Nuclear Rocket Propulsion

Redamy Pérez-Ramos[1,2]

[1]Institut Polytechnique des Sciences Avancées (IPSA)
Ivry-sur-Seine, France

[2]LPTHE, UMR 7589 CNRS & Sorbonne Université, Paris, France

Nuclear rocket propulsion for ELS students

Outline

- **Chemical and nuclear reactions: how much energy available for consumption?**
- **Yukawa's model of the nuclear interaction**
- **Neutronics Physics: the Boltzmann equation, chain reactions, criticality. . .**
- **Space nuclear reactor dimensions**
- **Nuclear Engine for Rocket Vehicle Application (NERVA) of NASA (1955-1973)**

Type of reactions

1. Chemical reactions involve electrons: exchanged among atoms and rule by electromagnetic interactions (i.e. chemical combustion). The range of the interaction is infinite.
2. Nuclear reactions involve nucleons (i.e. protons, neutrons and other participating particles like pions)
   1. Fission process (well known): from heavy to lighter nuclei. It can be spontaneous but very rare in nature. It should be neutron-induced for consumption in industry (i.e. nuclear power plants, nuclear weapons).
   2. Fusion process (less known): from light to heavier nuclei. Nuclear reactions inside the sun and the stars. For consumption on earth, deuterium and tritium confined inside the TOKAMAK (i.e. ITER in Cadarache, France).

Type of reactions

Other interactions in nature

Fission and fusion processes are ruled by extremely short range interactions: electronuclear and electroweak!

Part I

Chemical reactions

Chemical reactions involving oxygen

Examples:

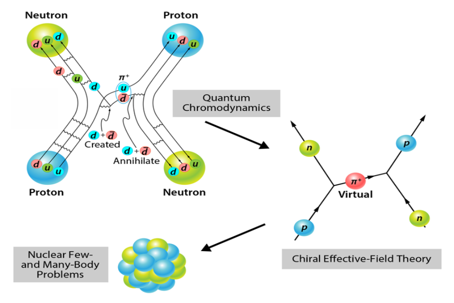
1. $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O + 3\text{eV}$: when one molecule of hydrogen burns in oxygen (or air), 3 eV of heat is produced.
2. $C + O_2 \longrightarrow CO_2 + 4.1\text{eV}$: where one atom of carbon is combusted into carbon dioxide under the production of 4.1 eV of heat.
3. For conversion: $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

Part II

Fission and fusion reactions

Yukawa's model of the nuclear interaction

- p-p, p-n, n-n, A-n, A-p interactions (Yukawa's pion exchange!)



$$R_p \sim \frac{hc}{4\pi m_\pi} \approx 10^{-15}\ \text{m}$$

$$\delta t \approx 10^{-23}\ \text{s}$$

$$\sigma_N \sim 10^{-28}\text{m}^2 = 1\ \text{barn}$$

$$\frac{\alpha_e}{\alpha_N} \sim \frac{1}{137}$$

Nuclear interactions

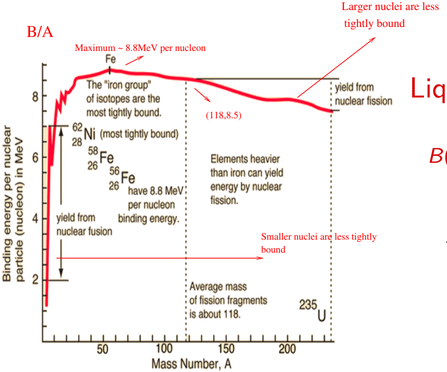
Pion mass (140 MeV) consistent with (i) nuclear interaction range ($\sim 10^{-15}$ m), (ii) typical time (10^{-23} s) of the nuclear interaction and (iii) order of magnitude of typical nuclear cross-sections ($\sim 10^{-28}$ m^2).

