A New Propulsion Concept for Interplanetary Missions

C. Dujarric
Directorate of Launchers, ESA, Paris

When tons of payload must be brought back from the planets to Earth, the current launch-system technology hits size limitations. The huge Saturn-V launcher that enabled the Apollo missions to go to the Moon would be dwarfed by a single launcher capable of sending men to a destination like Mars and bringing them back. Keeping interplanetary missions within a reasonable size and cost therefore requires technological progress in terms of both vehicle weight reduction and propulsion efficiency.

Introduction

Today's propulsion-technology know-how makes it possible to explore the celestial bodies of our Solar System with automatic probes. However, the design of the propulsion system becomes more critical when the mission includes the return of even a few kilogrammes of rock from other planets, because the total velocity increment required is so much higher. The sample-return capsule must be accelerated from Earth to escape velocity, decelerated upon arrival according to a trajectory suitable for a soft planetary landing, re-accelerated from the planet to escape velocity, and finally decelerated again to reenter the Earth's atmosphere. The high total velocity increment required strains the propulsion design, but remains feasible with classical means, albeit at the expense of long mission durations. It is still envisaged, for example, that Martian soil samples will be returned to Earth around 2013 using chemical propulsion.

Today's known categories of propulsion are shown in Figure 1. Classical chemical propulsion yields good acceleration capabilities, but its development is now asymptotically reaching the theoretical performance limits. New propulsion principles must therefore be harnessed.

As Figure 1 shows, electric propulsion can be interesting when the level of thrust required is low. It therefore finds application for satellite station-keeping, or orbital propulsion of automatic probes such as Smart-1. For manned interplanetary missions, however, the total trip time must be minimised. Current plans for a total duration of 3 years for a mission to Mars should not be exceeded, and should

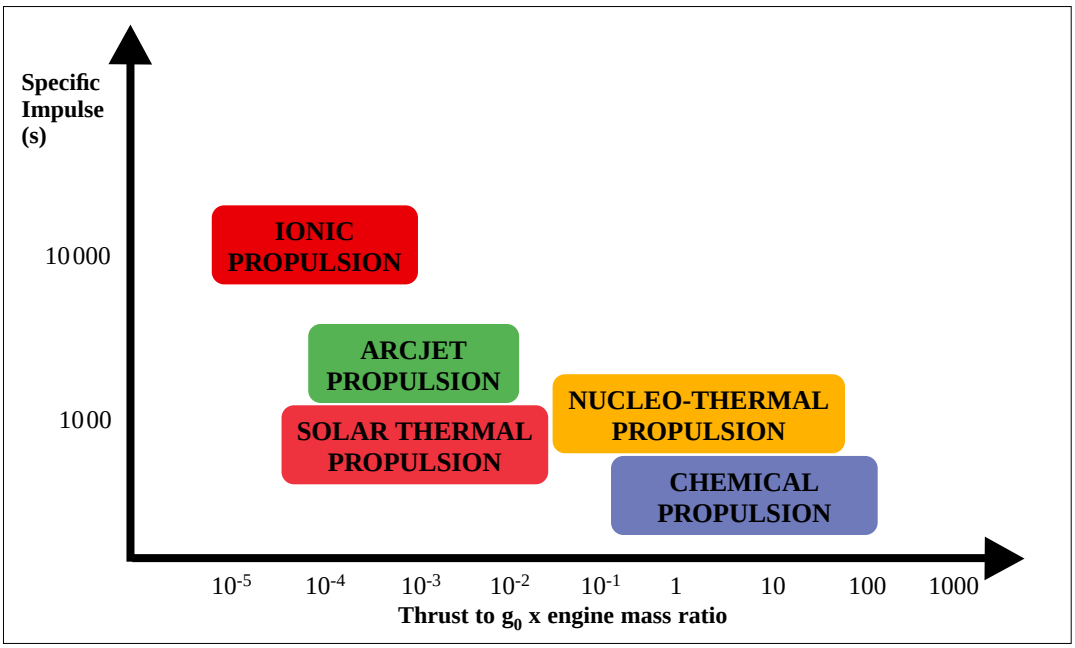

Figure 1. Performances of various types of rocket engines as a function of their thrust-to-mass ratios

preferably be reduced, owing to the psychological stresses on the crew and to the effects of cosmic radiation during interplanetary travel. Therefore, both a high thrust and a high specific impulse are required for manned interplanetary travel, and this high performance cannot be achieved at the cost of reliability and therefore safety.

