# NUCLEAR THERMAL PROPULSION/ THERMAL POWER PROCESSING UNIT REPORT

Prepared by R. A. Gabrielli (IRS)
A. Boxberger (IRS)
G. Herdrich (IRS)

Agreed by G. Herdrich

Approved by S. Fasoulas (IRS)
G. Herdrich

Authorized by C. Koppel (KCI) 07/09/2012

EC Approval

Date: 07/09/2012

*Traceability File name:*
DiPoP-IRS-RP-003 D23.3 Nuclear Thermal Propulsion TPPU06 PCS

SEVENTH FRAMEWORK PROGRAMME

# Distribution List

| DISTRIBUTION | Type |
|---|---|
| Research Executive Agency<br>*Mrs. Gabriella Soos/ Mrs. Paula Mota Alves* | Electronic SESAM |
| | |
| KopooS Consulting Ind.<br>*Mr. C. R. Koppel* | ftp.dipop.eu/DiPoP1/ProjectDocumentsReleased |
| Space Enterprise Partnerships<br>*Mr. R. Blott* | ftp.dipop.eu/DiPoP1/ProjectDocumentsReleased |
| D.L.R.<br>*Mr. F. Jansen* | ftp.dipop.eu/DiPoP1/ProjectDocumentsReleased |
| University Stuttgart<br>*Mr. G. Herdrich* | ftp.dipop.eu/DiPoP1/ProjectDocumentsReleased |
| C.A.U.<br>*Mr. H. Kersten* | ftp.dipop.eu/DiPoP1/ProjectDocumentsReleased |
| ISIS- RD<br>*Mr. C. Ferrari* | ftp.dipop.eu/DiPoP1/ProjectDocumentsReleased |

# Document Change Record

| Issue | Date | Page and / or Paragraph affected |
|---|---|---|
| 01 | 2/4/2012 – 12/4/2012 | New document: Draft |
| 02 | 16/4/2012 – 23/4/2012 | Second Draft |
| 03 | 2/5/2012 – 21/5/2012 | Third Draft |
| 04 | 1/6/2012 – 2/6/2012 | Final |
| 05 | 5/6/2012 – 15/6/2012 | First Revision |
| 06 | 07/09/2012 | Update, see revision marks<br>Use of Power conversion system (PCS) instead of Thermal power processing unit |

| AUTHORS | ORGANIZATIONS | ADDRESSES |
|---|---|---|
| R. A. Gabrielli (USTUTT IRS)<br>G. Herdrich (USTUTT IRS)<br>S. Fasoulas (USTUTT IRS) | IRS, University of Stuttgart | Pfaffenwaldring 29<br>70569 Stuttgart, Germany<br>Phone: +49 711 685 62412 -<br>Fax: +49 711 685 63596 |



| TITLE | | CI CHECKED: |
|---|---|---|
| | **Nuclear Thermal Propulsion /<br>Thermal Power Processing Unit Report** | **YES** NO |

| CODE | TYPE OF DOCUMENT | TIME COVERED | ISSUE DATE |
|---|---|---|---|
| DiPoP-IRS-RP-003 D23.3 Nuclear Thermal Propulsion TPPU06 PCS | Deliverable | | 07.09.2012 |

| PROGRAMME | | TITLE | FUNDING ORGANIZATION |
|---|---|---|---|
| **YES** | NO | Seventh Framework Programme | European Commission |

| PROGRAMME ELEMENT | | TITLE | FUNDING ORGANIZATION |
|---|---|---|---|
| **YES** | NO | DiPoP<br>Disruptive Technologies For Space Power And Propulsion | European Commission |

| MONITORING PERSON | CONTRACT No. | ADDRESS |
|---|---|---|
| Ms. Gabriella Soos<br>Mrs. Paula Mota Alves | 284081 | European Commission<br>DG Enterprises and Industry<br>Space Research and Development<br>Brussels – Belgium |

ABSTRACT

A brief overview on thermal propulsion is offered to give a motivation and to ease the understanding of Nuclear Thermal Propulsion (NTP). Then, a summary about major families of NTP encompassing systems with radioisotope, fission and fusion cores is given. Each subtopic offers a wide spread overview about the respective theory, the concepts (solid, liquid and gaseous), tested engines and their propulsion parameters if available. The last chapter gives an overview on thermal heat management in NTP, the Power conversion system.

This document provides a wide overview on NTP concepts and basic information on Power conversion systems.

KEY WORDS: DiPoP, Advanced Space Propulsion, Nuclear Rockets, Nuclear Thermal Propulsion, Nuclear Power, Heat Management, Review, Overview

AVAILABILITY

( X ) Approved for public release; distribution is UNLIMITED

(   ) Approved for LIMITED distribution; no part of this document can be disclosed to third parties without written permission

(   ) CLASSIFIED document for internal use only; no part of this document can be disclosed outside the company

## Table of content

## Table of figures

## Table of tables

# Reference documentation:


| | |
|---|---|
| [R 1] | FP7-SPACE-2011-284081 Grant agreement core; annex I DOW; annex II;…. signed 18/10/2011 |
| [R 2] | **www.DiPoP.eu** |
| [R 3] | **Boxberger, A., Lau, M., Le, Q. H., Syring, C., Wollenhaupt, B., Gabrielli, R.A. and Herdrich, G.**, Advanced Propulsion Systems Engineering Report, Disruptive Technologies For Space Power And Propulsion (DiPoP) Consortium, Deliverable D23.1, Report to the European Comission, Contract No. 284081, Stuttgart, Germany, 2012. |
| [R 4] | **Blott, R. and Valentian, D.**, Nuclear Electric Propulsion/ Power Processing Unit Report, Disruptive Technologies For Space Power And Propulsion (DiPoP) Consortium, Deliverable D23.2, Report to the European Comission, Contract No. 284081, Eastergate, UK, Paris, France, 2012. |
| [R 5] | **Zubrin, R.**, "Entering Space – Creating A Spacefaring Civilization", J. P. Tarcher/Putnam, New York, 2000. |
| [R 6] | **Shepherd, D.**, Aerospace Propulsion, American Elsevier Publishing Company Inc. New York, London, Amsterdam, 1972. |
| [R 7] | **Auweter-Kurtz, M.** Lichtbogenantriebe für Weltraumaufgaben; B. G. Teubner Verlag. Stuttgart 1992. |
| [R 8] | **International Thermonuclear Experimental Reactor**, ITER, Technical Basis: Plant Description Document, ITER EDA Documentation Series, International Atomic Energy Agency, Vienna, Austria, 2002. |
| [R 9] | **Messerschmid, E. and Fasoulas, S.**, Raumfahrtsysteme - Eine Einführung mit Übungen und Lösungen, Springer, Berlin, Heidelberg, 2004, (in German). |
| [R 10] | **Paus, H. J.**, Physik in Experimenten und Beispielen, Carl Hanser Verlag, München, Wien 2002, (in German). |
| [R 11] | **Bethge, K., Walter, G. and Wiedemann, B.**, Kernphysik - Eine Einführung, Springer, Berlin, Heidelberg, 2008, (in German). |
| [R 12] | **Ross, G. C., McQueen, H. S.**, Nuclear Rocket Propulsion, in: **Loh, W.H. (ed.)**, Jet, Rocket, Nuclear, Ion and Electric Propulsion: Theory and Design, Springer Verlag, Berlin 1968. |
| [R 13] | **Frisbee, R. H.**, Advanced Space Propulsion for the 21st Century, Journal of Propulsion and Power, Vol. 19, No. 6, November – December 2003. |
| [R 14] | **Clark, J. S., Borowski, S. K., McIlwain, M. C., and Pellaccio, D. G.**, Nuclear Thermal Propulsion Transportation Systems for Lunar/Mars Exploration, NASA Technical Memorandum 105870, Nuclear Power Engineering in Space-Nuclear Rocket Engines, Conference sponsored by the Research and Production Association "LUCH", Semipalatinsk, Kazakhstan, September, 1992. |
| [R 15] | **Herdrich, G., Bauder, U., Boxberger, A., Gabrielli, R.A., Lau, M., Petkow, D., Pfeiffer,M., Syring, C. and Fasoulas, S.**, Advanced Plasma (Propulsion) Concepts at IRS, Vacuum Journal, in press, 2012. |
| [R 16] | **Esnault-Pelterie, R.**, Considérations sur les résultats d'un allégement indéfini des moteurs," Journal de Physique Théorique et Appliquée, Vol.3, No.1 , 1913, pp. 218 - 230, Communication faite à la Société française de Physique : Séance du 15 novembre 1912 (in French). |
| [R 17] | **Romero, J.B.**, Potentialities of Radioisotope Propulsion for Space Probes, AIAA J. Spacecraft Vol.3 No. 4, pp 570-576, 1966. |
| [R 18] | **MacKay, J. S.**, An Evaluation Of Some Special Techniques For Nuclear Waste Disposal In Space, NASA Technical Memorandum NASA TM X-62,272, Ames Research Center, Moffett Field, California, USA 1973. |
| [R 19] | **King, M., Simms, R. and Stansel, J. C.**, Radioisotope Propulsion Technology Program (POODLE) – Final Report. Volume VI – POODLE Systems Analyses, TRW Systems Group, Contract No. AT (04-3) - 517, April 1967. |
| [R 20] | **Rom, F. E.**, Nuclear-Rocket Propulsion, NASA Technical Memorandum NASA TM X-1685, National Aeronautics and Space Administration, Washington D. C., USA, November 1968. |
| [R 21] | **IAEA**, The Role Of Nuclear Power And Nuclear Propulsion In The Peaceful Exploration Of Space, International Atomic Energy Agency Vienna, Austria, 2005. |
| [R 22] | **Borowski, S. K.**, Robotic Planetary Science Missions Enabled With Small NTR Engine / Stage Technologies, NASA Technical Memorandum 107094, 12th Symposium on Space Nuclear Power and Propulsion cosponsored by BMDO, NASA, DOE and USAF, Albuquerque, New Mexico, January 1995. |
| [R 23] | **Space Nuclear Propulsion Office – Cleveland Extension**, Phoebus-2 Nozzle Design Program Preliminary Design Phase Summary Report (Vol. I), Report No. RP-SR-0001, Contract SNPC-35, Aerojet General Corporation, National Aeronautics and Space Administration, Cleveland, Ohio, USA, August 1965. |
| [R 24] | **Altseimer, J.**, Summary of Nuclear Propulsion Applicability, Note, NASA 1971. |
| [R 25] | **Angelo, J. A. und Buden, D.** Space Nuclear Power; Orbit Book Company. Malabar 1985. |
| [R 26] | **Walton, J. T.** An Overview of Tested and Analyzed NTP Concepts; AIAA. 91-3503. 1991. |
| [R 27] | **IAEA**, Thorium fuel cycle – Potential benefits and challenges, IAEA-TECDOC-1450 International Atomic Energy Agency Vienna, Austria, 2005. |

| | |
|---|---|
| [R 28] | **Bhat, M.R., Kaiser, R.E., Carpenter, S. G., Reich, C.W., Leonard, B.R., Kottwitz, D.A., Thompson, J.K., Smith, J.R. Young, R.C., Moore, M.S., Poenitz, W.P., Hunter, R.E., Stewart L. and Hirons, T. J.**, Fission Crossection Data, MAT 9228, Revision 1, ENDF-6, IAEA, 1977, 1980. |
| [R 29] | **Zubrin, R.**, Nuclear Salt Water Rockets: Hight Thrust at 10000 Sec ISP, Journal of The British Interplanetary Society, Vol. 44, pp. 371 – 376, 1991. |
| [R 30] | **Robbins, W. H. and Finger, H. B.**, An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program, NASA Contractor Report 187154, AIAA-91-3451, National Aeronautics and Space Administration, Washington D. C., USA, July 1991. |
| [R 31] | **El-Genk, M. S.** Pellet Bed Reactor for Nuclear Propelled Vehicles: Pt. 1 - Reactor Technology; NASA Conference Publication 10079 Nuclear Thermal Propulsion. Cleveland 1991. |
| [R 32] | **Haloulakas, V. E.** Pellet Bed Reactor for Nuclear Propelled Vehicles, II.; NASA Conference Publication 10079 Nuclear Thermal Propulsion. Cleveland 1991. |
| [R 33] | **National Aeronautics and Space Administration, Lewis Research Center**, 21000 Brookpark Road, Cleveland, Ohio, 44135, *Press Release* for Friday, January 5, 1973, 4:00 p.m., announced by Bruce T. Lundin, Director |
| [R 34] | **Bowles, M. D. and Arrighi, R. S.**, NASA's Nuclear Frontier – The Plum Brook Reactor Facility, 1941-2002, NASA History Division, Office of External Relations, NASA Headquarters, Washington D.C., Monographs in Aerospace History Series, No. 33, August 2004 (NASA SP; 2004-4533). |
| [R 35] | **Parsley, R. C.**, Advanced Propulsion Engine Assessment based on a Cermet Reactor, Slides, Pratt & Whitney, Nuclear Propulsion TIM, October, 1992 |
| [R 36] | **Wetch, J. R., Goldin, A. Ya. und Koroteev, A. A.** Development of Nuclear Rocket Engines in the USSR; AIAA 91-3648. 1991. |
| [R 37] | **Marshall, A.C.**, An Assessment of Reactor Types for Thermochemical Hydrogen Production, Sandia Report SAND 2002-0513, Advanced Nuclear Concepts Department, Sandia National LaboratoriesAlbuquerque, New Mexico, USA, 2002. |
| [R 38] | **Barton, D. M. und Rutherford, D. A.**, A Critical Assembly to Demonstrate the Confinement of a Fissioning UF6 Gas in an Argon Vortex; AIAA 91-3501. 1991. |
| [R 39] | **McLafferty, G. H.** Gas Core Nuclear Rockets; Aerospace Nuclear Applications Proceedings. Huntsville 1970. |
| [R 40] | **Diaz, N. J., et al.**, Gas Core Reactor Concepts and Technology: Issues and Baseline Strategy: AIAA 91-3582. 1991. |
| [R 41] | **Howe, S. D.** Nuclear Rockets to Mars; Aerospace America, pp 39-43. August 2000. |
| [R 42] | **Latham, T.**, Nuclear Light Bulb; NASA Conference Publication 10079 Nuclear Thermal Propulsion. Cleveland 1991**.** |
| [R 43] | **General Dynamics Corp., General Atomics Division**, Nuclear Pulse Vehicle Study Condensed Summary Report, NASA Contract NAS 8-11053, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, USA, January 1964. |
| [R 44] | **General Dynamics Corp., General Atomics Division**, Nuclear Pulse Vehicle Study: Vol. I – Summary, NASA Contract NAS 8-11053, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, USA, September 1964. |
| [R 45] | **General Dynamics Corp., General Atomics Division**, Nuclear Pulse Vehicle Study: Vol. III – Conceptual Vehicle Designs and Operational Systems, NASA Contract NAS 8-11053, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, USA, September 1964. |
| [R 46] | **General Dynamics Corp., General Atomics Division**, Nuclear Pulse Vehicle Study: Vol. IV – Mission Velocity Requirements and Systems Comparisons, NASA Contract NAS 8-11053, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, USA, February 1966. |
| [R 47] | **General Dynamics Corp., General Atomics Division**, Nuclear Pulse Vehicle Study: Vol. IV – Mission Velocity Requirements and Systems Comparisons (Supplements) NASA Contract NAS 8-11053, George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, USA, February 1966. |
| [R 48] | **Reynolds, T. W.** Effective Specific Impulse of External Nuclear Pulse Propulsion System; J. Spacecraft, Vol. 10, No. 10, pp. 629-630. October 1973. |
| [R 49] | **Reece Roth, J.**; *Introduction to Fusion Energy*, Ibis Publishing, Charlottesville, Virginia, 1986. |
| [R 50] | **Kammash T., Lee M., Galbraith D., Cassenti B., Borowski S., Bussard R., Miley G., Chiang P.-R., Satsangi A., Choi C., Cox L., Watanabe Y., Gerwin R., Zubrin R., et al.**, Fusion Energy in Space Propulsion, volume 167, AIAA - Progress in Astronautics and Aeronautics, 181 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, USA, 1995. |
| [R 51] | **Romanelli F., Bruno C., Regnoli G.**, Assessment of Open Magnetic Fusion for Space Propulsion, Ariadna Final Report 04/3102 ESTEC Contract 18853/05/NL/MV, European Space Research and Technology Centre, Noordwijk, 2004. |
| [R 52] | **Santarius J.**; Fusion space propulsion - a shorter time frame than you may think, in: JANNAF, Joint Army Navy Nasa Air Force Interagency Propulsion Committee, Monterey, 2005. |

| | |
|---|---|
| [R 53] | **Petkow D., Herdrich G., Laufer R., Gabrielli R.A., Zeile O., Röser H.-P.**; Comparative investigation of fusion reactions for space propulsion applications, Transactions of Japan Society for Aeronautical and Space Sciences, Space Technology, Japan, Vol.7 (2009) Pb 59 – Pb 63. |
| [R 54] | **Petkow, D., Gabrielli, R.A., Herdrich, G., Laufer, R., Röser, H.-P.**; Generalized Lawson criterion for magnetic fusion applications in space, Fusion Engineering and Design, Vol. 87, Issue 1, pp. 30–38, January 2012. |
| [R 55] | **Petkow, D., Gabrielli, R. A., Herdrich, G., Laufer, R., and Zeile, O.**; A Generic Model for a Transpiration Cooled Fusion Propulsion System, 27th International Symposium on Space Technology and Science, Tsukuba, Japan, 2009. |
| [R 56] | **El-Guebaly, L. and Zucchetti, M.**, Recent developments in environmental aspects of D–$^3$He fuelled fusion devices, Fusion Engineering and Design 82, pp. 351–361, 2007. |
| [R 57] | **Zucchetti, M.**, The zero-waste option for nuclear fusion reactors: Advanced fuel cycles and clearance of radioactive materials, Annals of Nuclear Energy 32, pp. 1584–1593, 2005. |
| [R 58] | **Williams, C. H., Dudzinski, L. A., Borowski, S. K. and Juhasz, A.**, Realizing "2001: A Space Odyssey": Piloted Spherical Torus Nuclear Fusion Propulsion, NASA TM-2005-213559, NASA Glenn Research Center, Cleveland, Ohio, 37th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, SAE, AIChE, and ASME, Salt Lake City, Utah, USA, March 2005. |
| [R 59] | **Kammash, T. and Lee, M.-J.,** Gasdynamic Fusion Propulsion System for Space Exploration, Journal of Propulsion and Power, Vol. 11. No. 3, pp. 544 – 553, May, June 1995. |
| [R 60] | **Kammash, T. and Galbraith, D. L.,** Improved Physics Model for the Gasdynamic Mirror Fusion Propulsion System, Journal of Propulsion and Power, Vol. 14. No. 1, pp. 24 –28, January, February 1998. |
| [R 61] | **Mallove, E. F. and Matloff, G. L.**, The Starflight Handbook: A Pioneer's Guide to Interstellar Travel, Wiley, 1989. |
| [R 62] | http://www.icarusinterstellar.org – site retrieved June, 8, 2012. |
| [R 63] | **Huber, F.**, Antimaterieantriebe für interplanetare Raumfahrtmissionen, Dissertation, Institut für Raumfahrtsysteme, Universität Stuttgart, Germany, 1994, (in German). |
| [R 64] | **Rasor, N. S.,** Thermionic Energy Conversion Plasmas, IEEE Transactions on Plasma Science, Vol. 19, No. 6, 1991. |
| [R 65] | **Paramonov, D. V. and El-Genk, M. S.,** A Review of Cesium Thermionic Converters with Developed Emitter Surfaces, Energy Convers. Mgmt Vol. 38, No. 6. pp. 533-549, 1997. |
| [R 66] | **Tanner, P.G., Fraser, D.A. and Irving, A.D.,** Developments in Thermionic Energy Converters, IEE Proc.-Sci. Meas. Technol., Vol. 152, No. 1, 2005. |
| [R 67] | **Babanin, V. I., Ender, A. Ya., Kolyshkin, N., Kuznetsov, V., Sitnov, V. and Paramonov, D. V.** Next Generation Solar Bimodal Systems. |
| [R 68] | **Bogush, I. P., Gryaznov, G. M., Zhabotinskii, E. E. et al.,** Space thermionic nuclear power system in the "Topaz" program, principles of construction and operating regimes, At. Énerg., 70, No. 4, 211–214 (1991). |

# 1. Introduction

It remains one of mankind's unresolved projects to develop the solar system sustainably. This is requiring transportation in both an economic and a timely manner between Earth and interesting destinations in the solar system, such as Mars or the Jovian system or many others [R 3, 5]. 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 launchers. 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 optimization, such as proposed in [R 6, 7]. The considerations therein substantiate an overall benefit of raising specific impulse. However, it also arises from these references that this has to be tuned with the acceleration of the system and its masses and respective efficiencies. A simple derivation outlined in section 3.1 reveals that a significant augmentation of propulsion abilities requires a relevant raise of the mass specific power, which can thus be identified as the decisive system parameter.

