

Snecma Space Engines Division Six Decades of Liquid Rocket Propulsion

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Snecma's Space Engine Division located in Vernon can look on 65 years of experience in the field of liquid rocket engines. Resulting from mergers combining assets established in the mid-1940s, Snecma is the European leader in cryogenic rocket propulsion and also is the second oldest rocket engine company in the world. Until the early 1960's it had developed and produced propulsion systems that enabled France to become the third space power and gave the French Air Force the world's sole rocket-augmented jet fighter "Mirage III C" with a unique and fully reusable man-rated rocket engine. This technological experience was applied to the development of the European Ariane launcher's complete propulsion systems. Thus were born the Viking high-thrust storable propellant engines and the cryogenic HM7TM, Vulcain 1®, Vulcain 2® engines. Today, with the industrial production of Vulcain® and HM7TM and the pre-development activities of the Vinci expander engine, Snecma Space Engines Division remains at the forefront of commercial and industrial rocket engines.

Key words : liquid propulsion, history, man-rated, cryogenics, high-thrust

1 Introduction

1.1 French space propulsion pioneers

Even if the astronautical activities of the French pioneers are not as well known as the ones of their German, Russian or American colleagues, France was also the place of important scientific works on space and on rocket propulsion (both solid and liquid propellant) in the beginning of the 20th century. The first French rockets were military ones: during World War I, Yves Le Prieur (1885-1963) had developed air-to-air rockets to be launched by fighter aircraft against *Drachen* observation balloons. They were first operationally used in the spring of 1916. Le Prieur had gained fame in Japan in December 1908. As Military Attaché to the French Embassy, he achieved at Ueno (Tokyo) Japan's first gliding flight on a bamboo-frame biplane glider he had built with his friend Shiro Aibara. Another French pioneer, Louis Damblanc (1889-1969) started his research on solid propellant rockets, established equations governing rocket trajectories, and was also the inventor of the staged-rocket. Robert Esnault-Pelterie (1881-1957), who was first an aviation pioneer, devoted his research to scientific works on space exploration, foreseeing space travel to the Moon, Mars and Venus. He also experimented bipropellant rocket engine (1931), worked on combustion chamber (1932), and in particular focusing on the stability of combustion. His works were carried on by Jean-Jacques Barré (1901-1978), who is the father of the first French liquid-propellant rocket. The flight test of this rocket, *EA41*, took place in the South of France on March 15, 1945.

1.2 Snecma space activities historical outline

Snecma's Space Engines Division is the result of the combination of three entities : SEPR, LRBA and the SNECMA Space Division. SEPR and SNECMA Space

Division merged in 1969 creating the Société Européenne de Propulsion (SEP). Two years later, SEP was joined by the space activities of LRBA. Each entity having its own specificity, (established in 1944, SEPR was specialized in man-rated liquid rocket engines and in solid rocket motors; created in 1946, LRBA was specialized in storable liquid propulsion and high-thrust engines) the resulting company had a very wide range of products and experience. In 1996, Snecma, major shareholder of SEP since 1984, merged with its subsidiary, leading to the Vernon-based Space Engines Division.

2. Man-rated rocket engines

2.1 The proof-of-concept SEPR-25

The first demonstrator aircraft-rocket engine to be developed was the SEPR 25 : an engine burning Nitric Acid and Furaline (a mixture of 41% of furfuryl alcohol, 41 % of xylidine and 18 % of methyl alcohol) and delivering a thrust of 1.5 tons. Its pumps were mechanically driven by the aircraft's jet engine. The first rocket flight on the "*Espadon*" plane was achieved on June 15, 1952. On December 15, 1953, it reached Mach 1 on horizontal flight, becoming the first European supersonic airplane. A total of 89 rocket flights demonstrated the feasibility and advantages of the concept. This led the French Air Force to issue a requirement calling for the development of a mixed-power lightweight interceptor. Two companies built and flew prototypes : the Sud-Aviation *Trident* and the Dassault *Mirage*, SEPR providing rocket power for both.