Nuclear propulsion, which was studied in the USA and the Soviet Union in the sixties, yields a high level of performance, but its reliability has not yet been proved to be satisfactory. The development of nuclear propulsion was stopped at an already advanced stage, partly because the on-ground testing could not be continued under environmentally acceptable conditions. The core degradation during some tests showed that with the current technology the engine's lifetime was insufficient when operating at maximum performance.

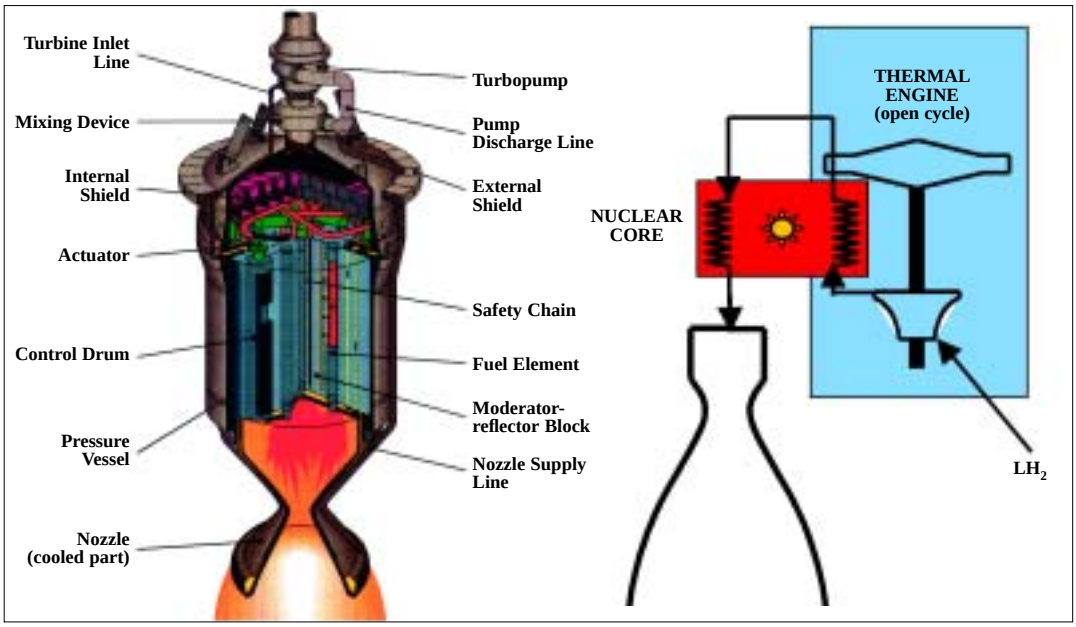

Figure 2. A state-of-the-art nucleo-thermal engine

Several possible solutions are currently under study around the world. The nuclear thermal propulsion concept described in this article features:

- a rocket-engine concept with a performance level at least equivalent to, and potentially better than that of the nuclear thermal engines developed in the sixties
- a design that provides a large technological margin for the operating temperature of the nuclear core, to achieve good reliability over a long engine lifetime
- a closed-loop test facility enabling long-duration on-ground testing of the engine without the rejection of nuclear contaminants.

How do nuclear thermal engines work?

Figure 2 (right) shows a schematic of the thermodynamic cycle of a state-of-the-art nuclear thermal rocket engine. The engine on the left was studied by the French CEA organisation in the framework of the MAPS project in 1990. Liquid hydrogen is first pumped at high pressure and used to cool down the core envelope and nozzle of the engine. Then the heated hydrogen is expanded in a turbine which drives the pump. This subassembly constitutes an open-cycle thermal engine. The hydrogen is then heated in the nuclear core at high temperature (up to 2500 K or more), and expanded through a rocket nozzle which produces the thrust.

The gas exhaust velocity V_e, which characterises the engine's performance, is given by the equation:

$$V_e \approx \sqrt{\frac{2R}{M}\left(\frac{\gamma}{\gamma-1}\right)T_c\left[1-\left(\frac{\Pi_e}{\Pi_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where γ is the ratio of specific heats, and R the universal gas constant.