This report focuses 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) [R 7].

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 concentrated in Table 1 beneath which is showing mass specific energy and power at atomic level[1]. Among nuclear power sources, radioactive decay is the least yielding. Concepts based on this process are discussed in section 3.2. The power released by fission is about two orders of magnitude more important. Fission systems are presented in section 3.3. 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 3.4. A special role is occupied by matter-antimatter-annihilation, which is not available as an energy source, but as a storage. Therefore, propulsions concepts relying on antimatter are only touched in section 3.5.

| Energy source | Mass Specific Energy / kJ/kg | Mass Specific Power / kW/kg |
|---|---|---|
| **Matter-Antimatter-Annihilation** | ca. $8 \cdot 10^{13}$ | ca. $2 \cdot 10^{13}$ |
| **Nuclear Fusion** | ca. $4 \cdot 10^{11}$ | ca. $1 \cdot 10^{11}$ |
| **Nuclear Fission** | ca. $8 \cdot 10^{10}$ | ca. $2 \cdot 10^{10}$ |
| **Radioactive Decay** | $2 \cdot 10^{8}$ to $3 \cdot 10^{9}$ | $7 \cdot 10^{6}$ to $7 \cdot 10^{8}$ |
| **Chemical Sources** | $4 \cdot 10^{2}$ to $2 \cdot 10^{4}$ | $2 \cdot 10^{1}$ to $7 \cdot 10^{3}$ |
| **Classical Physical Sources** | $4 \cdot 10^{-2}$ to $5 \cdot 10^{5}$ | $1 \cdot 10^{-2}$ to $1 \cdot 10^{4}$ |

Table 1 – Power Generation Process by Yield

[1] The rationale to consider mass specific numbers at atomic level consists finding an intrinsic ranking, as technical data not only varies by system but also by scaling, i.e. a large plant is much more compact than a small one.

The report summarises both disruptive and advanced systems. The distinction consists in the readiness of the base technology. Systems like NERVA (see section 3.3.2) which have undergone extensive investigation and even on ground testing and merely lack in flight experimentation can be considered as disruptive. In contrast, Fusion Propulsion which relies on nuclear thermal fusion not yet fully technically available is considered as an advanced concept. For the latter, a decisive breakthrough can be expected for the next two decades [R 8] and thus fusion propulsion is summarised in this report.

The report also briefly covers Power conversion systems (PCS) (formerly named Thermal Power Processing Units (TPPU)) which are considered to be a vital subsystem of such a highly powerful machine. Nuclear systems always involve enormous fluxes of heat. For one, there is the rejected process heat also called *waste heat*; then the *after heat*, more specifically the heat of radioactive decay in the case of radioactive remainders. A heat sink is vital, lest the space craft would accrete the heat which causes severe risks. The PCS manages these heat fluxes and can even make them subservient.

The report closes with a brief conclusion and an evaluation matrix providing a preliminary assessment of the discussed NTP concepts.

To prevent the scope of document from becoming too narrow with respect to the surveillance of relevant technologies the reader is recommended to also refer to the set of reports developed in the total project, especially [R 3, 4].

# 2. Nuclear Thermal Propulsion Concepts

## 2.1. 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 by ejecting a propellant with an exhaust velocity which is depending on the energy fed into the propellant and the propellant's molecular mass [R 9]. In the case of thermal propulsion, this consists in heat emerging from any given source of power. For example, there is chemical power yielded by combustion; there is also solar power and many other. In this report, the options to use nuclear power sources are reviewed.

There are four major nuclear processes that can be used [R 10, 11]:

- Radioactive Decay, which feeds Radioisotope Thermal Propulsion,
- Induced Nuclear Fission,
- Nuclear Fusion and
- Matter/Antimatter Annihilation.

Propulsion concepts using these four processes as a thermal power source are subject of the present report. A fifth process based on nuclear isomers is not considered. This classification of Nuclear Thermal Propulsion (NTP) is shown in Figure 1.

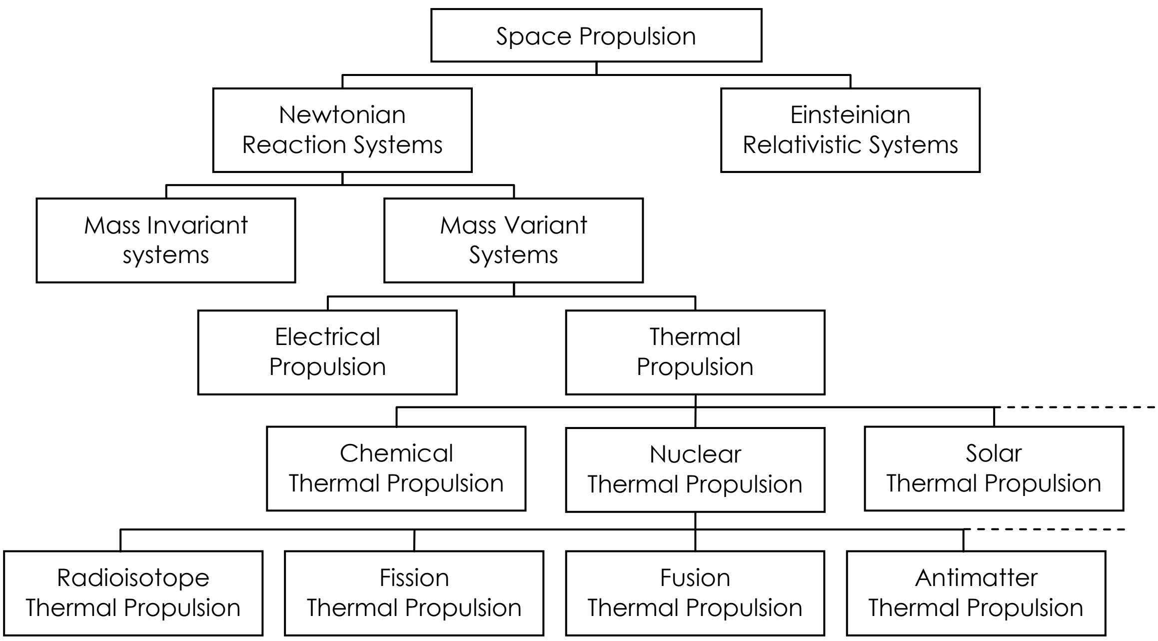


Figure 1 – Classification of space propulsion.

A system draft of an NTP is shown in Figure 2 on the next page: An NTP consists of a nuclear power source – called *(nuclear) core* in this report – 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 [R 12 – 14]. This synergetic use of a working medium is called *regenerative cooling* [R 9]. 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 systematically require a shield [R 10 – 12] due to the core's expected radioactivity that can be noxious to both the vessel's hardware and an eventual crew. For the latter, elevated doses of radiation constitute an important health risk. The hardware may suffer from activation. This phenomenon is encountered when radiation physically changes atoms in the material out of which hardware is constructed. Activation finally affects the chemistry of the material and thus its properties like the mechanic resistance. The detrimental effects of radiation may be addressed by appropriate shielding which can consist of radiation attenuating material or distance [R 11, 12]. Since there will always occur an immense flux of waste heat during propulsion – due to high mass specific power even despite high efficiency – or after-heat in *idle mode*, i.e. when no propulsion is performed, a heat flux sink needs to be implemented, called Power conversion systems (PCS). The PCS can both be employed to harvest the heat flux to generate electrical energy for the space craft, and to dump the ultimate waste heat via radiators to space.

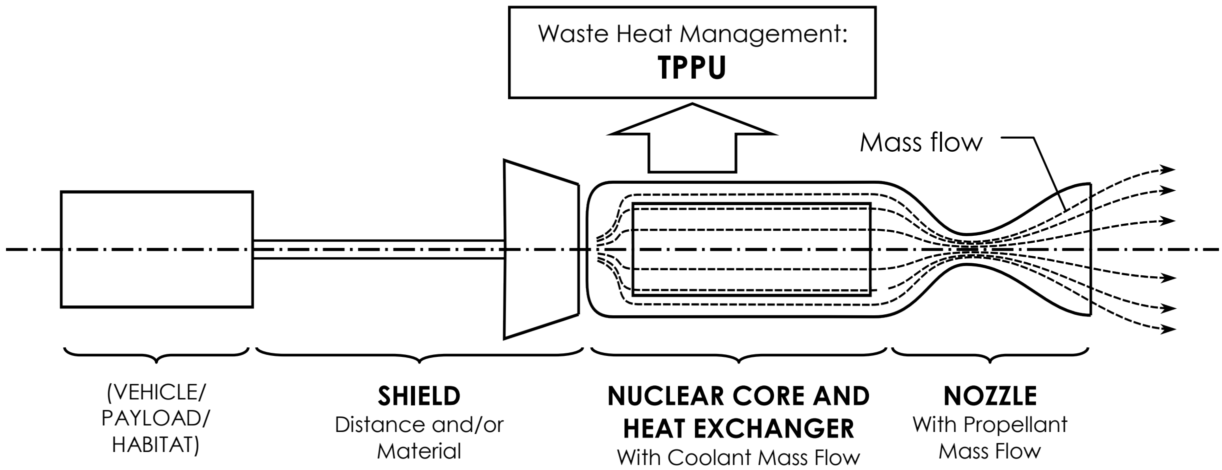


Figure 2 – Schematic presentation of Nuclear Thermal Propulsion Systems.

The basic motivation for the consideration of nuclear thermal systems consists in the eventually indefinite raise in mass specific power they can enable. The benefit of doing so can be derived from fundamental rocket equations. One important space flight parameter is the *velocity increment* $\Delta v$ [R 9]. It is characteristic for a given manoeuvre in space transferring the space craft from one trajectory to another. Usually $\Delta v$ is considered as the sum of all the mission's velocity increments. More ambitious missions generally imply larger total $\Delta v$. Thus, it defines the rockets propulsion requirements.

The velocity increment a rocket can perform is calculated with the Tsiolkovsky equation [R 9]

$$\Delta v = c_e \ln\left(\frac{m_0}{m_f}\right). \tag{1}$$

In this equation, $c_e$ is the *exhaust velocity*, $m_0$ is the initial mass of the rocket and $m_f$ is the final mass of the rocket. The difference between these masses is the propellant mass $m_p$. High $c_e$ enhances the ratio of final to initial mass and reduces $m_p$ for a given $\Delta v$. The consequences of the high $c_e$ requirement to the propellant are touched in Annex A. The Tsiolkovsky equation follows the assumptions that no external force is applied during the burn duration and that the *mass flow*

$$\dot{m} = \frac{dm}{dt} = \frac{m_p}{t_b} = \frac{m_0 - m_f}{t_b}. \quad (2)$$

remains invariant over the net burn time $t_b$. The thrust of the rocket is

$$F = \dot{m}\, c_e. \quad (3)$$

With respect to a characteristic mass $m_c$ an *acceleration*

$$a = \frac{F}{m_c} = \frac{\dot{m}\, c_e}{m_c} \quad (4)$$

is obtained. The mass specific jet power is defined

$$\alpha = \frac{P}{m_c} = \frac{\frac{1}{2}\dot{m}\, {c_e}^2}{m_c} = \frac{1}{2} a\, c_e \quad (5)$$

and can be used to identify a trade off among specific power, acceleration and exhaust velocity [R 15]. If the mass specific jet power is limited (i.e. 1/2 $a\, c_e \leq \alpha_{lim}$) – which is the case for most propulsion concepts – equation (5) reveals that either the acceleration may be raised leading to a rapid build up of $\Delta v$ and therefore eventually shorter mission time, or higher $c_{e,}$ which enables small propellant masses. To this day this trade off is severe. All state of the art propulsion systems can only provide for one of the two features. Both features can only be augmented if the power limit is raised considerably [R 15] which can be achieved in utilising nuclear power sources since the respective processes have the highest power output. Note that this is a requirement about the power, i.e. the energy yielded in a given time, and not about the energy totally contained in a source and that the latter has to be sufficient, too. The insight of space flights requirement of both an indefinite raise in power and large energy supply are rather old. French astronautics pioneer Robert Esnault-Pelterie concluded his talk from November 15, 1912:

> *« Si nous supposions maintenant un instant que nous avons à notre disposition 400 kilogrammes de radium dans notre véhicule de 1000 kilogrammes et que nous sachions en extraire l'énergie dans le temps qui nous convient, nous verrions que ces 400 kilogrammes de radium largement suffisants pour le trajet Vénus et retour, le seraient à peine pour le trajet Mars et retour […], de telle sorte qu'un réservoir d'énergie aussi formidable permettrait tout au plus à l'homme de visiter ses voisines immédiates.»*[2] *[R 16]*

This can be seen as the original idea on nuclear thermal propulsion. At the time Esnault-Pelterie made his talk, already a little was known about nuclear energy and a little was known about space flight. A chronic of the development summarising important stages is given in Table 2 on the next page.

[2] *„If we now suppose for a moment that we had 400 kg of radium available in our vehicle of about 1000 kg and that we knew how to extract this energy in the time suiting our aims, we'd see that these 400 kg of radium largely sufficient for a transfer to Venus and back and would barely be sufficient for a transfer to Mars and back […], would allow mankind to visit his next neighbours at the best.*"

| Years | in nuclear science | in space flight |
|---|---|---|
| **1896 -1901** | Henri Becquerel discovers radioactivity which is identified by the Curies to be physical. Ernest Rutherford understands the process. | Konstantin Tsiolkovsky derives the fundamental rocket equation. |
| **1905 - 1912** | Albert Einstein discovers the mass energy equivalent as an implication of relativity. | Robert Esnault-Pelterie proposes a thermonuclear rocket based on Radium. |
| **1919 - 1939** | While Rutherford achieves first nuclear reactions in the laboratory, among which DT fusion. Arthur Eddington proposes fusion as the energy source of the stars, which is supported by Hans Bethe and Carl Friedrich von Weizsäcker. | Robert Goddard and Hermann Oberth work on the advancement of spaceflight. Experimentation is put forward by Wernher von Braun. |
| **1942 - 1946** | Enrico Fermi's Chicago-Pile-1 is the first fission reactor. The team of the Manhattan Project uses fission as a weapon. | Von Braun develops A4 which became the forebear of later launchers. |
| **1946 - 1957** | Hydrogen bomb is developed. John Lawson proposes a fusion criterion for thermal fusion in terrestrial fusion reactors. Lev Artsimovich and his team propose the Tokamak design. | A series of articles on nuclear rockets appear in the Journal of the British Interplanetary Society. Sputnik is the first artificial satellite launched into lower Earth orbit. |
| **1961 - 1972** | Fission power is developed as a source for terrestrial power. | Yuri Gagarin is the first man in space. Manned spaceflight culminates in the Apollo program. NERVA engine developed and tested. |
| **1973 - 1985** | France has its first Tokamak experiment, the TFR (Tokamak de Fontenay-aux-Roses). JET (Joint European Torus) is installed in Britain. Beginning of ITER. | Project Daedalus presented in the Journal of the British Interplanetary Society as a concept of an interstellar probe propelled by fusion. |
| **1986 - 2005** | The Chernobyl disaster reveals the risks of fission technology. | Age of space stations: MIR, ISS. Nuclear power in Space is discussed as a part of the Strategic Defense initiative. |
| **2006 – 2012** | Renaissance of terrestrial nuclear power. Fukushima Daiichi nuclear disaster. | Renaissance of nuclear projects for space |

Table 2 – History of nuclear science and space flight [R 9, 11, 13].

# 2.2. Radioisotope Heated Thermal Propulsion

## 2.2.1. General Concept and Radioisotope Physics

Radioisotope Heated Thermal Propulsion (RHTP) [R 12, 17] systems use the heat from nuclear decay of radioactive isotopes to heat the propellant according to the general concept in Figure 2.

Atoms' cores are composed of *nucleons* i.e. neutrons and protons and there are as many electrons attributed to the atoms as there are protons in the core. Their number therefore characterising the chemistry of these atoms and all atoms containing the same number of protons are called isotopes. If there are too few or too many neutrons in the core of an isotope it will be unstable and *transmute* – i.e. change physically – into a more stable isotope with a certain probability over time. This process is called *radioactive decay*, proceeds exponentially and removes energy from the atom by the means of radiation. There are four types of radiation [R 10, 11]:

- **Alpha radiation**, which removes four nucleons forming an helium-core consisting of two protons and two neutrons, which has low shielding requirements
- **Beta radiation**, which may be an electron or a positron, which is the same mass with an opposite charge. Electrons come from a neutron transmuting into a proton. Positrons appear if a proton is changed into a neutron, which has medium shielding requirements
- **Gamma radiation**, which is a highly energetic photon from a core relaxation, which has high shielding requirements
- **Neutron radiation**, which consists in the core's loss of a neutron, which has high shielding requirements and which risks the space craft's activation.

