AA 284a
Advanced Rocket Propulsion

Lecture 15
Nuclear Rocket Propulsion

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Nuclear Rockets – Performance of Rockets

Propulsion System Type	Isp, sec	Thrust to Weight Ratio	Specific Power, kW/kg
Chemical			
Solid, Hybrid, Liquid Biprop	200-460	10^{-2}-200	10^{-1}-10^{3}
Liquid Monoprop	180-223	10^{-3}-10	0.02-200
Thermonuclear			
Nuclear Fission	500-860	10^{-2}-30	10^{-1}-10^{3}
Electric			
Resistojet	150-300	10^{-2}-10^{-4}	10^{-3}-10^{-1}
Arcjet	280-1200	10^{-5}-10^{-3}	10^{-3}-1
Electromagnetic	1200-6000	10^{-6}-10^{-4}	10^{-3}-1
Electrostatic - Ion	1200-5000	10^{-6}-10^{-4}	10^{-3}-1
Other			
Cold Gas Thruster	70-150	10^{-4}-10	-
Solar Sail	Infinite	10^{-5}-10^{-3}	-

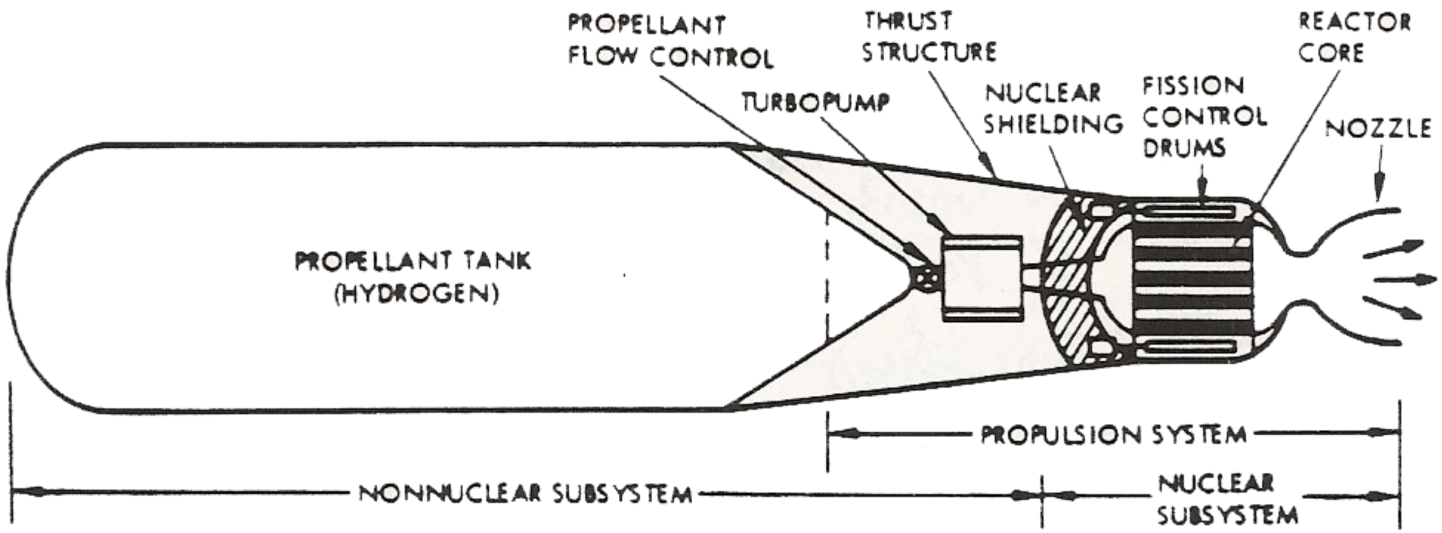
Nuclear Rockets - Introduction

- Discussion will be limited to thermonuclear rockets
- How it works?
  - Propellant: Low molecular weight mass stored in tanks
  - Energy Source: Use nuclear reactions

