readiness level of emerging ones. The previously mentioned Future Launcher Preparatory Programme (FLPP) led by the European Space Agency (ESA) is one the most significant of these programmes. The FLPP is proceeding to mature technologies for upper stages engines as well as high thrust engines [35,37].

As part of ESA FLPP, an expander engine demonstration based on the VINCI engine is on going.

In 2008 the cryogenic propellant VINCI engine tests continued with a goal of providing further information on the engine operation capability. The VINCI is an expander cycle upper stage engine with an increased performance and multiple firing specification, which is typical of what is currently required to enlarge the scope of missions and increase the capability of heavy expandable satellite launchers. Its overall system design is under responsibility of Snecma (France) under ESA contract. It is a key element of European future launcher evolution.

In parallel ESA and industry are preparing demonstrations activities for high thrust engines to be started by the end of 2008 in order to meet the propulsion requirements of post 2020 launchers.

The VULCAIN X is also one of the lead European demonstration programmes in the field of liquid propulsion [3]. It is using the VULCAIN 2, ARIANE 5 main stage engine, as a platform for implementing new technologies in various field of liquid propulsion.

The VULCAIN X programme aims at demonstrating new technologies and sub-systems architecture for introduction in future developments: a fuel turbo pump with fluid bearings, a gas generator with tri-coaxial injection elements, a sandwich technology nozzle and high band-width regulation valves. The VULCAIN X programme has been initiated by the French space agency (CNES) and has been extended at a European level.

As part of the VULCAIN X programme, VOLVO AERO of Sweden has developed a nozzle relying on the sandwich technology and advanced welding and metal deposition processes.

In addition to European programmes involving industrial partners of several countries, each national agency is often pursuing specific goals, which are related to historic field of expertise or specific national needs.

The CNES launchers roadmap covers the whole range of payloads from 30 kg in LEO to more than 12 ton in GTO. All these developments are foreseen to be implemented in a European frame.

CNES is promoting research on "green" and low cost upper stage propulsive system for nano/micro launch vehicles [9].

Germany is focusing on combustion with on-going works on LOX/LH2 combustion, LOX/methane combustion [29] and staged combustion.

The German Aerospace Agency is investigating various aspects of methane–oxygen combustion, such as propellant injection, atomization, ignition, high-pressure combustion, combustion instabilities, and performance of methane for regenerative cooling.

Italy is also promoting activities related to LOX–hydrocarbon engines [20].

6.1.3. Japan

Production and management of the Japanese key rocket of H-IIA, the first flight of which successfully occurred in 2001, was shifted from the Japanese Space Agency (JAXA) to MHI on April 2007 when entering into the commercial launch market. JAXA along with MHI and other industrial partners has been continuously improving the reliability of LE-5B and LE-7A engines to support H-IIA launch service.

New design techniques such as Probabilistic Design Approach (PDA) and sensitivity analysis were demonstrated with advanced Computer-Aided Engineering (CAE) technology as a pilot programme for future engine development.

JAXA and MHI are still focusing on technology development to improve engine reliability [26], which is the basis of the commercial launch service and will be also a major key driver for future manned vehicles, which will be part of Japanese space activities in the 21st century [22].

The choice of the open expander cycle, which is more tolerant to system failure, also contributes to improve reliability. For instance, the LE-5B engine can start up to full power in spite of unexpected interface conditions such as low inlet LH2 pressure and poor chill conditions.

With a focus on system simplicity, robustness and tolerance to failure, JAXA is applying this highly reliable, flight-proven open expander cycle technology to next generation 100 ton-class engine as designated "LE-X" for upgraded H-IIA family and next generation launcher in 21st century [4,27].

JAXA leads fundamental technology developments such as advanced inducer, combustion injector with the latest high-speed visualization technology.

JAXA's Engineering Digital Innovation (JEDI) Centre is developing the advanced computer simulation technology to support these fundamental programmes.

As part of a "Propulsion for exploration" programme, JAXA is also developing large range throttling LOX/LH2 engine for vertical assent/vertical landing reusable vehicle.

JAXA is also developing a LOX/LNG engine. Currently, the engine with gas generator and turbopump will be applied for 2nd stage of GX rocket [47].

6.1.4. China and India

China is expanding the family of Long March launchers adding increased capability and flexibility to this launch system. China is also actively engaged in a national space exploration programme the recent highlights of which were a manned flight around the Earth and the circumlunar flight of a scientific probe.

China develops new engine for the Long March 5 (LM5) heavy lift launcher. Development has been started for a 1200 kN LOX/kerosene booster and 500 kN LOX/LH2 upper stage engine. Long March 5 will be in the class of Ariane 5 and Delta 4 and operation is expected for 2014.

India is developing and upgrading the GSLV and PSLV launchers.