This equation shows that maximum performance is obtained with:

- the propellant gas of lowest molar mass M, which is why hydrogen is used
- the highest possible temperature T_c in the core region, the practical limit being set by the core material's degradation
- the highest possible nozzle expansion ratio Π_e/Π_c this parameter being limited by the external nozzle's bulk, while increasing it beyond classical values has only a limited effect.

In practice, an engine specific impulse in the 850–900 sec range can be obtained with current materials technology, accepting some core-material degradation.

How were these engines tested?
Developmental testing is a real problem for this kind of engine. In the sixties, numerous tests were performed in the deserts of New Mexico during the NERVA programme. The hot hydrogen was exhausted upwards directly to the atmosphere (Fig. 3), but nowadays this kind of test is no longer acceptable from an environmental point of view.

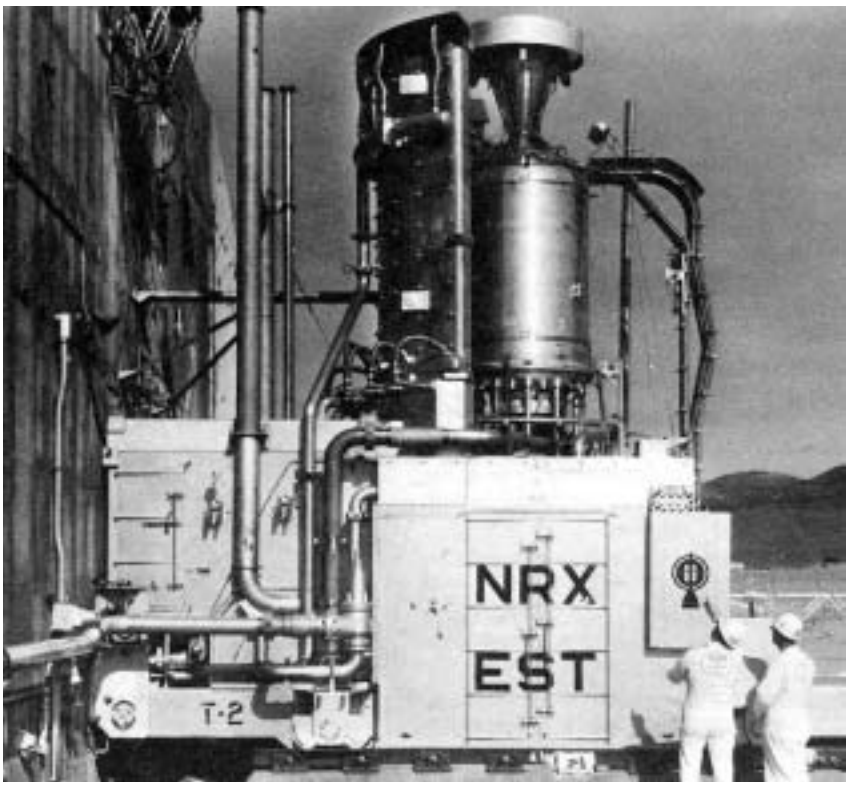

Figure 3. Nucleo-thermal rocket testing in the New Mexico desert

Evolutionary engines with improved performance, reliability and safety
The first step in the possible evolution of these engines is shown in Figure 4. It is simply an improvement of the turbopump cycle of the nuclear thermal engine. Since the liquid-hydrogen flow provides a cold source and the nuclear core a hot source, it is possible to engineer a closed-cycle thermal engine between the two which will drive the hydrogen pump. A Brayton cycle is preferable, using a mixture of helium and xenon as the closed loop's working fluid to take advantage of the low reactivity, high specific heat, and low sonic speed of this mixture. The advantage of this thermodynamic cycle is that it works between 15 and 2000 K, and therefore yields an excellent overall engine efficiency (better than 50%).