2.2 The SEPR 48 and 63 engines for the *Trident*

The *Trident* fighter concept was powered by a main rocket engine fitted in the fuselage and by two small auxiliary wingtip mounted turbojets. The initial prototype, "*Trident 1*" prototype, was powered by a single SEPR-48 engine. Its three chambers (thrust : 15 kN each) were fed by a single gas-generator-driven turbopump. They could be

ignited together or separately, enabling the overall thrust to be of 15, 30 or 45 kN. The maiden rocket flight of the prototype *Trident 1* took place on September 9, 1954. Only 24 rocket flights were made. The following step was the preproduction plane, the "*Trident 2*". Its SEPR-631 engine was similar to the SEPR-481, but had only two thrust chambers enabling longer duration runs. The first flight took place on December 21, 1955. The flight tests of the *Trident 2* were extremely successful : on March 31, 1958 the Trident set a climbing speed world record by reaching 15,000 m in 2mins 50secs. On May 2, the *Trident 2* set another world record by reaching the altitude of 24,217 m (79,660 ft). Unfortunately the programme had already been cancelled .



Figure 1. The Trident 2 at take-off with SEPR-631 engine

2.3 The Mirage and the SEPR 841/844 engines

This fighter was a small delta-wing plane powered by a SNECMA Atar 9C jet engine and by a single SEPR rocket engine, whose pumps were to be driven by the jet engine, thus simplifying the overall design. The final rocket engine family, SEPR 84, powered the operational *Mirage IIIC* (SEPR 841) and *Mirage IIIE* (SEPR 844) fighters. It was the most advanced man-rated engine to be developed by SEPR and the only one in the world to reach operational maturity. As propellants, the SEPR 841 used nitric acid and triethylamine-xylydine. It delivered a thrust of 750 or 1,500 kg and could be ignited twice during the flight. The SEPR 844 used kerosene (stored in the aircraft) as fuel, in order to increase simplicity and operational handling.

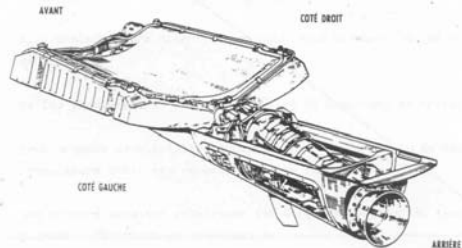


Figure 2. SEPR 844 engine

The acid tank, integral part of the engine, was made of stainless steel. The propellant feed system consisted of two centrifugal pumps driven by a shaft coming from the aircraft's turbojet engine. A gearing set permitted the desired pump speeds. Both pumps and impellers were machined of light alloy. The combustion chamber was double-walled, cooled by a flow of nitric acid, and was made of light alloy. The SEPR 841 entered operational service in December 1961 at the Dijon Air Base. To the end of its operational service in 1970, these engines completed 1,505 rocket flights (2,064 ignitions). The SEPR 844 entered operational service in June 1967 at the Colmar Air Base. A total of 164 SEPR 841 and 111 SEPR 844 engines were built and used operationally in France until 1984 and Switzerland until 1996. The *MIRAGE III* fitted with rocket engines have logged more than 10,000

rocket flights with a 99 % success rate. No plane was ever lost due to a rocket engine incident.