Fission and fusion processes: from many body problem

- (How much available energy for consumption?) Nucleus with atomic number A and charge Z has a binding energy with absolute value:

$$BE = \Delta m \cdot c^2 = \left[Z m_p + (A - Z) m_n - {}^{A} m_Z \right] \cdot c^2$$

- Fission and fusion processes result in reaching the final state with a higher BE/A ratio (most stable configuration)



Liquid-drop model of the nucleus:

$$B(A,Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z-1)}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} + C$$

$$\Delta\left(\frac{B}{A}\right) \sim 0.9 \Rightarrow 0.9 \times 235 \sim 210 \text{ MeV} / {}^{235}\text{U}$$

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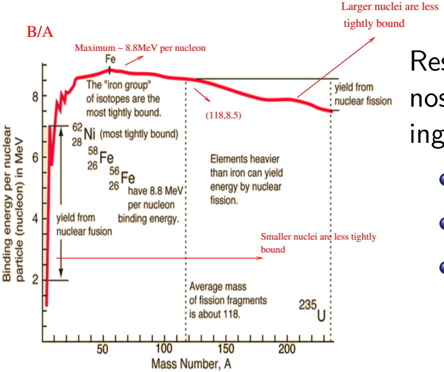

Responsible for 98.5% of the solar luminosity in the proton-proton cycle involving:

- $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$
- $\mathrm{p} + \mathrm{d} \rightarrow \gamma + {}^{3}_{2}\mathrm{He}$
- ${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{p} + \mathrm{p}$ reactions

30 MeV

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:

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

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): $\sim$ 24000 tonnes . . .

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Part III

Nuclear Fission: reactions involving neutrons

Reactions involving neutrons

Reactions involving neutrons in a nuclear reactor:

1. Scattering (soft and hard):
   $\mathrm{A + n(E) \rightarrow A + n(E' < E)}$
   $\mathrm{A + n(E) \rightarrow A^* + n(E' < E) \rightarrow A + n(E' < E) + \gamma}$
2. Neutron radiative capture (sterile capture):
   $\mathrm{A + n \rightarrow (A + 1) + \gamma}$
3. Fission (spontaneous and most frequently neutron-induced):
   $\mathrm{A + n \rightarrow FP_1 + FP_2 + \nu \cdot n}$ ($\nu \approx 2.43$)
4. Leakage:
   $\mathrm{n} \rightarrow \ldots$

Reactions involving neutrons

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   $\mathrm{A} + \mathrm{n(E)} \to \mathrm{A}^* + \mathrm{n(E' < E)} \to \mathrm{A} + \mathrm{n(E' < E)} + \gamma$
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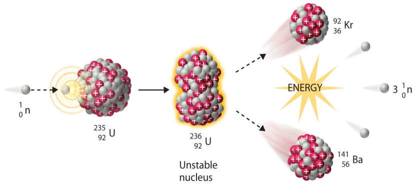
   $\mathrm{n} \to \ldots$

Neutron-induced fission of ^{235}U (nuclear reactor)

Total energy: 210 MeV

$^1_0\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^1_0\text{n}$ $\quad$ $^1_0\text{n} + {}^{239}_{94}\text{Pu} \rightarrow {}^{134}_{54}\text{Xe} + {}^{103}_{40}\text{Zr} + 3\,{}^1_0\text{n}$

Energy distribution among the fission remnants:



^{235}U fission	Energy (MeV)
Kinetic energy fission products	168
Kinetic energy prompt γ	7
Kinetic energy prompt neutrons	5
Kinetic energy capture γ	7
β decay (electrons)	8
β decay (neutrinos)	12

From Neutrons to Nuclear Reactor Physics

Neutron type	Energy range
Cold neutrons	0.0 – 0.025 eV
Thermal neutrons	0.025 eV (PWR)
Epithermal neutrons	0.025 – 0.4 eV
Cadmium neutrons	0.4 – 0.6 eV
EpiCadmium neutrons	0.6 – 1 eV
Slow neutrons	1 – 10 eV
Resonance neutrons	10 – 300 eV
Intermediate neutrons	300 eV-1 MeV
Fast neutrons	1 – 20 MeV (Breeder)
Ultrafast neutrons	$>$ 20 MeV