$$T = \dot{m} V_e$$

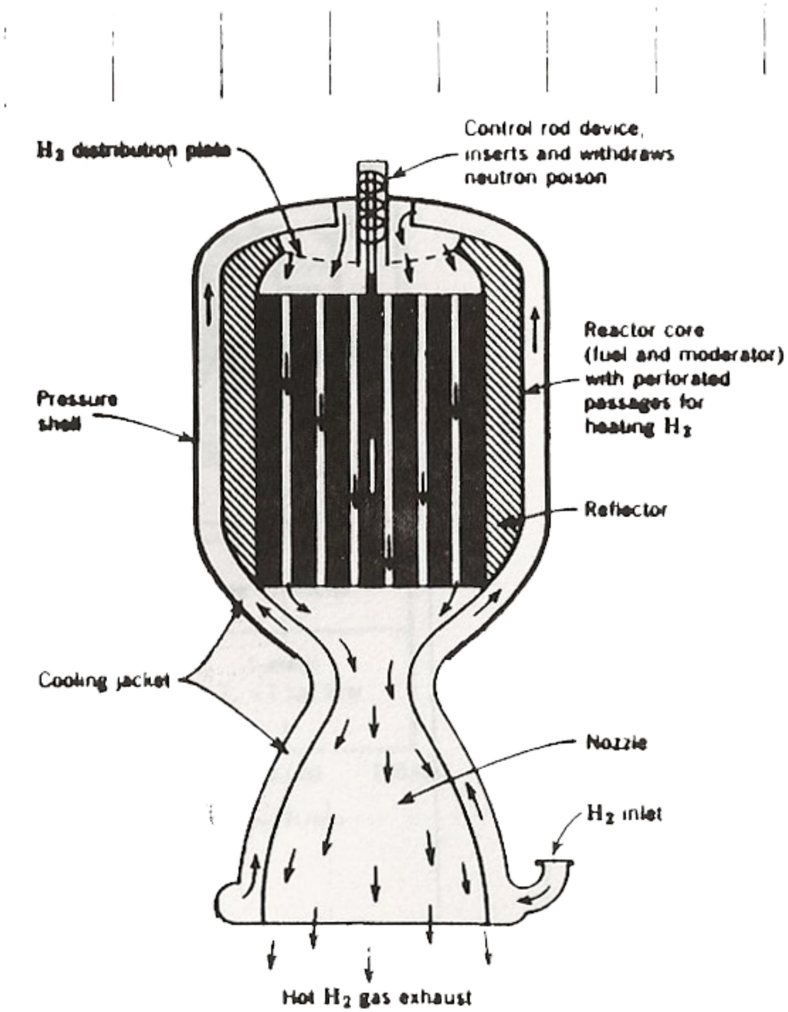
- Propellant temperature is increased by direct heat transfer from the nuclear reactor core
- History:
  - Idea goes back to early 1900's
  - Intense development followed the enhancements in the nuclear physics
  - First controlled release of fission energy was in 1942 (Fermi - US)
  - Significant development in the US between 1955-1972.
  - Major program in 1960's was NERVA (Nuclear Engine for Rocket Vehicle Applications).
  - Russians also had many programs.
  - Activities stopped following the "Atmospheric Test Ban Treaty" in 1972.
  - Until 1972, many nuclear propulsion systems have been ground tested.
  - No flight tests.

Nuclear Rockets - Introduction



- Nuclear rocket major components:
  - Propellant tank
  - Turbopump (including the gas generator)
  - Nuclear reactor
  - Chamber and nozzle

Nuclear Rockets - Introduction



- Main Topics in Nuclear Rockets
  - Reactor design
  - Heat Transfer
  - Radiation shielding
- Propellant selection:
  - Use materials with low molecular weight:
    - **H2**
    - He
    - Li
    - Be
    - B

Nuclear Rockets - Comparison

- Comparison to chemical propulsion:
  - Energy source is nuclear energy as opposed to the chemical bond energy. Very large energy per mass is available. Energy source and propellant are different.
  - Only single propellant is needed.
  - Significant safety and environmental issues with the nuclear propulsion. Shielding is needed.
  - Thermonuclear rockets are power limited compared to the chemical systems. Thus they are not suitable for applications with very large thrust requirements (such as launch system propulsion). Note that power capability of nuclear rockets is much better than the electric propulsion devices.
  - Better Isp performance (low molecular weight propellant – typically H2 - at reasonably high temperatures)
    - Typically 700-900 seconds for thermonuclear
    - 300-450 seconds for chemical

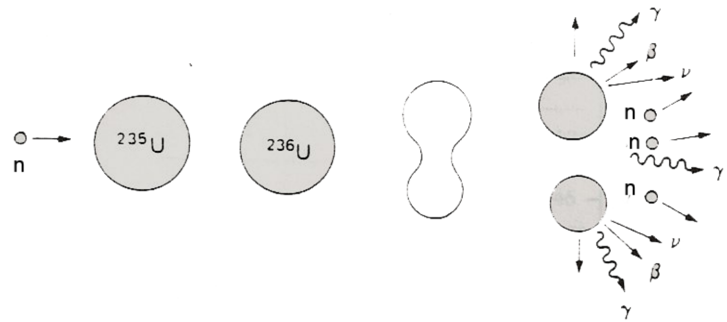
$$c^* = \left[\frac{1}{\gamma} \left(\frac{\gamma+1}{2} \right)^{\frac{\gamma+1}{\gamma-1}} \frac{R_u T_{t2}}{M_w} \right]^{1/2}$$

  - