NUCLEAR ROCKET PROPULSION

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INTRODUCTION TO NUCLEAR PHYSICS AND NUCLEAR ROCKET PROPULSION

Outline

- **Thrust, Power and Energy**

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- **Space Engineering: NERVA**

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- **Space Engineering: NERVA**
- **Advantages Limitations**

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- **Thrust, Power and Energy**
- **Space Engineering: NERVA**
- **Advantages Limitations**
- **Current projects: France, Russia, USA**

Nuclear Thermal Rocket

Definition:

A nuclear thermal rocket is a proposed spacecraft propulsion technology. In a nuclear thermal rocket a working fluid, usually liquid hydrogen, is heated to a high temperature in a nuclear reactor, and then expands through a rocket nozzle to create thrust.

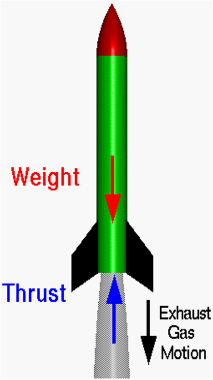
Part I

Power, Thrust and Energy

Thrust

Definition:

When a system accelerates mass in one direction, the accelerated mass will cause a force (thrust) of equal magnitude but opposite direction (reaction force described quantitatively by Isaac Newton's second and third laws).



Thrust

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A rocket is propelled forward by a thrust force:

$$F = \frac{dm}{dt} v_e + (p_e - p_a) A_e \overset{p_e = p_a}{=} \dot{m} v_e$$

in the ideal case where the exit pressure p_e of the exhaust gas equals the ambient pressure p_a at the exit plane A_e of the nozzle!

- $\dot{m}$: rate of change of mass with respect to time (mass flow rate of exhaust in kg/s),
- v_e: speed of the exhaust gases (exhaust velocity) accelerated through the rocket engine nozzle measured relative to the rocket!

Propulsive Power

Power in the exhaust stream, in J/s:

$$P = \frac{1}{2}\dot{m}v_e^2.$$

Quantities:

- $\dot{m} = \frac{dm}{dt}$: mass flow rate in kg/s,
- v_e: rocket exhaust velocity.

Energy

Propulsion energy contained in a kg of propellant:

$$\frac{P}{\dot{m}}\left(\equiv\frac{E/t}{m/t}=\frac{E}{m}\right)=\frac{1}{2}v_e^2,\text{ in J/kg.}$$

Energy requirement per unit mass of an interplanetary mission with a departure velocity of 11 km/s:

$$\frac{1}{2}V^2=60.5\,\text{MJ/kg.}$$

Chemical Rocket Engine:

Energy contained in 1 Kg of a fossil propellant (carbon-12) is 16 MJ such that 1 Kg of this propellant could accelerate 265 g of vehicle mass.

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Nuclear Rocket Engine:

The energy contained in 1 kg of pure uranium 235 is $\simeq 86\times10^6$ MJ; a single kilogramme of uranium 235 could accelerate a spacecraft weighing 1400 tons to interplanetary velocity, if its energy could be harnessed.

Motivation for nuclear propulsion

Propulsion energy contained in a kg of propellant:

$$\frac{P}{\dot{m}} = \frac{1}{2}v_e^2, \text{ in J/kg.}$$

Energy requirement per unit mass of an interplanetary mission with a departure velocity of 11 km/s:

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From 1 Kg of each propellant (1)C, (2) ^{235}U and (3)H:

1. Chemical ($\sim$ 2 eV): $\sim$265 g of vehicle mass can be boosted into space
2. Nuclear neutron-induced fission ($\sim$ 210 MeV): $\sim$ 1400 tonnes...
3. Nuclear fusion ($\sim$ 30 MeV): $\sim$ 240000 tonnes ...