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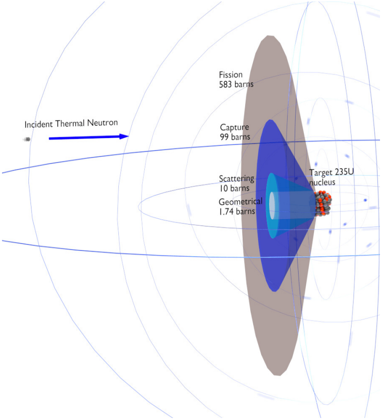
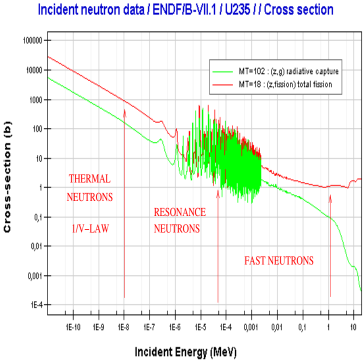
Neutron-induced $^{235}\mathrm{U}$ fission cross-section





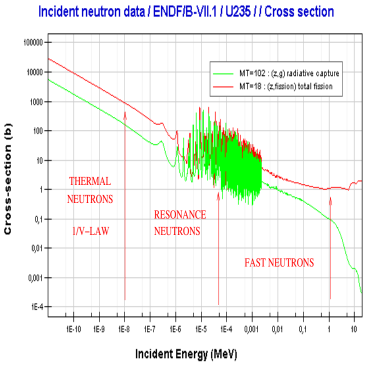
Comparison

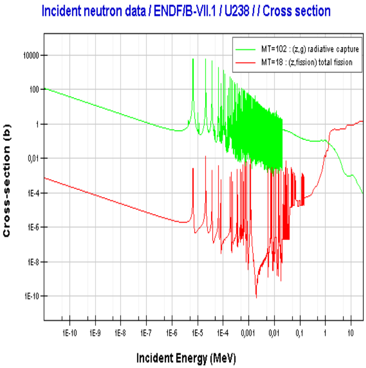
Much greater cross-section for slow neutrons $\sim$ more likely for absorption than faster (harder) neutrons $\Rightarrow 1/v$ absorption law!

Neutron-induced $^{238}\mathrm{U}$ fission cross-section

Uranium ores:

Natural Uranium consists of 99.3% of $^{238}\mathrm{U}$ and 0.72% of $^{235}\mathrm{U}$ (and some $^{234}\mathrm{U}$ $\Rightarrow$ Enrichment needed!)





Chain reaction

Multiplication constant

k: average number of new (fission) neutrons resulting from introduction of one neutron into the system (PWR)

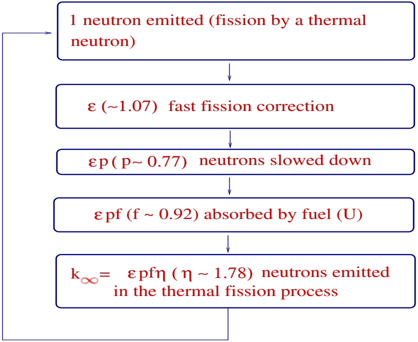
$$N \to kN \to k^2 N \to \dots$$

1. if $k > 1$ the number of neutrons grows exponentially (over-critical system)
2. if $k = 1$ the number of neutrons is constant and the system is critical
3. if $k < 1$ the number of neutrons decreases exponentially (sub-critical system)

Chain Reaction and Criticality

The Four Factor Formula: $k_\infty = \epsilon p f \eta$

1. ϵ: fast-fission corrective factor ($>$1)
2. p: resonance escape probability (during the slowing-down process)
3. f: thermal utilisation factor (absorption probability $<$1)
4. η: number of neutrons emitted in the thermal fission process ($>$1)