Table 1. Man-rated engine data

	SEPR 25	SEPR 481	SEPR 631	SEPR 844
Thrust (sea level) (kN)	15	15 – 30 or 45	15 – 30	15.3
Pump drive speed (rpm)	5,170	20,000	28,000	4,760-4,980
ISP (s)	200 s	208 s	192 s	208 s
Propellants	Nitric acid Furaline			Nitric acid Kerosene
Flights	89	30	196	> 10,000



Figure 3. Mirage IIIC rocket engine test

3 Sounding rockets

On March 1, 1949, the French Defence Ministry decided the development of a sounding rocket able to carry a 65 kg payload to an altitude of 60 kilometers. This vehicle was named "*Véronique*" and consisted of a nose cone housing the payload, a parachute for payload recovery, an hypergolic gas generator, propellant tanks for nitric acid and kerosene, the pressure-fed rocket engine (thrust: 4 tons) and four stabilising fins. It was launched for the first time from Hammaguir (in the French Sahara) on May 20, 1952. Unfortunately the first test flights demonstrated combustion instabilities. In order to remedy to this, a new injector was designed, and its flight tests were more satisfactory. However, some improvements were still necessary. A new version was designed, this time with the aim of having a fully operational vehicle. This was the *Véronique AGI*. Its longer tanks were made of lighter steel and its engine was of a totally new design : the injector made of light-alloy, the combustion chamber was of steel and its throat was of massive graphite. Kerosene fuel was replaced by turpentine, reducing the sensitivity to combustion instabilities and increasing the specific impulse by about 5 %. The combustion chamber was cooled internally by a film of fuel. A final version, *Véronique 61*, was designed in the early sixties. It had a more powerful engine (thrust 6 tons) and enlarged fins for better stability. About hundred *Véronique* rockets were built, the last one being launched in 1975 from Kourou. An enlarged derivative, *Vesta*, was designed in the early sixties and, by using an engine delivering 16 tons of thrust, could bring a 1 ton payload to an altitude of 300 km.



Figure 3. Véronique sounding rocket

Table 2. Sounding rocket data

	Véronique N	Véronique AGI	Véronique 61
First flight	1952	1959	1964
Thrust (kN)	40	40	60
Propellants	Nitric acid kerosene	Nitric acid turpentine	Nitric acid turpentine

4 Storable launch vehicle propulsion systems

4.1 Powering the French national launch vehicle Diamant

In 1959, the French government decided to establish a national deterrent force using ballistic missiles. Consequently, all key technologies (guidance, re-entry and large solid motors) were to be acquired through technology programs. A powerful launch vehicle was needed to test the control and guidance systems as well as the warhead re-entry vehicles. This multistage vehicle had a liquid-fuelled first stage (*Emeraude*), using the *Vexin* engine designed by the LRBA and based on the experience gained on *Véronique* and *Vesta*.

Burning Nitric Acid and Turpentine, it delivered a thrust of about 28 tons. The engine design was very similar to those of *Véronique* and *Vesta*, but the gas generator used a slow-burning solid propellant grain, its gases being mixed with water in order to increase their volume and decrease their temperature. As the vehicle was to be fully guided, the engine was gimbaled and actuated by two hydraulic jacks. In 1960, it was decided to use *Emeraude* as the first stage of the national launch vehicle *Diamant-A*, a three stage vehicle. On November 25, 1965, France became the third country to be able to launch its own satellites with its own launcher.

The *Diamant* program was pursued and a new and more powerful launcher, *Diamant-B*, was designed. This new vehicle used a new first stage. Called *Améthyste* it contained 17 tons of propellants (N2O4 and UDMH), using experience gained first with experimental engines and then with a second stage for the European launcher *Europa*. The stage was again pressure-fed, but the new gas generator used the same propellants than the main engine. This was the *Valois* engine, delivering a thrust of now 35 tons. This was the most powerful pressure-fed engine of LRBA, and *Améthyste* was the biggest pressure-fed stage ever built. *Améthyste* was used on *Diamant B* and the upgraded *Diamant BP4* from 1970 to 1975.

