THE NTER: A PROPOSED INNOVATIVE PROPULSION CONCEPT FOR MANNED INTERPLANETARY MISSIONS

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Abstract

Conventional propulsion technology (chemical and electric) currently limits the possibilities for human space exploration to the neighbourhood of the Earth. If farther destinations (such as Mars) are to be reached with humans on board, a more capable interplanetary transfer engine featuring high thrust, high specific impulse is required.

The source of energy, which could in principle best meet these engine requirements is nuclear thermal. However the nuclear thermal rocket technology is not yet ready for flight application. The development of new materials, which is necessary for the nuclear core will require further testing on ground of full-scale nuclear rocket engines. Such testing is a powerful inhibitor to the nuclear rocket development, as the risks of nuclear contamination of the environment cannot be entirely avoided with current concepts.

Alongside already further matured activities in the field of space nuclear power sources for generating on-board power, a low level investigation on nuclear propulsion has been running since long within ESA, and innovative concepts have already been proposed at an IAF conference in 1999.[1][7] Following a slow maturation process, a new concept was defined which was submitted to a concurrent design exercise in ESTEC in 2007. The pre-definition work made clear that, based on conservative technology assumptions, a specific impulse of 920s could be obtained with a thrust of 110kN. Despite the heavy engine dry mass, a preliminary mission analysis using conservative assumptions showed that the concept was reducing the required Initial Mass in Low Earth Orbit compared to conventional nuclear thermal rockets for a human mission to Mars. A patent was filed on the concept. Because of the operating parameters of the nuclear core, which are very specific to this type of concept, it seems possible to test on ground this kind of engine at full-scale in close loop using a reasonable size test facility with safe and clean conditions. Such tests can be conducted within fully confined enclosure, which would substantially increase the associated inherent nuclear safety levels. This breakthrough removes a showstopper for nuclear rocket engines development.

The present paper will disclose the NTER (Nuclear Thermal Electric Rocket) engine concept, will present some of the results of the ESTEC concurrent engineering exercise, and will explain the concept for the NTER

on-ground testing facility. Regulations and safety issues related to the development and implementation of the NTER concept will be addressed as well.

Introduction

The present paper focuses on inter-orbital propulsion, i.e. the propulsion needed to escape earth orbit and conduct space exploration, including return to Earth. For such missions the optimisation of the inter-orbital propulsion is a key driver for the overall mission cost, as the slightest performance gains on the interplanetary transfer engine has huge impacts on the size of the required Earth departure means.

The typical advantage of chemical propulsion is to provide a high spacecraft acceleration for a low engine mass, while electric propulsion may be preferred for its higher specific impulse whenever thrust can be applied for a long time without detrimental effect on the payload. R&D strives to mitigate the shortcomings and pushes the limits of each type of propulsion. However even taking into account the anticipated progresses of these technologies, a part of the long-term space exploration needs may lie beyond the physical limits of those conventional propulsion means.

Human exploration of space beyond the Moon orbit generates mission constraints which neither chemical nor electric propulsion can satisfy. The time of the interplanetary travel must remain sufficiently short to keep the space radiation effects to an acceptable level. The crew endures not only a cumulated radiation dose proportional to the duration of their travel at first order approximation, but also takes a proportionally cumulated risk of being hit by a solar flare or meteorite. Furthermore, on a long interplanetary ballistic trajectory, the crew cannot be left in a waiting mode and without effective means to influence decisively their fate, especially when facing non-nominal situations. It is mandatory to give them a propulsion mean on which they can rely to implement their decisions to restore their nominal mission or initiate a safeguard alternative and monitor the effect of their action within short delay.

Nuclear propulsion state of the art

Nucleo-thermal rocket propulsion was developed both in the U.S. and in Russia aiming to satisfy the simultaneous need for high thrust and high specific impulse.

The nuclear propulsion development efforts lasted in the U.S. from 1955 until 1972. Twenty rockets and furnaces were successfully ground tested in the frame of the KIWI and NERVA programs. The NERVA-NRX/XE, which featured Uranium carbide fuel core coated with Zirconium carbide, was the ground-qualified model the closest to a flight model.

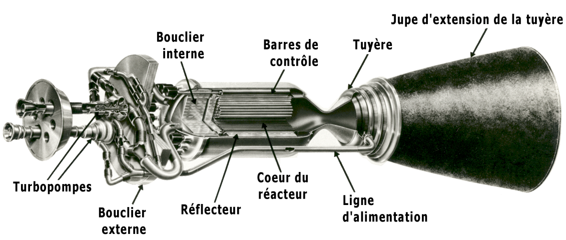

Figure 1: the NERVA NTR engine

The nuclear thermal propulsion development efforts started also in 1955 in Russia but lasted until 1989. Several engines (RD-0140, RD-0411 and RD-410) were designed in CIS and their nuclear fuel elements based on ternary carbide twisted ribbons were successfully tested, however not as part of an engine system.

More recent conceptual studies were conducted in the U.S., which are not yet tested at engine system level. The core technology investigations led to the ceramic-metallic (CERMET) fuel in a fast neutron reactor. This solution offers better resistance to hydrogen corrosion and a lighter design, but further work is still needed to reduce fission gas swelling effects in the fuel.

At system level, bimodal engines were investigated in the U.S. and in Russia to deliver electric energy to the spacecraft during cruise for example to keep the hydrogen in liquid state, and also to mitigate the hydrogen consumption during the nuclear core start-up/shutdown transients.

Some conceptual design work on nuclear propulsion also started in Europe with the French MAPS program in 1995, but this effort did not result in any hardware fabrication or testing.

