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REUSABLE MAN-RATED ROCKET ENGINES
The French Experience, 1944-1996.

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Abstract

Re-usable man-rated liquid propellant rocket engines were developed at Snecma Moteurs between 1948 and 1960. Two concepts were used : the rocket engine used as main propulsion for fighter planes and the rocket engine used as a "booster" enabling the fighter to reach its operational ceiling more rapidly. These concepts used either turbopumps with a gas-generator or mechanical drive from a jet engine for feeding the chamber with propellants. The proof-of-concept mechanically-driven engine SEPR 25 with a thrust of 15 kN, it performed its first flight on June 10, 1952 and demonstrated the feasibility and the advantages of the mixed propulsion principle. The SO 9000 "Trident 1" main power came from a powerful gas generator rocket engine fitted in its fuselage, the nitric acid and kerosene SEPR-48. The chambers could be ignited together or separately, enabling the overall thrust to be of 15, 30 or 45 kN. The pre-production plane SO 9050 "Trident 2" used the SEPR-631 which differed from the SEPR-48 in having only two thrust chambers. During a test flight, the Trident reached an altitude of 15,000 m in 2mins 50secs, setting a record for climbing speed The SEPR 841/fitted to the Mirage III were the most advanced aircraft engines to be developed. Burning nitric acid and kerosene, delivering a thrust of 750 or 1500 kg, they could be ignited twice during the flight. More than 20000 manned flights were accomplished with these operational engines. Europe demonstrated that highly reusable man-rated rocket engines and their routine operation were perfectly feasible.

1. Introduction

In France, activities began in 1948 in the design office of the SNCASO aircraft company. Mixed-power (i.e. turbojets and rockets) interceptor designs were being studied as they enabled a rapid supersonic transition as well as a step-by-step development logic. The rocket was to be used at take-off, in conjunction with the turbojets. The rocket would power the interceptor up to its interception ceiling, the turbojets being used alone for the return to the base, after completion of the intercept.

The Direction Technique et Industrielle de l'Aéronautique issued a contract to SNCASO for the study of this concept and to build an experimental aircraft powered by a three-chamber rocket engine. This rocket engine was initially to be based on SEPR's successful designs, used at that time on missile programs such as MATRA's M04. But the concept of a mixed-power interceptor being very new, its validity had to be demonstrated on a proof-of-concept aircraft.

2. Challenges and technologies

2.1 Challenges

The design of aircraft rocket engines, i.e. man-rated engines, was a real challenge for SEPR that had at that time only developed missile propulsion systems. The new engines had to display a very high reliability and availability, had to be easy to maintain, were not to require frequent disassemblies in order not to curtail the readiness of the military aircraft they were fitted to. Furthermore, the design had to offer a high degree of ruggedness in order to withstand the stresses of supersonic flight and maneuverability related to interceptors.

2.2 Technologies

2.2.1 Propellant selection

First, the propellant choice was of the utmost importance : neither liquid oxygen nor hydrogen peroxide could be used. The first propellant required cryogenic storage and transfer facilities that were unavailable on airbases and were totally ill-suited to operational uses, the latter was unstable and presented a potential explosion risk in case of an accidental decomposition. Furthermore, it required high levels of materials purity, of tank cleanliness and of temperature management. A simple heat increase in the tanks, that would undoubtedly happen in case of storing a fighter in a tropical area, would lead to decomposition. As this had happened on an experimental peroxide tank in the late 1940s, the obvious choice was **not** to use peroxide.

Furthermore, the propellants had to be easily obtainable and manufacturable, due to their use on military aircraft. No foreign, dependence was possible and the propellants had to be easily storable, on both the aircraft and the airfields. Their handling was to be as easy as possible in order to allow for quick turnaround times in case of emergencies. Finally, their cost should ideally be comparable with that of kerosene in order to allow for training of ground teams and pilot proficiency.

For these reasons, it was initially decided to select nitric acid (IRFNA : inhibited red fuming nitric acid, highly concentrated over 97.5%) as oxidizer, together with furaline (a mixture of 41 % furfuryl alcohol, 41 % xylidine and 18 % methyl alcohol) or TX (triethylamine xylidine) as fuels. Furthermore, both fuels were hypergolic, eliminating the need for a separate ignition system. Later on, when the rocket engines were used only as "auxiliary" propulsion systems, kerosene was substituted to TX, but this required however the addition of a small TX tank for the ignition of the engine, as both propellants were not hypergolic.

2.2.2 Materials selection

Directly resulting from the propellant selection. All materials had to be compatible with nitric acid, furaline or TX. Furthermore, the engine weight had to be minimized. Thus the thrust chambers were machined from light alloys and regeneratively cooled by a flow of nitric acid, including a dedicated nozzle throat cooling insert. The flow of nitric acid injected at the end of the nozzle was "guided" by stainless steel rods located between inner liner and outer cover.

2.2.3 Mechanical design

Apart from the thrust chamber design, one of the main difficulties encountered on an aircraft rocket engine is the cavitation in the pumps, due to the impossibility to pressurize the propellant tanks. In order to cope with this difficulty, it was finally decided to use static elements named "jet pumps".

Finally, the pump gearbox required to obtain the proper massflow on both pumps using a single drive shaft did require adequate treatment on its rear side, in order to obtain a very good leak tightness. This was not an easy task due to the relatively high rotation speeds of about 16000 rpm and to the pump reaction time of less than 0.5 seconds from zero to full speed.