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Part II

Space Engineering

Rover/NERVA Program (1955-1973)

1. NERVA=Nuclear Engine for Rocket Vehicle Application
2. 20 Reactors Designed, Built & Tested from 1955-1973
   - Total Cost 1.4 B
   - Reactors Kiwi, Phoebus, NRX, Pewee
3. 1100-4100 MW Reactors
4. 55-2700 K Fuel Temps
5. I_{sp} to 850 sec (Pewee)
6. “Burn" Durations 1-2 Hours

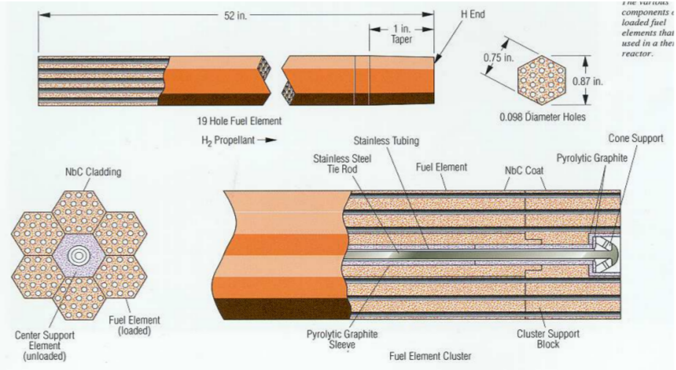
Main source:

Rocket and Spacecraft Propulsion, Principles, Practice and New Developments; Martin J. L. Turner (2005)

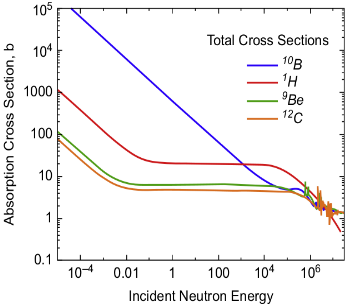
Nuclear Engine for Rocket Vehicle Application (1955-1973)

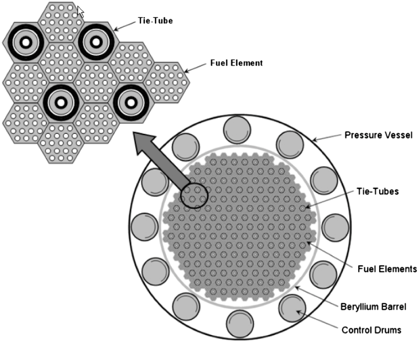
Fuel element assembly from the KIWI reactor core:

Fuel is enriched $^{235}\mathrm{U}$ oxide sphelules embedded in graphite. Each rod has 19 holes for the hydrogen to flow down. A cluster of six rods are held together by a stainless steel tie rod and the elements are coated with niobium carbide (NbC cladding).



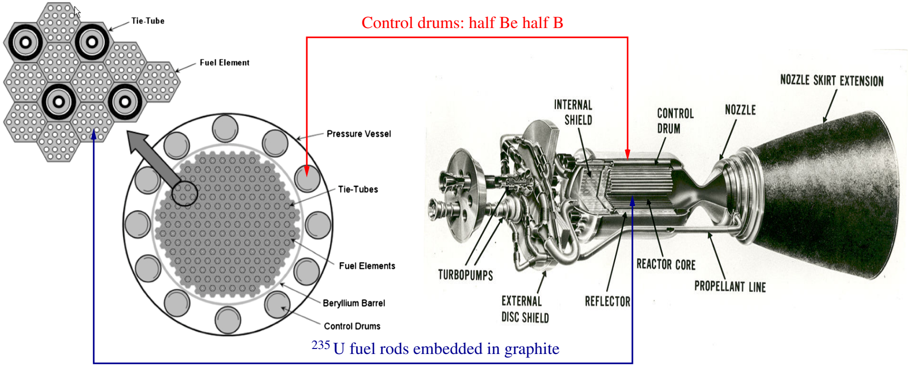
Nuclear Engine for Rocket Vehicle Application (1955-1973)





1. Control drums: half B (absorption) half Be (reflector) to maintain stable criticality,
2. Internal shield against γ-radiation: lead and tungsten.

