Nuclear Propulsion for Space Exploration: a Revival?

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1. Introduction

The decade of the 1960s was a particularly creative period in terms of exploration of new concepts for space propulsion systems and no concept of a totally new nature has emerged in the last 50 years. Technologies sustaining these concepts have evolved substantially, offering new perspectives, but the fundamentals were already outlined in that period.

Nuclear reactors used for heating hydrogen as a propellant (nuclear thermal propulsion) were among such systems and the current discussions around possible manned interplanetary missions in the decades to come have revived the interest for such a solution.

The objective of this paper is describing the efforts deployed in the mid-1960s by the European Launcher Development Organization (ELDO) for developing a low power nuclear propulsion system. Very little had been published on this work; in fact, there is only one paper which was presented at the 20th International Astronautical Congress in 1969 in Mar del Plata, Argentina. It is hoped that a further description of the work could be useful for designers of future systems. There always lessons to be learned from the past, notably from pioneering work performed at a time when “sky was the limit” for new ideas.

2. The concept

2.1. The missions

In the mid-1960s, bringing payloads as heavy as possible to the geostationary orbit for telecommunications, in particular semi-direct television, was an essential preoccupation at European level, hence the idea of a nuclear thermal propulsion system which could outperform chemical systems for the transfer from low to geostationary orbit.

At the same time, the interest for a scientific exploration of the interplanetary space was growing and finding adequate propulsion systems for space probes was particularly challenging. Again, nuclear thermal propulsion systems were considered as a potential competitor to electric propulsion systems such as electrostatic thrusters fed by a nuclear electric source. Both were deemed to be better than chemical systems for accelerating space vehicles to escape velocity.

2.2. The boundary conditions

The payload capability of the European launcher under consideration at that time constituted the guiding parameter for dimensioning the nuclear stage which would ride on top of this launcher. Additionally, for both types of applications, geostationary and interplanetary, a low mass to thrust ratio for the whole system (propellant tank- shield - reactor – exhaust nozzle) was a prerequisite and governed the choice of the reactor.

The projected Europa III launcher consisting of a Blue Streak core together with a solid booster and a LH^2/LO^2 upper stage presented a maximum capability of 8 metric tons in a 500 km equatorial orbit. This limited capability oriented immediately the design towards a low power reactor, 5 to 10 MW, ejecting hydrogen at high temperature, around 2400°K, with a fairly long time of operation for nuclear thermal propulsion, i.e. several hours.

Through the choice of such parameters, the European system differed, from the very beginning, substantially from those developed at the same time in the Soviet Union and the United States. As a point of comparison, the US NERVA nuclear rocket was designed as the nuclear-powered third stage of a Saturn launcher which would allow, in its upgraded version, to launch about 154 tons in a low earth orbit, leading to an upper-stage nuclear reactor producing about 5000 MW.

2.3. The reactor concept

The entire propulsion system is shown in the artist's view hereunder and detailed in figure 1 which gives a longitudinal cut of the system

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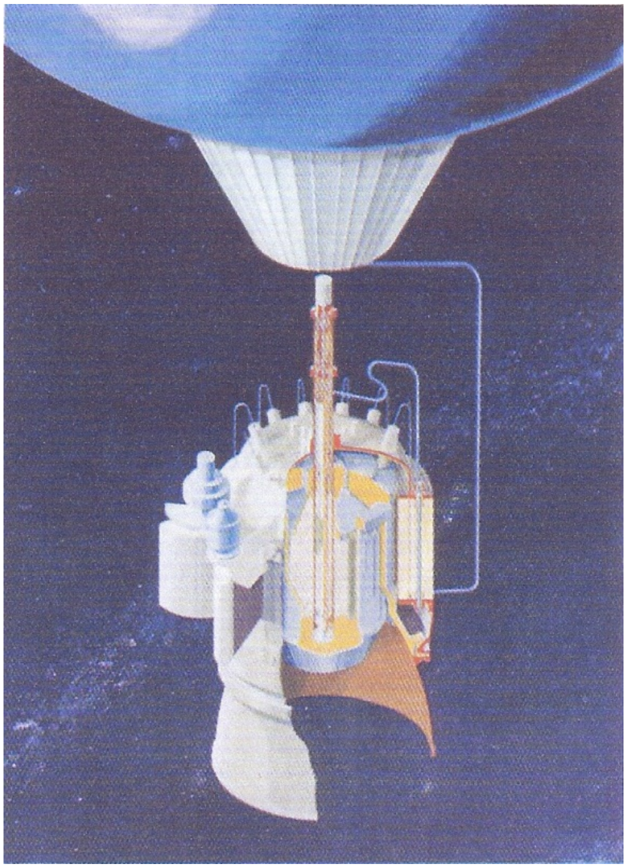