In a second step, realising that an extremely large quantity of heat can be obtained from the nuclear core and that, assuming a hydrogen mass flow of a few kg/s, a very large quantity of heat can be absorbed by the liquid hydrogen, the thermal engine's power output can be increased to several tens of Megawatts. This power can be used to drive an alternator which produces electricity. As described in an ESA patent, this huge amount of electric power can then be sent via a supercooled wire to a coil installed around the nozzle to produce an alternating electromagnetic field in the exhaust jet. In this region, the supersonic exhaust flow is reheated by magnetic induction. The

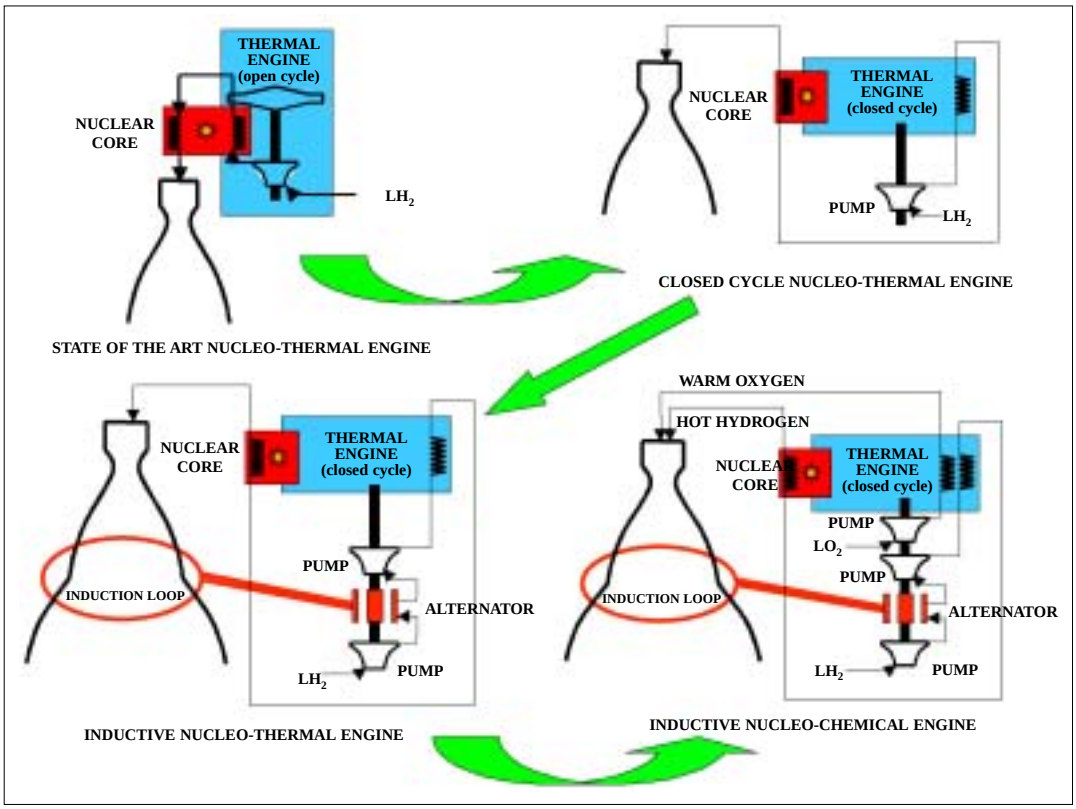

Figure 4. A possible evolution towards safer nuclear propulsion

induction coupling requires the flow to be seeded upstream, for example with caesium. The reheated flow is then expanded again in a downstream nozzle extension, thereby producing an increased thrust, somewhat like the afterburners on a jet fighter.

The gas exhaust velocity for this new type of 'inductive nucleo-thermal engine' is given by the following equation:

$$V_e \approx \sqrt{\frac{2R}{M}\left(\frac{\gamma}{\gamma-1}\right)\left[T_c + \frac{P_i}{Q\left(\frac{\gamma}{\gamma-1}\right)\frac{R}{M}}\right]\left[1-\left(\frac{\Pi_e}{\Pi_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

where Q is the exhaust mass flow rate, and P_i the power introduced into the exhaust gas through magnetic induction.

The terms of the previous equation can easily be recognised. A term has been added which is proportional to P_i. It is clear from this formula that, for a given core temperature T_c, the added power P_i increases the gas exhaust velocity V_e. Alternatively, the same engine performance V_e can be achieved with a lower nuclear core temperature T_c thanks to the power P_i introduced in the nozzle. The last step in the proposed evolution is the injection of oxygen in a combustion chamber sited up-stream of the nozzle of the inductive nucleo-thermal engine.