3. The proof-of-concept SEPR 25

The design office of the SNCASO aircraft company started pre-designing future interceptors in 1948.

SNCASO designed a lightweight interceptor powered by two small turbojets and relying on a powerful rocket engine to accelerate it to its service ceiling where it could intercept enemy bombers. The Direction Technique et Industrielle de l'Aéronautique issued a contract to SNCASO for the study of this concept and to build an experimental airplane powered by a three-chamber rocket engine. This rocket engine was initially to be based on SEPR's successful designs, used at that time on missile programs such as MATRA's M04. But the concept of a mixed-power interceptor being very new, its validity had to be demonstrated on a proof-of-concept aircraft that was also to demonstrate the man-rating of the new power-plants and their ability to be operated safely both by the crew and by the ground teams.

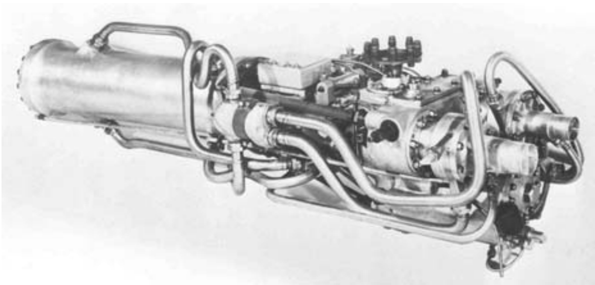

Figure 1 : SEPR 25 engine

The rocket engine developed for this demonstration was the SEPR 25. This was a pump-fed engine whose pumps were mechanically driven by the aircraft's jet engine. It burnt Nitric Acid and Furaline, delivered a thrust of 1,5 tons and its thrust chamber, made of light alloy, was regeneratively cooled by a flow of nitric acid. It was made of two assemblies :

- the thrust chamber fitted with its main valves,
- the pump group fitted with the mechanical drive connected with the aircraft's engine.

This engine was to be fitted to an existing jet prototype, the SNCASO SO6020 "Espadon", the rocket engine being fitted in a ventral "keel" that also housed the air intake (Air Force contracts 5307/46A3 and 2316/51).

Thrust (sea level)	1500 daN
Thrust (at 12000m)	1645 daN
Pump drive speed	5170 rpm
Specific impulse	200 s
Propellants	Nitric acid/Furaline

Table 1 : Characteristics of the SEPR 25

Following the first test run on October 30, 1950, the engine was fitted to its plane. The first test on the plane (at ground level) took place in may 1951 and finally it was one year later that it performed its first flight on June 10, 1952. A total of 76 rocket-flights were performed until July 7, 1955. On December 15, 1953, the SO2025 reached Mach 1 on horizontal flight, becoming the first European plane to do so. A second engine, SEPR 251 was derived from the SEPR 25, differing only for the architecture and having the same performance. It was fitted to the SO 6026 Espadon, where it was slung under the rear fuselage, the rocket propellants being contained in wingtip tanks. Its first rocket flight took place on March 28, 1953 and 13 such flights were performed until October 12, 1954. Both planes and their respective engines had demonstrated during their 89 rocket flights and 392 ground rocket tests the feasibility and the advantages of the mixed propulsion principle, opening the way to the lightweight mixed-power fighter prototypes.

Figure 2 : Rocket Flight of Espadon

4. The Light Weight Fighter competition

After the successful demonstration of man-rated demonstration engines on the *Espadon* prototypes, such propulsion systems soon became part of fighter requirements. On January 28, 1953, the French Air Force headquarters issued a request for proposal calling for the development of a lightweight interceptor, weighing less than 4 tons, powered by jet engines or rocket or by a combination of both, able to reach Mach 1.3,.possessing a high climbing rate as well as the ability to operate from makeshift airfields.

Three designs were actually built and flown, all three relying on SEPR rocket propulsion systems :

- SNCASE's *Durandal* mixed-power concept powered by a turbojet augmented by a small liquid propellant rocket engine,
- SNCASO's *Trident 2* rocket fighter with two small auxiliary turbojets,
- Dassault's MD 550 *Mystère Delta* using the same powerplant arrangement than the *Durandal.*

5. SEPR 48 for the Trident 1 prototype

This engine was a three-chamber derivative of the SEPR 25 family, but equipped with an autonomous turbo-pump driven by a gas generator. Possessing the ability to be ignited and extinguished at will, this type of engine was considered to be ideal for the purpose of an interceptor plane. The three combustion chambers, delivering each a thrust of 15 kN, could be ignited together or separately, enabling the overall thrust to be of 15, 30 or 45 kN. The propellants were nitric acid and kerosene while ignition was performed with TX (triethylamine-xylidine) However this engine only performed ground tests : for reasons of development simplicity, kerosene was replaced by furaline which was hypergolic with nitric acid, thus rendering the ignition system unnecessary. The engine number became SEPR 481.