Nuclear Engine for Rocket Vehicle Application (1955-1973)



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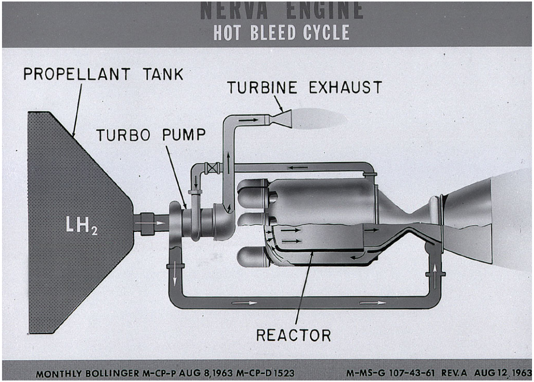
Hot bleed cycle

Hot gas extracted from the reactor chamber is used to drive the turbo-pumps and is then exhausted through a small auxiliary nozzle.

Auxiliary nozzle needed in order to compensate the reduced thrust from the main nozzle.



Nuclear Engine for Rocket Vehicle Application (1955-1973)

Thrust versus exhaust velocity and specific impulse

In rocket engineering the thrust and the exhaust velocity are universally quoted in terms of the specific impulse (I_{sp}):

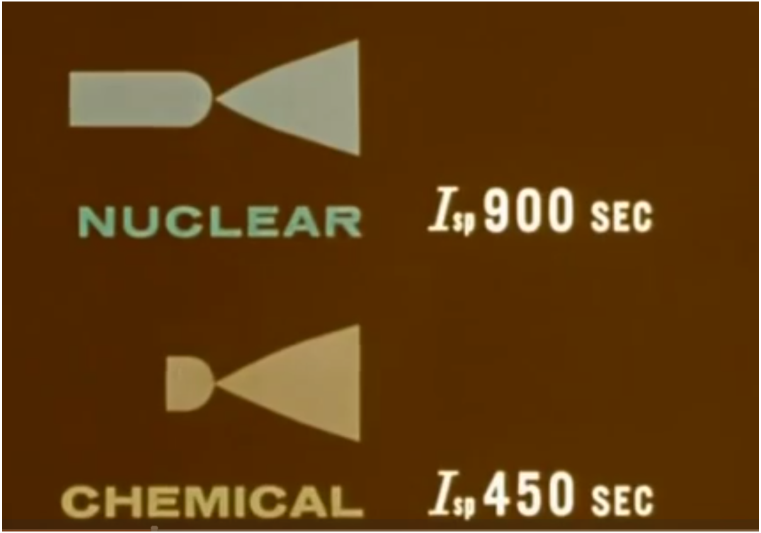
$$F = \dot{m} v_e \quad \text{where} \quad v_e = g I_{sp} = C_F c^*.$$

Characteristic Velocity

$$c^* = 1.54\sqrt{\frac{8.31 \times T_0}{\mathcal{M}}}$$

1. Chemical rocket exhaust velocity: $v_e = 4.25$ km/s for $\mathrm{H_2}$ fuel and $\mathrm{O_2}$ oxidant, mean $\mathcal{M} = 12$ g/mol and $T_0 = 3215$ K ($I_{sp} = 450$ sec)
2. Nuclear rocket exhaust velocity: $v_e = 8.86$ km/s for molecular hydrogen $\mathcal{M} = 2$ g/mol and $T_0 = 2330$ K ($I_{sp} = 850$ sec Pewee)

Nuclear Engine for Rocket Vehicle Application (1955-1973)



Nuclear Engine for Rocket Vehicle Application (1955-1973)