The result, called an 'inductive nucleo-chemical engine', harnesses three heat sources simultaneously: nuclear, chemical, and electric inductive. Table 1 shows the effect of increasing the oxygen/hydrogen mixture ratio: the engine's thrust is increased, due mainly to the higher mass flow rate, but its specific impulse decreases, due to the increase in the exhaust gas mean molar mass. Consequently, oxygen injection is of interest only when extra thrust is required for a short period, for example during planetary take-off or for orbit injection.

The idea of harnessing both nuclear and chemical power on a rocket is not new. It was pictured by Hergé in 1953 in his famous cartoon 'Tintin: Objectif Lune' (Fig. 5).

Table 1. Effect of oxygen addition

Mixture ratio Q_{02} / Q_{H2}	Specific impulse (s)	Normalised thrust
0	930	1
1	700	1.5
1.5	650	1.75
2	610	2
4	510	2.8
5	480	3.1

Why is the inductive nuclear engine safer and more reliable?

A state-of-the-art nucleo-thermal engine running with an average gas temperature of 2750 K in the core yields a specific impulse in vacuum of the order of 930 seconds. This temperature is close to the practical limit of the known materials for nuclear core design, bearing in mind that the temperature distribution in the core is not uniform and could locally reach 3000 K. Under these conditions, the lifetime of the engine is very short.

The same specific impulse of 930 seconds can be obtained using the inductive nucleo-thermal engine design with an average gas temperature of 2200 K in the core. With these conditions the lifetime of the core is unlimited, and there is even room for increasing the core temperature to improve the engine's performance. In fact, no element of the inductive nuclear engine ever reaches a temperature equal to the stagnation temperature of the exhaust flow. This is due to the fact that the induction energy is added to the flow only when it has already started to cool down, following its expansion in the nozzle.

How can one test an inductive nuclear engine on the ground?

The problem of the ground testing facility is illustrated in Figure 6. For a conventional nuclear thermal engine, the hydrogen entering the core is very cold. At the nozzle exhaust, the