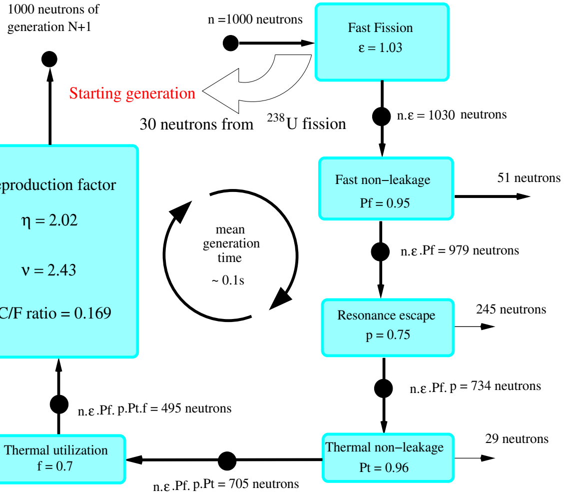


Example:

In a Pressurized Water Reactor (PWR) $k_\infty = 1.35$

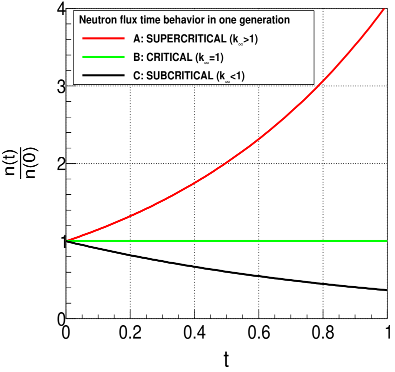
Chain Reaction and Criticality

$k_{eff} = \epsilon \mathcal{P}_f p \mathcal{P}_t f \eta$: 6 factors formula



Chain Reaction and Criticality

Neutron density : $n(t) = n(0)e^{\frac{\left(k_\infty - 1\right)}{\tau}t}$, τ : mean generation time



- Can be improved via the neutron diffusion equation ⇒

Neutron Diffusion Equation: homogeneous medium

Assumptions:

1. Neutrons: treated as classical (not quantum) particles (kinetic energy is $\sim$ 2 MeV, the neutron mass is $\sim$ 1 GeV) or as a mono-atomic gas.
2. Population of 100 million neutrons per cm^3 in average in the reactor core of a PWR $\rightarrow$ much less than the concentration of the nuclei ($\sim 10^{22}\ \mathrm{cm}^{-3}$).
3. This population can therefore be treated statistically via the neutron density *n*.
4. This density (*n*) is a mean number per units of volume.

Neutron Diffusion Equation: homogeneous medium

Assumptions:

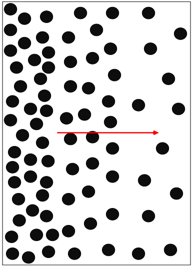
1. The density depends on the coordinates $\vec{r} = (x, y, z)$ and time t.
2. For completeness: the decay of neutrons can be neglected ($T_{1/2} = 10.2$ min).
3. Objective: write the neutron diffusion equation.
4. Some possible stationary solutions.
5. Powerful computers required for neutron simulations!

Neutron Diffusion Equation: homogeneous medium

Fick's law:

The current density vector $\vec{J}$ is negative $\propto$ to the gradient of the neutron flux Φ (number of neutrons travelling through a unit area in unit time) and D is the diffusion coefficient.

$$\vec{J} = -D\vec{\nabla}\Phi = -D\left(\frac{\partial\Phi}{\partial x}\vec{u}_x + \frac{\partial\Phi}{\partial y}\vec{u}_y + \frac{\partial\Phi}{\partial z}\vec{u}_z\right)$$



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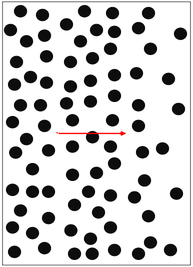

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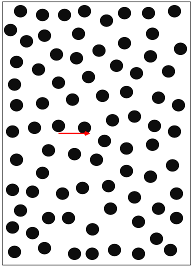

Neutron Diffusion Equation

Formulation of neutron diffusion equation based on the balance of neutrons in a differential volume element dV (β decay is neglected).

