「先端宇宙推進工学」

２限　原子力ロケット

1. 原子力熱ロケットの概念
2. 核分裂反応理論
3. 宇宙用原子炉と放射線シールドの設計法
4. NASA/NERVA計画
5. Technical Readiness Level

Reference: Space propulsion Analysis and Design, Ed. By Ronald W. Humble *et al*., Space technology series, The MacGraw Hill companies, Inc. 1995

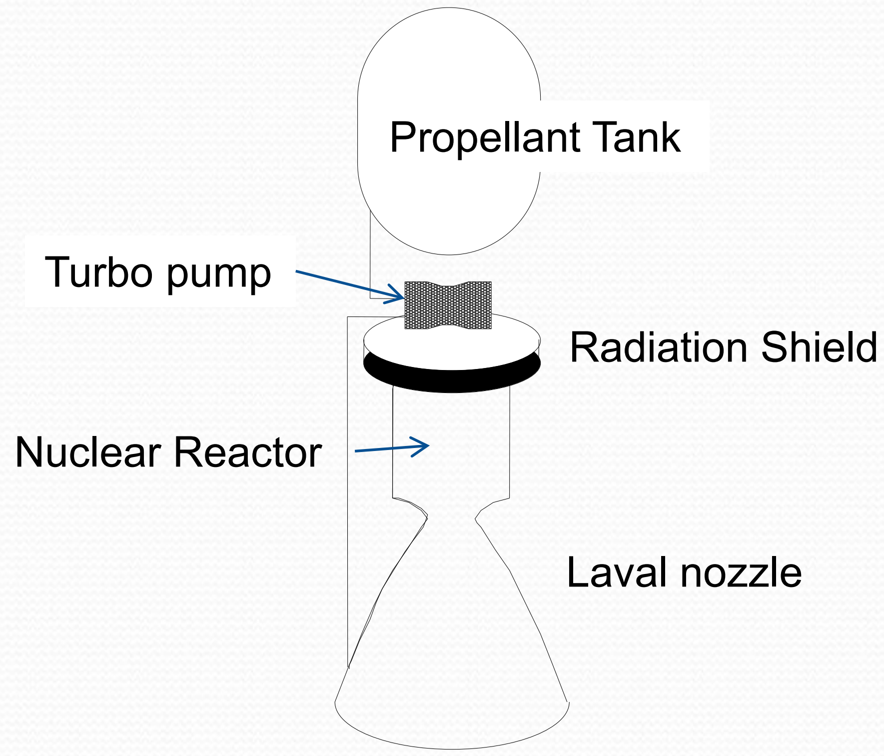
1. 原子力熱ロケットの概念

放射性同位体熱源と原子炉

- 動力源 (核燃料)
  - 放射性同位体熱源　(プルトニウム)
  - 原子炉　(ウラニウム)

- 推進システム
  - 直接加熱　(neutron decelerator)
    Nuclear Thermal Propulsion
  - 発電
    Nuclear Electric Propulsion, NEP (cf. SEP)

原子力熱ロケットの概念



核熱ロケット

原子力熱ロケットの特徴 (1)

1) **高パワー密度(thrust-to-weight ratio)**

- 電力密度: 0.5 MW/kg

  cf. 太陽電池 0.05 kW/kg

- NERVA プロジェクト (USA): 出力4 GW, 推力 4 ton.

2) **高排気速度 V_e**

- H_2, NH_3, H_2O

  No chemical reactions. Propellant molecules (H, He, C) work as decelerator of neutrons.

- 最高炉温度 3,000 K → V_e of 9,000 m/s with H_2.

原子力熱ロケットの特徴 (2)

3) **多様な使い方**

打上げ機 (ΔV=10 km/s)

- 4-6 times more payload than CP because of its double V_e.

軌道間輸送機 (ΔV=4-5km/s)

- 2 times more payload

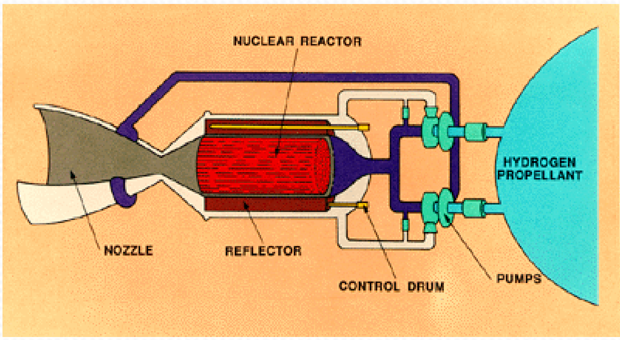
火星輸送 (ΔV=3.5 km/s for 200 days with CP)

- Shorten travel time to 40 days by ΔV=85 km/s.