Parameters	NRX XE	NERVA 1	New designs based on NERVA		
Fuel Rods	UO_2 beads embedded in graphite	UO_2 beads ZrC coat, embedded in graphite	$UC_2 + ZrC + C$ composite	$UC_2 + ZrC$ all carbide	$UC_2 + ZrC + NbC$ all carbide
Moderator	Graphite	Graphite+ZrH	Graphite+ZrH	Graphite+ZrH	Graphite+ZrH
Reactor Vessel	Aluminium	High-strength steel	High-strength steel	High-strength steel	High-strength steel
Pressure (bar)	30	67	67	67	67
Nozzle Expansion	100:1	500:1	500:1	500:1	500:1
I_{sp} (sec)	710	890	925	1020	1080
Chamber Temperature (K)	2270	2500	2700	3100	3300
Thrust (kN)	250	334	334	334	334
Reactor Power (MW)	1120	1520	1613	334	334
Engine Availability (yr)	1969	1972	?	?	?
Reactor Mass (kg)	3159	5476	5853	6579	?
Nozzle, pumps etc mass (kg)	3225	2559	2624	2624	?

Conclusion Of This Section

Conclusion 1:

High performance depends much more on the ability of a nuclear thermal engine to use hydrogen (the lightest of all elements), alone, as the propellant, than it does on the nuclear source of energy.

$$c^* \propto \frac{1}{\sqrt{\mathcal{M}}}$$

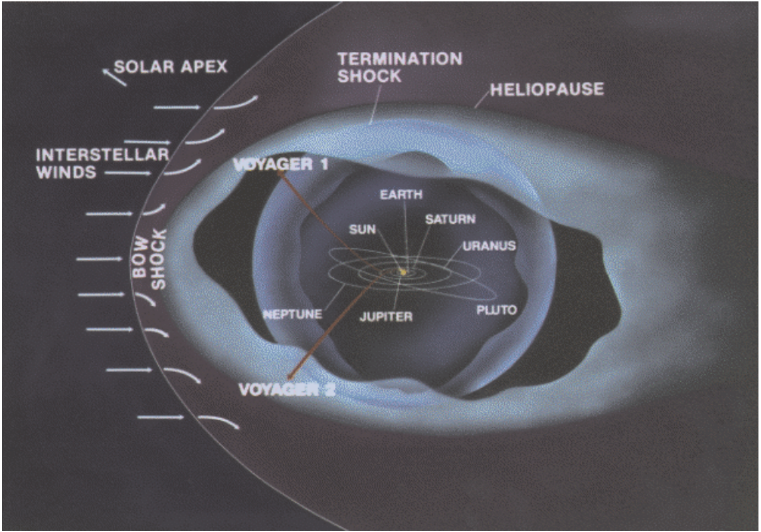
Conclusion Of This Section

Conclusion 2:

The nuclear engine is useful because of its high thrust related to the high power input from nuclear fission, coupled with its high exhaust velocity about twice that achievable with a chemical engine.

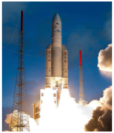
Part III

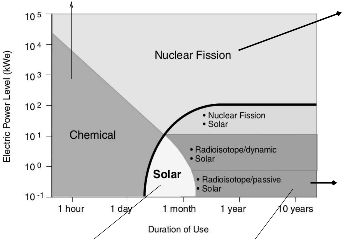
Advantages and Limitations

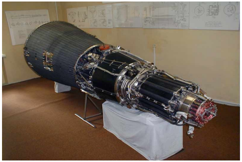


Across the Universe: Voyagers 1 et 2 (1977) alive??