4.2 The European ELDO program

Beginning in 1962, France, Germany, Italy, the United Kingdom, Belgium and the Netherlands had decided to jointly build a powerful launch vehicle called *Europa 1*, under the aegis of the European Organisation for Launch vehicle Development (ELDO). France was to design the second stage, named *Coralie*, for which LRBA was responsible for the propulsion system. This was a pressure-fed stage, using a liquid-fuelled gas generator and burning N2O4 and UDMH. This was the first use of these propellants. The total thrust was 28 tons provided by four identical thrust chambers of 7 tons each. Extensive tests were performed at LRBA, first on single chambers, then on the full propulsion bay and finally on the complete

stage itself. Flight-tests of *Coralie* were also performed using a dedicated version of *Coralie* used as the first stage of a test vehicle. This was a one stage rocket made up of *Coralie* (with short nozzles) fitted with a dummy *Europa* upper stage and fairings. Three such rockets were launched. As for *Coralie*, it was used six times on *Europa*, between 1967 and 1971.

4.3 The Viking engine family

4.3.1 M40 : the first turbopump-fed engine

Following feasibility studies performed in 1965 and 1966, a design team started work and designed a first experimental turbopump in early 1967 in order to finalize its design. In parallel, the thrust chamber had been designed and tested separately from April until May 1969. On June 5, 1969 the first engine hot run took place. This was an overwhelming success and it was followed by further 17 tests until April 1970. The total test duration was 560 s with the final two tests lasting 100 s each. It is noteworthy that as early as for the 8th test, a restart was performed : a 4 s run followed by a 24-hour rest followed by a successful 20 s restart, thus demonstrating the ability of the engine to withstand a launch abort.

The *M40* retained the basic design principles of all engines designed at Vernon since the beginning : a film-cooled thrust chamber fitted with a radial injector. Atop this was located the turbopump and its water-cooled gas generator as well as two regulators : the main regulator (which equalized the chamber pressure to the pilot pressure by "throttling" the flow to the gas generator) and the balance regulator that eliminated the influence of pumps efficiency or in-flight variations of pump inlet pressure on the mixture-ratio. A family of engines based on the proven *M40* principles was considered with thrusts of 55 and 110 tons.

4.3.2 Viking, the workhorse of Ariane

When the ELDO (European Launcher Development Organization) decided to develop its next-generation heavy launcher *Europa III*, the first stage was powered by four engines developing each a thrust of 55 tons and based on the *M40* : the *M55*. Later on, its thrust was increased to 60 tons. As this decision was taken prior to the first engine tests, it was decided to uprate the *M55* in order to develop the new thrust. Such an achievement was made possible by increasing the turbine speed from 9500 to 10100 rpm. At that time it was also decided to give the engine a name. The chosen one was *Viking*, pursuing the established tradition of names beginning with "V" (for Vernon). On April 8, 1971 the first *Viking* was ignited on the PF2 test stand. This first run was not uneventful as the nozzle literally flew away, being cut under the throat ! This incident was not as serious as feared : it had been caused by an insufficient film cooling flow and the use of a nozzle without thermal barrier coating. A total of six tests was performed as pure engine development tests and they were followed by a dozen further tests in the so-called "stage configuration". In this case, the test stand was modified in order to ensure the propellant tank pressurization using hot gases from the engine's gas generator, just like it would be on the launcher. In the meantime, *Europa III* had been cancelled and *Viking's*

destiny seemed rather cloudy. However Europe decided on 31 July 1973 to develop a new European heavy launcher (*Ariane*) with a higher payload and using existing technologies. Therefore, the *Viking* engines were selected for its first two stages.



Figure 5. Viking 2 engine

The first stage of *Ariane* was virtually identical to that planned for *Europa III* and was powered by four Viking 2 engines, developing a thrust of 60 tons each. However, the development of these engines, directly extrapolated from the M55, was not trouble free. The pumps had to be fitted with inducers, in order to increase their overall performance in cavitation. In 1976, it was decided to replace the conical nozzle with a bell-shaped one that increased the specific impulse by 8 seconds. Thus the *Viking 5* was born. On November 17, 1976 the first propulsion bay with four engines was ignited. Finally, three qualification tests were performed in 1979 that gave final approval for flight. These stage tests also were used for validating all procedures that should be used in case of an abort, i.e. if the engines are ignited and cut-off before release of the launch pad clamps.