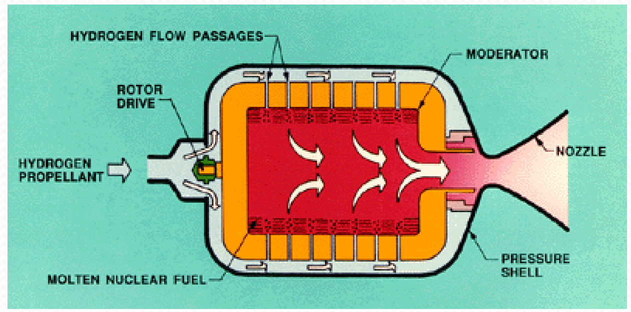
4) **安全性の懸念**

- 開発段階での試験環境
- 高濃度ウラニウムの使用
- 打ち上げ時の事故
- 使用後の廃棄

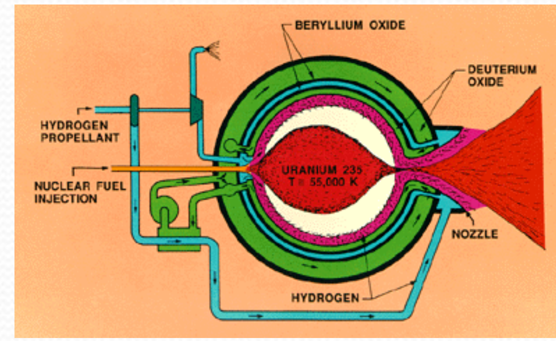
コア構造



固体コア



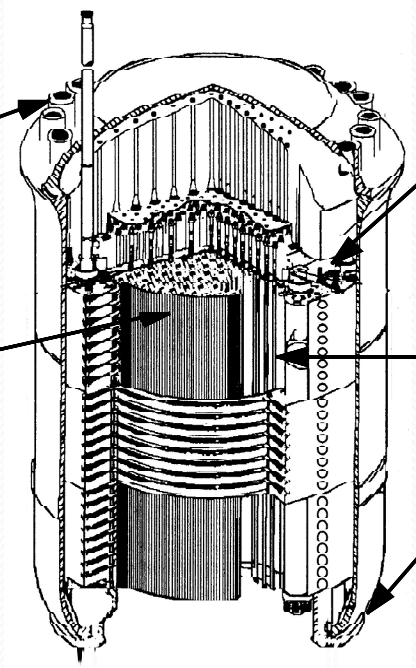
液体コア



オープン気体コア

コアタイプ	推進剤温度	問題点
固体コア	2,300～3,500 K	Heat resistance of structure materials
液体コア	3,000～9,000 K	Propellant droplet loss
気体コア	9,000～15,000 K	Plasma contamination

固体コア原子炉の構造 (1)



固体コアタイプ原子炉

圧力容器

Sustainable for 3 MPa to 8 MPa. Aluminum or composite materials.

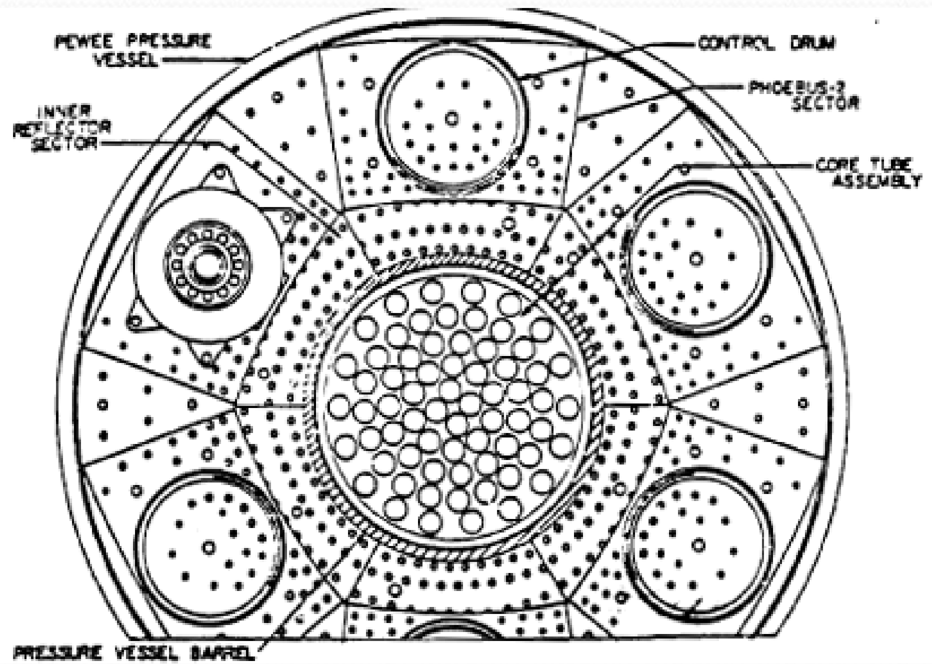
反射体

To cause a chain reaction in a small volume, fuel is surrounded by a reflective material, typically Beryllium. It is cooled by a coolant/propellant typically liquid hydrogen through fine channels.

燃料支持棒

- Axial stress is caused by the pressure difference between plenum chamber and the nozzle section. For example 3.96 MPa on the upper side. 3.10 MPa on the lower side at 3,000 K.
- A metallic supporting rod is used with cooling.

固体コア原子炉の構造 (2)



コア断面図

Rotary control drums

- ボロンB is a neutron absorber called as a poison for fission reaction.
- One side B absorber and the other side Be reflector.
- The number of neutron is controlled by its rotation

減速材（Moderator）

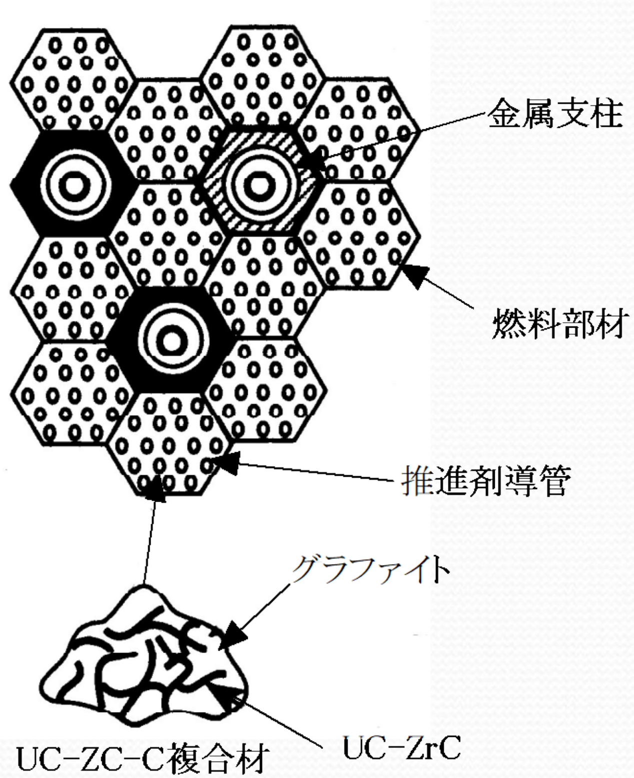
熱炉（Thermal reactor）

- Neutrons are slowed down to the energy less than 1 eV. Low atomic mass materials such as Be, plastics, LiH_2, ZrH, Graphite etc.
- Mix moderating materials to fuel materials.