Figure 5. An 'early' nucleo-chemical rocket concept

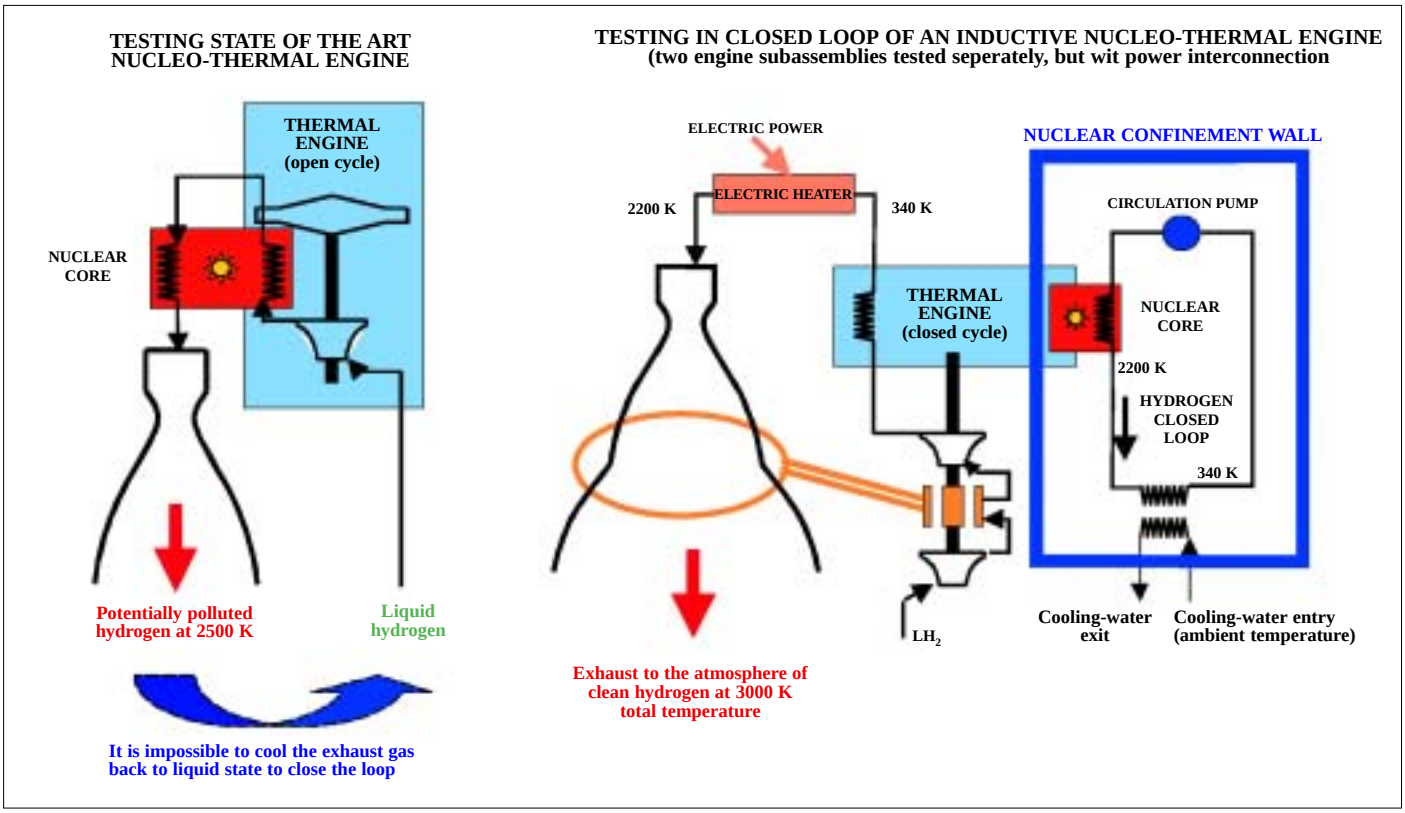

Figure 6. Testing facilities for nuclear propulsion

stagnation temperature is 2500 K or higher. It is therefore unrealistic to cool the exhaust hydrogen and liquefy it to re-inject it into the pump. Since the loop cannot be closed, the exhaust gas is dumped to the atmosphere, and part of its potential nuclear contaminants too, even when the gas is scrubbed.

The situation is quite different with inductive nuclear propulsion. Two independent fluid circuits go through the core. The Brayton cycle helium/xenon loop is already closed by design, and therefore creates no risk of pollution. In the propellant circuit, the hydrogen enters the core at 340 K and exits it at 2200 K. At this point the hydrogen can be cooled by a heat exchanger with external water at ambient temperature, brought back to 340 K, pumped through an auxiliary circulation pump, and sent back to the core to close the hydrogen loop. The nuclear core and any potentially dangerous loops are then entirely enclosed by a confinement wall, as shown in Figure 6. The nozzle and induction parts can be tested separately, fed by clean hydrogen that has been heated using an electric arc jet. The exhaust gas is dumped to the atmosphere or to a rocket altitude-test chamber. The resulting gas-heating and exhaust-pump installation looks very much like that of the recently developed Scirocco facility in Italy.

Hence, the inductive-propulsion concept can be qualified on the ground in two separated subassemblies, under environmentally clean and safe conditions, and with no duration limit except that resulting from the liquid-hydrogen storage.

Future prospects

From the dawn of humankind, the need to explore has driven human expansion across our planet. Expansion towards other planets in the Solar System is already underway with ‘virtual explorers’, namely robotic spacecraft. The question is, will human expansion continue? In the public consciousness, this is only a matter of time.

By 2020 to 2030, an international human mission to Mars may be a reality. It may use the Moon as a staging post to prepare for the great leap. The feasibility of such a mission is already being assessed, though the necessary technologies and capabilities still need to be developed. ESA’s Aurora Programme is designed to define and develop the strategic technologies in which Europe has to invest in order to be a key player in this international endeavour.

Today, it is too early to decide in favour of one specific type of propulsion. Trade-off studies will continue for some time. However, it is clear that current state-of-the-art chemical and electrical propulsion would impose very severe limitations on a human Mars mission and it is therefore necessary to continue to explore all options that might lead to an efficient and safe solution.

The nuclear-inductive propulsion concept described above may constitute a possible step in this direction. It builds on competences that already partially exist in Europe, for instance in the fields of turbo-machinery, nuclear furnaces, electric induction, high-power cryogenic circuitry and commutation, test facilities, and many other technical domains. The elements that need to be developed for this kind of concept may have spin-offs to applications in our day-to-day lives. Current research for a new generation of nuclear powerplants includes the consideration of high-temperature gas loops similar in design to the proposed Brayton-cycle nuclear power loop. High-power induction in a supersonic flow would assist in the design of higher enthalpy wind tunnels, while cryogenic high-power alternators are needed for a multitude of applications.