While the LH² propellant tank, the shield and the exhaust nozzle were based on technologies available at that time, the main challenge lied in the reactor itself. The option of a porous core reactor using a bed of fuel particles was chosen; liquid hydrogen should be injected centrally and should flow radially, the heated gaseous hydrogen being collected at the periphery and directed towards the exhaust nozzle.

The reactor was of the fast/epithermal type for minimizing the size and weight of the core, avoiding a heavy and bulky graphite moderated core or a zirconium hydride moderated core which would not withstand the high temperature required. There was a peripheral reflector and the control of the reactor was ensured by a central control rod containing fuel and 6 external control rods. Figure 2 gives a transversal cut of the reactor core.

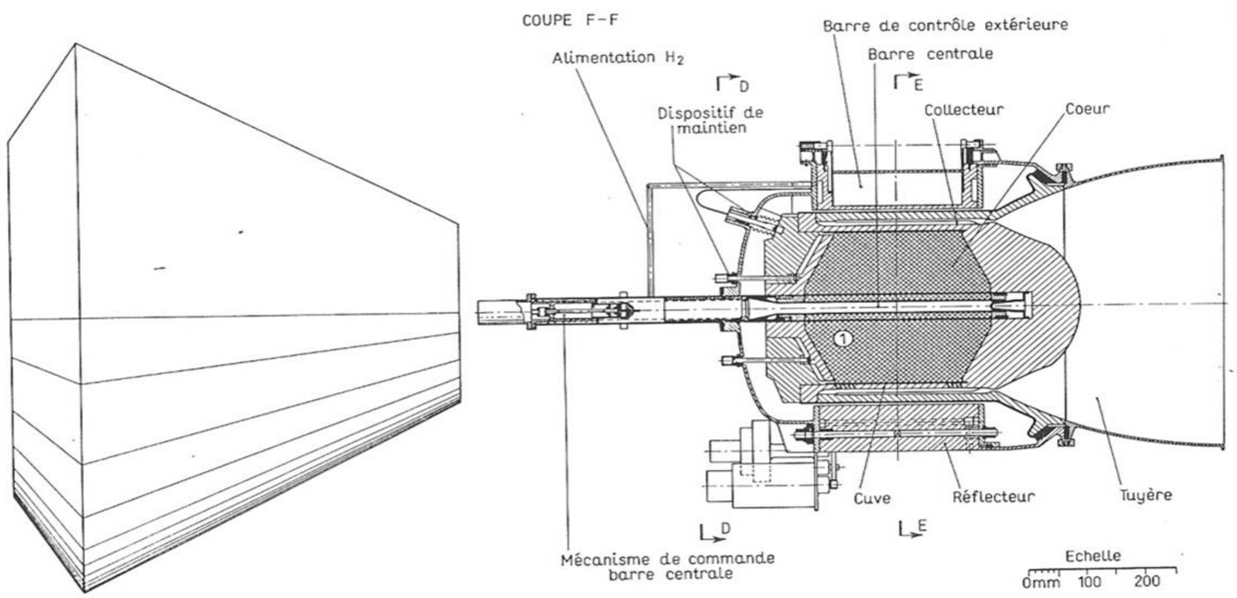

FIG. 1. Coupe F—F

Fig 1 Longitudinal cut of propulsion system

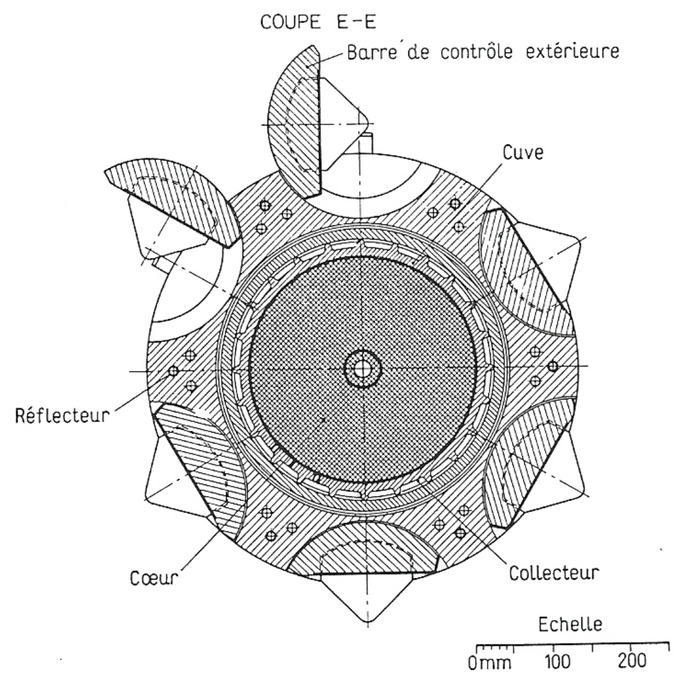

FIG. 2. Coupe E—E

Fig.2 Transversal cut of reactor core

The central control rod was inserted at start-up in the reactor core which remained nevertheless sub-critical under cold conditions, the subsequent start-up phase was ensured by the 6 external control rods which were in fact rotating segments of the reflector

Two types of fuel were considered: on the one side, cubes of sub-stoichiometric uranium carbide developed at the Centre d'Etudes Nucléaires of Grenoble, on the other side, spherical particles of uranium oxide (or carbide) coated with successive layers of pyrolitic carbon, silicon carbide and again pyrolytic carbon as shown in figure 3