高速炉（Fast reactor）

- No moderator. Utilize fission reactions at 100 KeV to 15 MeV. CERMET Reactor with metal composite fuel（UO_2-W, UO_2-Mo）graphite.
- Stable, Repeatable, continuous operation for more than 40 hours has been demonstrated.

燃料棒　(1)
Hexagonal UC-ZrC-Graphite composite type



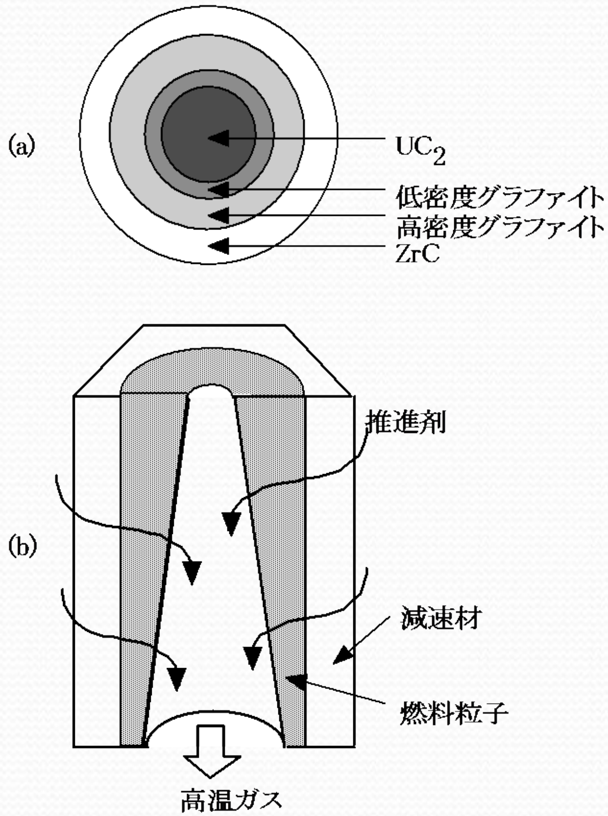
NERVA fuel elements

- Hexagonal UC-ZrC-Graphite composite fuel with coolant flow channels. (370 K→2700 K)

- Coolant channel and external surfaces are coated by ZrC to avoid erosion by hydrogen.

- Maximum thrust/weight of 5 was attained so far.

燃料棒　(2)
Particle Bed type



Particle-Bed type fuel elements. (a) Fuel particle, (b) cross section of channel flow.

-High heat exchange rate resulting in high power density and high thrust-to-weight of around 40.

- Surrounded by a porous hexagonal cylinder.

- Hydrogen propellant directly cools small (200-500 µm diameter) coated, particulate fuel spheres.

2. 核分裂反応理論

結合エネルギー

質量欠損Δは核反応前と後の質量差

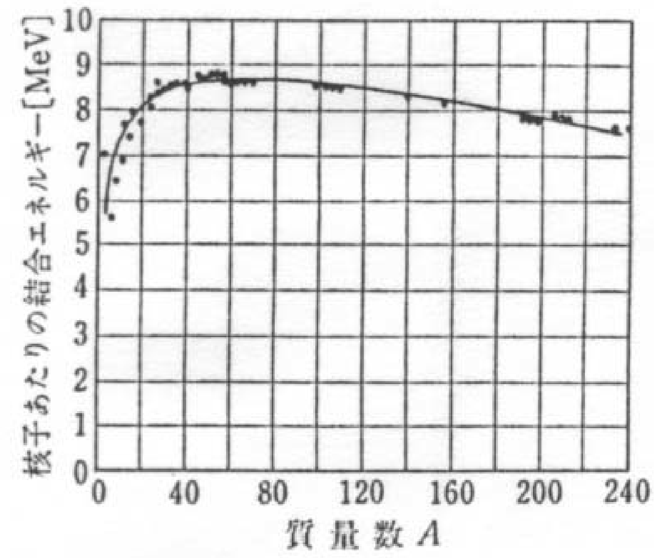
$$\Delta = \left[Z\left(m_{\mathrm{p}} + m_{\mathrm{e}} \right) + \left(A - Z \right) m_{\mathrm{n}} \right] - m_{\mathrm{atom}} \quad (1)$$

この質量欠損分は結合エネルギーとして蓄えられていた

$$E = \Delta c^2 \quad (2)$$

when a nucleus with A=240 is split into two fragments of A=120, binding energy of 0.9 MeV is released per nucleon.

$$E = 0.9 \times 240 \approx 200\mathrm{MeV} \quad (3)$$

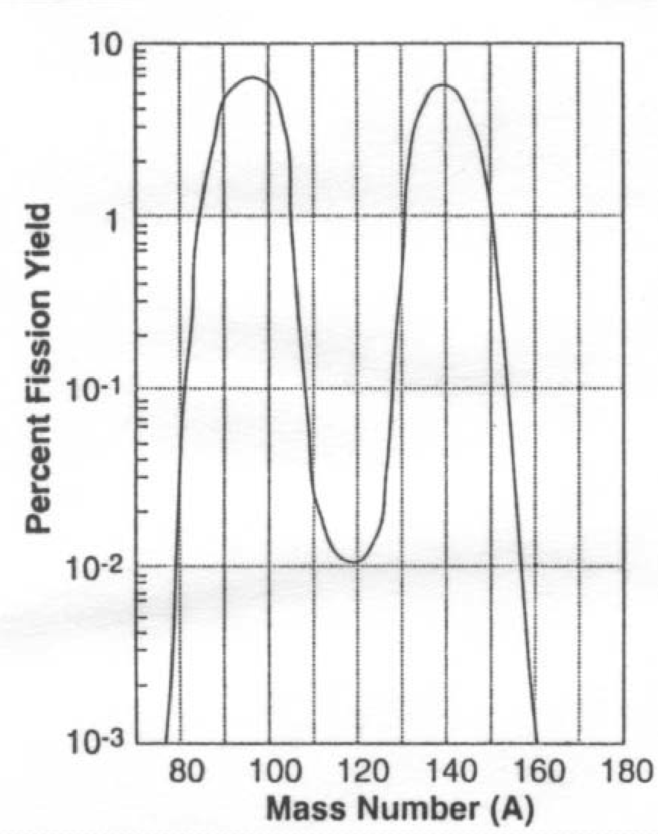


Binding energy per unit nucleon (*E/A*) as a function of mass number *A*.