Current status

Once the new propulsion concept had been patented by ESA, a preliminary analysis of its feasibility was performed by SNECMA (F). As a result, a number of design issues have been shortlisted which require deeper investigation, but no clear technical showstopper has been found. At this stage, the most significant unknowns relate to:

– The possibility of heating the gas under supersonic conditions by induction: A fundamental study is needed into this still-unexplored aspect of physics. Is there a minimal residence time for molecules to increase their energy by induction heating? A simple low-cost experiment at the Von Karman Institute's facilities could provide the answer. But even if the supersonic heating is found to be impossible, the concept can also be adapted for subsonic heating, as SNECMA has already shown.

– The overall mass of an engine of this type: The mass can be realistically estimated only after a deeper pre-design study, which has still to be carried out.

Conclusions

The advanced concept for future interplanetary propulsion that has been described above offers the prospect of high performance at reduced core temperature, together with improved lifetime and reliability. A test facility that allows the engine to be qualified on the ground under environmentally clean and safe conditions has also been described. Today the development of the concept is still at the working-principle level, and further pre-design work is needed to confirm its true advantages and practical feasibility. Simple physical experiments are also needed to confirm the feasibility of the supersonic induction.

Acknowledgement

The contribution of Mr Dominique Valentian of SNECMA to the analysis and improvement of the nuclear inductive propulsion concept is gratefully acknowledged. He also proposed the idea of a closed-loop ground-testing facility.

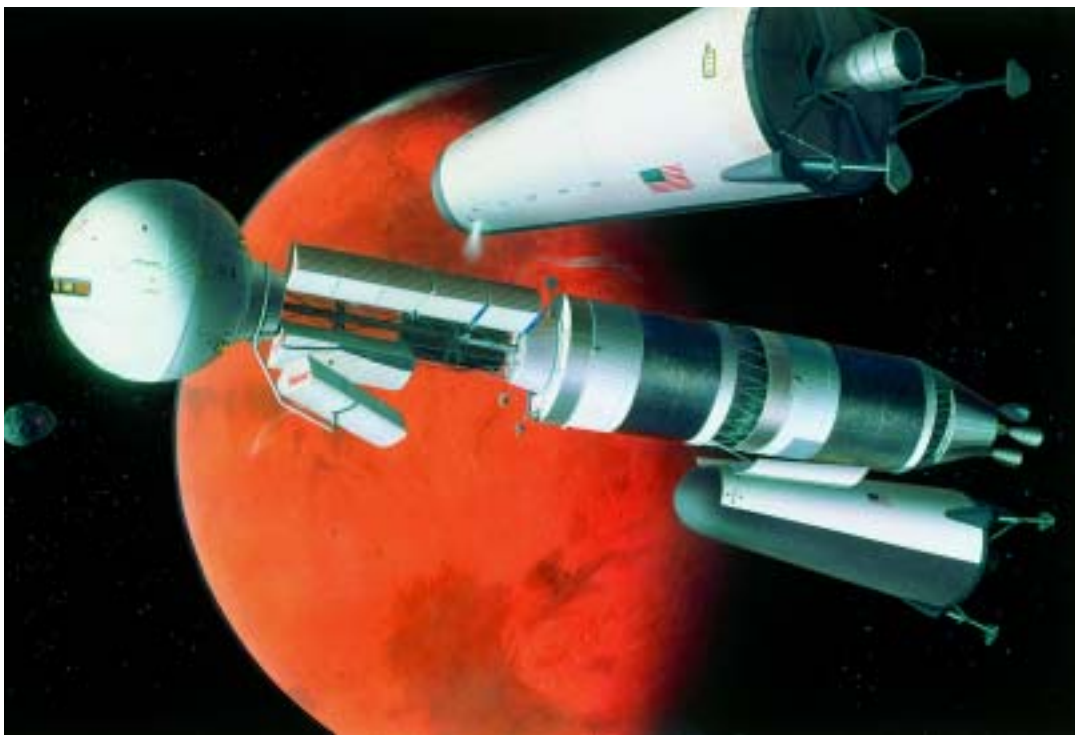

Figure 7. Arrival of an interplanetary vehicle in Mars orbit (artist's impression, NASA/NIX)