Thrust (sea level)	15, 30 or 45 kN
Thrust at 36000 ft	52 kN maxi
Engine weight	258 kg
Pump drive speed	20000 rpm
Specific impulse	208 s
Propellants	Nitric acid/Furaline

Table 2 : overall characteristics of SEPR 481

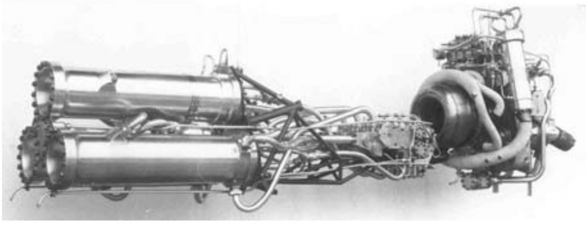

Figure 3 : SEPR 48 engine

The SEPR 48 engine consisted of three main assemblies : the turbopump, the 3 thrust chambers, the equipments. The pumps were of single-stage centrifugal type, the turbine being also a single-stage type. The gas generator burnt the same propellants that the main chambers, but a mixture of water and methanol was injected in the gas-generator in order to reduce the temperature of the gas and to increase its volume, not only reducing the strain on the turbine blades but also reducing the amount of propellant required.

Figure 4 : Hot fire of SEPR 481

The combustion chamber was made up of two distinct parts : the injection head and the nozzle, cooled regeneratively by nitric acid. Pump leakage control was obtained by stepped gaskets alongside the shaft and by the "counter-pump". Three jet pumps for water, furaline and acid ensure proper feeding of chamber and gas generator and avoid cavitation. An overheating detector was fitted to automatically cur the engine in case it overheated.

Chamber mass flow	4.8 kg/t.s
Chamber weight	100 kg
Turbo-pump weight	130 kg
Turbo-pump length	800 mm
Turbo-pump width	580 mm
Turbo-pump height	800 mm
Chamber diameter	620 mm
Chamber length	1800 mm

Table 3 : Main dimensions of SEPR 481

The maiden rocket flight of the sole rocket-powered prototype SO 9000-01 (the second prototype had been lost on its first jet-flight) took place on September 9, 1954. On this flight, only one of the three chambers had been ignited for 83 seconds, the plane reaching an altitude of 2400 M. The next flight saw the operation time increased to 115 s and the altitude to 4 km. On 6 July 1955, all 3 chambers were ignited for the first time. Only 24 rocket flights were made on the Trident 1 until its last flight on April 7, 1956.

Figure 4 : Trident on rocket flight

6. SEPR 63 for the Trident 2

The following step in the development was the pre-production plane, the SO 9050 "Trident 2". It used a new engine : the SEPR-631. Similar to the SEPR-481, it had only two thrust chambers that could be ignited separately producing a thrust of either 15 or 30 kN. This enabled the engine to run for a longer duration, increasing the plane's overall performance. Developed from September 1953 onwards, its first flight took place on December 21, 1955.

Thrust at ground level	15-30 kN
Engine weight	170 kg
Pump drive speed	28000 rpm
Specific impulse	192 s
Propellants	Nitric acid / Furaline

Table 4 : SEPR 632 main characteristics

This engine consisted of two subassemblies : the turbo-pump group and the chamber-distributor group. Each group was mounted on a rigid frame that was fitted on the plane. A dedicated trolley connecting both groups was used for ground handling. Both combustion chambers were machined of light alloy and were regeneratively cooled by a flow of nitric acid (speed : 10 m/s). The gas generator used the same propellants than the main chambers, but a mixture of water and methanol is injected in order to reduce the gas temperature to about 500 °C, which is an acceptable value for the turbine blades. The turbo-pump group consisted of the single-stage turbine and no less than five pumps (two main pumps for acid and furaline, three "micro-pumps" feeding the gas generator with water, acid and furaline). The turbine was located between these two pump assemblies. Additionally, all valves were electrically actuated.

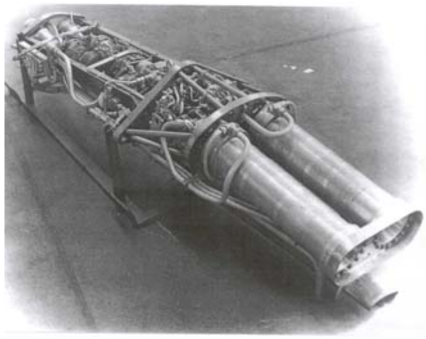

Figure 5 : SEPR 63

A battery-powered electric starter fed the gas generator with propellants. The resulting combustion then drove the turbine, itself driving the main pumps. When reaching the autonomous speed, the starter was automatically cut-off and the pump speed continued to increase until reaching the operational value of 28000 rpm. The staring process lasted 3 seconds. The SEPR 631 could be re-ignited easily with this process.
For the pilot, instrumentation was reduced to a minimum, thanks to the highly automated ignition and shut-down processes : one switch for ignition, one selector for rocket chamber selection (0, 1 or 2 used), one switch for quick venting, two lights for engine operation and venting.

The flight tests of the Trident 2 were extremely successful. Unfortunately, on May 21, 1956, the first prototype disintegrate in flight, killing its test pilot. No failure cause will ever be established, although it appears likely to another test pilot that the rocket engine might not be involved.

The main development difficulties encountered were ignition problems and back fire on SEPR 631 fitted to the Trident 2 number 04 and 05, some unexpected shutdowns on SEPR 63 fitted to the Trident 2 number 03 (during negative acceleration).