核反応の生成物

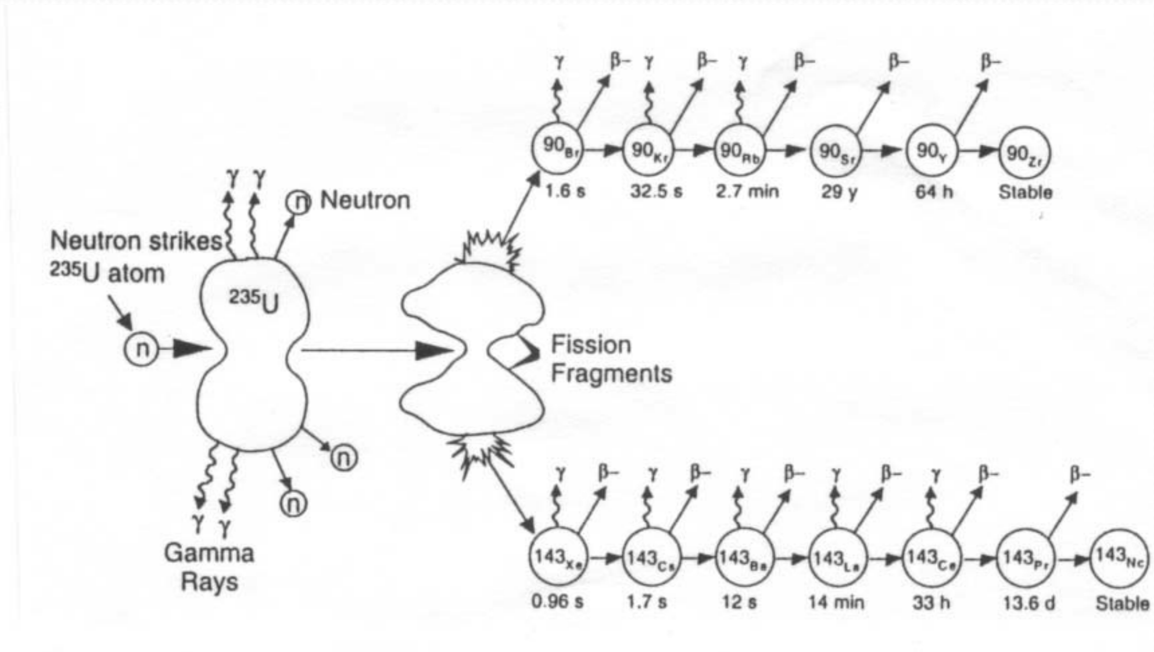
$$^{235}U+n \rightarrow 2F.P.+\gamma ray+2.4n \quad (4)$$

Two fission products with A=97 and A=139 are most likely.



Mass Yield Curve for Fission of ^{235}U by thermal neutrons.

放射性崩壊



Subsequent decay

核反応エネルギーの分配

Energy sources	MeV
fission fragments	168
neutrons	5
prompt γ ray	7
Delayed β ray	8
γ ray	12
Total	200

β 崩壊、 β 線 :e^- : ν:anti-neutrino

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\nu$$

γ 崩壊、 γ ray :photon, *:excited

$$^{60*}_{27}Co \rightarrow {}^{60}_{27}Co + \gamma$$

核反応の反応断面積

Cross section for thermal neutrons 0.25eV

	barns (10^{-24} cm^2)
^{235}U (fission)	577
^{235}U (absorption)	106
^{10}B (absober)	3840
^{1}H (coolant)	0.332

^{235}U has a large fission cross section at 0.25 eV and 1.0 MeV.

Thermal reactors: utilize 0.25 eV thermal neutron
Fast reactors: utilize 1.0 MeV fast neutron.

3.宇宙用原子炉と放射線シールドの設計法

炉体積設計

Reactor power density P_D is given as 1,570 MW/m^3 (typical value for NERVA reactors). Then V_{CORE} is designed for given output power P_{CORE}

$$V_{\mathrm{CORE}} = P_{\mathrm{CORE}} / P_{\mathrm{D}} \tag{5}$$

$$P_{\mathrm{CORE}} t_{\mathrm{b}} = 3.2 \times 10^{-11} \left(\mathrm{J}\right) N_{\mathrm{CONS}} = 3.2 \times 10^{-11} \frac{6.0 \times 10^{23} \left(\mathrm{mol}^{-1}\right)}{0.235 \left(\mathrm{kg/mol}\right)} m_{\mathrm{CONS}} \tag{6}$$

Uranium density is 19,100 kg/m^3

$$V_{\mathrm{CONS}} = m_{\mathrm{CONS}} / 19{,}100 = 6.4 \times 10^{-19} P_{\mathrm{CORE}} t_{\mathrm{b}} \tag{7}$$