The second stage was powered by a single *Viking 4* engine, basically a *Viking 2* fitted with a larger bell nozzle adapted for vacuum operation. Within the European framework of the *Ariane* development, the test of the second stage and its engine were performed in Germany at the DLR establishment of Lampoldshausen. The *Viking 4* engine was hot fired in a vacuum chamber and during these tests, the only important difficulty arose : the nozzle extension "shrunk" during a test where the mixture ratio was (intentionally) not nominal. A new stronger nozzle extension had to be developed. The failure took place in June 1978 and the new nozzle was tested in may 1979.

The maiden flight of *Ariane* was scheduled for Saturday, December 15, 1979. Up to this day everything had gone well and at 5.40 in the morning, the gantry was moved away from the launcher. The first two stages had been filled the day before. Countdown was nominal, and at 11.30, the four *Viking* engines were ignited...but *Ariane* remained anchored on the ground. Eight seconds after ignition, the engines were cut off. This was a launch abort: the most unlikely event had happened. A small explosion had occurred in a pressure sensor 1.7 s after ignition. The sensor then reported a pressure of 150 bar and the computers deduced that the engine had malfunctioned. Therefore, the lift-off was not authorized and the engines were cut off. *Ariane* was intact and could be relaunched. Teams of technicians and engineers were sent from

Europe to Kourou, as per the operational planning. Finally on December 24, 1979, at 14:14, *Ariane's* maiden flight was a complete success and also the most memorable Christmas for all those who had worked on it. Ten years after the first hot run of the M40 demonstrator, the *Viking* engines had performed their first flight.

4.3.3 Upgraded Vikings for *Ariane 3* and *Ariane 4*

In July 1982, the ESA Council authorized the development of two more powerful versions of Europe's heavy launcher : *Ariane 2* (2175 kg to GTO) and *Ariane 3* (2585 kg on GTO). They also permitted dual launches of two 1195 kg satellites. Compared to *Ariane 1*, the main modification for the *Viking* engines was 8% increase in the thrust on the first and second stage engines which implied a chamber pressure increase and a propellant change from UDMH to UH25 (75% UDMH and 25% hydrazine hydrate).

The original combustion pressure on *Ariane 1* was of 54.5 bar. In order to increase it to 58.5 bar without generating combustion instabilities, the injector had to be modified. The validity of the injector modifications and thrust chamber design improvement performed was shown in April 1981 when an injector tested with UH25 reached 61 bar combustion pressure without showing combustion instabilities, while the same injector tested with UDMH only reached 56 bar without instabilities. For all engine acceptance tests, the pressure to be reached was set to 64.5 bar, 10% higher than nominal. On August 4, 1984, the first *Ariane 3* flight (V10) orbited two operational telecommunication satellites: ECS2 and Telecom 1A.

As early as in spring 1979, the CNES disclosed its plans for a successor to *Ariane 3* : *Ariane 4*. Its payload capability in GTO was to be of 2900 kg. This was to be accomplished with a lengthened first stage containing up to 200 tons of propellants and the use of four solid boosters. In spring 1981, the performance goal was increased in order to cope with the increase in satellite weights. The first stage had only four engines and contained 190 tons of propellants. For the first time, liquid-propellant boosters were fitted to the first stage. Finally in June 1982, the definitive configuration of *Ariane 4* was frozen. The first stage had four engines and contained 220 tons of propellants. It could be fitted with up to four jettisonable liquid rocket boosters, designated PAL (*Propulseur d'Appoint à Liquides*). This required modifications of the engines for longer operation, of the propulsion bay and also the development of the liquid rocket booster propulsion systems.

The main challenge was the increase of the first stage operation time, from 135 sec to 209 seconds. To demonstrate this duration, a propulsion bay with *Ariane 4* type equipment was assembled on an *Ariane 1* thrust frame. Heavy tanks, previously used for the *Ariane 3* propulsion bay tests were used on the PF20 test stand. A short duration test was conducted in October 1984, and a long-duration 208 seconds test the following month. To demonstrate the new long operation duration of the *Viking* on the first stage after the propulsion bay tests it was decided to modify the old PF2 facility in Vernon by adding to this facility the heavy tanks used on PF20 during the *Ariane 1* propulsion bay tests. Thus the tests

duration could be increased to 300 seconds far above the flight 210 seconds.

The new "stage" on *Ariane 4* was the liquid rocket booster PAL. Carrying 39 tons of propellants, it was very similar to the second stage, yet it required new engineering and new engine shutdown studies. Full scale booster tests took place at the DLR's test facility of Lampoldshausen in Spring 1985, with the first actual booster.

On June 15, 1988 the maiden flight of *Ariane 4* in a configuration with two solid boosters and two liquid boosters PAL was a complete success. 7 Viking were flown that day. One year later on the flight *Ariane 44L* with PAL boosters, 9 *Viking* engines flew the same mission. Yet *Ariane 4*'s maiden flight on June 15, 1988 marked the end of the road for the *Viking* engine development.

Although having been entirely designed by Snecma, *Viking* became quickly a European production programme, with many countries and companies involved:

Table 3. Viking engine European partner companies

Germany	MAN Technologie	turbopump and gas generator
Sweden	Volvo Aero	thrust chamber and nozzle
Belgium	Techspace Aero	main valves
Spain	CASA	anti pogo device
Italy	ALENIA	booster valves
	AERMACCHI	thermal shields

The 500th engine was delivered to its customer, Arianespace, on May 19th, 1992, and performed flawlessly in flight on June 25, 1993 (Flight 57). The 1000th engine was delivered on June 4, 1999 and flew on Flight 127 on February 2, 2000. The last flight of the *Viking* was on February 2003 on Flight 159. The 1163th and final *Viking* engine left the assembly line in 2001 and is now resting in storage. Of these 1163 engines, 958 were used on the 144 flights of the *Ariane 1* to 4.

Table 5 : Viking engine data

Engine	Viking 4	Viking 5	Viking 6
Thrust	808 kN	760 kN	760 kN
Isp	292.7 s	278.5	278.3
Mixture ratio	1.71	1.71	1.71
Nozzle area ratio	30.8	10.5	10.5
Combustion pressure	58.5 bar	58.5 bar	58.5 bar
Weight	886 kg	826 kg	826 kg

5 Cryogenics

5.1 The HM4 demonstrator

In December 1961, SEPR performed a series of tests on water-cooled LOX/GH₂ combustion chambers. They continued until 1966 and cumulated 320 seconds of operation. In 1962, a contract was awarded by the armed forces for the replacement of the solid-propellant 2nd stage of the French launch vehicle *Diamant* by a cryogenic one. The planned H₂ engine had four chambers (overall thrust : 60 kN) fed by a single geared turbopump driving two pumps (LOX and LH₂) with a single turbine. The cycle selected was the gas-generator.

In 1963, the first tests of its oxygen pump started followed one year later by the hydrogen pump was tested. Gas

generator tests followed. In 1965, satisfied by the good results obtained so far it was decided to continue the engine development, its thrust being reduced from 60 to 40 kN and the engine re-named "*HM4*". First tests of turbines, LH₂ pumps, thrust chambers and turbopumps were also performed in 1966, and in early 1967 the first engine tests were initiated..