As part of this effort, India is developing a new 200 kN thrust gas generator upper stage cryogenic engine [38].

6.1.5. International landscape

One can see that each region/nation has its own propulsion system development for various political or security reasons.

In view of limited resources for each nation, one has to ask if the same kind of saving can be achieved "commercially" in propulsion systems development similar to commercial airplanes and gas turbines.

However, there is a huge difference between aeronautics and launchers: the series effect for commercial airplanes allows for a commercially funded development while the launch rate does not yet support this approach.

There is a general willingness among propulsion companies to cooperate in order to spread the development cost, but—except in the European case-this is somewhat hampered by export control rules.

6.2. Long term

When looking at the evolution of liquid propulsion over a century, one can observe that it relies on a few permanent simple Concepts that have been implemented in a more and more efficient way using the available technical Knowledge at the time when successive generations of engines were designed.

These Concepts are the following:

- liquids are one of the most efficient way to store chemical energy in a dense form;
- thrust and exhaust velocity are generated by the expansion of light molar mass gases; the higher expansion (high chamber pressure, high nozzle expansion ratio), the higher the thrust; and
- liquids should be stored at the lowest possible pressure and a system to increase their pressure may be required.

This last point is linked to another question: the use of densified cryogenic propellants. This technique has been proposed since several years but not applied up to now, except on Energia/Bouran. The application may be interesting in the future, especially for in-orbit propulsion (tank pressure below atmospheric pressure).

The available Knowledge obviously relies on state-of-the-art fluid mechanics, material and strength of material science, electrical engineering for auxiliary power and control.

Using this Concept/Knowledge approach and trying to project one self into a long term future, the questions to be asked are the following:

- Will the basic concept change?
- Will the available technical knowledge offer new solutions to implement these concepts?

A short sample of the questions arising from these general considerations can be expressed as follows:

- Could new energetic chemical combination further improve the energy versus density ratio of today's known propellants? Energetic propellants are already investigated relying on software that can help engineering new molecules and predict their properties.
- Shall we see a wider application of the pulse detonation engine?
- Will smart material with a capability of providing their deterioration status and heal their damage be used?

Besides technical aspects, as much as today, the evolution of liquid propulsion will remain driven by the "customers" needs (commercial, institutional or tourist).

The planetary exploration (automatic or manned) may be the main driver of liquid propulsion in the future [5,13].

The use of cryogenic propulsion for interplanetary mission will probably require active refrigeration, i.e. Zero Boil Off (ZBO) [17].

At least for LOX, In situ Propellant Production could drastically reduce the expenditure of recurring mission.

Another possible evolution—beyond the space tourism-is the suborbital passengers transport—i.e. the extension of liquid propulsion from launchers to hypersonic, airline-like transportation. The vehicle may use a two-stage concept, with airbreathing propulsion on the first stage and LOX–LH2 engines on second stage [34].

The considerable increase in the production rate and the requirements of reusability will have a deep impact on the launcher business.

On a more modest scale, the increase of launch rate for commercial missions will be the decisive factor to shift from expendable to partially reusable launchers.

For both expendable and reusable launchers, the simplification of launch procedure will be a decisive cost reduction enabler. To this end, a significant part of the ground support equipment and its software has to be transferred on the launcher, possibly using the resources of health monitoring system.

7. Conclusion

Although predicting long-term trends beyond the years 2020s is difficult, in particular the shift from expandable to fully reusable or the technological ruptures that may occur in the field of design and manufacturing, the following trends can be assumed without significant risk of error:

- a constant and increased need for reliability;
- the generalized use of new design tools which contribute to reduce development duration and new manufacturing/NDI methods which allow more innovative designs;
- an increased focus on the use of environmentally friendly technologies; and
- the need to meet the requirements of a wide array of customers: institutional customers with defence, scientific and space exploration programmes, commercial customers launching increasingly heavier satellites with a reduction of launch cost per kilogram, emergence of space tourism.

In order to meet the requirements of these new trends, liquid propulsion that is often seen as a mature technology has pushed the potentialities offered by modern engineering and manufacturing technologies to the limits.

This has led to a family of new engines with more margins, simpler to use and to produce, which were initiated as demonstration programmes or are still on the drawing board.

Since these development activities are still heavily relying on public funding, there is a need to engage, inspire and educate the public concerning the benefit that is coming from space exploration and from the use of space. There is also a need to strengthen existing and create new international partnerships in order to share the cost of these developments.

Almost a century ago, Tsiolkovsky and Goddard came to the conclusion that liquid propulsion was the most appropriate form of propulsion for long-range rockets. At the beginning of the 21st century, liquid propulsion is still not likely to be replaced as the most efficient way to provide the high energy propulsion which is required to keep man's dream of reaching outer space alive.

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