In many cases, the first decay does not yield a stable isotope so that a chain of decays ensues. The process is statistical for an individual atom [R 10, 11]. The average lifetime of the process is noted $\tau$. The amount of remaining radioactive atoms as a function of time $t$ is

$$N(t) = N_0 e^{\left(-\frac{t}{\tau}\right)} = N_0 e^{(-\lambda t)} = N_0 e^{\left(-\frac{\ln(2) t}{\tau_H}\right)} \quad (6)$$

in which $1/\tau$ has been replaced by the decay constant $\lambda$. For tangibility, the half time $\tau_H = \tau/\ln(2)$ is used, which is the time when half of the initial amount $N_0$ has decayed. The activity

$$A(t) = -\frac{dN(t)}{dt} = \lambda N(t) = \dot{n}(t) \quad (7)$$

is the rate of decays per second as a function of time. Since energy is yielded with each decay – in average $E$ – we obtain from that a decay power as a function of time

$$P(t) = E\,\dot{n}(t) = P_0 e^{(-\lambda t)} \quad (8)$$

with the initial power $P_0$. The power is directly proportional to the average energy yield and higher if the average life time of the isotope is shorter. However, the power will decay exponentially, too, which will reduce the thrusters performance, eventually. The latter is characterised by the thrust as a function of time

$$F(t) = F_0 e^{(-\lambda t)} \quad (9)$$

supposing time invariant exhaust velocity $c_e$. In this case, the mass specific thrust is ideally

$$\frac{F(t)}{m(t)} = \frac{F_0 e^{(-\lambda t)}}{m_0 - m_f(t)} = \frac{F_0 e^{(-\lambda t)}}{m_0 - \frac{F_0}{c_e \lambda}\left(1 - e^{(-\lambda t)}\right)} \quad (10)$$

with $m_f(t)$ the used fuel mass as a function of time. An exemplary evaluation with a given constant $c_e$ of 8000 m/s an initial thrust of 100 N and an initial space craft mass $m_0$ of 10000 kg is shown in Figure 3.

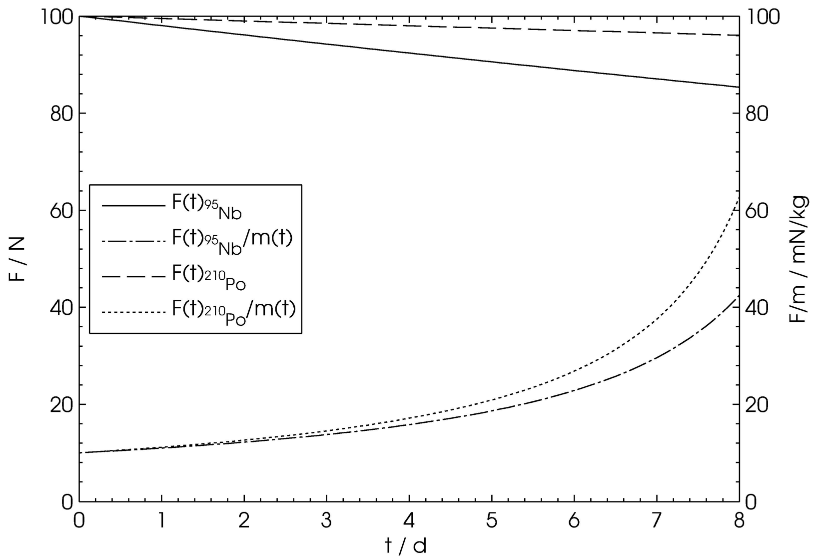


Figure 3 – Exemplary development of thrust and mass specific thrust as a function of time. Isotopes: Niobium 95 and Polonium 210; $m_0$ = 10000 kg; $c_e$ = 8000 m/s; $F_0$ = 100 N

The considered isotopes are the rather short lived Niobium 95 (95Nb) with a half life of 35 days and Polonium 210 (210Po) with a half life of 138 days. Niobium 95 is available as nuclear waste from terrestrial fission reactors but difficult to handle, due to its high activity and energy yield as gamma radiation. Polonium 210 on the other hand is best suited for isotope rockets but has to be bred on purpose [R 11, 12]. It can be seen from the graph that the characteristic acceleration is rising rapidly while the thrust is decaying only slightly during a few days for both isotopes. Yet, one has to recall that the thrust is directly proportional to the decay and that therefore, the thrust will have halved in 35 days for Niobium 95 and in 138 days for Polonium which are relatively small timeframes during the preparation of a space flight mission. The amount of the radioisotope needs therefore to be matched for the expected moment of ignition. Above that, it will yield heat that needs to be dealt with since it could thermally degrade the systems hardware. Another issue is the type of radiation yielded. Gamma radiation released by Niobium 95 demands massive shields to damp the dose. Polonium 210 however, is radiating purely helium cores. Another important isotope is Plutonium 238. An overview of considered radioisotopes is given in Table 3. It has also been proposed to use the system to recycle nuclear waste from fission plants [R 18].

From such system oriented considerations, it is possible to derive some technical radioisotope selection criteria for RHTP systems which are similar to the criteria for Radioisotope Thermal Generators (RTG). They group as follows and lead to the necessity of tradeoffs:

- **Propulsion criteria**
  - Low thrust variation, thus long half life
  - High energy yield, thus short half life or large $E$
  - Efficient power transfer to coolant/propellant:
    high cross section in medium, short thermalisation reach, thus alpha radiation
  - Mass specific thrust parameters: light weight of system, thus alpha radiation

- **Chemical safety criteria**
  - Crew/technician safety: substance non poisonous
  - Material safety: substance non corrosive
  - Space craft safety: decay products chemically safe
- **Physical safety criteria**
  - Crew/technician safety: radioactivity limited or well shielded
  - Material safety: limited yield of power, must withstand lack of cooling
  - Space craft safety: decay products lowly radioactive
- **Economic considerations / synergies**
  - ... use as an RHU (radioisotope heating unit) after propulsion use
  - Availability of radioisotope and
  - Cost of processing and handling

| Radioisotope | | $^{60}Co$ | $^{90}Sr$ | $^{106}Ru$ | $^{137}Cs$ | $^{144}Ce$ | $^{147}Pm$ | $^{170}Tm$ | $^{210}Po$ | $^{238}Pu$ | $^{242}Cm$ | $^{244}Cm$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\tau_H$ / a | | 5.3 | 27.7 | 1.0 | 30 | 0.75 | 2,6 | 0.35 | 0.38 | 86 | 0.45 | 18 |
| E / MeV | α | - | - | - | - | - | - | - | 5.3 | 5.49 | 6.11 | 5.8 |
| | β | 0.31 | 2.24 | | 0.53 | 1.32 | 0.22 | 0.96 | | | | |
| | γ | 1.17 | 1.73 | | 0.66 | 2.18 | 0.12 | 0.08 | 0.8 | 0.04 | 0.04 | 0.04 |
| Appearance | | Metal | $SrTiO_3$ | Metal | CsCl | $CeO_2$ | $Pm_2O_3$ | $Tm_2O_3$ | GdPo | $PuO_2$ | $Cm_2O_3$ | $Cm_2O_3$ |
| ρ / g/cm³ | | 8.7 | 3.7 | 12.2 | 3.6 | 6.6 | 6.6 | 8.5 | 9.9 | 10 | 9 | 9 |
| $\alpha_m$ / W/g | | 17.4 | 0.95 | 33.1 | 0.42 | 25.6 | 0.33 | 12 | 79.5 | 0.56 | 120 | 2.65 |
| $\alpha_V$ / W/cm³ | | 15.2 | 0.94 | 13.4 | 0.42 | 25.3 | 0.8 | 9.1 | 815 | 3.9 | 882 | 20.4 |
| Purity (%) | | 10 | 50 | 3.3 | 35 | 18 | 95 | 10 | 95 | 80 | 90 | 95 |
| A/P / Ci/W | | 65 | 148 | 102 | 207 | 126 | 2788 | 500 | 32 | 30 | 28 | 29 |
| *Shielding Req.* | | heavy | heavy | heavy | heavy | heavy | low | med. | low | low | low | med. |
| $T_{Melt}$ / °C | | 1480 | 1900 | 2450 | 646 | 2680 | 2270 | 2300 | 1675 | 2280 | 1950 | 1950 |

Table 3 – Overview on radioisotopes proposed for RHTP systems.

### 2.2.2. Solid Designs

The most intuitive design for an RHTP is a solid system [R 12, 17, 18]. The radioisotope is a solid encapsulated in a containment and transferring heat to the coolant/propellant through conduction, heat radiation or direct (radioactive) radiation. There are four major architectures to realise such a system and categorised through the cooling approach.

*Passive cooling* RHTP [R 17] are the simplest architecture and shown in Figure 4 on the next page. The radioisotope core is placed in a heat exchanger through which coolant/propellant streams in case of propulsion. The architecture relies upon a sufficient emission of heat radiation to the surrounding if no working medium is streamed along the radioisotope core, i.e. in *idle mode*. The concept is limited by the heat loads the material can sustain without softening or melting.

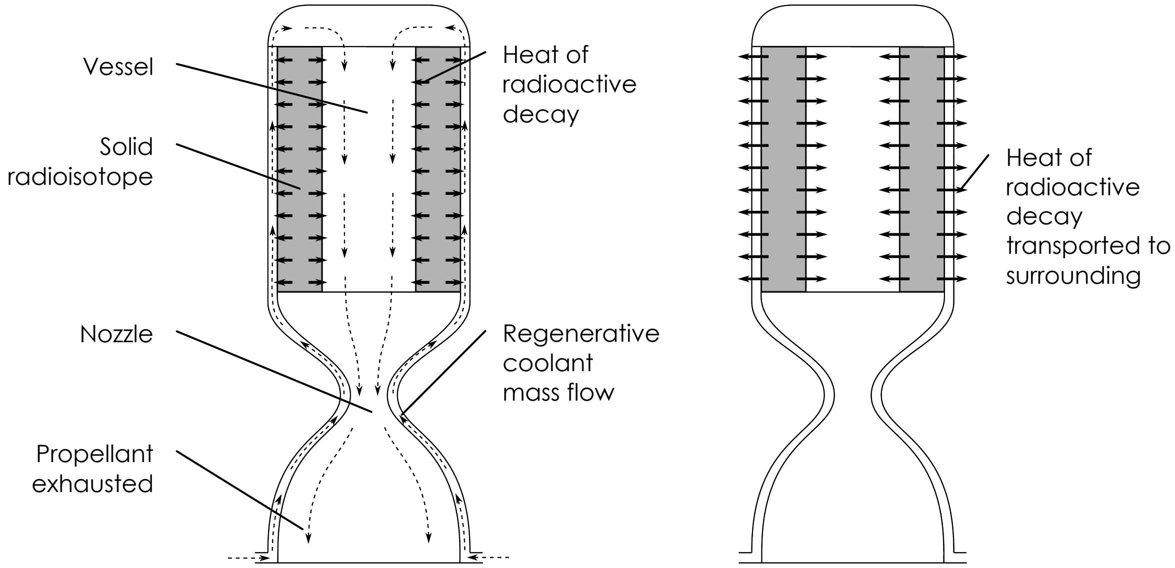


Figure 4 – Schematic draft of a solid core RHTP with passive cooling in idle mode.

This limitation can be responded to by providing sufficient cooling throughout the whole life cycle of the RHTP, e.g. through *active cooling*. A respective architecture is drafted in Figure 5. While the system is very similar to the basic passively cooled one during propulsion, a supplementary coolant is used to mitigate waste heat in idle mode and will transport it to system heat sinks such as radiators or storage devices. For example, this is necessary prior to the space craft's launch and can be provided by a water cycle transporting the heat into e.g. ground. During launch, a fraction of the launch engine propellant mass flow can be diverted through the RHTP. While cooling the latter, this mass flow can be preheated and enhance the launch engine efficiency. In space, the additional coolant can dump the waste heat through deployed radiators.

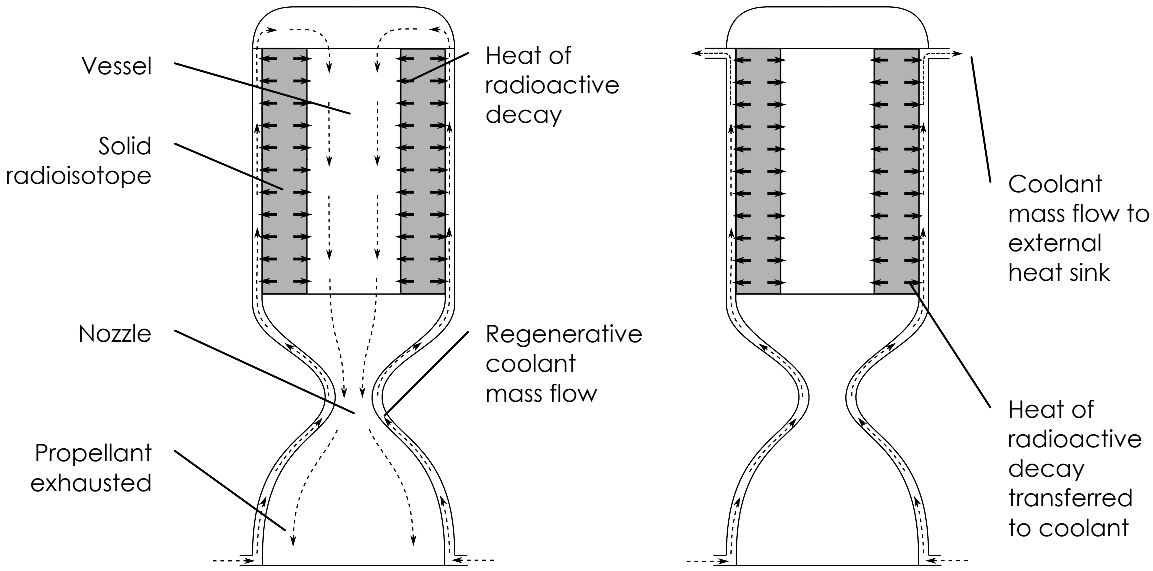


Figure 5 – Schematic draft of a solid core RHTP with active cooling in idle mode [R 16].

Other than mitigating heat loads through a coolant, they can also be reduced through an enlarged surface to radiate. This approach is depicted in Figure 6 on the next page and can be described as an *extendible core design*. The thruster consists of a vessel bearing stacked rings containing the radioisotope. This vessel and core can be telescopically extended by electrically actuated worm gears. The propulsive configuration in which it is collapsed and in which the vessel is shut tight is shown on the left of Figure 6. The working medium is flowing through the gaps of the rings. Without this cooling, heat would accrete considerably in the thruster's vessel. On the right, the extended configuration is shown. The heat of each ring can radiate directly to the surrounding.

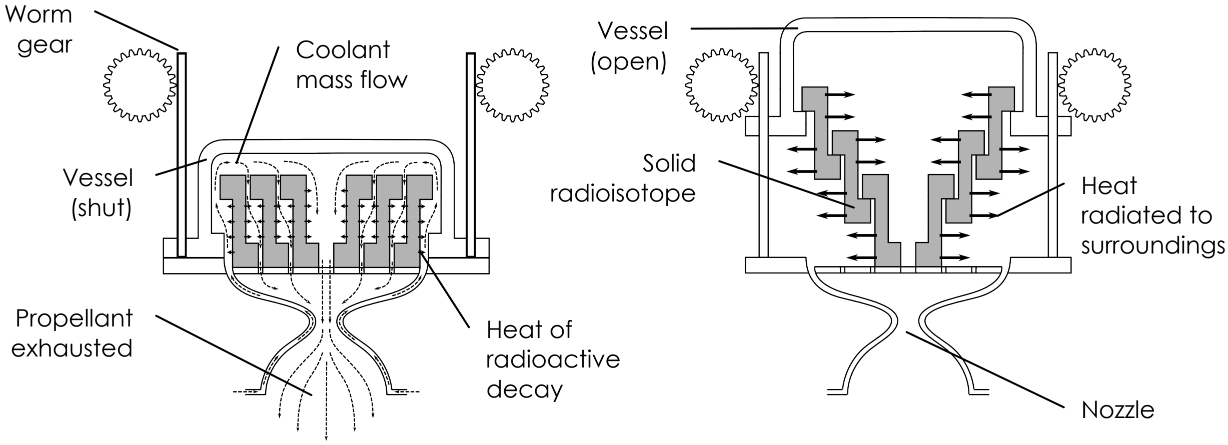


Figure 6 – Schematic of a solid core RHTP with extended core in idle mode [R 16].

### 2.2.3. Liquid Designs

As argued in Annex A, higher temperatures are beneficial to the exhaust velocity. If the thruster's core was allowed to *melt*, higher temperatures could be attained. An approach aiming at this option is shown in Figure 7 [R 16]. The hardware is similar to the one needed for the extendible core design. An insulation is slid over the thruster vessel with solid radioisotope material using worm gears. The vessel itself is attached to a rotor. In propulsive configuration, the insulation covers the thruster vessel and blocks the heat emerging from the radioisotope material sticking to porous walls where it starts to melt. In the micro gravity of space, the molten radioisotope is stabilised by the centrifugal forces exerted by rotating the vessel. The working fluid is fed into the porous walls and bubbles up through the molten material while collecting heat before being expanded isothermal.

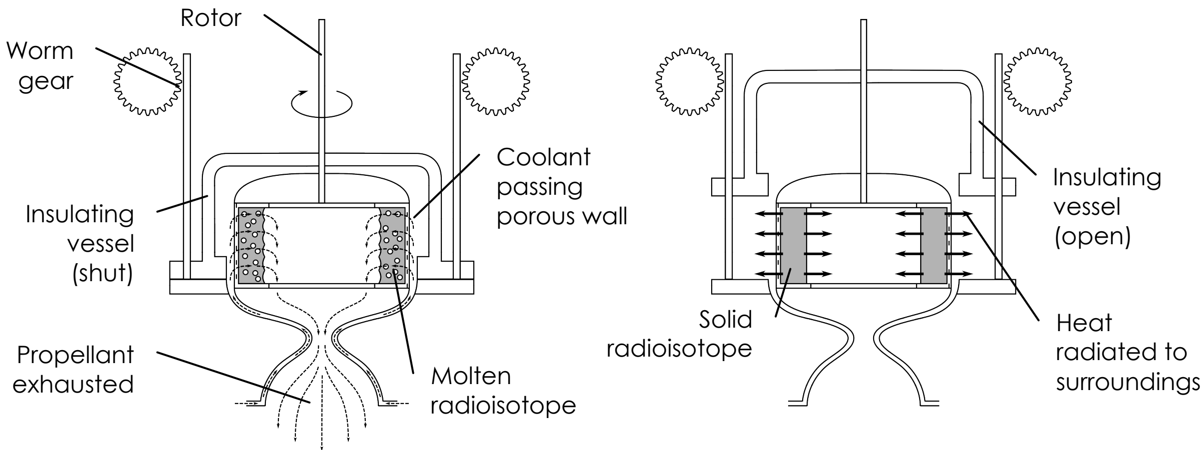


Figure 7 – Schematic draft of a liquid core RHTP [R 16].