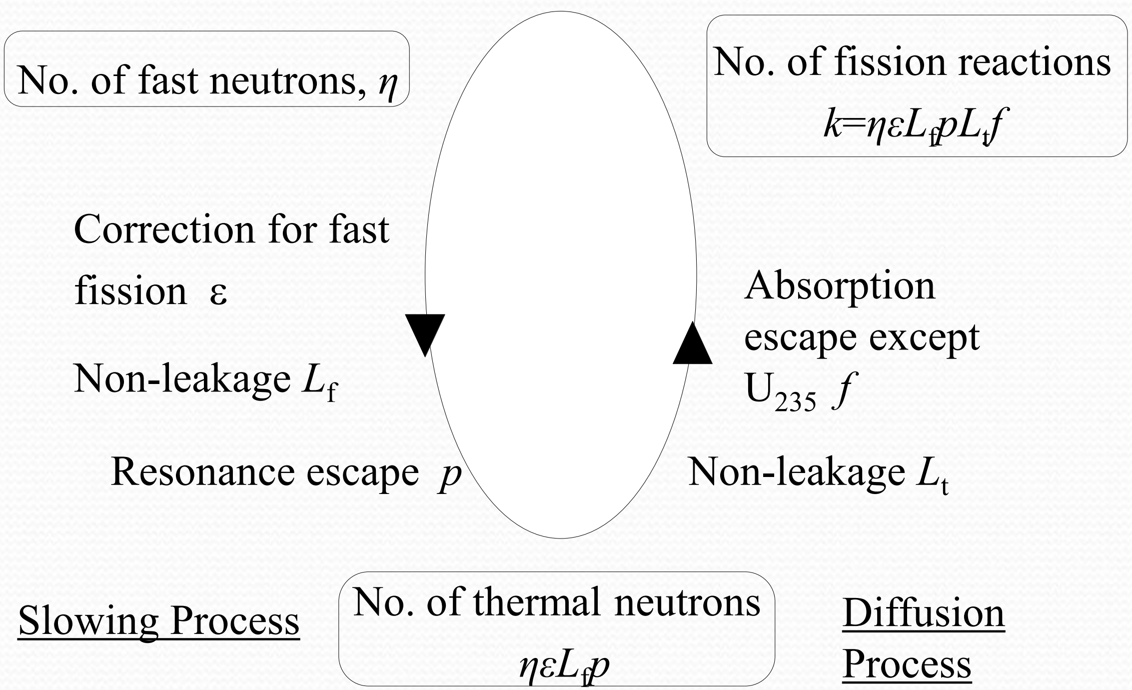
Then required core volume is

$$V_{\mathrm{CORE}} = P_{\mathrm{CORE}} \left(1/P_{\mathrm{D}} + 6.4 \times 10^{-19} t_{\mathrm{b}}\right) \tag{8}$$

If P_D=1G W/m^3, there would be no fuel-consumption effect for a several-year flight (10^8 sec).

臨界条件と連鎖反応

核分裂の一サイクル



Life-cycle of neutrons

Four-factor formula

$$k = L_f L_t \eta \varepsilon p f \qquad (9)$$

k: multiplication factor of neutron during its life-cycle.

減速過程

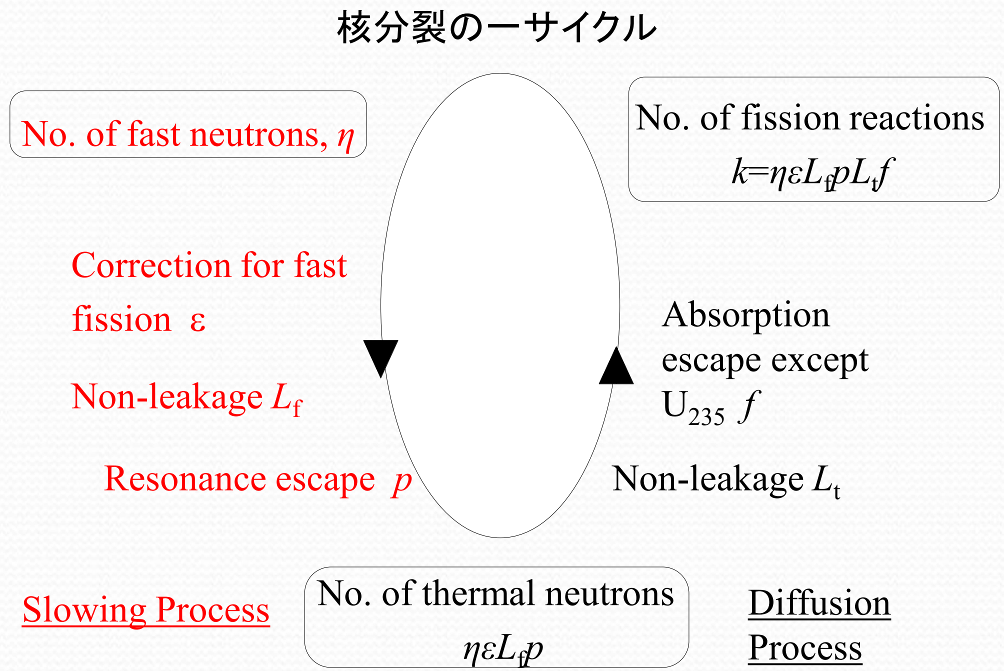
η : 再生率. = $\nu(\sigma_f/\sigma_a)$ Number of neutrons produced in a one fission event. ν=2.4, η =2.07.

ε: fast fission factor. 1.00 for fast reactor and 1.05 for thermal reactor.