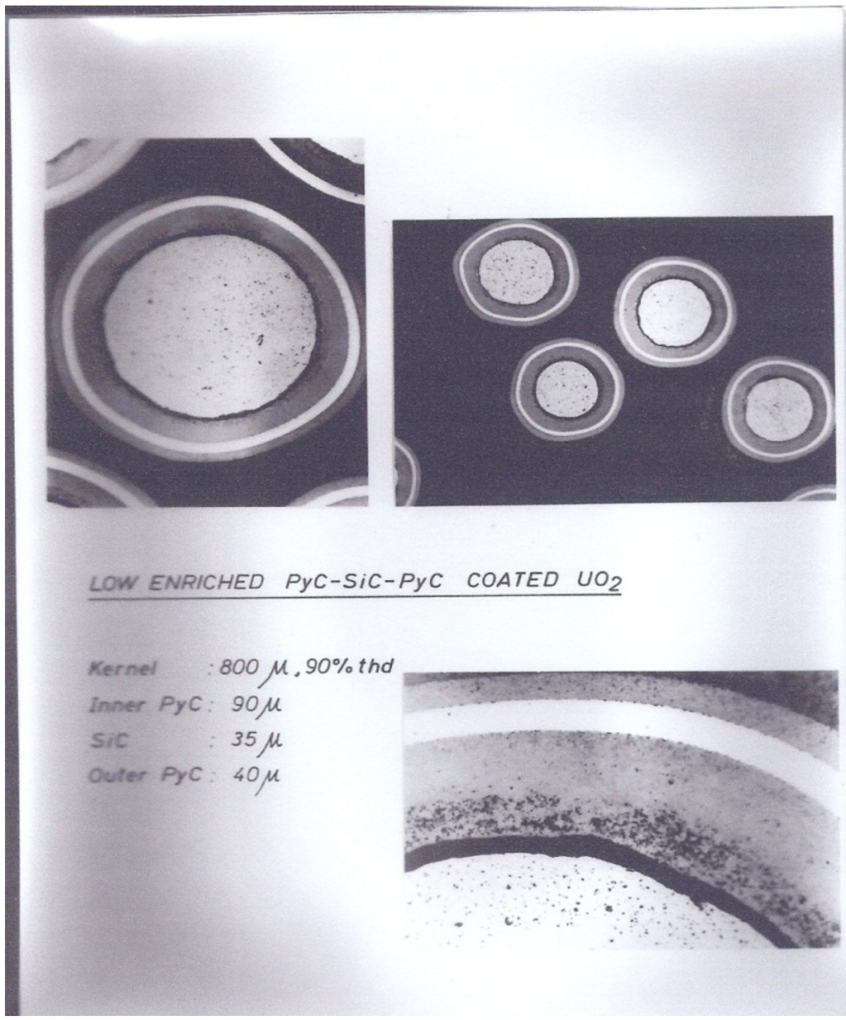

Fig. 3 Uranium oxide coated particles

A fairly wide experience existed in Europe in coated particles, thanks to the German AVR program in Jülich and the OECD/UKAEA DRAGON project in Winfrith Heath; SNECMA in France had acquired also experience in the behavior of graphite submitted to a flow of hydrogen at high temperature.

The power density for the complete reactor system was in the range of 15 to 20 kW/kg: this led, for a power level of 5MW, to a total mass between 250 and 330 kg, the nuclear fuel amounting to about 70kg in this total. The size of the cylindrical reactor was quite limited, of the order of 50cm height and 50cm diameter.

With projected specific impulses of 800 to 850 seconds, the thrust would be in the 1 to 2 kN range.

2.4. Safety considerations

Acceptance of nuclear systems was much more widespread in the mid-1960s than today but it did not mean that safety aspects of the propulsion concept were neglected. Studies were performed which led to the following considerations:

- During the phases preceding the launch (transport to site, assembly and integration to launch vehicle), any accidental criticality should be avoided, leading to the separate transport of the central control rod and the pivoting external control rods; they should be integrated to the rest of the reactor in the last phases of the countdown and blocked in external position until the system reached a safe parking orbit

- In case of a launch failure, noticeable contamination could not be expected on the launch site when dealing with a limited amount (70kg) of fresh low enriched Uranium fuel in the reactor core. A propellant fire engulfing the reactor core could not affect the fuel as it was designed for withstanding very high temperatures

- The reactor should only be started when the nuclear stage would have reached a safe parking orbit

- If, for any reason, the reactor should re-enter the atmosphere, the contamination would be strictly limited even if the reactor had been operated for a certain period of time, in view of the low fuel burn-up leading to a weak amount of fission products. Due to the resistance of the fuel to high temperatures, dispersion of such fuel over wide areas would be avoided.

Safety of the system was a component always present in the program activities but was not considered as the strongest challenge in the development of this particular type of nuclear space system.

3. *Program achievements*

Following internal preliminary work, ELDO entrusted to Belgonucléaire S.A. the conceptual study of the system. The first preliminary study was completed at the end of 1967. In 1968, work was initiated on experimental tests of the two types of nuclear fuel considered at that time, UO^2 coated particles and cubes of sub-stoichiometric Uranium carbide. While the tests of the second type were entrusted to CEN Grenoble, those of the first type were entrusted to Belgonucléaire S.A. (BN) together with the Université Libre de Bruxelles (ULB). The experimental set-up for the BN/ULB tests is represented in figure 4