This concept however risks slight loss of radioisotope material due to its melting and its direct contact with the propellant. Therefore, it is not suitable for use in or near biospheres since most employable isotopes present a radiologic and chemical risk. There are also expected issues with the molten material pouring through the porous wall and with the mechanical design.

### 2.2.4. Radioisotope Propulsion Technology Program (POODLE)

The study on RHTP culminated in the 1960s Radioisotope Propulsion Technology Program in the USA, known as POODLE [R 19]. The POODLE RHTP was supposed to be fuelled with solid Polonium 210 sufficient for an operational time of thirty days placed in three cartridge-like containment capsules and to be propelled with liquid hydrogen. The hydrogen was run through a helical duct around the Polonium capsules before being exhausted. Estimated parameters are collected in Table 4 [R 19]. A drawing of the thruster retrieved from the same reference is given in Figure 8. The reference gives an overview of the results of the program and concentrates considerations of the hard ware design encompassing both the capsules and the thruster and considerations for re-entry scenarios before concluding with a space craft description and rather extensive mission analysis. The report concluded that a POODLE RHTP would have various advantages over competing electrical or chemical thrusters of the 1960s. For example, solar probe injection could be conducted in 80 days which was about a fourth of the time allotted to a solar electric propulsion system. Missions to planets beyond Jupiter could be performed in a shorter time frame than with an initial hydrogen-fluorine thruster.

| F / N | $c_e$ / m/s | $P_{th}$ / kW | η / - | $T_{H^2,in}$ / K | $T_{H^2,out}$ / K | m / kg |
|---|---|---|---|---|---|---|
| 1.1 - 0.9 | 6940 - 6880 | 5.6 - 4.8 | 0.68 – 0.65 | 114 | 2200 | 23.6 |

Table 4 – Parameters of POODLE RHTP thruster. Data converted to SI. Value at Begin and End of Mission

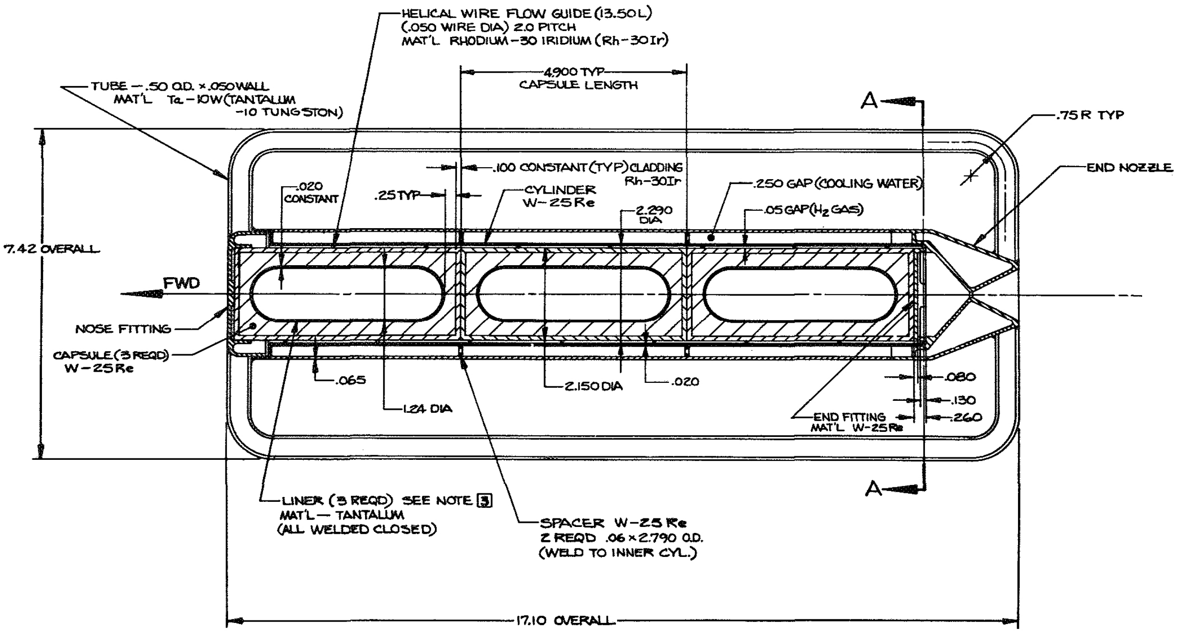


Figure 8 – POODLE drawing from [R 19]. Dimensions in inch (1 inch = 2.54 cm): d ≈ 0.19 m; l ≈ 0.44 m.

## 2.3. Nuclear Thermal Fission Propulsion

### 2.3.1. An introduction to fission propulsion

Nuclear Thermal Fission Propulsion (NTFP) systems have a critical fission reactor core which provides the energy needed to heat the expanding working medium [R 12 – 14, 20 – 26]. The fission reactor can be solid, liquid or gaseous. A special form of nuclear fission propulsion is the Nuclear Pulse Propulsion (NPP) which uses fission bombs to provide for propulsion.

While some larger isotopes like Californium 254 decay in spontaneous fission, nuclear fission is generally an induced nuclear process [R 11]. To achieve it, a fissile atom core needs to be destabilised. For this purpose a neutron is collided into the atom core turning it into a meta stable isotope which is finally split by the oscillation built up by the neutron's energy surplus. Other than nuclear binding energy new neutrons can be released in the process [R 11]. Typical fissile isotopes are Uranium 235 or Plutonium 239, but also Thorium 232 is discussed [R 27]. The fission of Uranium 235 can release from 0 to 5 neutrons and yields product isotopes such as Iodine 129, Caesium 137 and Strontium 90. Note that fission is not the only possible outcome [R 11]. It is as well possible that the neutron is simply absorbed into the core while the surplus energy emerges as beta or gamma radiation. It is also possible that the neutron scatters off, either elastically – i.e. conserving its energy changing merely its direction – or inelastically – i.e. losing energy.

Some of the neutrons released through fission appear immediately and are called *prompt neutrons*. The other neutrons are yielded with a delay. Since the new neutrons can potentially split other fissile atoms nearby, there is a probability of triggering a *chain (fission) reaction*. The development of a chain reaction can be qualified using the *criticality or reproduction number k* which relates the numbers of neutrons of two consecutive generations [R 11]. It is defined

$$k = \frac{N_{n+1}}{N_n}. \tag{11}$$

If the number of neutrons of the following generation $N_{n+1}$ is smaller than the number of neutrons of the current generation $N_n$ and thus $k < 1$ less reactions will occur in from generation to generation and the chain reaction will stop eventually. In this case, the reactor is qualified *subcritical*. If both numbers are equal – i.e. $k = 1$ – then the chain reaction is maintained in a stationary manner. The number of reactions will be the same from generation to generation. The reactor is *critical*. It is *supercritical* if $k > 1$ [R 11]. As long as the prompt neutrons of the population are not able to maintain the chain reaction alone, this mode can be used to start up a reactor and increase its power yield in a controllable manner. If however they are able to maintain the chain reaction alone and criticality is raised further, the release of neutrons will augment exponentially and rapidly beyond control and with it the power surge. This process is used in thermo nuclear weapons. In general, reactors should be designed such as to avoid this mode.

Criticality is controlled using (neutron) *moderators* and neutron *absorbing materials* [R 11]. The latter are able to remove a fraction of the released neutrons which is reducing the criticality. An excess of these substances, e.g. Gadolinium or Boron, can extinguish the fission chain reaction. The moderator is slowing the neutrons down which can raise the criticality of a Uranium reactor since slow i.e. thermal neutrons are more likely to engage into fission. This is depicted for Uranium 235 in Figure 9. The plot shows the *cross section* which indicates the reaction

probability as a function of the neutrons' kinetic energy which is proportional to the square of their speed.
While high cross sections appear on the left at low neutron kinetic energies, the cross sections on the right at high energy levels (*fast neutrons*) are rather limited. Resonances can be found in the middle. The cross sections' dependence on the neutrons energy has also consequences to the reactors inventory. While low-enriched fissile material is able to be used for thermal reactors relying on thermal neutrons, so called fast reactors relying on fast, i.e. high energy neutrons, need highly enriched fissile fuels. For propulsion purposes, thermal reactors are preferred.

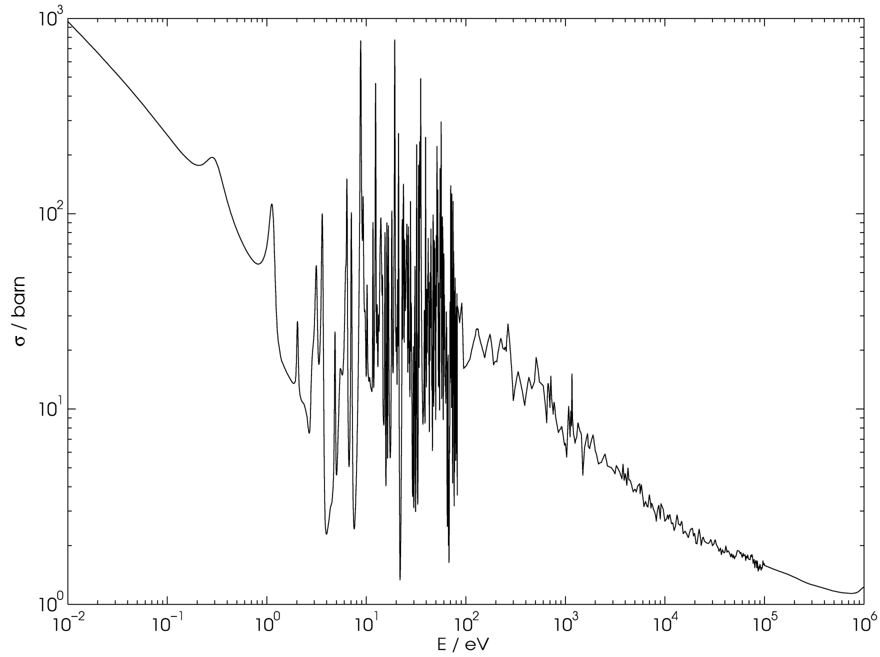


Figure 9 – Fission cross section of $^{235}U$ using a neutron as a function of its energy. (1 barn = $10^{-28}$ m²) [R 28]

A suitable moderator is hence composed of atom cores able to scatter neutrons inelastically – i.e. extracting a portion of their energy. From a consideration of the conservation of momentum it can be concluded that atoms with masses similar to a neutron's mass are more suitable for this purpose. The number of collisions that a rapid neutron has to perform with cores of a given isotope until it achieves thermal energies is estimated in Table 5. Moderator materials can also be employed to provide the reactors reflector, which is the subsystem preventing a part of the neutrons to leave the containment. Note, that some of these moderators or their chemical compounds – for example hydrogen or methane $CH_4$ – are often considered as a working medium in NTFP and that hence, the reactor criticality has to be adapted.

| Moderator Element/Isotope | H | D | Li | Be | C | O | Fe | U |
|---|---|---|---|---|---|---|---|---|
| Number of nucleons | 1 | 2 | 7 | 9 | 12 | 16 | 56 | 238 |
| Approximate number of collisions until thermal energy level | 18 | 25 | 70 | 86 | 114 | 150 | 510 | 2172 |

Table 5 – Estimation of the collision number a released neutron needs to perform on a given isotope core.

The use of hydrogen or its compounds has also a couple of implications for the mechanical design. For example the surfaces exposed to the hydrogen need to withstand corrosion or reaction. Especially graphite elements need a special coating. If non solid cores are used, there may also be a risk in saturating the working medium with the fuel and losing it. In addition this saturation can slow down the exhaust velocity due to magnifying the average Molar mass in the propellant (cf. Annex A).

From all of the above it is possible to derive some primordial technical criteria for NTFP systems. They group as follows and lead to the necessity of tradeoffs:

- **Propulsion criteria**
  - High energy yield of the core
  - Efficient power transfer to working medium
  - Avoidance of excess propellant saturation with heavy fission products or educts
    - Thus: low fuel vaporisation or erosion rates
  - Mass specific thrust parameters: light weight of system and/or compact volume
- **Chemical safety criteria**
  - Crew/technician safety: substances non poisonous
  - Material safety: substance non corrosive or susceptible to corrosion
  - Space craft safety: fission educts and products chemically safe
- **Physical safety criteria**
  - Crew/technician safety: radioactivity limited or well shielded
  - Fission safety: avoidance of prompt criticality, only controlled criticality
  - Material safety: limited yield of power, must withstand lack of cooling
  - Space craft safety:
    fission products lowly radioactive or injected in escape trajectory
- **Economic considerations / synergies**
  - ... use as a power plant after propulsion use (bi mode conception)
  - Availability of fissile material and
  - Low rates of fuel loss
  - Cost of processing and handling

### 2.3.2. Solid Core Reactor Fission Propulsion

Nuclear thermal fission propulsion has been considered since the late 1940s. Designs with reactor cores containing the fissile fuel have been studied most thoroughly and are considered to be the most mature Nuclear Thermal Propulsion systems [R 13]. Some, like NERVA or its Russian counterpart RD-0410 have even seen ground based testing. Both thermal systems relying on neutron moderation (both heterogeneous and homogeneous architectures) and fast reactors relying on highly enriched fissile fuel have been studied [R 20, 29]. It has been considered to store the fissile material in either rods or balls or stacks according to these criticality concepts.

*Heterogeneous thermal reactors* for fission propulsion can be used with relatively lowly enriched fuel. However, they need a moderator in order to slow the fission yielded neutrons to thermal levels. Fuel and moderator are contained in separated bodies, typically rods [R 12, 13, 20, 21]. The moderator can be actuated in order to control the criticality. In general, reactors based upon this concept have limited temperatures due to heat load requirements. This consequently leads to limited exhaust velocities (cf. Annex A). In the same time, this heat load limitation may lead to high coolant mass flows which can enable relatively high thrust. Many solid core NTFP systems rely on this concept. An intrinsic problem of such a concept consists in the corrosion induced by the working medium which reduces the system's life span compared to other approaches [R 30]. The often suggested use of hydrogen or its compounds is particularly detrimental. Graphite moderation rods need to be coated with e.g. Zirconium to prevent chemical reaction. A generic draft of such a system is displayed in Figure 10.

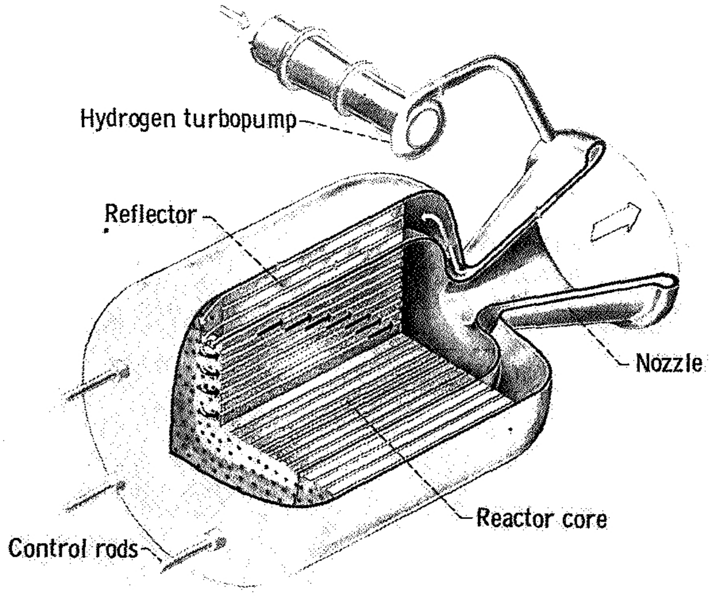


Figure 10 – Schematic view of a generic heterogeneous solid core NTFP [R 20]

Higher temperatures and thus better exhaust velocities can be attained with *homogeneous thermal reactors*. The moderator is contained in the same body as the fuel and exposed to extreme heat load. The latter can be mitigated in offering a relatively large surface to volume ratio which can be achieved with fissile fuel balls like they are studied for terrestrial high temperature pebble bed reactors such as shown in Figure 11 [R 13, 31, 32].

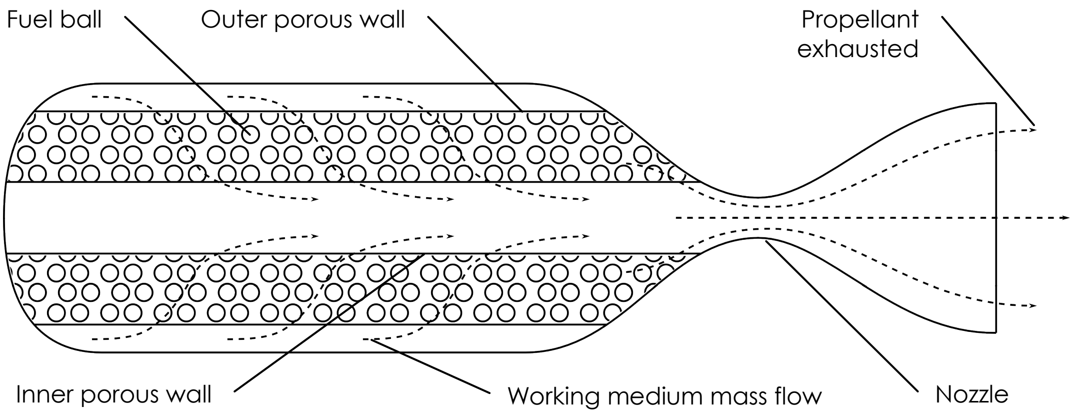


Figure 11 – Schematic draft of a pebble bed NTFP

In *fast reactors*, the high enrichment in fissile isotopes compensates the fast neutrons' low cross section. Thus, no moderator is needed for the chain reaction – which enables a rather compact size of the reactor core – and the fissile body can transmit its heat directly to the working medium. To manage the thermal loads, relatively large surfaces of the fissile body are required. Fissile bodies in the shape of stacks or balls like in a pebble bed reactor are considered. Note, that fast reactors with liquid metal cooling are often considered for Nuclear Electric Space Applications due to their relatively compact size and longevity. Examples for such systems are the American SNAP-2, SNAP-8 and the flight experienced SNAP-10A, or the Russian Romashka, BUK, TOPAZ I and II a.k.a. Yenisey [R 21].