ESA's initial proposals to upgrade the nucleothermal propulsion performance

Several ideas were already investigated in the 1990's, in particular by Aerojet in the U.S., to take advantage of the unlimited power available from the nuclear core to increase the specific impulse of the engine as compared to what is obtained by a simple heat transfer to the hydrogen. These studies were stopped in view of the complexity of the thermal machines involved, and their consequent mass.

Along these lines, ESA proposed its first ideas in 1999, which consisted in using the electric power obtainable from a bimodal engine to heat the hydrogen plasma supersonic exhaust by electric induction. [1][2] This nuclear inductive concept is recalled in Figure 2:

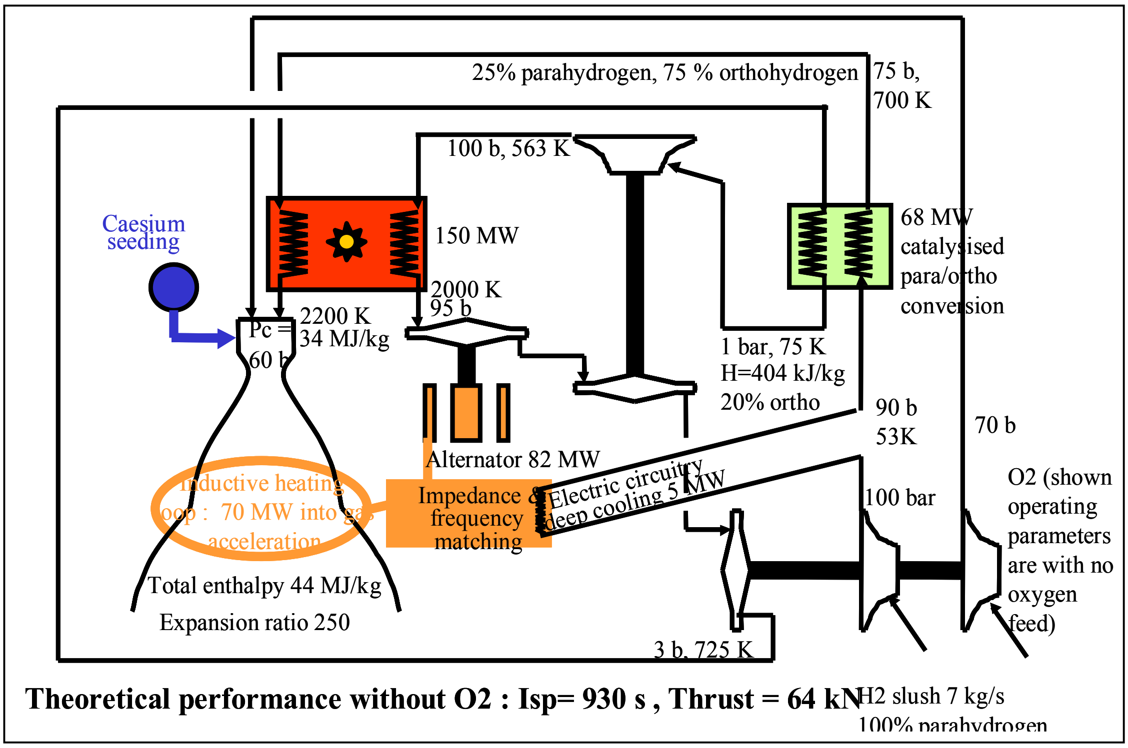

Figure 2: the nuclear inductive concept

One particular benefit of the idea was the synergy and efficiency gain, which was achieved by using as a cold source for the Brayton cycle the incoming cryogenic propellant. Variants of this concept included mixed chemical/ nuclear inductive propulsion to increase the thrust when necessary, to the detriment of the specific impulse.

The nuclear inductive concept offered some advantages, such as a high expected specific impulse (930s) despite a moderate core temperature (hydrogen temperature at the nuclear core exit of 2200K). It produced large thrust (64kN) at the highest Isp, while offering the possibility to further multiply the thrust level by a factor 3 at the expense of a large specific impulse decrease (480s). Since the additional energy was introduced in the supersonic zone of the exhaust flow where the flow is already cooling down, no part of the engine had to sustain a temperature equal to the stagnation temperature of the exhaust flow.

However the concept also presented a number of weaknesses: mainly its complexity and anticipated dry mass, but also the development risks which resulted from the non-well mastered physics of the electric induction in the supersonic hydrogen plasma. Induction heating experience does exist at relevant pressure with various gases at VKI in Belgium, but not in supersonic conditions. While further fundamental research is worthwhile to consolidate and identify the limits of the supersonic plasma induction idea (in particular with respect of the plasma thermal non equilibrium effects), it is prudent to look for a variant of this concept, which would suppress the biggest identified drawbacks, and mitigate the remaining weaknesses.

The NTER concept

From 2000 till 2007 the nuclear inductive concept went through a slow maturation process during which the inductive heating of the supersonic exhaust plasma was proposed to be replaced by conductive heating of the hydrogen in the subsonic area. This change removed all uncertainties and most potential inefficiencies due to the non-well mastered plasma physical behaviour.

A major goal of this evolution was also to reduce the engine dry mass; therefore the transmission of energy from the Brayton cycle to the hydrogen had to be simplified. In this respect, an innovative device called turbo-inductor, which is the object of a European patent has been described.[3] This new device reshapes the whole engine architecture, whose name becomes now the NTER (Nuclear Thermal Electric Rocket) engine. The description in this paper of the concept will not detail the nuclear core design, as there is presently no on-going activity in this domain at ESA, but will cover only with the thermo-mechanical device, which is installed around the core, which is meant to increase the engine performance.

Figure 3 shows the NTER concept around a CERMET-type nuclear core. Indeed, the remaining fuel swelling problems of this type of core must be resolved before this type of core can eventually be selected. In case the CERMET-type nuclear core in the end cannot be retained, another variant of the NTER is described in Figure 5, which builds on the older but already proven NERVA-derived nuclear core and proposes a work-around solution to the now well understood hydrogen corrosion problem.

Two main fluid circuits, hydrogen and helium, are shown on Fig. 3:

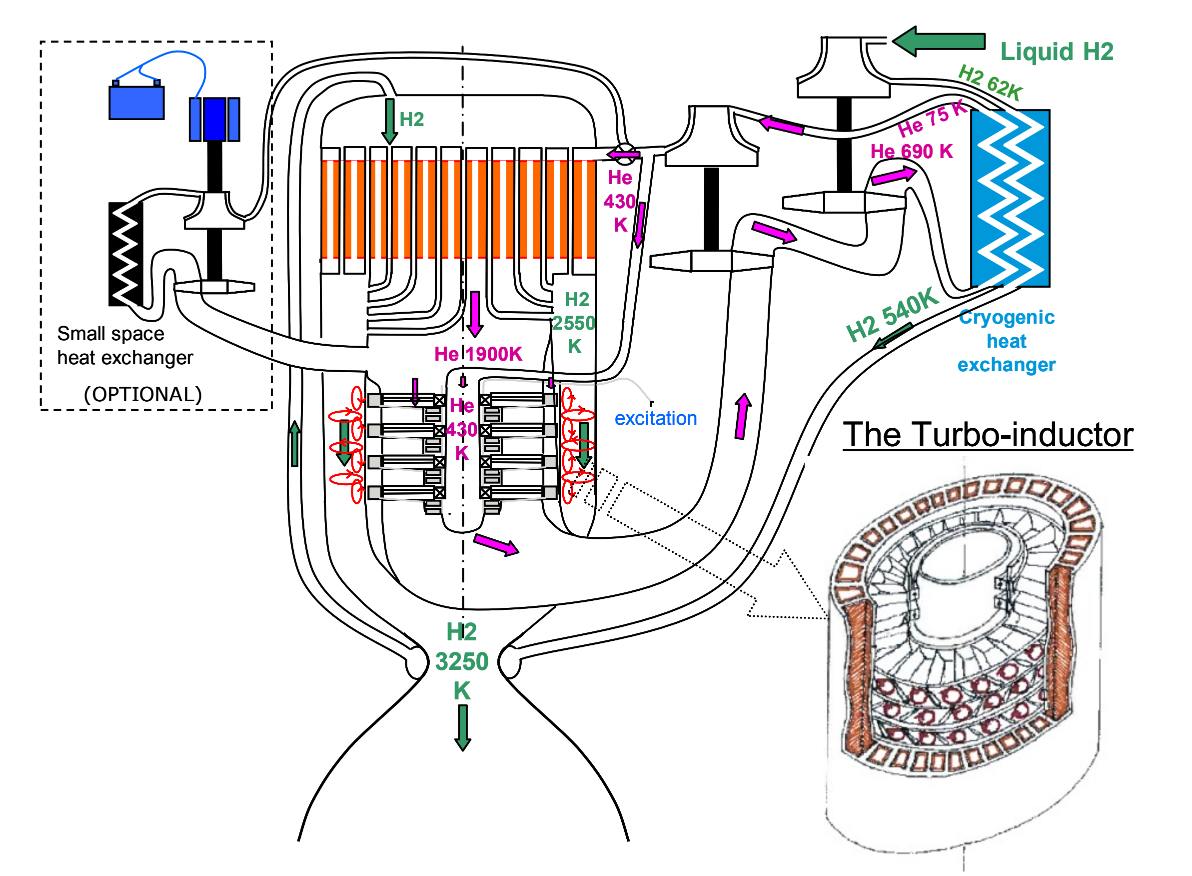

Figure 3: the NTER concept

- The cryogenic hydrogen is first pumped at high pressure, and then flows through a heat exchanger to be used as cold source for the Brayton cycle. At the exit of the exchanger, the warm hydrogen can optionally provide some cooling to the throat area to protect the throat from excessive heating. At this point the hydrogen enters the nuclear core at a temperature beyond 540K. It is heated by the nuclear core up to an assumed temperature 2550K, which takes into account ample margin with respect to the CERMET core technology. Then the hydrogen flows through the longitudinal channels of a turbo-inductor, which will be described in Figure 4 below. Its temperature is increased to 3250K by convection. Finally, the hydrogen is exhausted through a nozzle to produce the thrust.
- A Brayton cycle using Helium is implemented. The cold source is the heat exchanger with the cryogenic hydrogen, where the Helium is cooled down to 75K (this very low temperature yields an excellent Brayton cycle thermodynamic efficiency, but condensation prevents using additional Xenon). Helium is then pumped at high pressure and then heated by the nuclear core flowing through bimodal-like dedicated channels. The heat

exchange through these channels is tuned such that the helium temperature remains with margins below the temperature limit for the turbine stages, which are installed in the turbo-inductor placed downstream. At the exit of the turbo-inductor, the helium is further expanded through two turbines, which drive the two pumps, and returns to the hydrogen heat exchanger.

Two auxiliary circuits are also shown on Figure 3:

- An Helium bleed circuit which picks Helium at the exit of the pump around 430K and feeds the cooling circuits of the turbo inductor to maintain its bearings and electric subsystems at acceptable temperature.
- Taking advantage of the already implemented bimodal architecture of the nuclear core, an optional bimodal circuit can be installed to provide electric power when the propulsion is off. This circuit also could help to manage the thermal transients of the core during the propulsion start-up and shut-down.

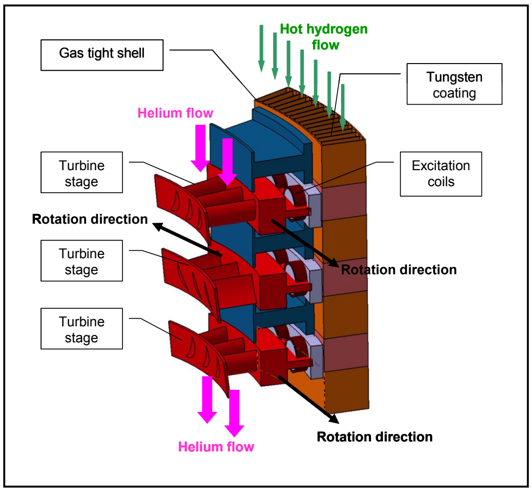

Figure 4 : the turbo-inductor stages

The turbo-inductor, which is the innovative part of the concept, operates as shown on Fig. 4:

Several successive turbine stages are installed on individual bearings and are freely rotating without any mechanical power transmission. These turbine stages are powered by the Helium expansion. Two consecutive turbine stages are contra-rotating. No stator is therefore needed, which avoids the energy losses due to stator stages. At the tip of the turbine blades a ring is installed which bears coreless coils creating radial fields. One coil can be installed between two consecutive blades. Two consecutive coils on a ring present opposing poles. The ring constitutes basically the rotor of an alternator, but no magnetic core is installed due to the high local temperature (which would disable any ferromagnetic property) and to the high local acceleration.

Longitudinal channels are installed around the rings, which duct the hot hydrogen from the nuclear core towards the nozzle. These channels are coated internally with tungsten. At any channel location a longitudinally and radially variable magnetic field is generated by the coils installed on the nearby contra-rotating stages. As a consequence, Foucault currents are created in the tungsten coating along transverse and orthoradial planes. These currents heat the tungsten by ohmic effect, which in turn heat the hydrogen by convection.

Given the excess of power available from the Brayton cycle, the 3250K limit to the hydrogen stagnation temperature as shown on Figure 3 is imposed by the melting of the tungsten. This technology limit sets the specific impulse of the engine.

Even higher performance could be obtained, subject to confirmation by additional R&D,

if no tungsten is installed in front of the last turbine stages; then induction and heating would occur directly in the hydrogen subsonic plasma), with an energy transfer efficiency which remains to be determined.

In the case the CERMET-type fast neutron nuclear core is not finally retained due to technological hurdles the NERVA-derived epithermal neutron core remains a valid candidate as it has been tested on a rocket model on ground in the sixties. Then the problem discovered during these tests, which is the problem of core erosion by hydrogen, needs to be resolved. The NERVA-derived core design features a graphite core matrix protected from the hydrogen flow by a zirconium carbide coating. This coating is applied by chemical vapour deposition at 1500 K. Due to the thermal expansion coefficient mismatch with the graphite, the coating cracks after fabrication during its cooling. During the NTR operation, the degradation is moderate in the region of the hydrogen entrance into the core because cold hydrogen does not spontaneously react chemically with the

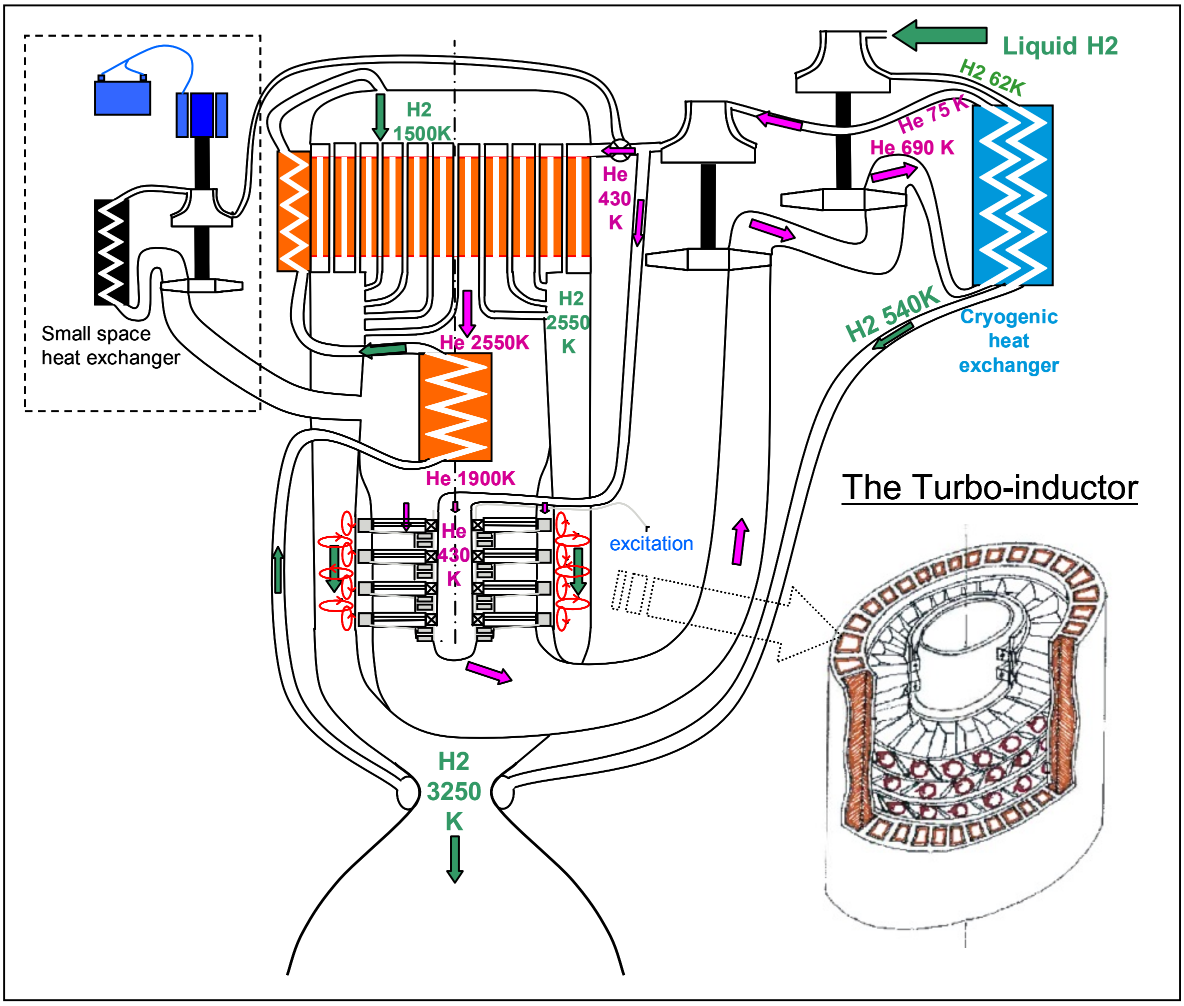

Figure 5: The NTER concept for a NERVA-derived nuclear core

graphite matrix. However, in the core region above 1000K, hydrocarbons form which get mixed with uranium particles into the exhaust flow. In the region above 1500K, due to the thermal expansion of the zirconium carbide, the cracks close again, and material creeping makes the coating gas-tight.

The NTER architecture offers a unique opportunity to work around this problem, as shown on Figure 5: Unlike the NERVA engine, the hydrogen does not enter the nuclear engine at low temperature, since the NTER cryogenic heat exchanger already heats the hydrogen above 500K. On this NERVA technology variant, an additional heat exchanger with Helium pre-heats the hydrogen beyond 1500K before the entrance of the nuclear core channels, i.e. beyond the temperature range where cracks can appear in the ZrC coating. For this purpose, the Helium comes out of the nuclear core at a temperature of 2550K, the same as for hydrogen. In addition, this heat exchanger is dimensioned such as to bring the Helium exit temperature down below the technological temperature limit for the turbine entry; if necessary, further heat is provided to hydrogen by heat exchanger with the nuclear core structure and internal tubing as was already achieved in NERVA.

The NTER predesign at ESTEC CDF

The ESTEC Concurrent Design Facility has performed in 2007 a feasibility assessment of the NTER concept.
Reference Performance requirements were defined based on a possible application for a Human Mission to Mars. Those are:

- Specific impulse ~900 s
- Thrust ~ 100 kN
- Restartability > 3 times
- Engine dry mass < 30 tons

The main design issue was to find an optimal sharing of the fixed nuclear reactor power between the one used to heat up directly the propellant flow and the one used to heat up a fluid working within a thermodynamic cycle that generates induction power later transferred to the propellant fluid at a given point of the engine nozzle.

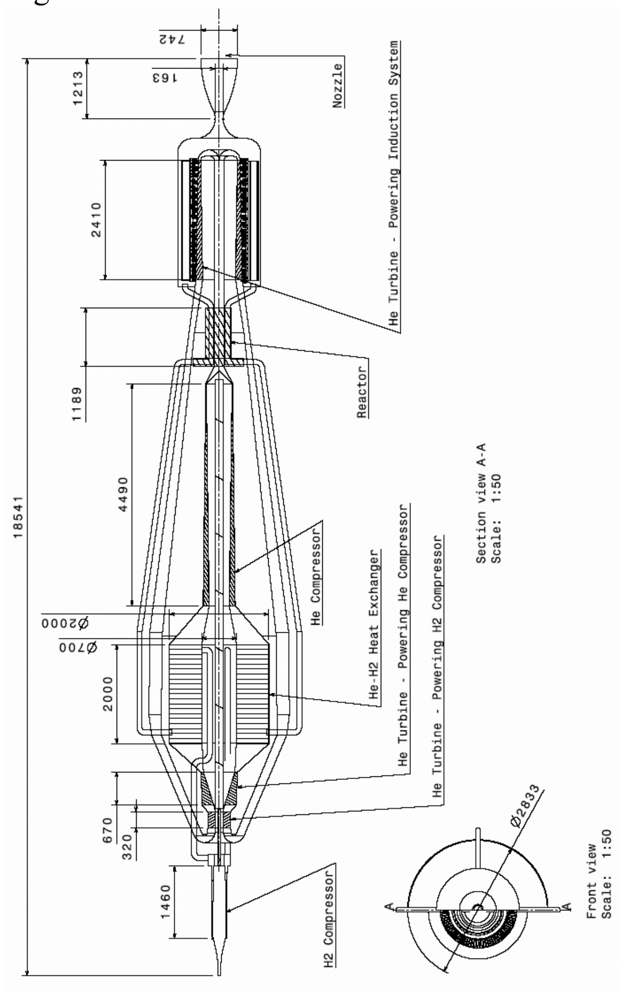

Figure 6: CDF design of the NTER engine

The power handled by the thermodynamic cycle needs to be commensurate with the physical and technological limits of its components (heat exchanger and turbo-machinery), with the total mass and volume of the system and with the characteristics and constraints of electromagnetic induction (inductor design). Above a certain power

threshold either the efficiency of the thermodynamic cycle (and thus system performance) decreases dramatically, or the dimension of the engine (including the inductor) become unrealistic. Below a certain power threshold the additional complexity of the thermodynamic cycle does not pay off.
Figure 6 shows the configuration of the NTER engine as from the CDF study.
All components are arranged axially with all the thermodynamic cycle elements on the aft part and the nuclear reactor, the inductor and the nozzle at the end. This is the simplest configuration albeit not the most compact. Possibilities exist to come to a more parallelised configuration or to reduce the total length by for instance using a centrifugal H_2 compressor instead of an axial one.

System, fluido-dynamics and thermo-dynamic analysis was performed leading to the following performance results:

Dry Mass excl Margins	23,500 kg
Nozzle Inlet Temperature	3250 K
Nozzle Inlet Pressure	42.15 bar
Propellant Mass Flow Rate	12.0 kg/s
Thrust in vacuum	111.2 kN
Isp in vacuum	921 s (with exp ratio =100)

Table 1: NTER rough performance estimate

The testing of the NTER on ground

Another benefit of the NTER concept is that its architecture offers the unique opportunity to test the engine system on ground in fully confined closed loop conditions. This opportunity results again from the warm to high temperature of entry of the hydrogen into the nuclear core. The test facility concept is presented on Figure 7 for a NERVA-derived core engine.

The test facility concept is the following: The whole engine (except its nozzle) is tested in closed loop under a confinement wall.

Downstream the sonic nozzle throat, a shock brings back the flow to subsonic conditions and the extremely hot hydrogen flow is sent towards a heat exchanger which evacuates the heat through the confinement wall to the outside environment, e.g. water flowing naturally from an altitude lake (The facility shall be resistant to natural disasters such as earthquakes; therefore a natural altitude lake seems preferable to an artificial water dam). Water ducts would be redundant and feature over-dimensioned bellows

Hydrogen is then pumped by a circulation pump. This pump is a part of the test equipment, not part of the engine tested. It uses external power only when the test is going on. The power is tuned such that the hydrogen pressure reaches the value it should have on an isolated engine at the entry of the heat exchanger with helium.

The external water flow is tuned such that the temperature of the hydrogen at the exit of the circulation pump equals the temperature it should have on an isolated engine at the entry of the heat exchanger with helium.

The equality of hydrogen pressure and temperature at the circuit exit and at the intermediate entry of the engine enables closing the loop for the part of the hydrogen, which comes in contact with the nuclear core. The helium circuit is anyhow already nominally working in close loop. In case nuclear fission products are released in the hydrogen or helium by erosion or even as the consequence of an engine malfunction, those products remain confined under the wall.

On the cold side of the hydrogen circuit, the heat exchanger is fed with cryogenic hydrogen coming from the outside, with a mass flow rate tuned equal to the mass flow rate in the closed hydrogen circuit. The hydrogen at the exit of the heat exchanger can be either burnt as shown on the figure, or stored to be re-liquefied later at a slower rate using a reasonably dimensioned liquefaction plant for subsequent reuse.