Neutron Balance (i.e. continuity equation):

Rate of change of neutron density = production rate - absorption rate-leakage rate

- Neutron change rate $= \iiint_V \frac{\partial n}{\partial t} dV$ with n: density of neutrons.
- Production rate $= \iiint_V s\, dV$ with s: rate at which neutrons are emitted from sources per cm^3, either external sources or from fission ($\nu\Sigma_f\Phi$):
  1. $\Sigma_f = N_f\sigma_f$ is the fission macroscopic cross-section,
  2. N_f is the density of fissile atoms in the fuel and σ_f the microscopic fission cross-section.
  3. Rates based on the neutronics fundamental equation: $R = \Sigma\Phi$!

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- Absorption rate $= \iiint_V \Sigma_a \Phi dV$ with macroscopic absorption cross-section $\Sigma_a = N_a \sigma_a$, N_a is a density of material atoms and σ_a is the microscopic absorption cross-section.

- Leakage rate $= \oiint_S \vec{J} \cdot \overrightarrow{dS} = \iiint_V \vec{\nabla} \cdot \vec{J} dV$.

Neutron Diffusion Equation: homogeneous medium

Formulation of neutron diffusion theory based on the balance of neutrons in a differential volume element dV (β decay is neglected).

Neutron Balance (i.e. continuity equation):

Rate of change of neutron density(1)

$$\frac{\partial n}{\partial t} = s - \Sigma_a \Phi - \vec{\nabla} \cdot \vec{J}$$

(1)

Neutron Diffusion Equation: homogeneous medium

Formulation of neutron diffusion theory based on the balance of neutrons in a differential volume element dV (β decay is neglected).

Neutron Balance (i.e. continuity equation):

Rate of change of neutron density(1) = production rate(2)

$$\frac{\partial n}{\partial t} = s - \Sigma_a \Phi - \vec{\nabla} \cdot \vec{J}$$

(1) (2)

Neutron Diffusion Equation: homogeneous medium

Formulation of neutron diffusion theory based on the balance of neutrons in a differential volume element dV (β decay is neglected).

Neutron Balance (i.e. continuity equation):

Rate of change of neutron density(1) = production rate(2) - absorption rate(3)

$$\frac{\partial n}{\partial t} = s - \Sigma_a \Phi - \vec{\nabla} \cdot \vec{J}$$

(1) (2) (3)

Neutron Diffusion Equation: homogeneous medium

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Neutron Balance (i.e. continuity equation):

Rate of change of neutron density(1) $=$ production rate(2) - absorption rate(3)- leakage rate(4)

$$\frac{\partial n}{\partial t} = s - \Sigma_a \Phi - \vec{\nabla} \cdot \vec{J}$$

(1) (2) (3) (4)

Criticality for $(1) = 0$

Neutron Diffusion Equation: homogeneous medium

Formulation of neutron diffusion theory based on the balance of neutrons in a differential volume element dV (β decay is neglected).

Neutron Balance (i.e. continuity equation):

Rate of change of neutron density(1) = production rate(2) - absorption rate(3)- leakage rate(4)

Neutron Diffusion Equation: homogeneous medium

$$D\Delta\Phi(\vec{r},t) - \Sigma_a\Phi(\vec{r},t) + s(\vec{r},t) = \frac{1}{v}\frac{\partial\Phi(\vec{r},t)}{\partial t}$$

Neutron Diffusion Equation: homogeneous medium

Formulation of neutron diffusion theory based on the balance of neutrons in a differential volume element dV (β decay is neglected).

Material Buckling: B^2

Parameter describing the characteristics of the fuel material in an infinite medium.

Neutron Diffusion Equation: homogeneous medium

$$\Delta\Phi(\vec{r},t) + B^2\Phi(\vec{r},t) = \frac{1}{D_0}\frac{\partial\Phi(\vec{r},t)}{\partial t}, \quad B^2 = \frac{(k_\infty - 1)\Sigma_a}{D}, \quad D_0 = vD$$

Solution

Nuclear cylindrical reactor of height H and radius R:

- Initial condition coming from first neutron source : $\Phi(\vec{r}, 0)$
- Boundary conditions $\Phi(R, z, t) = \Phi(r, 0, t) = \Phi(r, H, t) = 0$: set by reflector (i.e. light, heavy water, graphite...) at the surface.