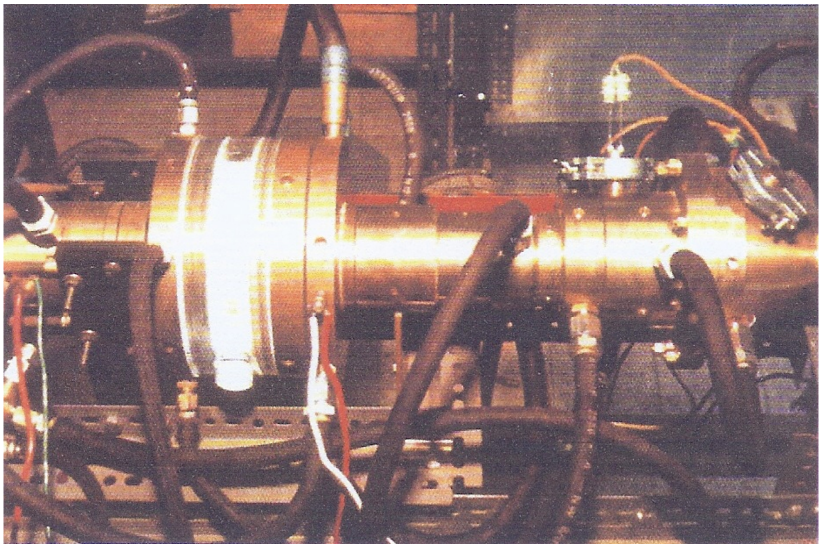

Fig.4 BN/ULB Experimental test rig

The experimental program, together with short duration irradiation tests of coated particles in the BR2 reactor and with further theoretical work, gave positive results, even if the erosion of the pyrolitic carbon covering the coated particles could lead to the production of methane which meant a decrease in the specific impulse of the propulsion system. A continuation of the program was decided for the following years culminating in 1972 with an ELDO contract to Belgonucléaire S.A. for a Develoment Cost Program aimed at estimating the technical and financial efforts to be consented for constructing a ground prototype of the propulsion system. The proposal was for a development in two phases: firstly, a study phase focused on the resistance of fuel materials, the thermohydraulic behavior of the porous core and the kinetics of the control system, and secondly, the development of the ground installation itself with a particular attention to safety issues. Costs were estimated at 400,000 UC of 1967 for the first phase and 12 Million UC of 1967 for the second phase. The UC, introduced in 1967, was the European Unit of Account (replaced in 1979 by the European Currency Unit); at that time, it was equivalent to the US Dollar. Even considering the important devaluation of the buying power of the currency over the years (about a factor of 700% between 1967 and 2011), these figures could be viewed as quite low.

The work was never brought to fruition as a fundamental revision of the European space program led to the termination in 1973 of all ELDO activities related to nuclear propulsion

4. Any future for such a system?

It is postulated that any possible future for nuclear thermal lies in manned interplanetary missions using launchers with a much greater low orbit payload capability than the one considered in the 1960s, this capability was the limiting factor in the development of the concept. Such limitation could be lifted for future applications; as the development of any future nuclear thermal propulsion system would most probaly occur within the frame of international cooperation, a wide range of heavy launchers could be considered.

The reactor concept used in the ELDO system has not experienced any significant further evolution after the early 1970s but it remains a sound one with a potential for larger power levels. Progress made in the technology of the non-nuclear parts of the system, notably cryogenic storage, could ease future development.

Studies on potential applications should be based on requirements for future missions; they should establish both the technical feasibility and the degree of competitiveness of the concept for such missions.

5. Conclusion

Many issues would require sustained attention if the concept were to be revived. The most critical one would be the availability of the expertise acquired in the past decades. This expertise is dwindling: actors of the past program are disappearing, archives are dispersed or incomplete or not catalogued.

It his hoped that this paper could generate renewed attention to the efforts consented in a distant past and stimulate further efforts for consolidating a knowledge base which should not be just a piece of technological history but should remain a stepping stone for future ventures in space.

References

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Acknowledgments

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The author wishes also to pay tribute to the foresight of the late Professor Paul Ruden who headed the Future Programmes activities of ELDO. Professor Ruden, who had already at that time experienced a distinguished career in turbomachines, mentioned when taking his position at ELDO in 1963 three key objectives in the future development of space: a jump in the performance of electronics allowing new space applications, the realization of a permanently manned space station in earth orbit and the development of non-chemical propulsion systems. The two first objectives have been met, let us hope that it will also occur for the third one!