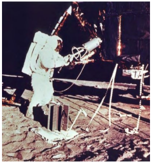
Space power sources



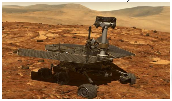


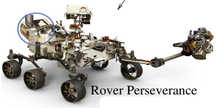


TOPAZ nuclear reactor



Removal of SNAP–27 RTG from lunar module by G. Bean during Apollo–12 on the moon 1969





Rover Perseverance

Space power sources

Static:

1. Thermoelectric (Thermocouples on RTGs)
2. Thermoionic emission generator (TEG)

Dynamic:

1. Brayton cycle
2. Rankine cycle
3. Stirling cycle
4. ...

Space power sources

- Thermionic emission is the thermally induced flow of charge carriers from a surface or over a potential-energy barrier.
- Richardson's law & Nobel Prize in Physics in 1928 "for his work on the thermionic phenomenon and especially for the discovery of the law named after him": $J = A_G T^2 e^{-\frac{W}{kT}}$, where
  - T and W temperature of the metal, W is the work function of the metal,
  - k, the Boltzmann constant and A_G, the Richardson constant.
- Cs vapor (very low ionisation energy) used to optimize the electrode work functions!
- Very high temperatures needed for effective use of thermionic converters. This is impractical in terrestrial applications, but very good for space application where radiant heat rejection is required (higher temperature of the radiator $\rightarrow$ smaller radiator!

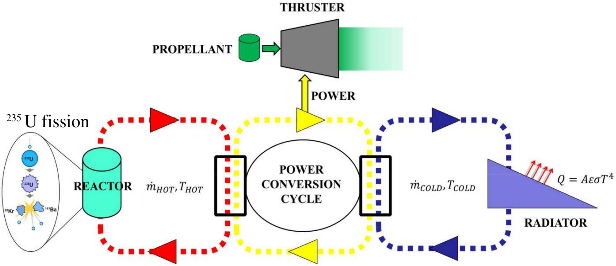
Space power sources

NPS type	Electrical power range (module size)	Power conversion
RTG	Up to 500 W(e)	Static: thermoelectric
Radioisotope dynamic conversion generator	0.5–10 kW(e)	Dynamic: Brayton Organic Rankine
Reactor systems: Heat pipe Solid core Thermionics	10–1000 kW(e)	Static: Thermoelectric Thermionics Dynamic: Brayton Rankine Stirling
Reactor system: Heat pipe Solid core	1–10 MW(e)	Brayton Rankine Stirling
Reactor: Solid core Pellet bed Fluidized bed Gaseous core	10–100 MW(e)	Brayton (open loop) Stirling Magnetic hydrodynamic

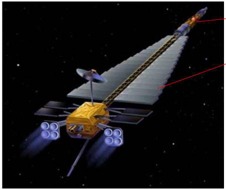
Main technical issue:

Heat rejection in space and energy conversion systems!

Main technical challenge: radiation is the only heat rejection mechanism in space!



JIMO:



550 KWt

177 m² radiator for reactor and converter waste heat rejection

$$\text{Area} = \frac{Q_{waste}}{\varepsilon\,\sigma\,T^4}$$

Source: PROMETHEUS PROJECT Final Report

Heat rejection: Jupiter Icy Moons Orbiter (JIMO)

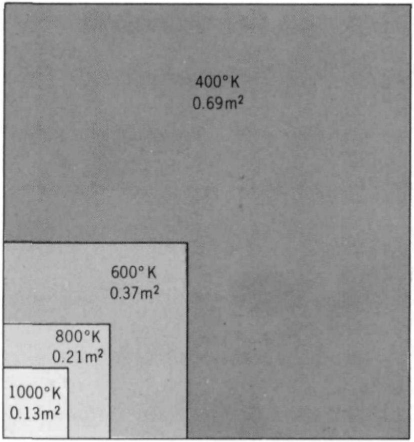
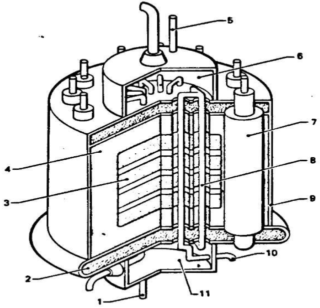
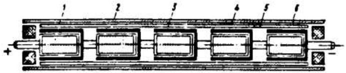