Also, various increments and synergies have been proposed [R 13]. The propulsion concept can be enhanced by hybridising electrically or chemically. The *Electric Propulsion (EP) hybrid NTFP* applies when the principal thruster is idle. Then, the after-heat of the reactor can be used for electrical power generation. It is however also thinkable to maintain the fission process with the NTFP reactor connected to a closed coolant cycle. The electrical power is fed to an arbitrary EP system with typically rather high exhaust velocity [R 13]. A typical manoeuvre scenario for such a setup would consist in having the principal NTFP provide for the escape acceleration at high thrust and low exhaust velocity, and having the secondary EP provide for a sped up cruise at low thrust, yet high exhaust velocity – and thus reduced propellant consumption.

The *Chemical Propulsion (CP) hybrid NTFP* is aiming at an inverse manoeuvre scenario in which the cruise is performed by the NTFP while space craft accelerates using the CP hybrid NTFP. A CP can consist in a liquid oxygen augmentation in which oxygen is injected in the propellant flow downstream of reactor core in case hydrogen is used as a principal propellant. This constitutes a thrust enhancement through augmentation of mass flow. In the same time, it reduces the exhaust velocity [R 13]. An energetic advantage can however only be obtained, if the hydrogen flow has temperatures low enough to allow for an exothermal chemical reaction.

Both hybridisations are depicted in Figure 12.

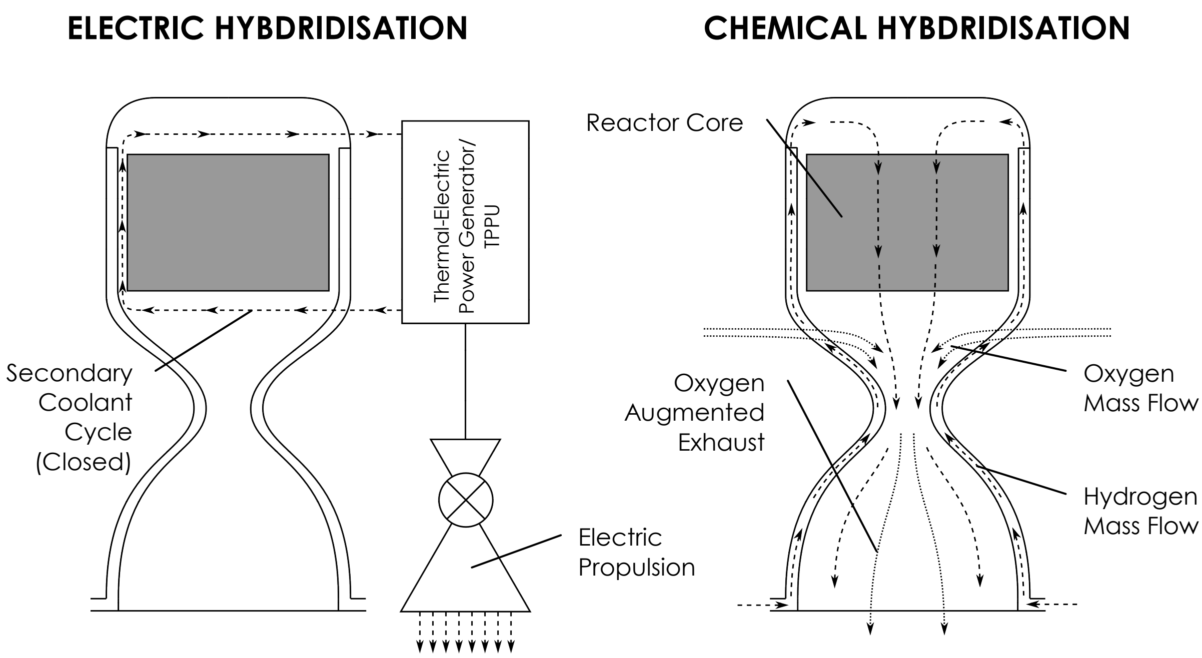


Figure 12 – Hybridisation of solid core NTFP

### 2.3.3. Historic Solid Core Reactor Fission Propulsion Projects

Many solid core NTFP have already been studied and some have even experienced ground testing. The most prominent example is the NERVA Nuclear Rocket Engine Technology Program [R 21, 23, 25, 26, 30]. NERVA is an acronym for *Nuclear Engine for Rocket Vehicle Application*. The programme – known as Rover – took up prior investigation of NTFP conducted in the United States of America in 1954 and invested about 2 billion Dollars – which would amount approximately 7 billion given today's Dollar value – until being terminated in 1972/1973 due to a lack in political support for long term research activities without immediate return [R 33, 34] and due to a lack in suitable launchers[3]. The programme is relatively well documented and NERVA is the most mature NTFP system to this day. Details on the project's history can be retrieved from [R 30]. The testing timeline given in this reference is reproduced in Figure 13.

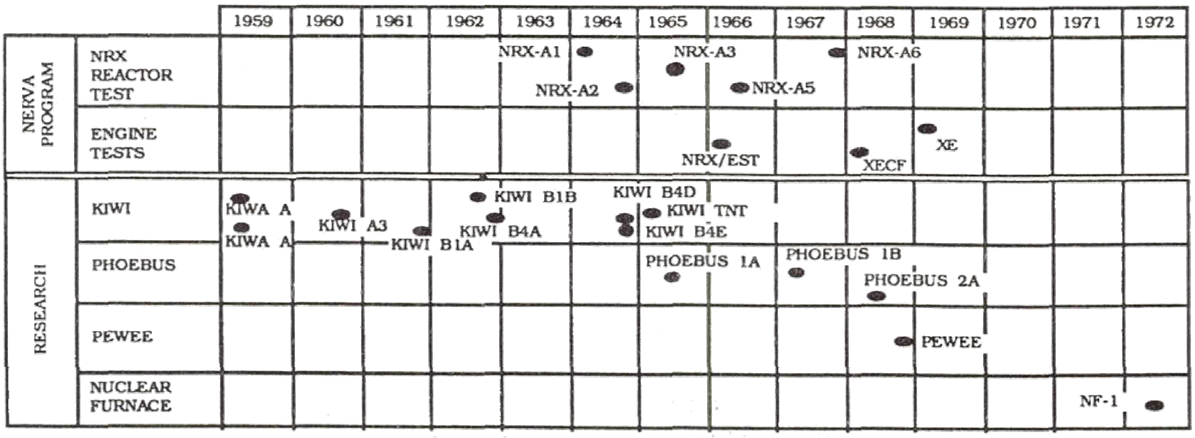


Figure 13 – Chronology of Major Nuclear Reactor Tests [R 30]

Many engineering problems were addressed during the programme, among which the design of the working medium provision cycle, reactor alleviation and reduction of corrosion. The first reactors developed in the scope of this program were the KIWI[4] reactors which aimed at basic research of space borne reactors. The terminal KIWI B4E test (KIWI-TNT was an experiment to study the explosive destruction of a NTFP thruster) featured 937 MW of thermal power at a mass flow of about 32 kg/s. The working medium was heated from 104 °K at the inlet to 2330 °K at the outlet. The vessel pressure was at about 4 MPa [R 25, 26].

The next step was to develop the KIWI reactors into reactors being able to be launched, which was conducted in the Nuclear Reactor Experiment (NRX) and the Experimental Flight Engine Prototype (XE) projects. NRX-A6 had parameters similar to those of KIWI B4E. The resulting NERVA 1 is shown in Figure 14. PHOEBUS 1A and B aiming at the development of NERVA 2 were tested in 1965 and 1967 (see Figure 15), respectively. Another major development step consisted in PHOEBUS 2 which offered about 4 GW of thermal power making it the most powerful single fission reactor block in history. The data of the NERVA program is collected in table 6. Most notable is the high thrust of NERVA 1 being at about 350 kN with an exhaust velocity of 8100 m/s [R 25, 26]. All ROVER reactors are heterogeneous graphite moderated reactors.

[3] Following Apollo, Saturn V was scrapped in favor of the Space Shuttle.
[4] "Kiwi" are flightless birds from New Zealand.


Figure 14 – NERVA 1

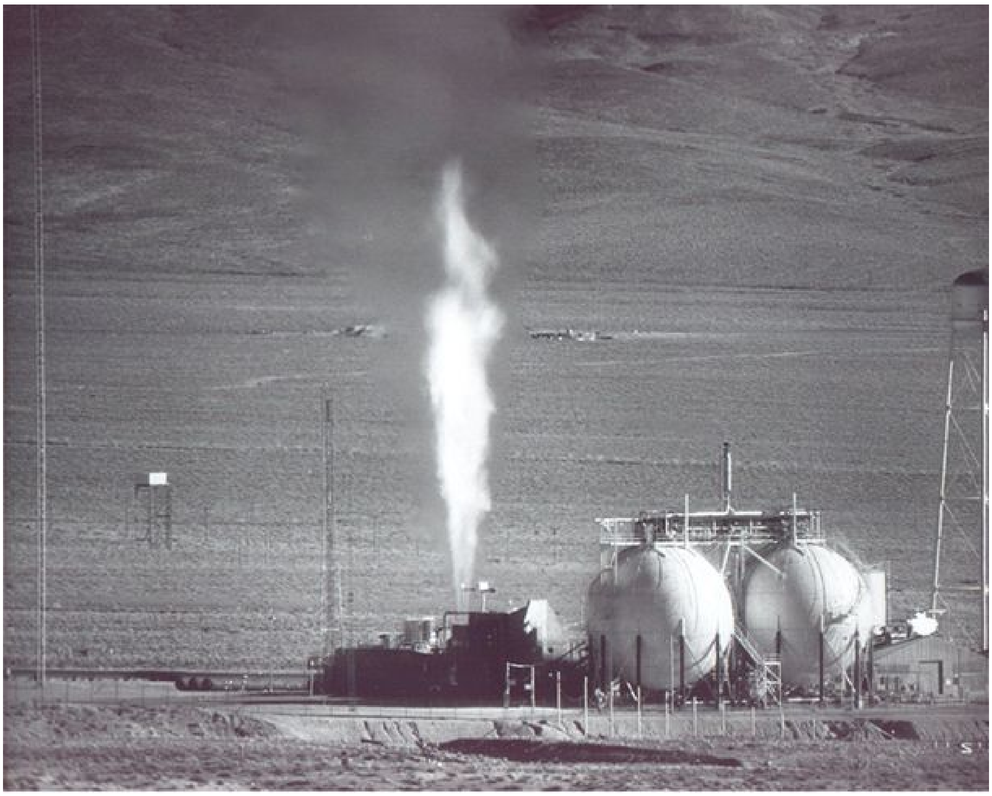

Figure 15 – PHOEBUS test in Nevada

Project Timberwind is a more recent US American investigation of NTFP. The project was initiated in the frame of the Strategic Defense Initiative in 1987 and became a part of the US Air Force's Space Thermal Nuclear Propulsion programme [R 35]. The project considers various state of the art reactor designs, among which CERMET reactors and particle bed concepts. The data of Timberwind designs is also collected in table 6. Two other projects are the Safe Affordable Fission Engine (SAFE) with about 400 $kW_{th}$, and the Heat Pipe Operated Mars Exploration Reactor (HOMER) with about 15 $kW_{th}$ [R 21].

NTFP systems were also investigated in the Soviet Union from the 1950s to 1990 and in the Russian Federation from the late 1990s [R 13, 21, 36]. The project leading to RD-0410 was started 1965 [R 36]. However, it is difficult to detect relevant literature.

| c | KIWI-4BE | NRX-A6 | NERVA-1 | Phoebus-2A | NERVA-2 | Pewee-1 | Timberwind 45 | Timberwind 75 | Timberwind 230 | RD-0410 | IRGIT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{th}$ / MW | 950 | 1167 | 1570 | 4080 | | 507 | - | - | - | 196 | |
| $^{dm}/_{dt}$ / kg/s | 31,8 | 32,7 | 41,4 | 119,2 | | 18,6 | | | | | |
| $T_{exit}$ / K | 2330 | 2472 | 2700 | 2283 | | 2556 | - | - | - | - | |
| $T_{vessel}$ / K | 1980 | 2342 | 2360 | 2256 | | 1837 | - | - | - | - | |
| $p_{Vessel}$ / MPa | 3,49 | 4,13 | 3,1 | 3,83 | | 4,28 | - | - | - | - | |
| $T_{core,inlet}$ / K | 104 | 128 | - | 137 | - | 128 | - | - | - | - | |
| $p_{core,inlet}$ / MPA | 4,02 | 4,96 | - | 4,73 | - | 5,56 | - | - | - | - | |
| $T_{reflector,inlet}$ / K | 72 | 84 | - | 68 | - | 79 | - | - | - | - | |
| $p_{reflector,inlet}$ / MPA | 4,32 | 5,19 | - | 5,39 | - | 5,79 | - | - | - | - | |
| $^{dm}/_{dt}$ / kg/s (periphery) | 2,0 | 0,4 | - | 2,3 | - | 6,48 | - | - | - | - | |
| $c_e$ / m/s | - | 8310 | 8093 | 7900 | 8110 | - | 9830 | 9830 | 9830 | 8920 | |
| F / kN | - | 216 | 334 | 922,6 | 867 | - | 441 | 736 | 2452 | 35.5 | |
| $\eta_T$ / - | - | - | 0,86 | - | - | - | - | - | - | - | |
| d / m | - | - | - | - | 10.6 | - | 4.25 | 2.75 | 8.7 | 1.2 | |
| L / m | - | - | - | - | 43.7 | - | - | - | - | 3.7 | |
| m / kg | - | - | 9000 | - | 34000 | - | 1500 | 2500 | 8300 | 2000 | |

Table 6 – Parameters of selected solid core NTFP systems.

### 2.3.4. Liquid Core Reactor Fission Propulsion

Similar to RHTP systems temperatures and thus exhaust velocities can be enhanced in choosing a *liquid fission reactor core* instead of a solid one [R 20, 37]. In such a reactor, the fissile fuel may either be a molten metal (Plutonium in a molten carrier metal, e.g. lead), a molten fissile salt (Uranium Fluoride in a molten carrier salt like Lithium Fluoride), or a solution/emulsion of the latter (Uranium Oxide in e.g. water) [R 37]. In the reference, these concepts are assumed to have advantages for the use as a closed fission plant. On the safety side, the liquid fuel is not susceptible to damaging and its product inventory can be processed while operating. On the economic side, the fuel production is simplified and the use of the fissile fuel as a heat conducting medium enhances the plants efficiency. The latter is an extremely interesting property for NTFP applications in which the liquid fissile can be brought into direct contact with the working medium. In contrary to the closed terrestrial plant concept this can be considered as an “open” approach, which however poses the general issue of a loss of fission reactor inventory, both educts and products. The propulsion systems exhaust can therefore be radiotoxic which should be considered in operation. Another important issue of the open liquid core approach is the vaporisation of fuel [R 20]. The process taps a part of the heat of the core which is thus no longer available to heat the working medium. Another loss mode consists in the poisoning of the propellant with heavy particles which slow the exhaust velocity (cf. Annex A). A counter measure suggested in [R 20] consists in diluting the fuel with a substance which has a lower vapour pressure.

The most intuitive approach is indeed similar to the RHTP drafted in Figure 7 on page 1 [R 20]. While not indicating how to control the liquid fissile in this system, the reference enumerates expected difficulties such as the mechanical design, the loss of both fissile fuel and of fission products and the risk of molten fuel backflow through the porous wall. The latter could be resolved if the working medium was directly fed through the main chamber instead through porous walls [R 20]. Such a rotationally stabilised *backflow free system* is outlined in Figure 16. While the prior concept implied a direct contact of working medium and heat source, i.e. molten core, heat transfer can only occur through radiation in this case. Thus, it is required for the working medium to be sufficiently opaque to absorb the radiation from the core. A technical approach to enhance the absorbance of hydrogen consists in seeding solid impurities such as Carbon particles to the working medium mass flow. According to [R 20], there are additional thermal issues with the solid containment of the molten fissile fuel.

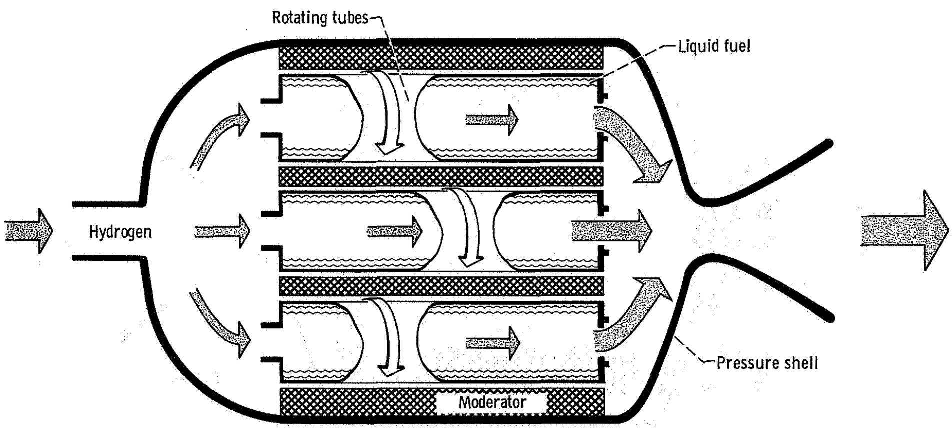


Figure 16 – Drawing of a rotationally stabilized backflow free Liquid Core Reactor NTFP system [R 20]

The performance of the system without back flow is retrieved from [R 20] and summarised in Table 7. However, the reference states that the loss of fissile fuel reaching up to 2 % of the mass flow is excessive.

| $^{dm}/_{dt}$ / kg/s | $c_e$ / m/s | F / N |
|---|---|---|
| 0.045 | 15000 - 16500 | 680 - 740 |
| 0.068 | 13500 – 16000 | 920 - 1090 |
| 0.091 | 12000 - 15000 | 1090 - 1370 |

Table 7 – Approximated parameters of a rotationally stabilized backflow free Liquid Core Reactor NTFP system [R 20]

A third liquid core concept is proposed in [R 20] named *Droplet Liquid Core Reactor (DLCR)*. It is assumed to achieve similar thermal loads as the intuitive porous wall concept but with a reduced mechanical complexity and simplified containment. The DLCR consists in a portion of liquid fissile fuel turned around by a high pressure regenerative cooling stream of hydrogen which is additionally heated up in the process before leaving the plenum. This approach is shown on the example of an aero-spike like nozzle in Figure 17. Remaining challenges are the loss of reactor inventory and the mechanical design of the reactor start up subsystem.