Critical stationary solution and geometrical buckling B_g

$$\Phi(r, z, t) = \phi_0 e^{D_0(B^2 - B_g^2)t} \phi(r, z)$$

• In power reactor core, the neutron flux can reach about 3.11×10^{13} neutrons $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ (depending on type of fuel, fuel burn-up, fuel enrichment...).

Critical dimensions of the reactor

Crucial link between the reactor geometry and criticality: $B^2 \equiv B_g^2$.

Solution

Nuclear cylindrical reactor of height H and radius R:

Minimal critical dimensions of the reactor

$$\frac{k_\infty - 1}{L_r^2 + L_s^2} = \left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{H}\right)^2$$

"Neutron flux"

$$\phi(r,z) = \phi_0 J_0\left(\frac{2.405}{R} r\right)\cos\left(\frac{\pi}{H} z\right)$$

- $k_\infty = \epsilon f p \eta$: 4 factors formula (material)
- L_r: neutron diffusion length
- L_s: neutron slowing down length (if moderator)

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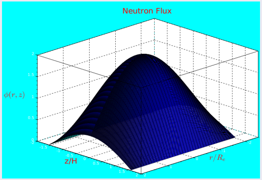

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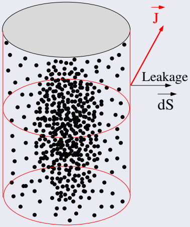

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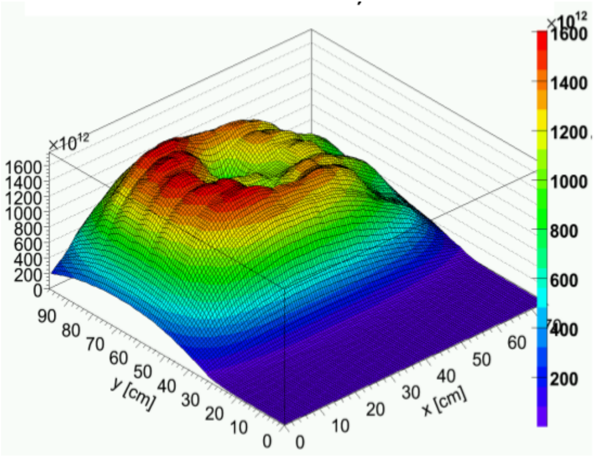


Figure: Neutron flux inside a PWR: experimental profile!

Solution

Nuclear cylindrical reactor of height H and radius R:

Minimal critical dimensions of the reactor

$$\frac{R}{H} = \frac{2.405}{\sqrt{2}\pi} \approx 0.55, \quad V_{cr} = \frac{3\sqrt{3}\pi^2(2.405)^2}{2B^3(k_\infty)}, \quad m_{cr} = \rho V_{cr}$$

- $k_\infty = \epsilon f p \eta$: 4 factors formula (material)
- L_r: neutron diffusion length
- L_s: neutron slowing down length (if moderator)

Power plant versus space reactor

Reactor	ϵ	f	p (cm)	η (cm)	k_∞ (cm)	^{235}U(%)
Ground	1.00	0.66	0.923	1.73	1.054	2
Space	1	1	1	2.07	2.07	93

Reactor	L_r (cm)	L_s (cm)	B (cm^{-1})	H (cm)	R (cm)	V_{cr} (cm^3)
Ground	52	19	$4 \cdot 10^{-3}$	$13 \cdot 10^3$	$7 \cdot 10^3$	$2 \cdot 10^{12}$
Space	1.2	0	0.86	6	3.43	234

Conclusion

This demonstrates the usual folklore about pure $^{235}\mathrm{U}$ (i.e., that a few kilograms ($\sim$ 4.5 Kg) of the pure material, in a 'grapefruit sized' sphere, can become critical)!