Figure 17 *Relative areas required to radiate waste heat to empty space at different temperatures. Increasing the radiator temperature rapidly brings down area and weight. (Figures given are calculated for 1 kilowatt of heat and perfect emissivity.)*

TOPAZ-I and TOPAZ-II Reactors





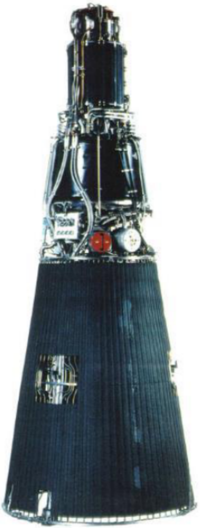
Basic arrangement of the TOPAZ thermionic fuel element (TFE): 1) fuel pellet; 2) emitter; 3) collector; 4) interelectrode gap; 5) collector insulation; 6) sheath.

DESIGN FEATURES OF THE TOPAZ THERMIONIC REACTOR SYSTEM[4,5,6]

Parameter	Value
Thermal Power	130 - 150 kWt
Electrical Power (maximum)	5 -10 kWe
Fuel Material	UO_2
Fuel Loading (^{235}U)	12 kg
Enrichment of Fuel	~90% ^{235}U
Moderator	ZrH
Neutron Spectrum	Thermal
Reflector	Be
Reactor Mass	320 kg
Core Diameter	0.3 m
Core Length	0.4 m
Reflector Thickness	0.08 m
Control Drums	12 Rotary, Be with B_4C backing
Coolant	NaK
Converter Characteristics	
Efficiency	4 - 7 %
Number of Converters	5 (of variable length) per TFE, totaling 395
Emitters	Mo or W (may be W-coated Mo)
Collectors	Nb
Emitter Temperature	~1725 K
Collector Temperature	~ 925 K

Characteristics of TOPAZ-1 reactor

TOPAZ-I and TOPAZ-II Reactors



Description	Value
Maximum electrical power at the reactor unit terminals supplied to consumer (kW)	5.5
Current type	Direct
Voltage (V)	27
Reactor thermal power (kW(th))	135
Maximum coolant temperature at the reactor outlet (°C)	550
Maximum emitter temperature (°C)	1650
Lifetime corroborated by nuclear tests (a)	1.5
Reactor unit mass (kg)	1000
Dimensions of the reactor unit:	
Length (mm)	3900
Maximum diameter (mm)	1400
Radiation situation over a plane of diameter 1.5 m at 6.5 m from the core centre:	
Fluence of neutrons with energy >0.1 MeV (n/cm^2)	5×10^{12}
Gamma radiation exposure dose (R)	5×10^5
Core diameter (mm)	260
Core height (mm)	375
Number of TFEs in the core	37
Number of rotational control elements in the side reflector	12
Loading of uranium-235 in the core (kg)	25
Effective neutron multiplication factor (control elements out, cold state) (k_{eff})	1.005
Total reactivity temperature effect (Δk/k)	0.012
Worth of 12 control elements (Δk/k)	0.055
Peak to average power density:	
Along to the core radius	1.1
Along to the core height	1.26
Lifetime ensured by the reactivity margin	3

Configuration and characteristics of the reacteur TOPAZ-II

Power and flight tests of the engines

	Romashka	SNAP-10A	TOPAZ-I	TOPAZ-II
$\mathcal{P}^{th}$ (kW)	28.2	34	150	≤ 135
$\mathcal{P}^{el}$ (kW)	1	1	1	2.07
Time (months)	24	1.5	6-12	18
Tests	1 (1964)	–	7 (1970-1984)	6 (1975-1988)
Launches	–	1 (1965)	-	2 (1987)

Part IV

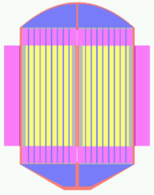
Current projects: France, Russia, USA

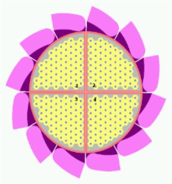
Current design projects (France)

- "Optimized Power Unit for Spacecraft" (OPUS) is a space nuclear reactor of 100-500 kW, developed in France (2002-2004).
- Not designed for specific mission: 3 years of operation at full power and 10 years of mission!
- OPUS is a fast neutron and gas-cooled reactor coupled to a Brayton conversion cycle.
- The OPUS fuel consists of uranium dioxide particles distributed in a carbon matrix, enriched to 93% in U-235.
- Four separable sub-critical parts for safety and launch!