Further flight testing was very successful, two American test pilots participating to some flights in 1957: Joe Walker and Ivan Kincheloe. On March 31, 1958, during a test flight, the Trident reached its altitude of 15,000 m in 2mins 50secs, setting a record for climbing speed. However, on April 26, 1958, the French government decided to cancel the TRIDENT program. The test team decides then to "strike" and prepares another record flight. On May 2, the Trident 2 nr. 06 took-off for a record flight : the altitude of 24,217 m (79,660 ft) is reached, setting a world record. These two records did not save the Trident from cancellation. The Trident 2 planes had cumulated 196 rocket flights. The Trident 3 was to have been the operational version of the family. The main difference between them and the Trident 2 prototypes was the use of new turbojets fitted with reheat. They were to have been put in service by the end of 1960. The Trident 3 were to retain the SEPR-632 rocket engines used by their predecessors, as these had shown their ability to be used on an operational basis. The first airframes were being built when the program was cancelled and while the design team worked on a Trident 4 able to reach Mach 3 !

7. SEPR 65 for the Durandal

The proposal from SNCASE was the SE-212 Durandal. This was a small delta-wing interceptor powered by one SNECMA Atar 101F jet engine and by a single SEPR 65 rocket engine. This engine was pump-fed, the pumps being driven by the aircraft's jet engine through an auxiliary gearbox. Its thrust was 750 kg, it burnt Nitric Acid and TX (Triethylamine-Xylidine). The SE-212 was finally rejected in favor of the MIRAGE 3.

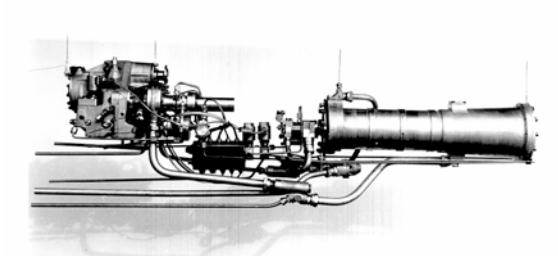

Figure 6 : SEPR 65

The development of the engine started in December 1953. The selected architecture was similar to the SEPR 25 : the propellant pumps were mechanically driven by a shaft connected to the aircraft's jet engine. The first ground test occurred on 4 November 1954 and the first rocket flight of the first prototype SE 212-01 happened on 19 December 1956. The second prototype performed its first rocket flight in April of the following year. When the program was abandoned, the last rocket flight took place on 7 May 1957. A total of 45 rocket flights had then been performed on both prototypes.

Nominal thrust [1]	7.5 kN
Propellants	Nitric Acid / TX
Isp [1]	232 s
Shaft speed	5050 rpm
Power	49 kW
Weight [2]	61 kg

Table 5 : SEPR 65 main data

[1] at an altitude of 8000 m (26300 ft.), [2] without propellant tanks

A derivative, SEPR 651, was intended to be fitted to the small delta-wing interceptor Nord 1405 "Gerfaut", but was never used.

8 .The SEPR 66 for the Dassault Mirage 1

The design from the Dassault company was a small delta-wing concept, the MD-550 *Mystère-Delta*, Due to be powered by two Turboméca Gabizo turbojets and by a single SEPR 66 rocket engine, the Gabizo were replaced by licence-built Armstrong-Siddeley Viper engines. The SEPR-66 rocket engine was autonomous like the SEPR 63 its pumps were driven by a gas generator. It was to delivering a thrust of 1500 kg, burning Nitric Acid and Furaline. It was neatly "slung" underneath and between the turbojets (see fig. 8)

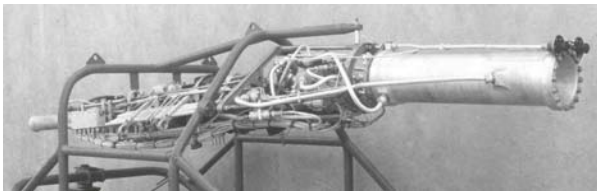

Figure 7 : SEPR 66 on transport dolly

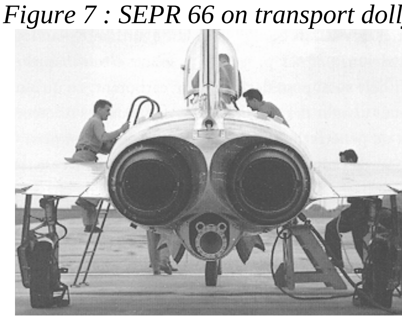

Figure 8 : Rear view of the MD 550 showing the engine arrangement

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Thrust at ground level	15 kN
Engine weight	151 kg
Turbine speed	28000 rpm
Weight	151 kg
Turbine power	110 kW
Specific impulse	190 s
Propellants	Nitric acid/Furaline

Table 6 : SEPR-66 Technical data

The SEPR 66 comprises two main valves, fitted with jet pumps, feeding the main propellant pumps. These are driven by a single turbine powered y the gas generator. Nitric acid is used as a coolant for the thrust chamber, before being injected in it. On every valve body inside the distributor, a diversion valve closes when the main injection valve opens and reciprocally. This allows for a constant turbine power operation, whether or not the chamber is ignited. The use of pressure switches allows for fully automatic start and shutdown processes. A rigid frame connects all engine subsystems together and allows for easy removal from the airframe.

Developed from September 1953 onwards, the first tests took place on the SEPR test stands on 10 January 1955. One year later, on 19 January 1956, the SEPR 66 performed its first flight on the *Mystère* IV B05 'flying test stand'.