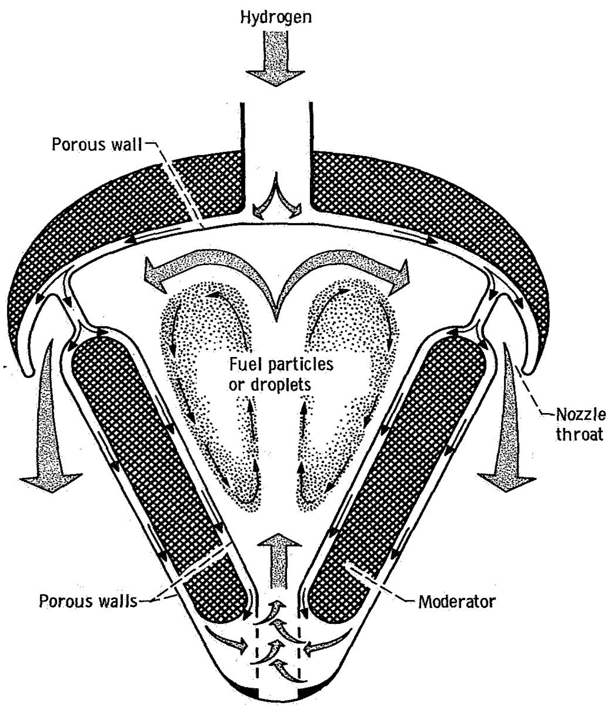


Figure 17 – Drawing of a DLCR propulsion system [R 20]

### 2.3.5. Gaseous Core Fission Propulsion

In solid core fission propulsion, the exhaust velocity was restricted to a maximum of about 10000 m/s due to the cores limited thermal and chemical resistance. In liquid core fission propulsion, the restriction was lifted to approximately 17000 m/s. The limitation consisted mainly in the thermal loads at the liquid to solid boundary and the losses of fissile fuel caused by its vaporisation. An ultimate approach to attain higher exhaust velocities with a contained fission reactor core consists in using *gaseous* fissile material or even fissile plasmas which can endure the highest temperatures. Such concepts have been investigated since the mid 1950s and also experienced testing [R 13, 20]. An example of an early design is depicted in Figure 18. The thruster vessel contains a spherical plasma of a fissile fuel – typically Uranium Tetraflouride or Uranium Hexaflouride – which is stabilised by the working medium mass flow streaming into the vessel through porous walls before being exhausted at velocities above 20000 m/s [R 13, 38 – 40].

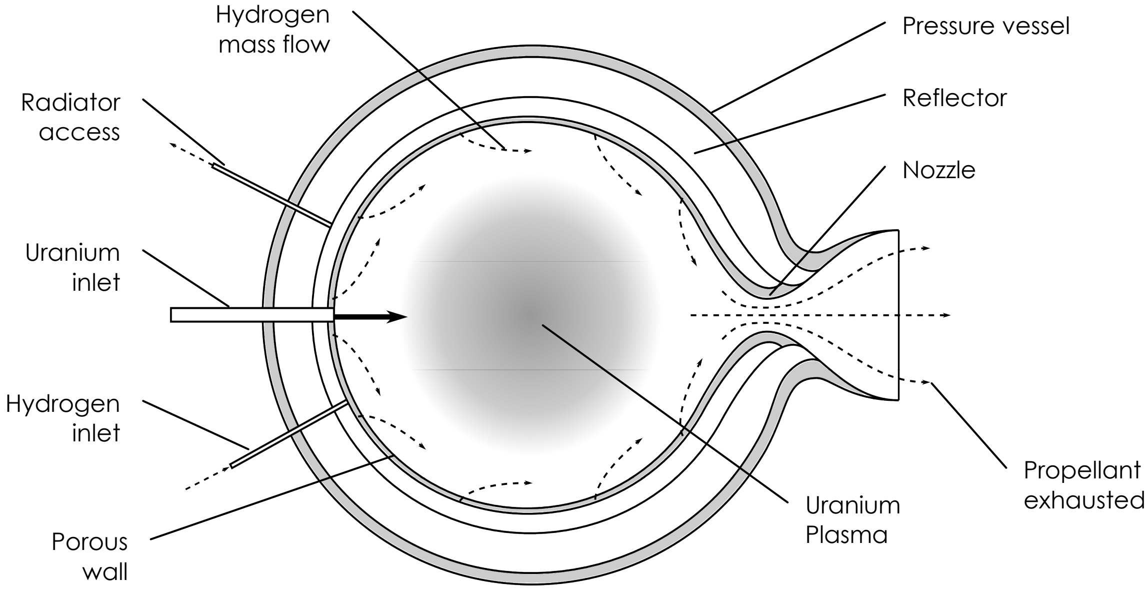


Figure 18 – Schematic draft of a generic Gas Core NTFP

Like in solid or liquid core designs, hydrogen and its compounds are considered as a working medium. Unlike in the majority of these designs – except for the backflow free liquid core fission propulsion design – the heat transfer from the fission core to the medium is not accomplished by conduction and convection but almost exclusively by thermal radiation. The plasma is assumed to behave like a black body radiator. One of the major technological challenges of the gas core concept consists in increasing the working medium's absorbance of the thermal radiation, an aim for which it has been suggested to add Carbon particles to the hydrogen mass flow [R 13, 20].

Another important issue is the fissile fuel loss: Similar to the liquid concepts, the coolant mass flow can saturate with fuel resulting in the same drawbacks, i.e. reduction of exhaust velocity due to poisoning with heavy atoms and depletion of the reactor inventory. Further, it is thinkable to lose the entire gaseous core at once.

The last problem consists in the pressures needed to achieve and contain the critical fission plasma. The latter is generated by feeding particles of Uran-Flouride into the vessel. If the density of particles is high enough to form a critical mass the chain reaction would yield the heat to form the plasma. However, it would also expand due to this heat and the density would be reduced below criticality. Therefore, the plasma needs to be pressed by the coolant which can be described as a gaseous containment. Note that due to the expected high temperatures of 40000 °K beyond any material resistance, a contact with the thruster solids is highly disadvised. Estimations reported in [R 20] hint at vessel pressures of several hundred atmospheres. The pressure needs to be exerted by the coolant mass flow. Propulsion data is given in Table 8.

| Type | m / t | p / bar | T / K | $c_e$ / m/s | F / kN | P / MW |
|---|---|---|---|---|---|---|
| GCR [R 20] | 45 | 1000 | 44000 | 15000 – 25000 | 1000 | 7500 – 12500 |
| GCR [R 13] | 60 – 200 | - | 55000 | 30000 – 70000 | 67 | 1000 – 2300 |
| NLBR [R 42] | 32 | 500 | 9000 | 20000 | 400 | 4000 |

Table 8 – Approximate parameters of various GCR. (T – Temperature in fissile. P – Jet Power, calculated.)

Since the proposal of gas core fission reactors, various enhancements have been investigated. One of them is the application of a toroidal fissile plasma in place of the spherical geometry of the initial design. This concept proposed by Los Alamos National Laboratory aims at achieving a better stabilisation and containment of the fission plasma at lesser pressures and better heat transfer to the working medium. The torus is generated through blowing an important fraction of the working medium straight through the fission gas which will then roll up into a vortex as drafted in Figure 19 [R 41].

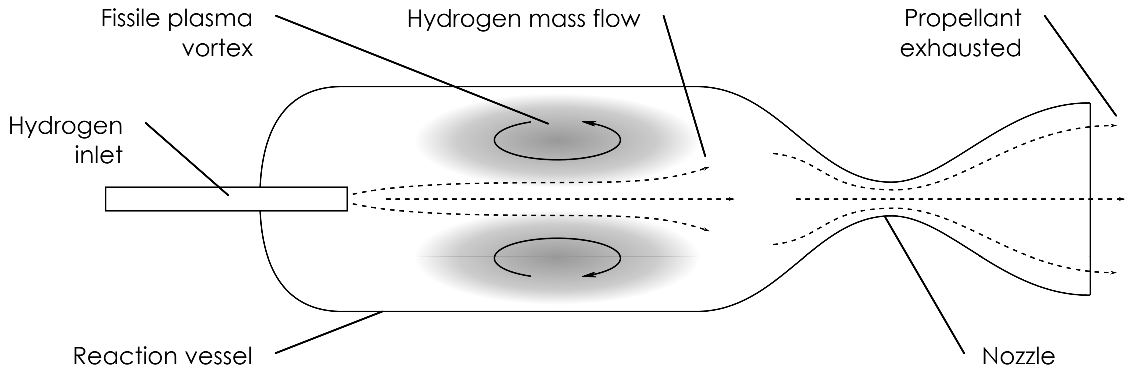


Figure 19 – Schematic draft of a toroidal vortex stabilised Gas Core NTFP

Another concept using a gaseous fissile is shown in Figure 20 on the next page. There is however a major difference between this so called "closed cycle" or *Nuclear Light Bulb Reactor (NLBR)* concept [R 42] and the prior presented GCNTFP systems: The fissile is enclosed in a containment of Quartz resembling an eponymous light bulb. The advantage is primarily the elimination of the loss of fissile to the coolant. The latter is like in the other concepts a stream of Carbon seeded hydrogen heated by thermal radiation. This is possible, because the Quartz wall is largely transparent to the thermal radiation. The contained plasma of temperatures around 8000 °K itself is vortex stabilised in a manner similar to Figure 19. To protect the Quartz containment against the heat loads, an inert bypass mass flow – gaseous Neon – is injected between the plasma and the wall. The Quartz itself is cooled by another mass flow streaming through its ducts. However, the containment imposes limitations to the temperature of the working medium temperature and thus an exhaust velocity of about 18000 m/s [R 42] – comparable to liquid core fission systems. Further parameters are summarised in Table 8.

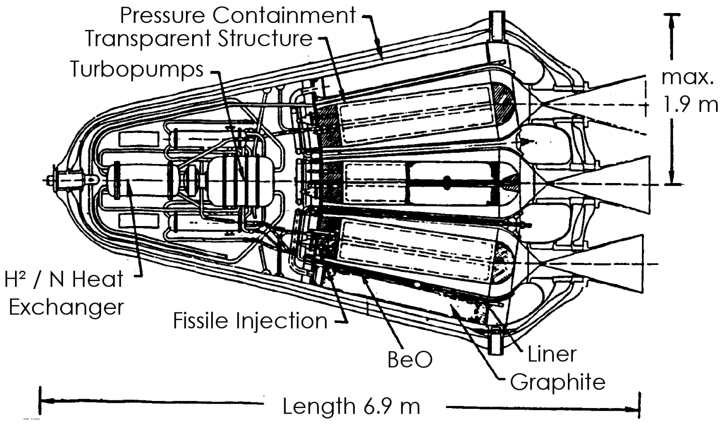


Figure 20 – Cut of a Nuclear Light Bulb Gas Core NTFP

### 2.3.6. Prompt Supercritical Fission Propulsion

While prompt super criticality is in general an unwanted state for systems discussed hitherto in this report due to reactor control and thus safety aspects, systems relying on highly prompt super criticality are thinkable. The most notorious related concept is the ORION[5] [R 43 – 48].

ORION was investigated from 1957 to 1965 by a team led by Freeman Dyson and Theodore Brewster Taylor and based on Stanislaw Marcin Ulam’s proposal to use Nuclear Fission Bombs for propulsion. It envisaged using the nuclear detonation’s energy to vaporise and accelerate a plastic propellant covering the bomb. The plastic vapour or plasma would hit the space craft and transfer its momentum to the latter. Since the power released would be rather excessive and the respective acceleration challenging to the space craft’s structure and the potential crew’s health, it would be necessary to absorb the momentum with a shock absorbing pusher plate damping the acceleration down to mitigable levels. A resulting space craft design is outlined in Figure 21.

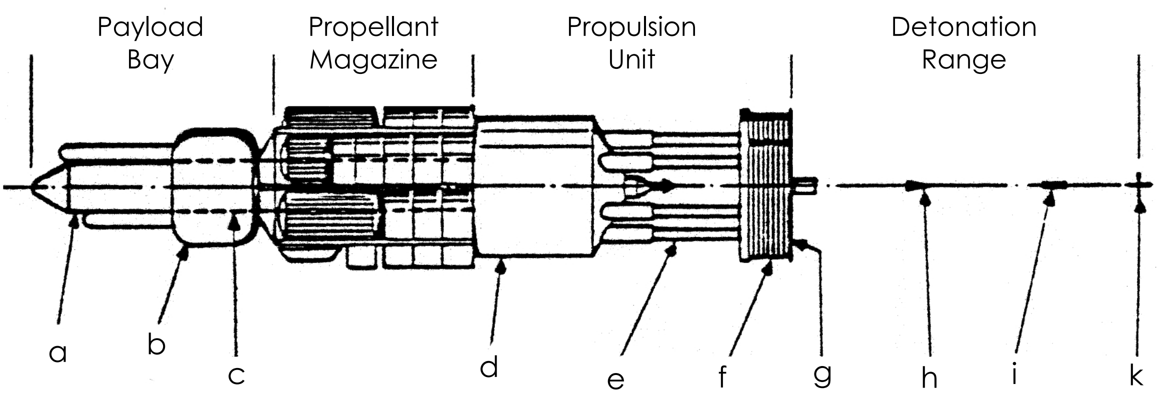


Figure 21 – Overview of an ORION Space Craft
(a – Lander; b – Habitat; c – Central Truss; d – Basic Structure and Bomb Ejector; e – Second Stage Shock Absorber; f – First Stage Shock Absorber; g – Pusher Plate; h – Bombs’ Trajectory; i –Ejected Bomb; k – Detonation Point)

[5] Not to be confounded with the recent space craft concept from the Constellation programme.

The Orion space craft was estimated to provide an exhaust velocity of 30000 m/s to 50000 m/s at 300000 N to 1.6 $10^6$ N of thrust [R 48] and deemed advantageous compared to other propulsion concepts of the 1960s.

The concept of the pusher plate was proven in actual experiments during the 1960s in which propulsion was provided by conventional "grenades". However, the intended use of nuclear bombs leads to other restricting implications. Unlike the grenade demonstrator which was lifting off the ground and also proved claimed advantages of the approach, the actual system cannot be used as a launcher. This is not only due to political issues and obvious highly limited public acceptance, but also due to the fact that the nuclear explosions' neutrons are reflected by the surrounding atmosphere. The payload and eventual astronauts would be exposed to dangerous doses of radiation. This would limit the use of the system to space.

Another important problem would be the risk of proliferation. The nuclear bombs intended for propulsion could be abused as weapon system. Also, storage and explosion of atom bombs in space is ruled out by international treaties. Project ORION was terminated in 1965.

A concept to overcome the latter problems in using prompt nuclear fission and make its advantages available to space flight is the Nuclear Salt Water Rocket (NSWR) proposed by R. Zubrin [R 29]. The concept's name is due to the use of an aqueous solution of salts of fissile material like Uranium as UBr4 with Bromine. Other solutions could be based on Thorium 232 and bred Uranium 233 or Plutonium 239. These solutions are stored in small portions containing subcritical amounts of the fissile salt in containments made of neutron absorbing / deflecting material. Upon ignition, the containments are emptied in the reaction plenum where – other than in most other NTFP systems – prompt super criticality is achieved and where the fission chain reaction surges power vaporising the solvent in a steady detonation. The vapour is expanded via the system's nozzle. This setup is drafted in Figure 22.

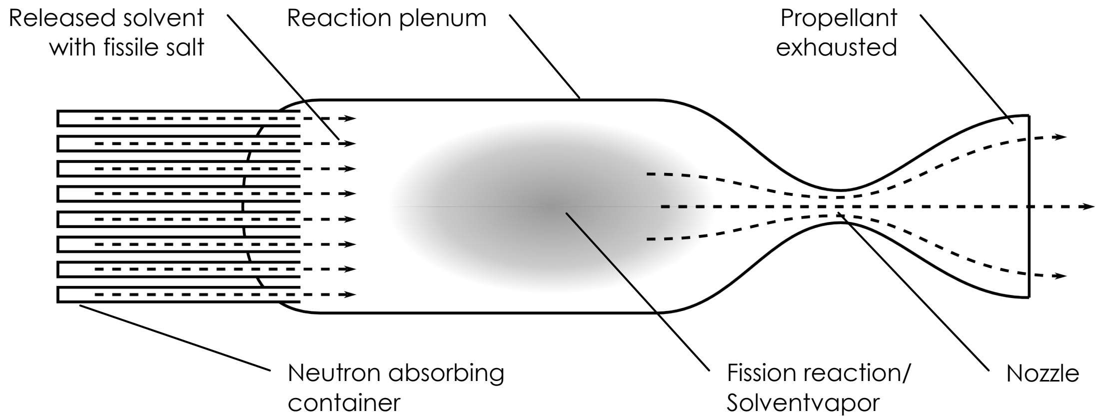


Figure 22 – Schematic draft of a NSWR.

A simplified model and its exemplary evaluation are given in [R 29]. It is assumed that the concentration of Uranium-Bromide in the aqueous solution is about 2%[6]. Since prompt super criticality is envisaged, the Uranium is enriched to 20%. The plenum calculated in the reference seems rather small, having an inner diameter of about 6.2 cm and a length of 65 cm. The solution needs to be sprayed into the plenum with a speed of about 66 m/s. The nozzle mass flow is calculated to 196 kg/s while the exhaust velocity is estimated to 66000 m/s for an assumed

[6] Sea-water has a salt concentration ranging from 0.5 % to 4 % depending on the ocean.

nozzle efficiency of 0.8. The thrust is thus 12.93 MN and the jet power 427 GW. The parameters are also available in Table 9.

| Conc. / % | Enr. / % | F / MN | $c_e$ / m/s | $P_{th}$ / GW | $\eta_{Nozzle}$ / - | $^{dm}/_{dt}$ / kg/s |
|---|---|---|---|---|---|---|
| 2 | 20 | 12.93 | 66000 | 427 | 0.8 | 196 |

Table 9 – Parameters of NSWR. Conc. – Aqueous solution concentration of $UBr_4$. Enr. – Enrichment.

A concluding mission analysis in [R 29] is based on a manned mission to Titan (Saturn) with a space craft of 300 tons and depicts that there are important mass advantages as compared to Chemical Propulsion (CP), Nuclear Electric Propulsion (NEP), Solid Core (SCNTFP) and Gas Core NTFP (GCNTFP) as a kick stage in low earth orbit. The data is summarised in Table 10.
An important issue of the system discussed in [R 29] is that the radio toxic fission products are expelled together with the solvent vapour and risk to contaminate Earth's biosphere. It is however argued that at an exhaust velocity of 66000 m/s the fission fragments are injected on a hyperbolic trajectory leaving Earth's gravity, assuming an orbit tangential burn.

| Low Earth Orbit Kick Stage | CP | NEP | SCNTFP | GCNTFP | NSWR |
|---|---|---|---|---|---|
| Initial Mass in Low Earth Orbit / t | 2207 | 610 | 834 | 582 | 384 |
| Kick Stage and Propellant Fraction / % | 53 | 49 | 64 | 47 | 20 |

Table 10 – Mission analysis comparison [R 29]. Manned mission to Titan (Saturn).