Current design projects (France)

Optimized Power Unit for Spacecraft (OPUS)

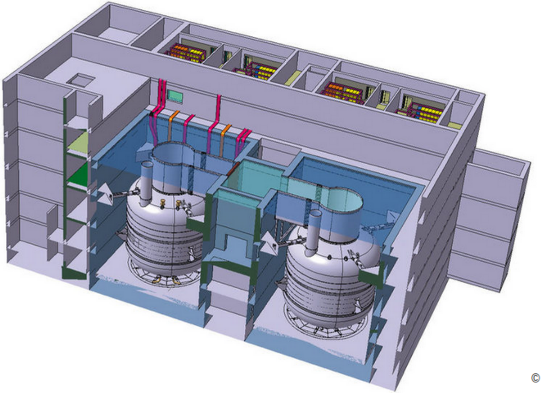




Electrical power	100-500 kW	
Thermal power	245-1725 kW	
Coolant type	He-Xe, 85 g/mol	
Fuel type	Graphite matrix with coated particles	
-matrix type	IG-110 graphite	
-particle type	BISO GBR4,	∅1.40 mm
-fissile kernel	UO_2 (93% of ^{235}U),	∅0.85 mm
-filling fraction	45%	
Uranium masse	193 kg	
Reflectors		
- axial	8cm of BeO	
- side	8cm of Be	
Vessel	Nb1Zr alloy	
-thickness	1cm	
Inlet core temperature	880 K	
Outlet core temperature	1300 K	
Coolant flow rate	3.6 kg/s	
Radiator	Two-side inconel radiator	
-Area	80 m^2	
-inlet gas temperature	550 K	
-outlet gas temperature	350 K	
Specific mass	33.5 kg/KW	

Current design projects (France)

In association with TechnicAtome, Naval Group and the CEA, EDF is betting on an ultra-compact SMR (small modular reactor) to replace coal-fired power plants: Nuward, an integrated unit with two 170 MWe pressurized water reactors expected in 2035.



Current design projects (Russia)

- Last planned version of a very large space tug propelled by electric motors powered by a nuclear source.

- From the dawn of the space age, the TEM (Transport and Energy Module) concept attempts to marry a nuclear reactor with an electric rocket engine.

- Electric propulsion systems heat and accelerate an ionized gas to create a thrust-generating jet and are therefore known as ion or plasma engines.

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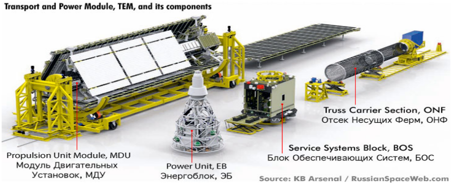

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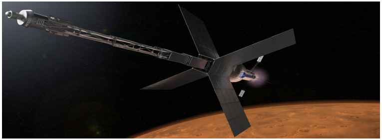
Current design projects (USA)

- NASA is studying two types of nuclear propulsion systems: nuclear electric propulsion and nuclear thermal propulsion.



1. At low thrust, nuclear electric propulsion systems accelerate spacecraft for extended periods of time and can propel a mission to Mars for a fraction of the propellant of high-thrust systems.

2. Nuclear thermal propulsion technology provides high thrust and twice the propellant efficiency of chemical rockets. Heat from the reactor converts liquid propellant into gas, which expands through the nozzle to create thrust (NERVA).

Merci beaucoup pour votre attention!