Due to cold temperatures encountered in high altitudes, an ignition delay during the 10^{th} rocket flight severely damaged the rear fuselage. This problem was rapidly solved and at the end of the test campaign, the *Mystère* IV B05 had performed 55 rocket flights, proving the validity of the concept and its performance.

The MD550 *Mirage I*, as the *Mystère Delta* was renamed, flew for the first time on 25 June 1955, the SEPR 66 being ignited for the first time in flight on 17 December, reaching an altitude of 12 km and a speed of Mach 1.6. At the end of January 1957, the *Mirage* program was stopped, only 5 rocket flights having been performed.

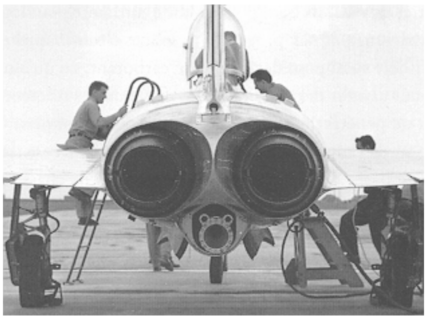

Figure 9 : SEPR 66 On the MD550

These flights had shown a limited range and the armament was considered as too light by the French Air Force. Dassault began designed a 'heavy' version, named *Mirage II*, which was to be powered by two Gabizo turbojets and a single SEPR 661 engine. This was a dual chamber (unit thrust : 7.5 kN) version of the SEPR 66. The SEPR 661 was only used on SEPR's ground test facilities. Another derivative, SEPR 663, burning nitric acid and TX, was also developed for the *Mirage I* : only 2 ground tests were performed on the *Mystère* IV B05.

9.The SEPR 84 family for the Dassault Mirage 3

9.1. The initial SEPR 84 to 841 versions

After the successful tests of the Mirage I, Dassault refined the design and the result was the Mirage III : a longer and slender fuselage using the supersonic area-rule and powered by a single turbojet : Snecma's ATAR 9C. It also was fitted with a new auxiliary rocket engine, SEPR 84.

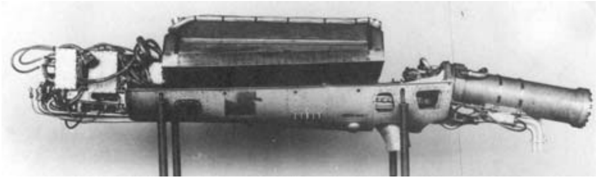

Figure 10 : SEPR 84

The overall performances were thus improved, as can be taken from the following table :

	Mirage I	Mirage III 001
Max weight	5600 kg	6900 kg
Gross weight	3330 kg	4840 kg
Max level speed	M 1.25	M 1.8
Ceiling	14600 m	16500 m

Table 7 : Performance comparison Mirage I vs. Mirage III

The SEPR 84 was a new design as it contained the oxidizer tank. It also had the same interfaces with the airplane that an auxiliary fuel tank which it could replace. It powered the prototype Mirage IIIA (SEPR 84 and 840), its derivatives SEPR 841 being used on the operational MIRAGE 3C. The final version, SEPR 844, was used on the MIRAGE 3E fighters. It was the most advanced aircraft engine to be developed by SEPR and the only one to reach operational maturity. Fed by pumps driven by the aircraft's jet engine, burning nitric acid contained in a stainless steel 300 liter tank and TX contained in a dedicated tank within the airframe, (triethylamine xylidine), delivering a thrust of 750 or 1500 kg, it could be chemically ignited twice during the flight. In the lower part of the nitric acid tank, a small tank contained TX2 which was hypergolic with it and served for the engine ignition. The amount of TX2 was sufficient for two ignitions. The engine was connected to the airplane with explosive bolts : in case of an emergency it was easily jettisonable. Additionally, An absolute safety has been introduced in the distribution system : safety for the bad closures of the valves, safety in case of propellants total consumption and safety for the jettisoning of the rocket engine. The propellant feed system consisted of two centrifugal pumps driven by a shaft coming from the aircraft's turbojet engine. Both pumps and impellers were machined of light alloy. A gearing set permitted the desired pump speeds and a shear shaft protected the rocket engine from over-torque. Chemically neutral oil was used for lubricating ball bearings and gears. The combustion chamber was double-walled, cooled by a flow of nitric acid, and was made of light alloy.

The design of the SEPR 84 started end 1956, the first rocket flight taking place on the Mirage III 001 on 12 July 1957. A total of 30 rocket flights will be performed. An "pre-production" variant, SEPR 840, was designed from June 1957 onwards, its first test taking place on 18 February 1958. Its first test flight took place on 6 May 1958 on the Mirage IIIA 02. A total of 15 flights will be performed. Finally, the operational version SEPR 841 was initially tested on 4 December 1958, the first test flight on the Mirage III A 02 taking place on 20 June 1959. This aircraft alone performed a grand total of 444 rocket flights.

The main development difficulties encountered during development were initially some nitric acid tank corrosion (solved by changing the alloy used), damage to fuselage underside caused by jet divergence during very high altitude test flights (solved by reinforcing) the fuselage thermal protection). In early 1959, most acid leakage and chamber damage were solved.

The production variant of the Mirage 3, the Mirage 3C, was fitted with the SEPR 841 engine and made its maiden flight in 1960. 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 1505 rocket flights (representing 2064 ignitions). A total of 164 SEPR 841 was built, used mainly by the French air force.