Space Rocket Propulsion

Exhaust velocity and specific impulse

In rocket engineering the exhaust velocity is universally quoted in terms of the specific impulse (I_{sp})

$$v_e = gI_{sp} = C_F c^*.$$

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 H_2 fuel and 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)

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

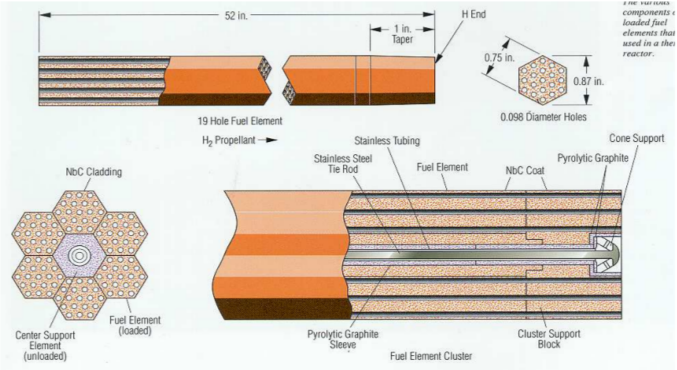
Main source:

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

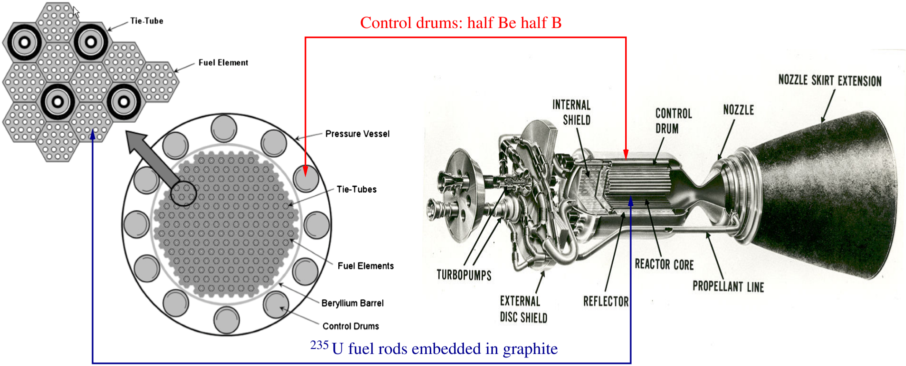
Nuclear Engine for Rocket Vehicle Application (1955-1973)

Fuel element assembly from the KIWI reactor core:

Fuel is enriched $^{235}\mathrm{U}$ oxide spherules 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)



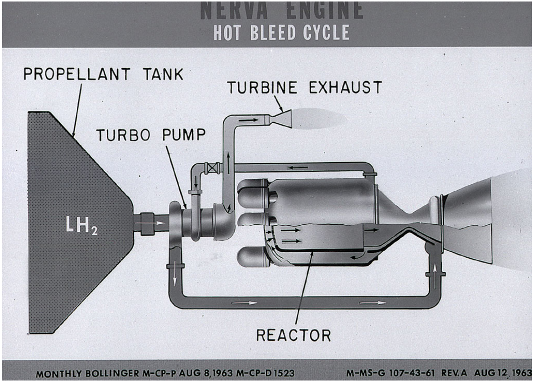
1. Control drums: half B (absorption) half Be (relfector) to maintain stable criticality,
2. Internal shield against γ-radiation: lead and tungsten

Nuclear Engine for Rocket Vehicle Application (1955-1973)

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.

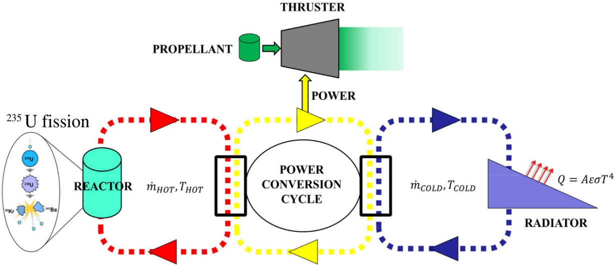


Nuclear Engine for Rocket Vehicle Application (1955-1973)

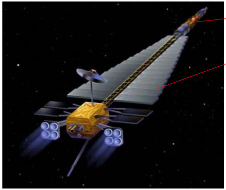
Parameters	NRX XE	NERVA 1	New designs based on NERVA		
Fuel Rods	UO_2 beads embedded in graphite	UO_2 beads ZrC coat, embedded in graphite	$UC_2 + ZrC + C$ composite	$UC_2 + ZrC$ all carbide	$UC_2 + ZrC + NbC$ all carbide
Moderator	Graphite	Graphite+ZrH	Graphite+ZrH	Graphite+ZrH	Graphite+ZrH
Reactor 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	?