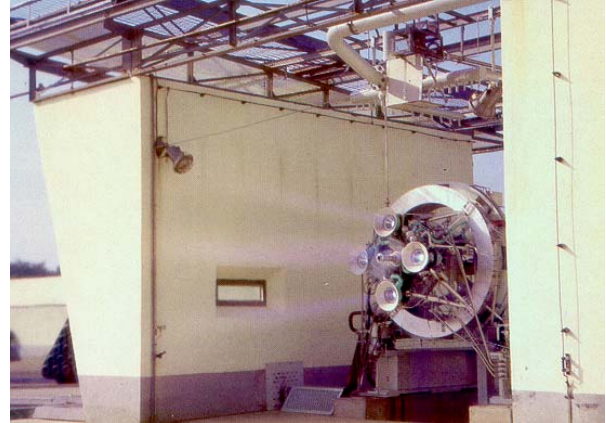


Figure 6. HM4 engine ground test

On March 29, the *HM4* was ignited for the first time. A violent explosion happened at ignition, damaging both the engine and the test facility. The analysis showed that a combination of atmospheric elements (fog, cold), a high mass flow of chamber chill-down hydrogen and an improper ignition sequence had caused the mishap. On 31 July, the second engine test was a full success. Tests continued until 1969, when *HM4* was finally abandoned, as no launcher program using it could be envisioned.

5.2 The HM7TM, upper stage engine for Ariane

Ariane's upper stage was to be a cryogenic one, powered by a new engine closely based on the *HM4* engine and retaining its cycle (gas-generator cycle) and its turbopump. Developed by SEP, it had a single thrust chamber designed by MBB in Germany. SEP also had the responsibility for the development of the propulsion system of the 3rd stage, system made of the *HM7TM* engine, the propellant system (tanks, helium tank, pressurisation systems, feed-fill-drain systems) and the thrust frame with the power and piloting systems.

Following the initial design, sub-assembly tests started at SEP on gas generators, turbines, pumps and valves as well as at MBB in Ottobrunn on the thrust chamber where a dedicated test facility was established. New engine, propulsion system and stage test facilities were built at SEP Vernon. The step by step approach was pursued with engine and stage tests, with a gradual integration of flight equipment : first came engine tests on 7 November 1975, then tests of the propulsion system and finally the stage tests that began in October 1977. The overall development went rather smoothly, only few problems appeared. These were mostly linked with hydrogen leaks that caused minor explosions. All efforts were crowned on December 24, 1979 when the first *Ariane* performed a flawless maiden flight.

The decision to develop the more powerful *Ariane 2* and 3 versions had impacts on the *HM7TM* engine. Its specific impulse was increased, the nozzle was lengthened by 200

mm and the combustion pressure was increased from 30 to 35 bar. This modified version was designated *HM7bTM*. As for the 3rd stage, it was lengthened in order to increase the propellant mass from 8 to 10 tons. This led to change the mixture ratio from 4.47 to 4.76 and to increase the burn time. This stage flew on all *Ariane 2*, *3* and *4* flights. The *HM7bTM* engine is still being produced at a rate of about 8 a year for *Ariane 5* and over 200 engines have been manufactured so far of both versions.



Figure 7. *HM7bTM* engine

5.3 Vulcain 1

The first studies of a new powerful (500 kN) cryogenic upper stage engine HM 50 began in 1978. By the end of 1979 various engine cycle trade-off studies (topping cycle or gas generator) had been performed. At that time it was decided to select the gas-generator cycle, due to reliability and for safety reasons and to set the thrust to 1000 kN, in order to use it on *Ariane 5*'s core stage. On 12 December 1984 the engine programme was officially launched and it was named *Vulcain®* in October 1986 reviving the old tradition giving all engines and launchers designed in Vernou a name beginning with "V".

Full scale development started in 1988 with the first sub-system tests (hydrogen turbopump, thrust chamber). They proved the soundness of the new designs. On 4 April 1990, the first hot run was performed flawlessly. The first 600s full duration hot run was performed on 13 June 1991. A year later, a renewed emphasis on GTO performance yielded the requirement for a *Vulcain®* thrust increase from 1025kN to 1140kN. In June 1995, *Vulcain®* was qualified, after 300 tests on two test facilities and a cumulated duration of 80,000 seconds.