Figure 11 : SEPR 841 ignited on Mirage III C

9.2 SEPR 844 for the Mirage III E

The SEPR 844 version used kerosene instead of TX2, This kerosene was pumped directly from the aircraft's tanks, consequently suppressing the need for a specific tank, even though it slightly complicated the general architecture of the propellant feed system. As both propellants were not hypergolic, a small tank of TX was fitted into the engine and contained enough TX for two ignitions.

The 300 liter partitioned nitric acid tank was manufactured from stainless steel with low carbon content. It was fitted with two poppet connectors for tank filling (one for actual filling, the other for air venting) avoiding any nitric acid vapor emission. In the lower part of the acid tank was located the piston pressurized TX2 tank (a binary mixture of tried1y1amine and xy1idine which was hypergolic with nitric acid and initiated the combustion).

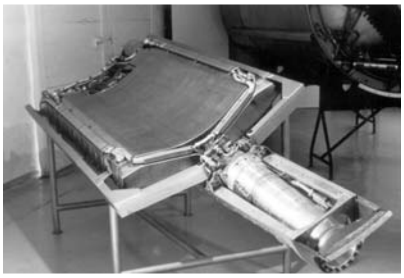

Figure 12 : SEPR 844

The SEPR 844 used either TR0 (JP1) or TR4 (Jet B) kerosene stored in a tank of the Mirage III E combat aircraft. The propellant feed system comprised two centrifugal pumps driven by an intermediate shaft coming from the aircraft turbojet engine. A gearing set permitted the desired pump speed and a shear shaft protected the rocket engine from over-torque. A chemica1ly neutral oil was used for the ball bearings and the gears. A pneumatically jet pump system. using a part of the pressure given by the pump to increase the average static pressure of the liquid before the pump inlet, was used for both propellant pumps in order to avoid cavitation. The propellant feed valves were opened pneumatically and spring-closed. The pneumatic system required 0.8 MPa air contained in a 15 MPa pressurized tank.

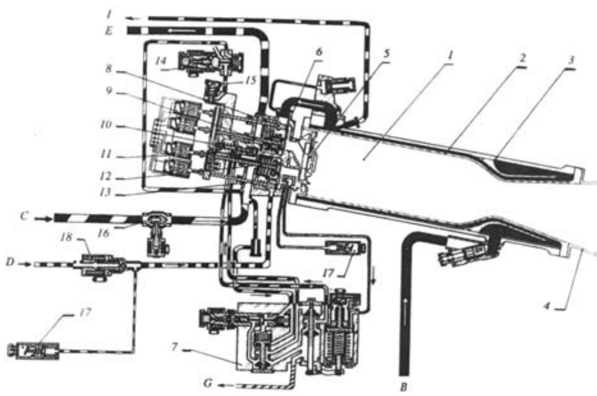

Figure 13 : Distribution and chamber system

The propellant distributor (location 6 on fig. 13) comprises 4 injection valves: 2 for the ignition (ensuring, TX2 and HNO3 flow during ignition phase), two for the steady state operation (ensuring switching to Kerosene and nitric acid). Theses valves are operated by 2 hydraulic actuators. The distributor and its control valve have been designed in order to obtain an absolute safety at ignition and cut-off. The following automatic safety devices have been implemented :

- not operation if one of the form injection valves is not correctly closed,
- no operation if the valve actuator is not closed,
- immediate closure of the TX2 and kerosene injection valves when the engine is cut-off.

The distributor control valve (location 7) controlled the hydraulic feed of the "double stage" distributor actuator (location 10 and 1l) which controlled the two propellant valves (location 13 and 8) for the ignition (actuator first stage moving) and then the kerosene valve (location l2) and the second acid valve (location 9) for the steady-state operation (actuator second stage moving). The closure of the TX2 feed for the steady state rate was obtained with an upstream electric valve (location 18). The high pressure kerosene was used as hydraulic fluid.

Safety provisions had been introduced in the distribution system :

- safety for the bad opening or bad closure of the valves,
- safety in case of propellant full consumption,
- safety for the rocket engine jettison.

The combustion chamber was regeneratively cooled with internal circulation of nitric acid. The guidance and good repartition of the coolant fluid was obtained by steel rods set alongside the nozzle and by broached fillers along the cylinder part. The inner wall was fixed at one tip and was free at the other to allow for longitudinal dilatation. The chamber combustion system was in aluminium alloy. It was mandatory to replace the combustion chamber after 50 ignitions, but it has been demonstrated it could withstand 70 ignitions without problems.

The stainless steel chamber injector was constituted by injection holes located on three concentric rings : the two internal ones were acid and kerosene impinging doublets and the external one was kerosene injection used for film cooling along the inner wall. Eight attachment points connected the engine to the airframe. The SEPR 844 thrust axis made a 9° 30 angle with the aircraft thrust axis and could be jettisoned at low speed.

9.3 Health monitoring

After each flight, a recording made by a small SEPR-designed apparatus enabled to check the overall operation of the engine and to authorize a further flight. In case of an in-flight problem, this recording enabled to find its source. No other controls than leakage and leak-tightness were authorized between flights. As for the cockpit instrumentation, it was limited to one switch for ignition, one handle for thrust level selection and 2 control lights (rocket operation/rocket anomaly).