Heat rejection: Jupiter Icy Moons Orbiter (JIMO)

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

$$Area = \frac{Q_{waste}}{\epsilon\sigma T^4}$$

Source: PROMETHEUS PROJECT Final Report

ORION project on nuclear propulsion

ORION Project (wiki)

Project Orion was a study of a spacecraft intended to be directly propelled by a series of explosions of atomic bombs behind the craft (nuclear pulse propulsion).

Early versions of this vehicle were proposed to take off from the ground with significant associated nuclear fallout.

Later versions were presented for use only in space.

Six non-nuclear tests were conducted using models.

ORION project on nuclear propulsion

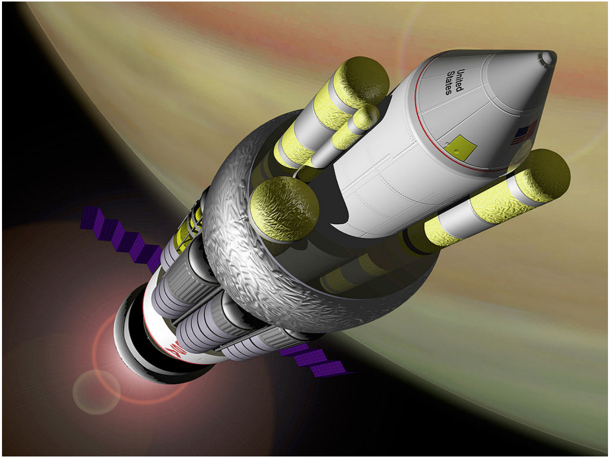


Figure: Artist's conception of the NASA reference design for the Project Orion spacecraft powered by nuclear propulsion

Direct Fusion Drive (DFD)

Direct Fusion Drive (wiki)

Direct Fusion Drive (DFD) is a conceptual low radioactivity, nuclear-fusion rocket engine designed to produce both thrust and electric power for interplanetary spacecraft.

The concept is based on the Princeton field-reversed configuration reactor invented in 2002 by Samuel A. Cohen, and is being modeled and experimentally tested at Princeton Plasma Physics Laboratory, a US Department of Energy facility, and modeled and evaluated by Princeton Satellite Systems.

Direct Fusion Drive (DFD)

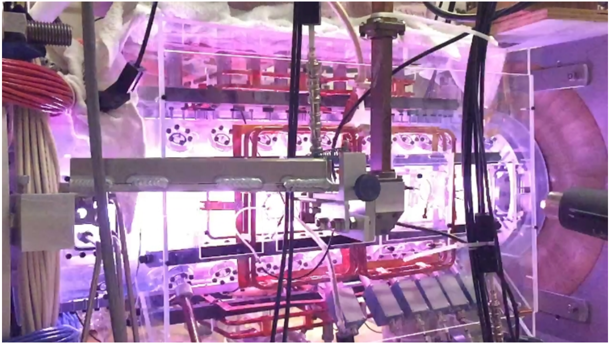


Figure: One rotating magnetic field pulse of the Princeton field-reversed configuration (PFRC 2) device during testing

Summary

- Crucial correlation between criticality and geometrical dimensions of a nuclear reactor: from simple stationary solutions of the neutron diffusion equation

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- Main advantage: 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

Summary

- Crucial correlation between criticality and geometrical dimensions of a nuclear reactor: from simple stationary solutions of the neutron diffusion equation
- Main advantage: 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
- Main challenges: heat rejection in space, nuclear reactor weight, radiation waste management (γ-rays)...

Nuclear Rocket Reactors

Merci beaucoup pour votre attention!