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Review of Nuclear Thermal Propulsion Systems

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ABSTRACT

This article offers a summary of past efforts in the development of Nuclear Thermal Propulsion systems for space transportation. First, the generic principle of thermal propulsion is outlined: a propellant is directly heated by a power source prior to being expanded which creates a thrusting force on the rocket. This enables deriving a motivation for the use of Nuclear Thermal Propulsion (NTP) relying on nuclear power sources.

Then, a summary of major families of NTP systems is established on the basis of a literature survey. These families are distinguished by the nature of their power source, the most important being systems with radioisotope, fission, and fusion cores. Concepts proposing to harness the annihilation of matter and anti-matter are only touched briefly due to their limited maturity. For each family, an overview of physical fundamentals, technical concepts, and – if available – tested engines' propulsion parameters is given.

Contents

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1. Introduction

It remains one of mankind's unresolved projects to develop the solar system sustainably. This is requiring transportation in both an efficient and a timely manner between Earth and interesting destinations in the solar system, such as Mars or the Jovian system or many others [1,2]. The limited access even to the closest planets arises from the limited technical abilities especially in the field of propulsion, which is intuitively known for conventional launchers [3]. Even when it comes to interplanetary transfer, present day's propulsion systems' characteristically low performance restricts missions by forcing prohibitively long voyage durations. The engineering objective in advancing existing mass ejection propulsion systems can be identified performing analyses and optimisation, such as proposed in References [4,5]. The considerations therein substantiate an overall benefit of raising the specific impulse. However, it also emanates from these references that this has to be tuned with the acceleration of the system and its masses and respective efficiencies. A derivation outlined in Section 2 reveals that a significant augmentation of propulsion abilities requires a relevant increase of mass specific power, which can thus be identified as the decisive system parameter.

This review focusses on Thermal Propulsion (TP) which has principally better overall efficiencies and higher system mass specific power for the same energy source due to the omission of one stage of conversion systematically proper to Electrical Propulsion (EP) [5]. With the motivation to provide highest mass specific energy sources, nuclear ones can be discerned as the most promising for thermal propulsion concepts, consequently called Nuclear Thermal Propulsion (NTP). This is summarised in Table 1 which is showing mass specific energy and power at atomic level. The rationale to do so consists in finding a common ranking, as technical data not only varies by system architecture but also by scaling, i.e. the proportion of a large plant's subsystem may be less important than of a small one.

Among nuclear power sources, radioactive decay is the least yielding. Concepts based on this process are discussed in Section 3. The power released by fission is about two orders of magnitude larger. Fission systems are presented in Section 4. While these two processes are already technically available, fusion, which is another order of magnitude more powerful than fission, still remains a technical challenge. Fusion propulsion systems are introduced in Section 5. A special role is occupied by matter–antimatter-annihilation, which is not available as a primary energy source, but as a storage. The respective propulsions concepts have remained the least mature among the considered ones and are thus only touched in Section 6.

Apart from this, the article summarises both disruptive and advanced systems. Disruptive innovations arise from existing technologies and may enable hitherto unexpected applications, resulting in the replacement of previously dominating technologies. For example, fission thrusters like NERVA (see Section 4.3) permit new, more cost-effective, and flexible mission profiles unachievable by established chemical thrusters. While this application is unprecedented in space transportation, NERVA's technology has undergone extensive development and even ground testing. In contrast, Nuclear Fusion Thermal Propulsion is an advanced concept for relying on a power generation process which is not yet fully technically available. Nevertheless, once established – which may be expected during the next two decades [6] – it may disrupt space transportation significantly, likely entailing an even more thorough paradigm shift of mission architecture and spacecraft design. Most NTP concepts presented in this review range between these two extremes.

Table 1
Power generation process by yield.

Energy source	Mass specific energy (kJ/kg)	Mass specific power (kW/kg)
Matter–antimatter-annihilation	ca. 8×10^{13}	ca. 2×10^{13}
Nuclear fusion	ca. 4×10^{11}	ca. 10^{11}
Nuclear fission	ca. 8×10^{10}	ca. 2×10^{10}
Radioactive decay	2×10^{8}–3×10^{9}	7×10^{6}–7×10^{8}
Chemical sources	4×10^{2}–2×10^{4}	2×10^{1}–10^{3}
Classical physical sources	4×10^{-2}–5×10^{5}	10^{-1}–10^{4}

2. Thermal Propulsion Overview

The term *Thermal Propulsion* describes a family of Newtonian Reaction Engines for propulsion in space. Their working principle is based upon the conservation of momentum. In the case of time variant system mass, they are commonly called *rockets*. A rocket is accelerated in one direction by ejecting a propellant in the opposite one with an exhaust velocity which is depending on the energy fed into the propellant and its molecular mass [3]. In the case of thermal propulsion, this consists in heat emerging from any given source of power, for example solar power collected from Sun's radiation, or chemical power yielded by combustion, or nuclear sources. This article reviews a variety of concepts using the four major nuclear processes [7,8], i.e.

- radioactive decay,
- induced nuclear fission,
- nuclear fusion and
- matter–antimatter-annihilation

as a thermal source. A fifth process based on nuclear isomers [9] is not considered. This classification of Nuclear Thermal Propulsion (NTP) is shown in Fig. 1.

A system draft of an NTP system is shown in Fig. 2: an NTP system consists of a nuclear power source – called (nuclear) core in this article – a heat exchange system in which the heat yield of the core is fed to a medium acting as a coolant to the core before being ejected as a propellant through a suitable nozzle [10–12]. This synergistic use of a working medium is called regenerative cooling [3]. Generalised provision cycles for the working medium are presented in the same reference. In a generalised view, these subsystems are so far similar to those of other thermal propulsion systems. Other than that, NTP systems systematically require a radiation shield [7,8,12] due to the core's expected radioactivity. For a potential crew, elevated doses of radiation constitute an important health risk, and, notably if the radiation contains neutrons, the vessel's hardware may suffer from activation. The latter phenomenon is encountered when the radiation physically changes atoms in the material out of which the hardware is built. The changed atoms may be unstable isotopes and emit secondary radiation, noxious on its own turn. Finally, activation also affects the chemistry of the material and thus its properties like the mechanical resistance. The detrimental effects of radiation may be addressed by appropriate shielding which can consist of a radiation attenuating material or increased distance or both [8,12].

As in every spacecraft, a heat flux sink needs to be implemented to deal with the waste heat. In the case of NTP, the size of such a subsystem will be considerable. Especially in highly performing systems the waste heat may be immense even despite high efficiency due to the overwhelming power release from the core. This can be made tangible by assuming a general efficiency of 90% and comparing the remaining 10% waste heat of a 1 kW_{th} Solar Thermal Thruster with that of a 100 kW_{th} Nuclear Thermal