9.4 Maintenance

The engine was delivered in a container, already affixed to its transport carriage. It was then moved to the mobile test stand and fitted to it. This mobile facility was constituted by a tubular frame mounted on wheels and anchored on the ground by special fittings. A front platform supported the propellant tank, a small power group (diesel engine made by Hispano-Suiza)that drove the rocket engine pumps. Pressure sensor and propellant flowmeters were also part of the mobile facility. A mobile control cabin enabled the operation of the facility and of the rocket engine subjected to the test. In this cabin were grouped all measuring/recording instrumentation as well as an electrical generator. The nitric acid mobile tanks were designed by SEPR, as was the TX mobile tank. Fitting the engine onto the airframe is quick : about 30 minutes. However, replacing a kerosene tank by the rocket engine requires a good half-day of work.

Figure 14 : control stand

The most subsystem whose control was the most delicate was the distributor. As the valve closure on the kerosene side had to be very quick, the "quality" of this closure had to be verified. A special control box was designed for this purpose. Using a "chrono-frequencymeter", it checked that the value was of 20 ms. All ancillary equipment was grouped in a special control carriage.

In its repair planning, the SEPR 844 had to be removed from the Mirage III every 50 ignitions. The most critical parts had to be changed : it concerned mainly acid subsystems like the acid pump, the acid valve and the acid filter. The chamber inner wall had also to be changed, but it had been demonstrated operationally that this element could complete 70 ignitions without any damage.

There was no routine test bench ignition test after such subsystems removal, but a hot fire test was required when the rocket engine had been totally disassembled (after every 200 ignitions or after 15 months of acid laying). The presence of nitric acid never generated maintenance incident.

9.5 SEPR 84 Family Conclusion

A total of 275 such engines were built (164 SEPR 841 and 111 SEPR 844) and used operationally in France, and Switzerland. The MIRAGE III C, III E and III S fitted with rocket engines have logged more than 20000 rocket flights with a 99 % success rate.

10. SEPR 77, the swansong

In 1956, SNCASO studied the SO 4060, an radar-equipped interceptor able to fly at Mach 1.3. In April 1957, a bomber version of SO 4060 and Mirage IV were placed in competition as vector of the Strategic Nuclear Weapon. The delta formula of Mirage IV seemed to better correspond to the mission rather than the SO 4060 sweptback wing. This last suffered from an high empty weight and under-motorization, despite the SEPR 77 rocket engines. Both projects were finally cancelled in autumn 1958, even though the SEPR 77 had undergone prototype manufacturing and testing. This was SEPR's final man-rated reusable rocket engine design. The SEPR 77 was a dual-chamber engine, delivering a thrust of 30 kN.

11. Postscript : the SEPR S178

The Ludion ("*cartesian diver*") was a concept for a military "one-man hopper" aimed at giving troopers the ability to cross rivers or trenches using a simple rocket-powered backpack. The backpack design having quickly proven its impracticability, it was replaced by a skeleton structure supporting the rocket system and the "pilot". Following studies initiated in 1965, Sud Aviation was awarded the development contract together with Bertin (for the jet pumps) and SEPR was to develop the rocket propulsion system.

The Ludion was to be powered by two SEPR S178 monopropellant rocket engines fitted with a thrust-augmentation device ("jet pump") designed by the Bertin company. The first ground test of a Ludion with its rocket propulsion system took place on January 24, 1968, on the test airfield of Villaroche.

Although the powered flights were deemed to be successful, the Ludion was abandoned as it was too impractical due to its sheer size and the "bulky" protective clothing its operations required. The first prototype still resides at the Paris Le Bourget air & space museum today.

12. Record-setting engines

12.1 On the Trident

On March 31, 1958, during a test flight, the Trident reached its altitude of 15,000 m in 2mins 50secs, setting a record for climbing speed. When on April 26, 1958, the French government decided to cancel the TRIDENT program, the test team decided "strike" and prepared another record flight. On May 2, the Trident 2 nr. 06 took-off for a record flight reaching the altitude of 24,217 m (79,660 ft), setting a new world record.

12.2 On the Mirage III

The NATO "Air Defence" competition was won by the Colmar Squadron in April 1970, and included turn-around operations of four identical aircraft after each mission. The Colmar Mirage III E equipped with SEPR 844 made turnaround times of 12 min 9 seconds and 14 min 55 seconds.

On the SEPR 841, it was noted that using the rocket engine at 3800 ft allowed the Mirage III C to accelerate from Mach 1 to Mach 2 in only 90 s instead of 4 minutes on turbojet power only.

During development testing, one engine, SEPR 844 nr. 35 cumulated 152 flights constituting an absolute world record.

On 25 January 1960, the Mirage III A02 reached 25500 m with the help of its SEPR rocket engine.

Other record achievements :
- most built aircraft engine (275 built)
- most used man-rated rocket engine (over 20000 flights)
- world record of manned rocket flights (over 20000 flights)
- world's most reusable rocket engine (average of 35 flights per engine)

13. Man-rated liquid rocket engines in other countries

13.1. United States

Although not widely know and overshadowed by their achievements in large man-rated engines for manned space vehicles, the United States did develop a few man-rated engines for airplane applications.