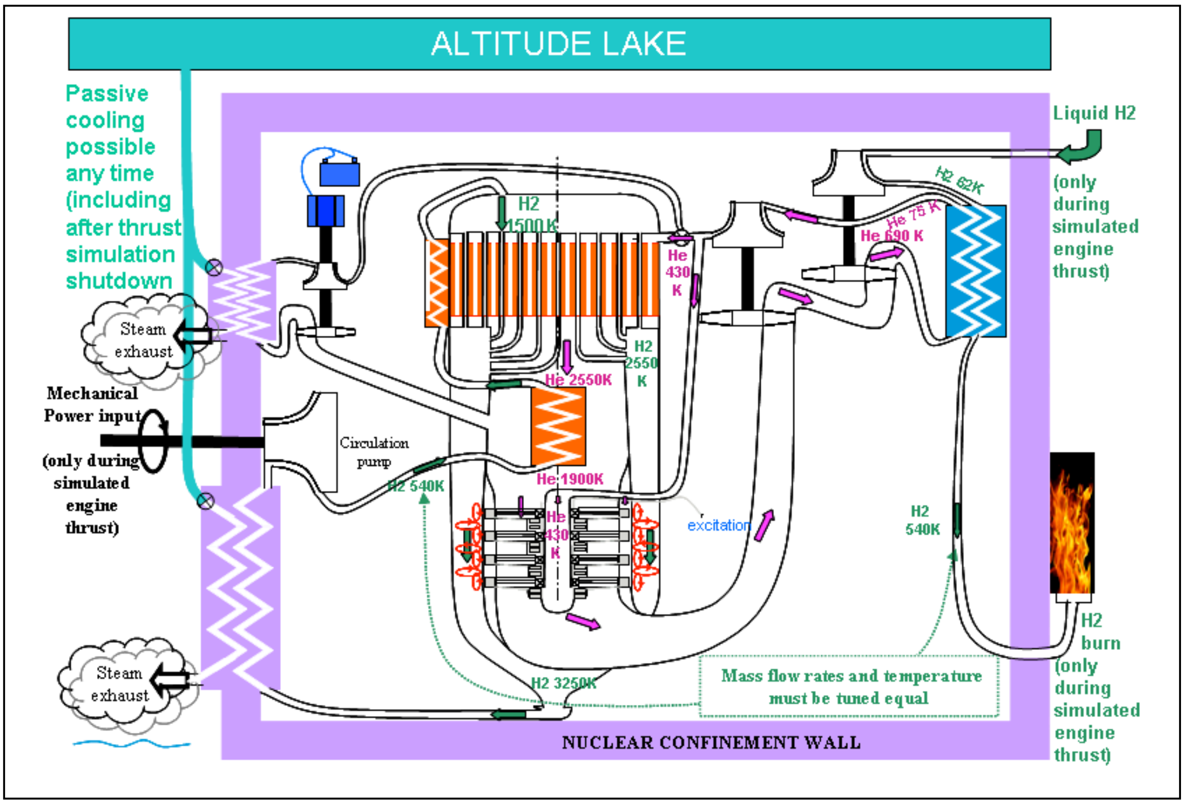

Figure 7: ground test facility concept for the NTER engine

Since the purpose of this facility is to qualify an engine which will operate in space for a relatively short time (of the order of one hour), the testing duration in the facility will be in total only a few tens of hour. If such facility is installed in a region with low seismic activity and out of reach of natural disaster like tsunamis, a situation requiring stopping an on-going test is unlikely to happen. Should such situation still happen, the facility is designed to stop the thrust simulation and operate autonomously its cool-down using its auxiliary Brayton cycle, which by the way generates and stores its own electricity independent from the grid. The cold source is provided by water flowing naturally from an altitude lake, without any need for external mechanical or electric power nor for any other fluid to be continuously provided to the facility. The capacity of the lake might be considered unlimited if it is fed by a river with sufficient flow rate.

Of course the same kind of test facility can be designed with a CERMET-type core design.

Advantages and drawbacks of the NTER

As an outcome of the studies performed in ESTEC CDF, the following advantages and shortcomings of the NTER concept have been identified:

Advantages compared to other concepts:

- High specific impulse, high thrust
- No necessity to operate the nuclear core to its technological temperature limit for getting a good performance (operating at lower temperature increases the core life duration and the safety margins)
- Less thermal stresses in the nuclear core
- Availability for NERVA technology of a workaround solution to avoid the hydrogen corrosion snag
- Strong synergy with bi-modal functions.

Advantages over the nuclear inductive concept previously proposed by ESA:

- Plasma physics uncertainties avoided
- Mass gains due to the suppression of a large amount of intermediate subsystems: turbine stator, mechanical shaft, alternator, impedance adapters, lines, coils, nozzle extension, offset by very few additions (turbo-inductor rings and tungsten channels)
- Reliability gain also due to intermediate subsystems suppression

Remaining shortcomings:

- Engine system mass and complexity
- Engine development costs (huge!)

However the most decisive advantage is perhaps the possibility offered by the NTER to test the engine in fully confined test conditions, robust to catastrophic events from outside the containment wall.

It cannot be envisaged to skip future nuclear engine system tests on ground, whatever the engine design chosen. The only technology, which is already extensively tested is the NERVA technology, but the test results show it needs anyhow to be modified and re-tested. All other concepts relying on different core technologies must be verified at the engine system level.

Several solutions have been proposed to perform the engine level tests, but none provides fully confined gas protection. Scrubbing the exhaust gases cannot be efficient 100%, especially in case an engine malfunction occurs, as it did occur with NERVA. Dumping the exhaust gases in deep ground cavities can help to dilute and filter the radioactive particles, but this solution creates unbounded quantities of polluted soil, with no certainty that the pollution will never migrate back to the surface.

The sensitivity of the population to environmental protection is growing, and the fear related to nuclear activities in general has not vanished.

Therefore after a successful development and qualification of all the necessary subsystems, the engine system testing issue may remain in the end the only real showstopper for future nuclear thermal rocket engines, unless the ground facility concept linked to the NTER engine is used.

Safety and regulatory aspects

After the early experimental phases of nuclear physics and engineering, when the safety of these activities played only a secondary role which was mainly dealt with at laboratory level, the defence sector developed some early nuclear safety requirements that were subsequently serving as a basis for the general nuclear safety framework developed in parallel to the large-scale development of civilian nuclear energy applications.

Together with the Atoms for Peace programme of the US government starting in the early 1953 and which led to the creation in 1957 of the main international nuclear organisation also dealing with nuclear safety, the Vienna-based International Atomic Energy Agency (IAEA), nuclear safety has early on been recognised as being of international, trans-border and eventually global concern. As part of its core mandate, the IAEA establishes international standards and guides covering nuclear safety, radiation protection, radioactive waste management, the transport of radioactive materials, the safety of nuclear fuel cycle facilities and the associated quality assurance. Under the umbrella of a recently agreed high-level publication, the so-called "Safety Fundamentals",[4] the IAEA safety standard series include generic standards as well as specific ones for

- Nuclear Power Plants,
- Fuel Cycle Facilities,
- Research Reactors,
- Radioactive Waste Disposal Facilities,
- Mining and Milling,
- Application of Radiation Sources,
- Transport of Radioactive Material.

In parallel, the specifics of space applications of nuclear power sources have triggered the development of dedicated, separate recommendations for the safety of nuclear power source applications in space.[5][6]

For the purpose of this paper, the concept is briefly analysed with respect to the provisions in these documents. For such an analysis, it is useful to keep the separation between nuclear safety aspects related to the purely terrestrial activities and those related to in-space activities.

Given the scope of the paper, regulatory and safety aspects related to the engineering, laboratory work as well as transportation of associated nuclear material are not covered since these are relatively straight forward and not different from many other nuclear activities. For terrestrial, pre-flight activities, the focus therefore will be on the regulatory and safety aspects related to the ground testing of the NTER concept.

Concerning the space activities, one could argue that the 1992 principles do not or only partially apply to the NTER concept due to the affirmation in the preamble that the set of principles "*applies to nuclear power sources in outer space devoted to the generation of electric power on board space objects for non-propulsive purposes, which have characteristics generally comparable to those of systems used and missions performed at the time of the adoption of the Principles*". The NTER concept clearly has some characteristics that are different to the systems used at time of adoption of the principles and the nuclear energy is used for propulsive purposes in this concept.

One might still argue that the electric power generation aspects of the NTER, which are not directly linked to propulsive purposes but for other energy needs of e.g. human missions would fall under the scope of the principles. In this case, the most relevant *technical* provisions of the principles would be those in Article 3, e.g. related to the prevention of potential contamination of outer space and the restriction to using only highly enriched Uranium 235 as fuel.

The international *Safety Framework for Nuclear Power Source Applications in Outer Space*, adopted end 2009 as part of the UN COPUOS report to the UN General Assembly follows a different approach than the NPS Principles from 1992. The safety framework intends to be a model safety framework for implementation at national or international level. It provides guidelines for governments, management as well as technical guidelines to achieve its objective of "protecting people and the environment in Earth biosphere from potential hazards associated with relevant launch, operation and end-of-service phases of space nuclear power source applications". Contrary to the principles, the framework specifically includes all applications of nuclear power sources, thus also those for propulsion, but it also excludes some aspects included in the principles, such as the protection of outer space and of humans involved in missions that use space NPS applications.

It is useful to make a further distinction between the type of use of the NTER concept: in case the system is used in Earth orbits, which include the option of collisions with other objects or space debris and the option of re-entry, the safety assessment would be slightly different than if the nuclear reaction would only be started once on an interplanetary trajectory with no possibility of any re-entry into Earth and thus also excluding Earth swing-by manoeuvres. For the following assessment, the later is assumed as a baseline.

Chapter 5 of the framework deals with technical recommendations. The prime provisions therefore would be related to the state of the nuclear reactor during launch and early launch phases. The reactor most likely would have undergone only 0-power testing and would thus not contain any significant amount of radioisotopes. The main focus therefore would be on the prevention of any accidental criticality in case of launch accidents and situations created by launch accidents. These might include scenarios such as intact or partially intact accidental landing of the reactor core in water, wet sand or other media, which could provide conditions for accidental chain reactions.

One of the main advantages of the proposed design over other nuclear propulsion options is the option to test the nuclear reactor, the engine and the associated conversion system in a fully confined environment with an essentially closed-loop system. Since such development and operational tests are to be conducted on ground, terrestrial regulations related to nuclear installations will determine the details of the safety related aspects of such an installation. The general approach to nuclear safety is handled slightly differently in different countries. For example, the safety of French nuclear reactors is based essentially on a deterministic approach, while others such as e.g. the UK and the US rely more on probabilistic safety assessments. At this stage it is of little added value to speculate on the location of an eventual development and testing facility. Therefore the considerations made so far are referring to the basic safety principles adopted by all national regulations and consensually expressed within the IAEA safety standards series.

Given the novel nature of such an installation as well as the one-off type, the most suitable IAEA safety series documents seem to be those related to research reactors.

Research reactors are defined by the IAEA as “nuclear reactors used mainly for the generation and utilization of radiation for research and other purposes, such as the production of radioisotopes. This definition excludes nuclear reactors used for the production of electricity, naval propulsion, desalination or district heating.” [8] While the type of ground testing installation for the NTER concept is not specifically included, it is also not excluded and given the strong R&D aspect of it, these regulations seem most appropriate to take as a working baseline. Paragraph 1.9 of the IAEA Safety Requirements documents for research reactors confirms this approach by providing specifically for similar cases as the one discussed that “Research reactors with power levels in excess of several tens of megawatts, fast reactors, and reactors using experimental devices such as high pressure and temperature loops, cold neutron sources and hot neutron sources may require the application of standards for power reactors and/or additional safety measures.[…] For facilities of these kinds, the standards to be applied, the extent of their application and any additional safety measures that may need to be taken are required to be proposed by the operating organization and to be subject to approval by the regulatory body.” [8]

The IAEA Safety Requirements [8] intends to establish requirements for all important areas of the safety of research reactors. In addition to requirements for design and operation, it also includes requirements on regulatory control, management, verification of safety, quality assurance and site evaluation. While some of these requirements are the same as or similar to those for nuclear power reactors, they are applied in accordance with the potential hazards associated with the reactor by means of a graded approach.

The key principle that the intended terrestrial NTER testing installation will have to conform with is the general concept of defence in depth, applied to all safety related activities: organizational, behavioural or design related. Application of the concept of defence in depth throughout design and operation provides a graded protection against a wide variety of transients, anticipated operational occurrences and accidents.

The key mechanism for the assessment of the safety of such installation is a safety analysis which needs to include all planned normal operational modes of the nuclear installation and its performance in anticipated operational occurrences, design basis accident conditions and event sequences that may lead to beyond design base accidents. These analyses usually need to be independently assessed by the operating organization and by the regulatory body.

Technically, the defence in depth approach includes also the three basic safety functions mentioned, which can be summarized as 1. shutting down the reactor, 2. cooling, in particular the reactor core, and 3. confining radioactive material. These are usually fulfilled by incorporating into the design an appropriate combination of inherent and passive safety features, safety systems and engineered safety features, and by applying administrative procedures over the lifetime of the reactor (e.g. the appropriate choice of materials and geometries to provide prompt negative coefficients of reactivity). Even though NTER firing times are planned to be relatively short in time, these requirements will still likely shape some of the designs of the ground testing as well as possibly the reactor design itself.

Conclusions

Human far space exploration constitutes a challenge, which is commensurate only with global cooperation. The Nuclear Thermal Electric Rocket engine proposed in this perspective may potentially be a technical enabler for a manned exploration mission to Mars as well as other farther exploration missions

This propulsion concept is offered to be deeper investigated at worldwide Agencies level in order to assess its benefits as compared to other propulsion options.

Worldwide know-how and technologies will be needed to contribute to the development of a manned interplanetary propulsion system, but except for the nuclear core itself, many of the technologies relevant to the NTER concept are readily available in Europe.

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