# 2.4. Fusion propulsion

## 2.4.1. Generalities

The use of fusion for NTFP applications has been investigated as long as fission and also as long as it has been discussed for the use in terrestrial power plants [R 49]. Many experiments for the latter have been conducted so far and to this date, none successfully. There is however a well founded expectation that in terrestrial fusion a breakthrough may occur during the operation of the current international ITER project, i.e. by 2025 [R 8].

A fusion NTFP uses a fusion power source to heat up the working medium [R 15, 50 – 55].

Fusion is the complimentary nuclear process to fission: Instead of splitting one heavy atom core into two lighter cores, fusion joins two lighter separate cores into a single one. The two cores need to be placed close enough to each other as to allow the strong interaction to apply, a process in which energy is released. Then they appear as one solid core with respective chemical properties [R 49]. Under normal conditions this process occurs almost never because the cores' charges push them away from each other and the more so, the closer they get. It is only in the ultimate proximity of the core this Coulomb force is overwhelmed by the strong interaction. The culmination of the Coulomb interaction is called *Coulomb wall*. This is shown in Figure 23.

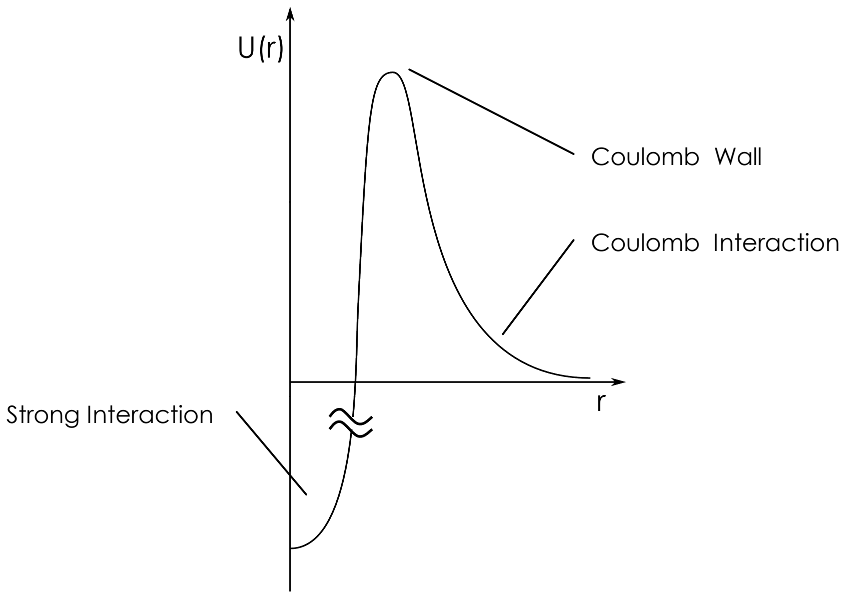


Figure 23 – The Coulomb wall

To overcome the Coulomb wall, fusing particles need to be really rapid which means that they need an extremely high kinetic energy at least equal the peak of the Coulomb potential. If it was attempted to provide this energy in a gas by heating, temperatures above 100 Million Kelvins would have to be reached which would make the process impractical. However, a quantum physical effect that eases this problem by one order of magnitude to about 10 Million Kelvins was identified. For practical reasons, these temperatures are indicated in kilo Electron-Volt (1 keV = 11 609 000 K). It is possible that particles with lower energy than necessary "tunnel" through the Coulomb wall. This tunnel effect was first identified by George Gamow. The fusion cross sections of the most pertinent reactions (D-T, D-$^3$He, $^{11}$B-p and $^3$He-$^3$He) are shown in Figure 24. It is important to note that the range of relevant energies is from 10 keV to 10 MeV, compared to 10 meV to 1 MeV for fission and that the range of relevant cross sections is from 10 mbarn to 1 barn compared to 1 barn to 1 kbarn: Even despite the alleviating tunnel effect, fusion is more exigent than fission.

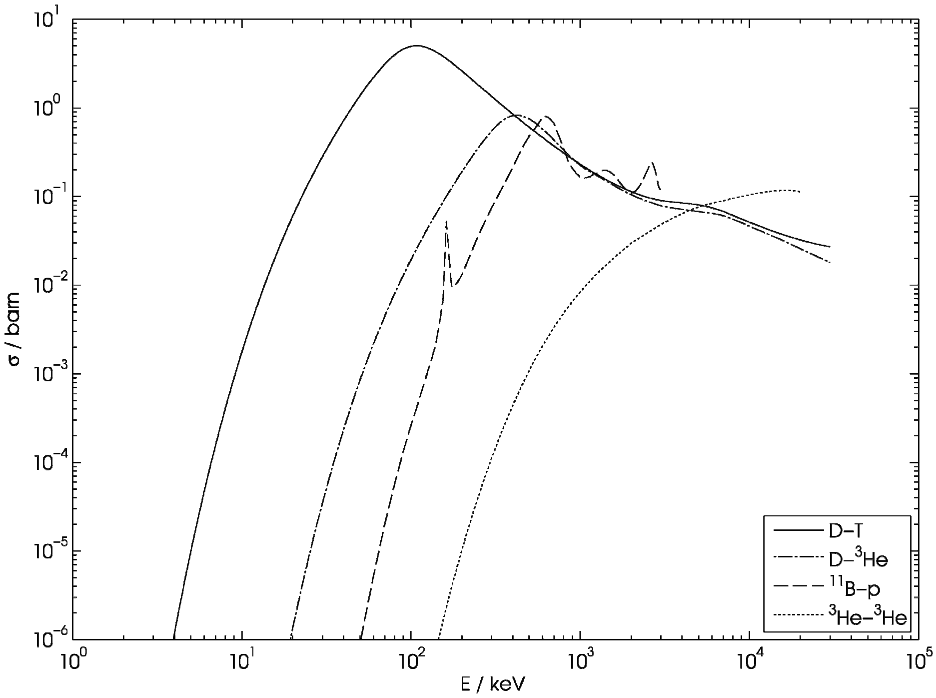


Figure 24 – Fusion cross sections

There are various approaches to reach the temperatures and cross sections from Figure 24. The most commonly discussed is *thermal fusion* which consists in generating high enthalpy plasma in which fully ionised atoms would achieve respective temperatures and in which fusion would occur. The plasma needs to be around 10 keV to 10 MeV and would consequently destroy any material, surpassing even the best heat resistances. This is the cause for a magnetic plasma confinement. The thermal ions in the plasma can be deviated and thus kept from walls by magnetic fields. Several geometries and respective open and closed reactor designs have been proposed so far. The most mature design is the Tokamak concept which is also the basis of ITER [R 8]. Tokamak is a Russian acronym meaning "Toroidal Chamber with Magnetic Coils" (***To****roidal'naya* ***Ka****mera s* ***Ma****gnitnymi* ***K****atushkami*). Other notable toroidal designs are the Stellarator, the Spherical Torus and the Field Reversed Configuration. Further, there are also linear confinement concepts such as mirror machines which have a particular interest for propulsive devices. These Magnetically Confined Thermal Fusion approaches usually contain rather rarefied plasma in which particles can move multiples of the plasma's diameters before encountering any other particle. A few Gasdynamic Fusion concepts with a magnetic confinement have been proposed in which the ions can only move a small fraction of the plasma's diameter before encountering another one [R 50].

Another concept to confine a thermal plasma relies rather than on magnetic fields on an interplay of electrical fields and inertia. In such a generic *Inertial Electrostatic Confinement (IEC)*, a spherical and strongly negatively biased grid is placed concentrically in a grounded, evacuated, spherical cavity flooded with plasma. Its ions are then accelerated to the grid centre as a point of stable equilibrium. Due to inertia, they overshoot before being attracted again. While the majority of ions do not take part in fusion processes, occasional events may occur if the ions' energies are sufficient. The concept is however not perceived as mature for power provision and is therefore not considered as a core of a fusion NTFP in this document [R 15].

In laboratories, fusion is often achieved by colliding particle beams. Recently it has been proposed to obtain fusion energy by targeting a Boron target with a beam of protons.

Finally, Inertial Fusion is considered for thermal fusion ignition. The concept is also known as "LASER Fusion" because it consists in imploding a small (Millimetres) pellet of solid fusion fuel with LASER beams aimed at its centre in which the implosion waves culminates and provides the necessary pressures and particle densities to ignite fusion [R 49].

In nature, fusion occurs in stars. These natural reactors use tremendous gravity for containment.

In contrast to fission, radioactivity issues are relaxed in fusion [R 49]. The principal issue is secondary radiation from neutron activated reactor elements. Among the four pertinent fusion reactions D-T, D-$^{3}$He, $^{11}$B-p and $^{3}$He-$^{3}$He, the first one has the most important yield in neutron radiation since about 80% of the released energy is yielded as this form of radiation. However, the expected amount and impact of activated material, i.e. radiologic waste is considerably reduced in comparison to fission waste. The remaining three reactions have considerably less radiologic issues and are nominally aneutronic [R 54, 56, 57]. This is – asides the considerably larger yield of energy and rich abundance of most fusion fuels in the solar system [R 50] – a decisive advantage of fusion among nuclear power sources.

### 2.4.2. Magnetically Confined Fusion Propulsion

*Magnetically Confined Fusion Propulsion (MCFP)* is a thermal propulsion concept. Its models are used for current generic fusion propulsion studies in Europe [R 15, 53, 54, 55]. The power is provided by the excessively hot magnetically confined fusion plasma. The propellant may consist in fusion products – the so called ash – but it is also thinkable to aliment the system with an additional coolant heated by the plasma and ultimately ejected as propellant [R 53].

The propulsion system relies on the fusion plasma whose operation is defined by the fusion criterion yielded by an *energy and particle balance* from which the characteristic *triple product* $n_i \tau_E T_i$ made up of the first species' ions' particle density $n_i$, the energy confinement time $\tau_E$, and the ions' temperature $T_i$ can be calculated [R 54].

The thermal power of the products in so called *ash drives (AD)* is assumed to be expanded with the exhaust velocity

$$c_{e,ash} = c_0 \left[ 1 - \left( \frac{\frac{3}{2} k_B T_i \tilde{\tau}_{Ea} \Psi}{c_0^{\,2} m_{pyr}} + 1 \right)^{-2} \right]^{\frac{1}{2}} . \qquad (12)$$

In equation (12), $c_0$ is the vacuum speed of light, $m_{pyr}$ the product mass yield per reaction, $\Psi$ the product particle multiple, and $\tilde{\tau}_{Ea}$ the ratio of ash to energy confinement time. The Boltzmann constant is noted $k_B$. Equation (12) is result of a relativistic derivation from a balance of thrust power / available heat and the resulting kinetic power in the jet. It is necessary to respect the relativistic, Einsteinian effects since the classical, Newtonian consideration yields exhaust velocities above the speed of light for the given high heat and low ash masses. This would not be physical. The thrust calculates from

$$F_{ash} = m_{pyr} R_{ik} c_{e,ash} \,. \tag{13}$$

using the reaction rate $R_{ik}$. The thrust efficiency $\eta_{TH}$ can be approximated by the ratio of product to reactant density.

In *working gas drives (WGD)*, the power losses of the plasma are partly recovered by the working medium. These parts sum up to $P_{T,wg}$. A relativistic derivation analogous to the one leading to equation (12) yields the exhaust velocity of working gas drives

$$c_{e,wg} = c_0 \left[ 1 - \left( \frac{P_{T,wg}}{c_0^{\ 2} \frac{dm_{wg}}{dt}} + 1 \right)^{-2} \right]^{\frac{1}{2}} . \tag{14}$$

The mass flow of the injected medium is noted $dm_{wg}/dt$ and needs to assure the necessary cooling of the system.

Both system concepts call for subsystems such as the reactors hardware, i.e. the first wall, a blanket which has to be porous in case of WGDs, magnets assuring the plasma confinement, and a cryo system providing operational temperatures of the magnets. Moreover, there have to be shields to protect the vessel against harmful radiation in case of D-T fuelling and there have to be radiators since the spatial vacuum prohibits waste heat disposal by convection and conduction leaving radiation the only resort. Note that the regenerative recovery of waste heat for propulsive means in WGD will lead to a considerably diminished radiator size compared to AD and therefore better propulsion system mass MP.

The system setup of a generic WGD and its power fluxes are depicted in Figure 25.

Once more, hydrogen is destined to be used as working medium for its excellent caloric and propulsive properties. As for the fusion fuel, in general four reactant couplings are considered: D-T, the "classic" fusion reaction considered for terrestrial power generation, and the three advanced couples D-$^3$He, p-$^{11}$B and $^3$He-$^3$He. The major advantage the advanced couples promise

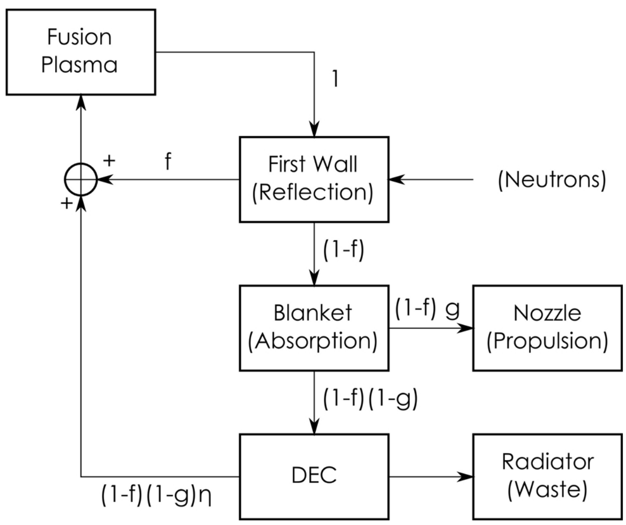


Figure 25 – Generic system setup of WGD MCFP [R 54]

is a considerable reduction in neutron radiation and hence lightweight shields. However, investigations [R 54] showed that only D-$^3$He is worthwhile as a fuel in MCFP.

Estimated propulsive data based on the MCFP models is documented in Table 11.

| System | $T_i$ / keV | B / T | P / W | $c_e$ / m/s | F / N | $\eta_{TH}$ / % | m / t | ε / % | τ / d |
|---|---|---|---|---|---|---|---|---|---|
| D-T – AD | 22 | 3 | 3.0 e 6 | 2.2 e 6 | 2.8 | 1 | 480 | 99.94 | 2700 |
| D-T – WGD | 22 | 3 | 5.3 e 8 | 6.0 e 3 | 1.8 e 5 | 94 | 460 | 3.43 | 220 |
| D-$^3$He – AD | 90 | 14 | 7.8 e 7 | 5.1 e 6 | 30.7 | 4 | 170 | 99.85 | 477 |
| D-$^3$He - WGD | 90 | 14 | 1.9 e 9 | 1.8 e 5 | 2.0 e 4 | 91 | 100 | 35.69 | 20 |
| p-$^{11}$B - AD | 165 | 106 | 5.1 e 10 | 6.0 e 6 | 1.7 e 4 | 26 | 10000 | 99.62 | 160 |
| p-$^{11}$B - WGD | 165 | 106 | 1.8 e 11 | 2.8 e 4 | 1.3 e 7 | 93 | 3200 | 18.42 | 80 |

Table 11 – Propulsive characteristics of MCFP systems (generic system, 10m³ of plasma, B magnetic containment)[7]

### 2.4.3. Other magnetic fusion propulsion approaches

Due to its intrinsic advantages, fusion propulsion has been subject of various studies [R 50, 51]. John F. Santarius conducted studies concerning fusion based on $^3$He. These cover both the acquisition of the substance in the solar system, from Lunar regolith or the atmosphere of the gas giants, and the setup of a respective system. Concepts by further authors stipulate magnetic field geometries, such as Spheromaks, Spherical Tori (STR) or Field Reversed Configurations (FRC) [R 50, 51, 58]. Other designs rely on tandem mirror configurations of on the common Tokamak design. Reference [R 58] was an extensive systems study considering astronautic missions to Jupiter also covering many aspects other than the propulsion system. Two illustrations from [R 58] are shown in Figure 26 and Figure 27. Relevant data is collected in Table 12.

.

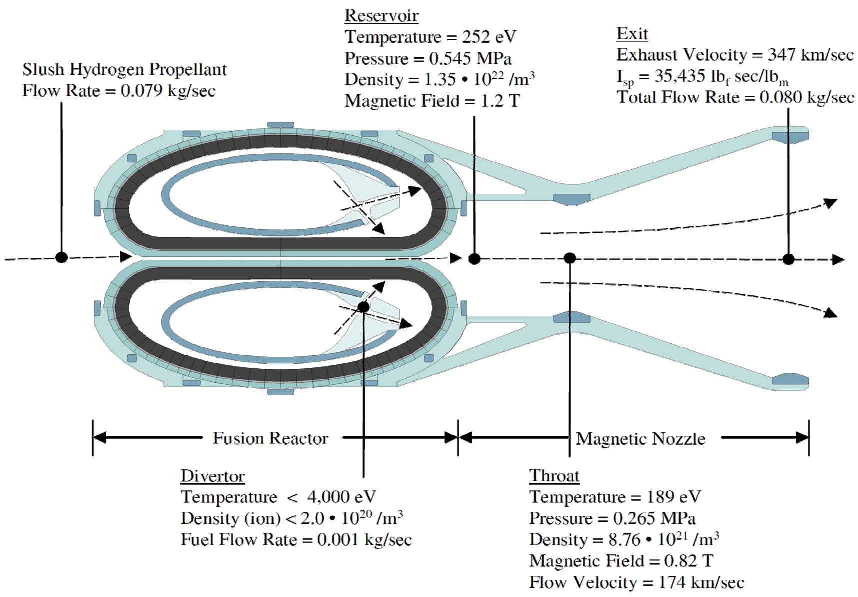


Figure 26 – Fusion NTFP according [R 58]

[7] $^3$He-$^3$He systems do not ignite.

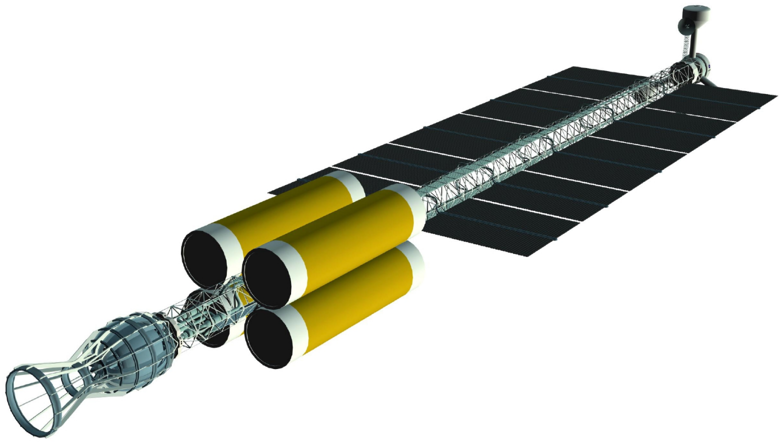

Figure 27 –Discovery II space craft [R 58]

Another interesting approach was proposed by Terry Kammash [R 50, 59, 60]. While thermal fusion propulsion is generally based upon so called collisionless confinement concepts, Kammash proposes the so called *Gas Dynamic Mirror (GDM)*. The approaches are distinguished in the densities of the plasmas. While confined plasma particles can travel several lengths of the containment in collisionless approaches before eventually colliding with another one, this not possible in gas dynamic confinements in which the mean free path is much shorter resulting in gas dynamic properties. Thus, Kammash comes to conclusions fundamentally different from those in MCFP if it comes to the role of a working medium. In the latter, the working medium was needed to provide for significant a mass flow because the plasma ashes and other ejecta were not sufficient to create a relevant level of thrust. In gas dynamic fusion propulsion, this is however not the case and the working medium can be omitted. Another important feature of the gas dynamic mirror is the confinement itself which formed a magnetic nozzle. A drawing is given in Figure 28 beneath.