- ***Curtiss-Wright XLR-27*** : this 40 kN thrust engine was developed for the Republic XF-91 "Thunderceptor". The difficulties in its development resulted in its replacement by the well-proven XLR-11. But by the time the plane was flown, it had become obsolete and was cancelled after performing only a handful of rocket flights.
- ***Reaction Motors XLF-40*** : in 1957, the Vought aircraft company studied the installation of this rocket engine in the tail of a couple of F8U-1

"Crusader" naval fighters. The XLF-40 was to provide an additional 8000 pounds of thrust and was fuelled by a mixture of hydrogen peroxide and jet fuel. Unfortunately, its prototype exploded during an early ground text, causing Reaction Motors to pull out of the project. However, Vought decided to continue the project using a Rocketdyne engine.

- ***Rocketdyne XLF-54*** : this engine of 6000 pounds of thrust replaced the XLF-40. Although the project never reached flight status, dummy engines were installed above the F8U-1's tail cone just behind the rudder. The reasons why the project was abandoned remain unclear, but the toxic nature of hydrogen peroxide probably was in some way responsible for this, as it would have seemed risky to store such hazardous chemicals abord a warship. The rationale behind this design was to gave a fighter able to reach a ceiling of 60,000 feet which was deemed to be the operational ceiling of Soviet bombers.
- ***Rocketdyne AR-1*** : burning HTP and JP4, this engine was initially developed for the Chance Vought F8U-3 Crusader III, which was abandoned. It was later flown on two North American FJ4 Fury used as test-beds. The AR series went-on to see use in the NF-104 aircraft.

13.2 Soviet Union

- ***Glushko/Dushkin RD-2M-3V*** : developed for the first postwar soviet rocket fighter Mikoyan MiG I-270. Burning nitric acid, kerosene and hydrogen peroxide, it featured a high thrust (1050 daN) chamber for take off (thrust) and a 'lower thrust' chamber (about 390 daN) for cruise flight. The first rocket flights took place as early as 1947, but the concept was abandoned soon thereafter, due to the appearance of the more powerful jet-powered MiG-9.
- ***Dushkin RU-013*** : with a thrust of 31 kN, was developed in 1955-56 for a performance augmentation package designed for the MiG-19. Known as the SM-12PMU this version of the MiG-19 was flown in 1958-59 and was followed by the SM-50. Only half- a dozen were built and flown, with very good performance.
- ***Dushkin S-155*** : a variable-thrust engine (19 to 38 kN) developed also in the 1955-56 timeframe was designed for the Mikoyan Ye-50 variant of the swept-wing Ye-2. high-altitude interceptor designed in 1954. Basically a swept-back MiG-21 prototype fitted with a Dushkin S-155 rocket engine, this was to be a high altitude fighter. Its first rocket flight took place on June 8, 1956. It reached the speed of Mach 2.33 with rocket ignited in 1957. However, the difficulties connected with the handling of rockets resulted in the cancellation of further activities

13.3. United Kingdom

- ***D.H. Spectre*** : The De Havilland Spectre was conceived as a boost engine for high performance aircraft. It later went on to be used in the Saro SR-53 jet + rocket fighter. The Spectre was a HTP/Kerosene-fueled single-chamber motor. It was rated at 35.6 kN.
- ***Armstrong Siddeley Snarler :*** burning LOX and methyl-alcohol-water and producing a thrust of 900 kg. It was used on an experimental fighter, the Hawker P. 1072, proving the feasibility of "rockets on planes"
- ***Armstrong Siddeley Screamer*** : planned for the AVRO 720 jet + rocket fighter. It delivered a thrust of 3600 kg, burning LOX and kerosene. The AVRO 720 was cancelled in 1956.
- ***Napier NRE 19*** **:** Napier rocket engine for helicopter rotor tip applications. HTP / catalyst rocket engine. Test-flown on a Saro Skeeter.
- ***Napier Scorpion*** **:** HTP / Kerosene. World altitude record (70310ft) set by English Electric Canberra fitted with Double Scorpion on 28/8/57. Fitted to two Canberras. Also Triple Scorpion. Rated at 17.8 kN for the standard version, at 35,6 kN for the Double Scorpion and at 53,4 kN for the Triple Scorpion.

14. Conclusion

The only reusable man-rated aircraft rocket engines to reach operational status on fighter planes was the French SEPR 841 and SEPR 844 with over 20000 manned flights and an average of 35 flights per engine. This unequalled world record , demonstrates that highly reusable man-rated rocket engines are feasible and that Snecma Moteurs can proudly consider itself among the pioneers of manned rocketry and reusability.

Production milestones :

Engine family	***Production***	***Flights***
SEPR 25	< 5	89
SEPR 48	About 10	30
SEPR 63	< 50	196
SEPR 66	About 20	50
SEPR 84	275	Over 20000
SEPR 65	< 5	45
TOTAL	**> 350**	**> 20410**

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Acronyms

SEP : *Société Européenne de Propulsion*, merged with Snecma in 1997, now the Space Engine Division of Snecma Moteurs
SEPR : *Société d'Etude de la Propulsion par Réaction*, established 1944, became SEP in october 1969 by merging with Snecma's Missile and Space Division
SNCAC : *Société National de Constructions Aéronautiques du Centre*, ceased activities in 1949.
SNCASE : *Société Nationale de Constructions Aéronautiques du Sud-Est*, now part of EADS.
SNCASO : *Société Nationale de Constructions Aéronautiques du Sud-Ouest*, now part of EADS
SNECMA : *Société Nationale d'Etude et de Construction de Moteurs d'Aviation*, established in 1945 by merging all French aircraft engine companies.