L_f : 散逸を音がれる確率 during the slow-down process of fast neutron.

p : 共鳴吸収を逃れる確率

Resulting thermal neutrons = $\eta\varepsilon L_f p$



Life-cycle of neutrons

拡散過程

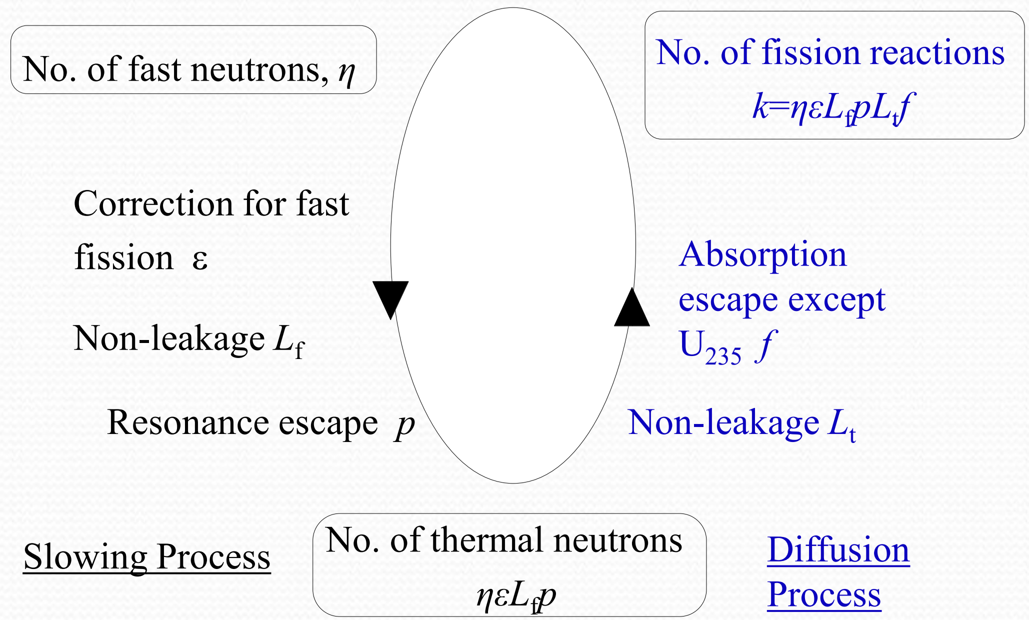
L_t : 散逸を逃れる確率 during the diffusion process of thermal neutrons.

f : thermal utilization efficiency . the ratio of the rate at which thermal neutrons are absorbed in fuel to the total rate at which they are absorbed in the entire core.

Resulting neutrons which cause fission reaction $= f L_t\ (\eta \varepsilon L_f p)$

$$k = L_f L_t \eta \varepsilon p f$$

核分裂の一サイクル



Life-cycle of neutrons

Design L_f and L_t to achieve $\underline{k=1.1}$. Then control the criticality by adjusting the rotary control drums.

反応断面積

Elements' reaction cross sections in a reactor

Isotope	N	σ_a	Σ_a	σ_s	Σ_s	σ_t	Σ_t	σ_f	Σ_f	A	ξ
^{235}U	9.74E-04	106	1.032E-01	0.00	0.000E+00	683	6.652E-01	577	0.562	235	0.008
^{238}U	7.33E-05	7.6	5.571E-04	8.30	6.084E-04	16	1.173E-03	--	--	238	0.008
C	0.057	0.004	2.280E-04	4.80	2.736E-01	4.8	2.736E-01	--	--	12	0.158
H	3.74E-06	0.33	1234E-06	38.00	1.421E-04	38	1.421E-04	--	--	1	1.000
Be	0.099	0.01	9.900E-04	7.00	6.930E-01	7.01	6.940E-01	--	--	9.01	0.207

σ_a = microscopic absorption cross section (cm^2)
Σ_a = macroscopic absorption cross section (cm^{-1})
σ_s = microscopic scattering cross section (cm^2)
Σ_s = macroscopic scattering cross section (cm^{-1})
σ_t = microscopic total neutron removal cross section (cm^2)
Σ_t = macroscopic total neutron removal cross section (cm^{-1})
σ_f = microscopic fission cross section (cm^2)
Σ_f = macroscopic fission cross section (cm^{-1})
ξ = lethargy ≈ (2/(atomic weight + 2/3)

炉のアスペクト比決定

$$V_{\mathrm{CORE}} = \pi R_{\mathrm{CORE}}^2 H_{\mathrm{CORE}} \tag{10}$$

L_{f} and L_{t} are the functions of H_{CORE} and R_{CORE}.
Material buckling coefficient B_{m} is

$$B_m^2 = \frac{1 - L_{\mathrm{f}} L_{\mathrm{t}}}{L_{\mathrm{f}} L_{\mathrm{t}} \left(L_{\mathrm{CORE}}^2 + \tau \right)} \tag{11}$$

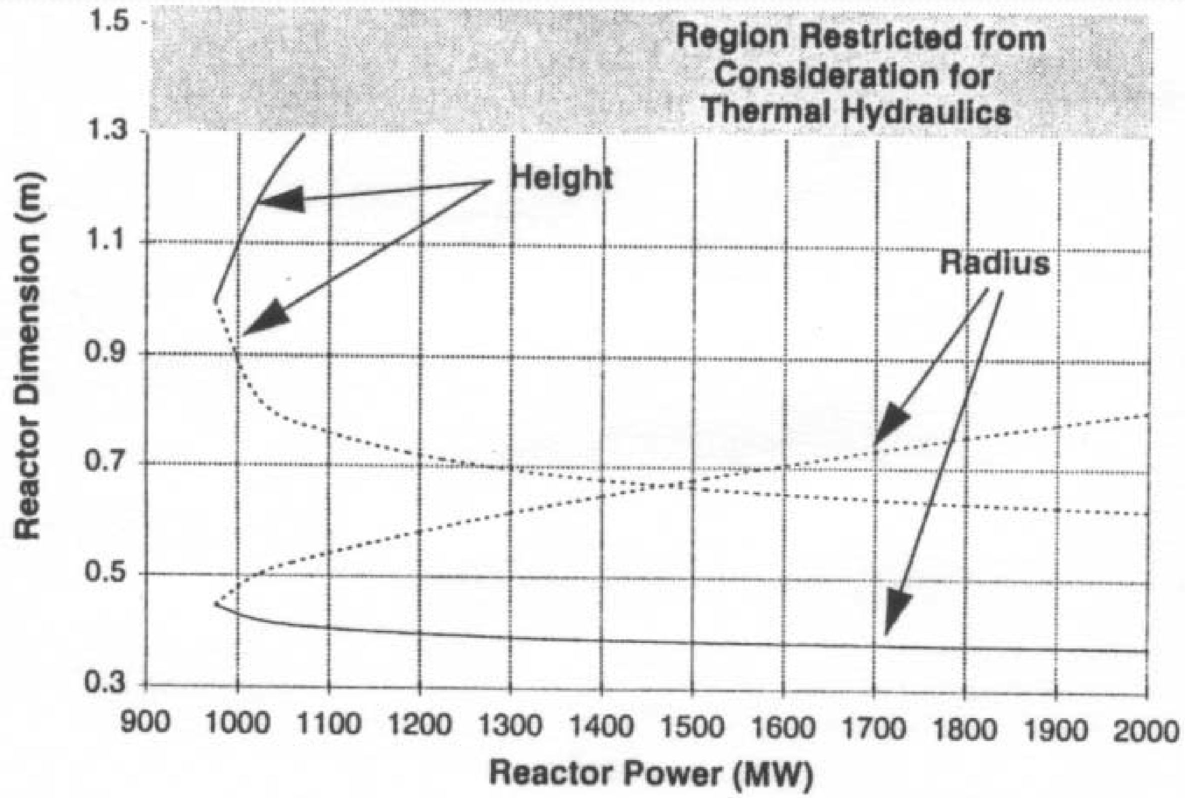
Where, τ is the neutron's average lifetime in a core of the magnitude of 100cm^2.
Geometrical buckling coefficient B_{G} is

$$B_g^2 = \left(\frac{\pi}{H_{\mathrm{CORE}}} \right)^2 + \left(\frac{2.405}{R_{\mathrm{CORE}}} \right)^2 \tag{12}$$

B_{m} must be identical to B_{G}. Then we have a following cubic equation,

$$\left(R_{\mathrm{CORE}}^2 \right)^3 - \left(\frac{B V_{\mathrm{CORE}}}{\pi^2} \right)^2 R_{\mathrm{CORE}}^2 + \left(\frac{2.405 V_{\mathrm{CORE}}}{\pi^2} \right)^2 = 0 \tag{13}$$

４次関数の根



Roots of the cubic equation

放射線シールドの設計

The engine releases 10^7 rem/year.

We need to attenuate the radiation to 10 rem/year (100 mSv/year) to protect the crew. (0.25 rem/year on the ground）

Radiation (γ ray and neutron ray) level decreases by a factor of $1/\text{distance}^2$.

For attenuation, a shadow shield composed of Be, W and LiH_2 is usually used.

Be : neutron reflector
W: neutron absorption and γ ray attenuation
LiH2: light weight. Neutron slowing by H and absorption by Li.

Radiation attenuation capabilities
（distance necessary for 50% attenuation, cm）

	Be	W	LiH_2
Specific mass	1.85	19.3	0.5
Neutron ray	622	0.571	**0.205**
γ ray	**6.67**	0.564	15.6

放射線シールドの設計例

Example design of a shadow shield

	Be	W	LiH_2
thickness/cm	18	2	5
γ 線 透過率	0.1538	0.0854	0.8011
中性子線 透過率	0.9802	0.0882	4.7E-8
3層での γ 線 減衰率	0.1538	0.00131	**1.05E-3**
3層での中性子線 減衰率	0.9802	0.0864	**4.0E-9**

4. NASA/NERVA計画

4.1 米国Roverプロジェクト

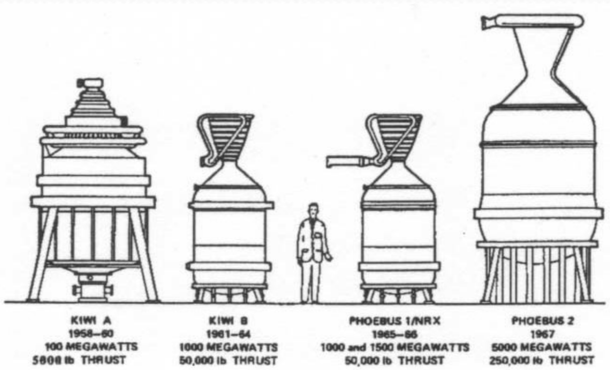
1942-1947:   マンハッタンプロジェクト

1952 :   Los Alamos Scientific Laboratory began researching nuclear rockets

1955-1972:   Project Rover by Los Alamos, U.S. Atomic Energy Commission, U.S. Air Force, NASA

NERVA/Rover Reactors

	Developed year	Power GW	thrust ton	
KIWI A	’55-‘65	0.1		Research
KIWI B	’55-‘65	1		Research
Phoebus1/NRX	‘67	1.5		Research
Phoebus 2	‘68	4	100	Research
Pewee-1	‘68	0.5		Life test
NF-1	‘72	0.044		Life test
NRX	’64-‘67			Demo.
XE	-‘69			Demo.



Source: S. V. Gunn, (1989) "Development of Nuclear Rocket Technology", AIAA paper 89-2386

フェーズ 1: “KIWI”リアクター

- Kiwi, named after the flightless bird. Eight reactors tested between 1955 and 1964.

KIWI A

-First test successfully demonstrated the principle of nuclear rockets

-uncoated UO_2 plates as fuel elements that were not representative of later tests.

-reached a maximum temperature of 2,683 K and a power level of 70 MWt.

-vibrations during operations produced significant structural damage in the reactor core.

“KIWI”

A flightless bird native to New Zealand.

It is approximately the size of a domestic chicken.

“PEWEE”

An exclusively small bird.

フェーズ 2: “Phoebus”リアクター

Phoebus tested twice between 1964 and 1969.

Both Kiwi and Phoebus became part of the NERVA program.

<u>Phoebus 2A</u>

-most powerful nuclear reactor with a design power level of 5,000 MWt.