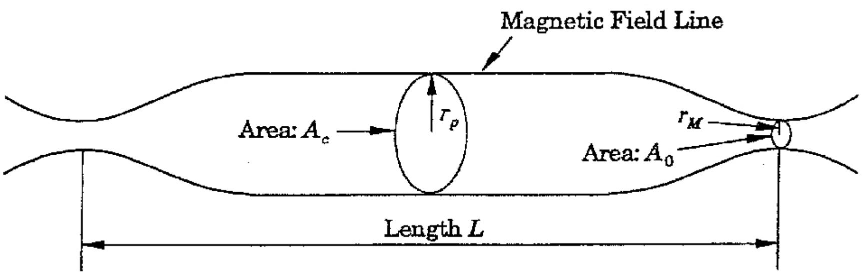


Figure 28 – Gas Dynamic Mirror [R 59, 60]

| Type | m / t | $c_e$ / m/s | F / kN | $B_b$ / T | P / MW |
|---|---|---|---|---|---|
| GDM (D-T) [R 50] | 7230 | 1136000 | 50 | 16 | 55000 |
| GDM (D-$^3$He) [R 50] | 358000 | 5000000 | 6700 | 184 | 2.773 $10^7$ |
| GDM (D-T) [R 60] | 400 | 1270000 | 2.5 | 9 | 1350 |
| STR (D-$^3$He) [R 50] | 200 | 200000 | 62 | N. A. | 6200 |
| STR (D-D) [R 50] | 200 | 2700000 | 41 | N. A. | 55000 |
| Discovery II (D-$^3$He) [R 58] | 360 | 350000 | 28 | 9 | 4900 |

Table 12 – Approximate propulsive characteristics of selected Thermal Fusion Propulsion systems

### 2.4.4. Inertial Fusion Propulsion to the stars: Daedalus and Icarus

Far more advanced concepts in Nuclear Thermal Propulsion rely on *Inertial Fusion Confinement (ICF)*. An object of study is the VISTA space craft which merits to be mentioned. The space craft has a characteristic diameter of approximately 80 m and is supposed to deliver 100 t of payload at Mars in a round trip time of about 130 days and to Jupiter in a little more than a year.

More audacious applications based on ICF approaches encompass studies on *interstellar precursor missions*, such as Daedalus [R 61]. Daedalus was a project run by the British Interplanetary Society and consisted of two inertial fusion driven stages. The first stage should accelerate the space craft over two years to the boundaries of the solar system were the upper stage (also burning for two years) was separated and bound for Barnard's Star, almost 6 light years away. The target was chosen for being suspected to have a planetary system like Earth's sun. The voyage would take at a cruising speed of 12% of the speed of light approximately fifty years, and could thus reach Barnard's Star within a human life time. Robotic wardens hovering around the space craft were stipulated to tend it during the voyage. At the arrival, the space craft would deploy several smaller robotic probes intended to conduct all sorts of exploration and science in Barnard's Star's System. Daedalus' parameters were for the first and the second stage respectively 7500 kN and 700 kN of thrust, and 10000 km/s and 9000 km/s of exhaust velocity. The upper stage was estimated to be about 50000 t and the second one to be about 5000 t. Each stage included 90% of propellant and the overall length would be 200 m.

The concept is currently being overhauled under the name Project Icarus[8]. Icarus aims at conducting this precursor mission by the beginning of the 22nd century [R 62].

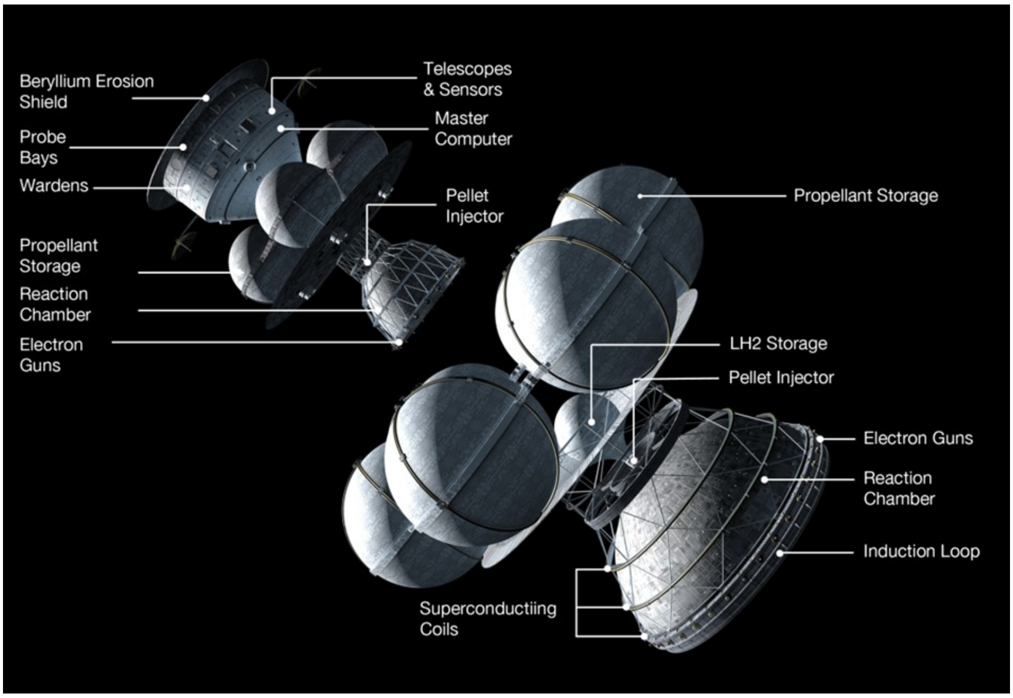


Figure 29 – Daedalus Space Craft – Artist's Rendering (courtesy Adrian Mann) [R 62]

[8] In classic Greek mythology, Icarus was the son of Daedalus.

## 2.5. Matter-Antimatter-Annihilation propulsion

As noted in Table 1, the most yielding nuclear process is *Matter Antimatter Annihilation (MAA)*. Space propulsion concepts relying on this process are relatively common in popular culture. While two concepts are technically thinkable, scientific authors doubt its feasibility and utility [R 13]. Thus, this process is merely touched in this report.

Antimatter is a substance made up of anti-particles. Anti-particles have the same mass, spin and magnetic momentum as their "normal" correspondents. Particles and anti-particles carry different charges. For example, the positron is like an electron, but while the latter is negatively charged, the positron is positive as indicated in its name. The proton has a negatively charged anti-particle which is simply called *antiproton*. If electrons and positrons come close enough their masses disappear and yield energy in the form photons of respective wavelength [R 10]. According to the Einsteinian mass equivalent ($E = mc^2$) the energy yield is the maximum possible. In the case of proton antiproton annihilation, also a pion appears which contains 22% of the initial mass.

The first concept to use this energy aims at exploiting the resulting photons and pions for propulsion. Purely photons are yielding the maximum possible exhaust velocity – the speed of light. The available thrust by photons is however limited if not considerable masses of matter and antimatter are brought to reaction. Then, the spacecraft would have to extend about 7 km in diameter. The second concept resembles the WGD MCFP and uses the matter-antimatter reaction contained in a vessel to heat up a working medium penetrating the cavity through a porous blanket. Estimations [R 63] yield however both lower thrust and lower exhaust velocities than WGD MCFP.

The main issue in this concept is however the availability and storage of antiprotons [R 13]. They do not appear in nature and need to be produced in particle accelerators. The production is extremely power consuming. According to [R Hub], this process has an efficiency of 1/109 at best, i.e. for anti-matter enabling 1 J of energy, 1 GJ needs to be consumed. The world antiproton production rate is also limited to 1 ng per year and seen that the first interesting applications require several grams of antiprotons this implicates infeasibility. Above that the process produces extremely radioactive waste. Further note that antiprotons cannot be stored in tanks since they would react immediately with random protons of the surrounding material and disappear. Antiprotons can only be stored in ionised state in a magnetic containment similar to those in MCFP and the current maximum storage duration does not exceed a couple of hours adding to the concept's current infeasibility.

At the current state, this approach seems far too advanced.

# 3. PCS Concept overview

As discussed before, NTP systems use heat released in nuclear processes to generate thrust. Many of these systems yield a power superior to that of conventional systems. It is a typical feature of NTP to have rather high efficiencies, some tested systems like NERVA were reported to reach up to 90% of thrust efficiency [R 25, 26].

However, even with so much power used for the actual purpose – propulsion in this case – large heat fluxes are expected in the system. This can be as much as about 500 kW in the case of a PHOEBUS II with 90 % efficiency. A waste heat of 500 kW is about four times as much as consumed by the International Space Station. This poses a severe challenge to the space craft. In space, waste heat can only be dumped through radiation. With a small available surface of the engine the latter runs the risk of getting critically hot. Thus, a heat sink of radiators is commonly considered to be a part of the NTP. Wanting higher overall system efficiencies this waste heat can also be reaped for electrical energy provision. This would become particularly interesting if the engine in idle mode would also offer the heat of radioactive decay of fission after heat.

The electrical energy obtained from that can then be provided to other space craft systems or auxiliary Electric Propulsion. There are many available conversion systems [R 4]. The reference gives a fair overview on available processes and technologies in the fields of thermo-electric and thermo-voltaic conversion.

The more advanced thermionic energy converter (TEC) is a static device which converts heat directly into electrical energy. A TEC consists of very hot emitter, i.e. a cathode at 1500-2500 °C and significant colder collector or anode. Emitter and collector are placed very close to each other. Due to thermionic electron emission from the emitter, the electrons flow from emitter to collector producing net current flow. In order to achieve the highest efficiency an optimum between emitter and collector is required. The most pertinent TEC devices are:

- closed spaced vacuum thermionic diode,
- Caesium gas filled thermionic diode,

and can have flat or coaxial cylindrical shape [R 64]. While closed spaced vacuum thermionic diodes have no leakages problems, the leakage of Caesium in the gas filled diode can decrease the life time of the TEC. The fill gas is used to decrease charges improving this way the electron flow and allowing larger gap distance between emitter and collector [R 64]. Additionally the Caesium ions decrease the work function of collector made of Tungsten and increasing intricacy of voltage characteristics between emitter (cathode) and collector (anode). Furthermore, additional auxiliary discharge arc (steady state or pulsed) can be used in order to increase the ionization of Caesium gas (Ignited Caesium diode) [R 64, 65]. Here, external power is needed to induce sufficient ionization and provide for charge compensation. In order to decrease the emitter's temperature at high current densities for the sake of longevity, small cavities formed in the emitter surface were investigated for generation of ions without additional external power, thus reducing the voltage drop in the plasma and effectively increasing the emission from the emitter surface [R 65]. The use of developed surface emitters in TEC appears promising, operating at low emitter temperatures, which are applicable to power systems with low temperature heat sources or in converters used for a topping cycle in Power conversion system (PCS) [R 65].

TEC systems can achieve energy conversion efficiencies in the range between 5 and 17 % [R 64, 66, 67]. However, the leakage and loss of caesium has tended to be a significant life-limiting factor. TECs operating with ignited plasmas in Caesium-Oxygen vapor may eventually operate at temperatures of 1800-2000 K, and with low thermal emissivity collectors at temperatures of 600-800 K, yielding efficiencies of 20-25% at power densities of 10-20 W/cm² with a life time of 5-10 a. This lifetime would make thermionic energy converters very attractive for space nuclear power systems [R 64]. TECs operating with emitter temperatures between 2400-2800 K would allow even high power density and efficiency with a very limited operational life time (less than one year) [R 64]. Thermionic energy converters were already tested by Russians in space environment with the 5 kWe TOPAZ-1 reactor [R 68].

Thermodynamic processes such as the Sterling cycle, Brayton cycle and Rankine cycle [R 4] would be however more interesting. The Brayton cycle is used in gas turbines in terrestrial power plants. It consists of four work steps. At first the gas will be compressed by a compressor. Then it is heated isobaric and expanded in a turbine which drives the compressor. In the same time, it generates electric power. Finally the gas will be cooled down and will re enter the compressor. Terrestrial applications with Brayton cycle achieve nowadays efficiencies of up to 60 %.

Rankine cycle is used in water steam turbine by most terrestrial power plants. The cycle works at the wet steam region of the medium. The liquid medium is pumped from low to high pressure. The pressured medium enters a boiler where it is heated at constant pressure by an external heat source to become a dry steam. The dry saturated steam expands through a turbine generating power. This decreases the temperature and pressure of the steam, and some condensation may occur. The wet steam then enters a condenser where it is condensed at a constant temperature to become a saturated liquid and enters the pump. The efficiency is merely limited by the Carnot's.

# 4. Conclusion and evaluation matrix

The present report covers Nuclear Thermal Propulsion approaches and explains numerous examples of conceptual designs ranging from disruptive to advanced technologies basing on four nuclear power processes. A focus was set on Radio Isotope Heated Propulsion (RHTP) and Nuclear Thermal Fission Propulsion (NTFP). Among the latter, NERVA based NTP still remain the most developed propulsion systems. Fusion based Thermal Propulsion was introduced. These systems constitute the most interesting propulsion systems currently proposed. With Fusion expected to be available by the mid of the century, they compose a group of potentially disruptive technology of the next generation. Advantageous features of these NTP have been identified to be in generally large mass specific power, high exhaust velocities and good thrust levels. More advanced mission approaches and fast interplanetary transfer seem attainable with NTP due to high accelerations as well as payload mass fractions relevant for a sustainable development of the solar system due to high exhaust velocities.

Table 13 on the next page concentrates characteristics of various NTP approaches in a system focussed evaluation matrix.

During the preparation of the report it was observed that many of these systems have a long research tradition. The consequences of this fact is that there is a lot of literature available of which only a small part was reviewed due to the limited extent of the DiPoP project. It was however also observed, that information on a given NTP is often scattered and incoherent. Occasionally, referenced documents are not available, or lost. These circumstances make a case for an extended literature research on NTP technology and analytical studies for the sake of veryfying the available data. With the information consolidated and founded with analytic means, an educated decision on which systems to focus is enabled and more detailed studies on system setups, subsystems and physics can be conducted in a determined and rational manner. This also covers Power conversion systems (PCS) which highly depend on a given NTP design. It is recommended to generalise the PCS and Electric Power Processing Units (EPPU) in further studies.

| | Solid RHTP | Liquid RHTP | Solid NTFP | Liquid NTFP | Gaseous NTFP | ORION | NSWR | MCFP (WGD) | GDM |
|---|---|---|---|---|---|---|---|---|---|
| **Relative Technological Readiness** | *** | * | *** | * | * | *** | * | ** | * |
| **Available information** | ** | ** | *** | ** | *** | ** | * | ** | ** |
| Principle | *** | *** | *** | *** | ** | ** | * | ** | ** |
| Scaling models | ** | * | ** | * | *** | ** | *** | *** | *** |
| Experimental data | ** | * | *** | * | ** | ** | - | - | - |
| Project documentation | ** | - | *** | * | ** | ** | - | - | - |
| **Safety** | | | | | | | | | |
| Power controllability | - | - | *** | ** | ** | ** | * | *** | *** |
| Passive accident prevention | - | - | ** | * | * | - | ** | *** | *** |
| Radiologic safety | | | | | | | | | |
| Avoidance of loss of radiologic inventory | ** | * | ** | * | * | - | - | ** | ** |
| Low severeness of radiation | * | * | * | * | * | * | ** | *** | *** |
| Low health issues | ** | ** | ** | * | * | * | ** | *** | *** |
| Low chemical risks | *** | *** | ** | * | * | ** | ** | *** | *** |
| System safety | | | | | | | | | |
| Insusceptible to single point failures | *** | * | ** | * | * | * | * | ** | ** |
| Low system level failure severeness | | | | | | | | | |
| Safety means | | | | | | | | | |
| Shield | *** | *** | * | * | * | * | ** | *** | *** |
| Distance | *** | *** | ** | * | * | - | * | *** | *** |
| Containment | *** | * | ** | * | * | - | ** | *** | *** |
| Low maintainance | *** | *** | ** | ** | ** | * | * | *** | *** |
| System degradation | - | - | ** | * | * | ** | * | *** | *** |
| **Fueling** | | | | | | | | | |
| Cost | ** | ** | *** | ** | ** | * | ** | * | * |
| Availability | ** | ** | ** | ** | ** | ** | ** | * | * |
| Fuel readiness | *** | *** | *** | ** | ** | * | ** | ** | ** |
| In Situ Resources | * | * | ** | ** | ** | * | * | *** | *** |
| **Propulsion characteristics** | | | | | | | | | |
| High exhaust velocity | * | ** | * | ** | *** | *** | *** | *** | *** |
| High characteristic acceleration | * | * | ** | ** | *** | *** | *** | *** | ** |
| High mass specific power | * | * | ** | *** | *** | *** | *** | *** | *** |
| Parameter invariance | - | - | *** | ** | ** | ** | *** | *** | *** |
| Parameter controllability | - | - | ** | ** | * | ** | * | ** | ** |

Table 13 – Evaluation Matrix of concepts of NTP
(- - very bad or intrinsically impossible; * - relatively bad; ** - average; *** - good )

# Annex A: Exhaust velocity implications

The exhaust velocity of thermal propulsion systems is approximately

$$c_e = \sqrt{\frac{2\gamma}{\gamma - 1} \cdot \frac{R\,T}{M_A}}\,, \tag{A}$$

in which $\gamma$ is the ratio of heats, $R$ the gas constant, $M_A$ the molecular mass of the propellant and $T$ its temperature. The equation reveals that higher temperatures are better for augmented exhaust velocities as well as minimum molecular masses. It can be shown [R 7, 9] that the influence of $\gamma$ is not as important. Further, it can be concluded that hydrogen is the optimal propellant. Hydrogen has also the best heat properties making it the best coolant as well. However, it is difficult to store and will likely make a case for cryogenic tanks.