5.4 Vulcain 2®

Quite early in the *Vulcain®* development it was obvious that however powerful the new launcher was, it was not enough. So an upgraded launcher has been designed, with an increased performance core stage. To maximize stage performance, the upgraded engine is designed with maximum thrust and mixture ratio allowed by the hydrogen turbopump and combustion chamber life. The engine thrust increase is obtained mainly through the engine LOX mass flow increase. Modifications are limited

to the following sub-systems : redesign of the LOX turbopump, the thrust chamber and the nozzle, the hot-gas valve and a small adaptation of the gas generator, the LH2 turbopump and the liquid helium re-heater. All other components are unchanged and all interfaces between sub-systems are the same as for *Vulcain®*.



Figure 8. *Vulcain 2®* engine

Table 6. *Vulcain* engine data

	Vulcain 1®	Vulcain 2®
Thrust	1145 kN	1340 kN
Isp	430 s	431 s
Mixture ratio	5.2	6.10
Nozzle area ratio	45	60
Combustion pressure	110 bar	115 bar
Weight	1680 kg	2100 kg

5.5 With Vinci® towards the 3rd millennium

The market studies for *Ariane 5* have shown once again the need to increase the payload capability up to beyond 11 t in GTO by the year 2005. To reach the required performance it appeared necessary to replace the *HM7bTM* engine by a new re-ignitable engine with a high performance level: *Vinci®*. It will give *Ariane 5* a long term potential thanks to a high flexibility. The *Vinci®* engine was initially developed as a reignitable upper stage cryogenic engine demonstrator within the framework of the ESA Future Launcher Preparatory Program (FLPP). Its vacuum Isp is targeted at 465 s, which seems technologically feasible with a thrust of 180 kN. *Vinci®* has an expander cycle. This is the best choice as it avoids high temperature circuitry. The hydrogen pump is two-stage, while the oxygen pump is single stage. No boost pumps are required. Coming from the hydrogen turbopump outlet at high pressure, hydrogen warms up through the regenerative chamber circuit. It then drives the turbines in series. Two turbine by-pass lines are installed, to tune the engine operating point, in terms of thrust and mixture ratio. Oxygen is directly injected in the thrust chamber. *Vinci®* is fitted with a deployable carbon-carbon nozzle extension. Two engines have been built and tested so far : re-ignitions have been successfully demonstrated This new engine is a challenge for Europe and will benefit from our long history of successful developments.

Table 7. Cryogenic upper stage engine data

	HM 4	HM 7TM	HM 7bTM	VINCI®
Thrust	40.4 kN	61.6 kN	64.8 kN	180 kN
Isp	412 s	441.4 s	445.6 s	465
Area ratio	42	62.5	83	240
Combustion pressure	23.3 bar	30.5 bar	36.2 bar	60 bar
Mixture ratio	5.2	4.47	4.76	5.80

5. Conclusion

After more that 6 decades of activity in the liquid rocket propulsion business, having delivered over 1500 engines, Snecma Space Engines Division is now preparing future additions. The next decades of rocket propulsion in Vernon are being written in our design offices.

References

- 1) Rothmund C. : 50 years of rocket propulsion in Vernon, IAA-97-IAA.2.3.07
- 2) Rothmund C.: 40 years of upper stage engines at Snecma Moteurs, IAA-01-IAA.2.3.07
- 3) Rothmund C.: Forty years of French-German cooperation in space propulsion, IAC-03-IAA.2.2.04
- 4) Rothmund C.: Reusable man-rated rocket engines - the French experience 1944-1996, IAF-04-IAA.6.15.3.02
- 5) Rothmund C.: The first European cryogenic engine was tested forty years ago, the HM4 cryogenic engine story, IAC-07-E4.2.07