-Niobium Carbide coating UO_2 fuel

-Operations in 1968 were limited to 4,000 MWt due to premature overheating of aluminum segments of pressure vessel clamps.

-Total of 12.5 minutes of operations at 2,310 K included intermediate power level operations and reactor restart.

フェーズ 3: “PEWEE”リアクター

Pewee tested between 1969 and 1972. Pewee 1 and Pewee 2 were much smaller and they conformed to the smaller budget available after 1968.

PEWEE

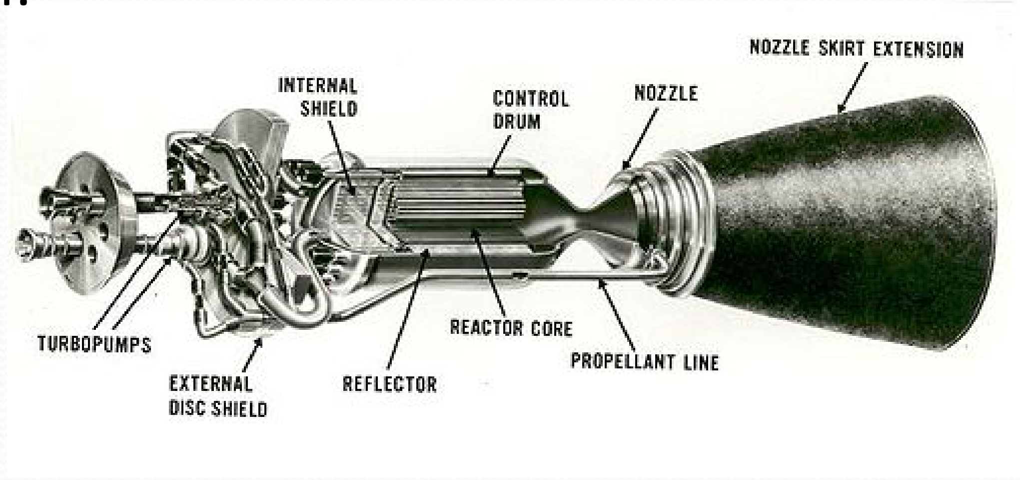
-Small reactor test bed
-Zirconium Carbide coating UO_2 fuel
-With a peak operating power of 503 MWt at 2,550 K,
-core power density of 2,340 MWt/m^3 average and 5,200 MWt/m^3 peak)
-demonstrating a specific impulse of 845 seconds

NERVA (Nuclear Engine for Rocket Vehicle Application) project

1958: NASA was founded. Space Nuclear Propulsion Office was responsible for all the rocket technologies except for reactor design and fabrication.

1961: NERVA project began.

1966: NRX(Nuclear Rocket Experimental) Engine System Test with KIWI-A reactor.



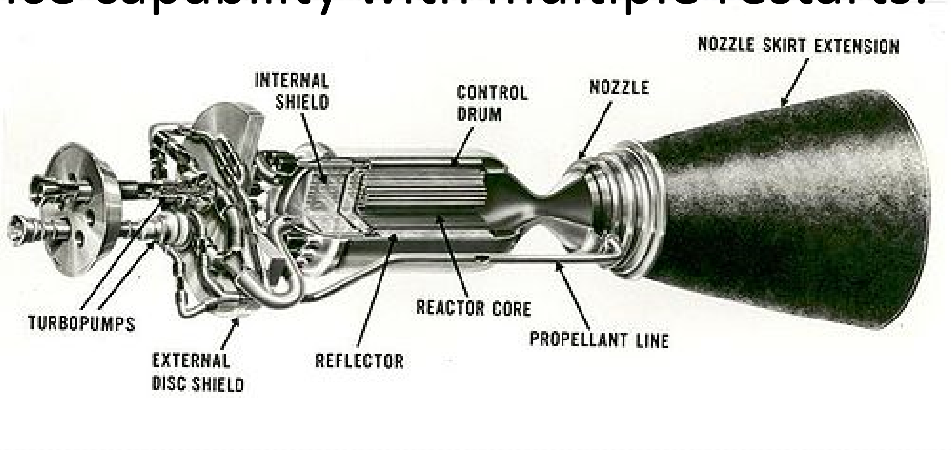
NERVA (Nuclear Engine for Rocket Vehicle Application) project

Objectives

1. Demonstrate the feasibility of engine start and restart without an external power source.

2. Evaluate the stability and control mode during startup, shutdown, cool down and restart for a variety of initial conditions and over a broad operating range.

3. Investigate the endurance capability with multiple restarts.



XE エンジン

<u>XE'</u>

This 1100 MWt engine was a prototype engine, the first to operated in a downward firing position. It accumulated a total of 28 start cycles in March 1968 for a total of 115 minutes of operations. Test stand coolant water storage capacity limited each full power test to about 10 minutes.

https://www.youtube.com/watch?v=GmxPRCyR-Co

NRX/XE engine

1968: Second engine NRX/XE designed as close as possible to a complete flight system, using a flight-design turbo pump. The engine was reoriented to fire downward in reduced-pressure.

Objectives

1. Demonstrating engine system operational feasibility
2. Showing that no technology issues remained as a barrier to flight engine development.
3. Demonstrating completely automatic engine startup.

1972: With the NASA budget cut after Apollo project (1961-1972), Rover/NERVA projects were suspended.

diameter	10.55 m
length	43.69 m
weight	178,321 kg (full)
thrust	867,000 N
specific impulse	825 s (vacuum)
burn time	1,200 s

NASA/NERVA計画まとめ

1. Nuclear thermal rocket development begun as an application of atomic energy technology to aerospace propulsion in U.S. after World War II.

2. High power density of 0.5 MW/kg is available.

3. Double V_e of 9,000 m/s is expected with H_2 propellant.

4. Criticality for the fission reactions are controlled by a rotary drum.

5. NERVA project demonstrated its technical feasibility as a rocket system.

6. The project was suspended with NASA budget cut in 1972.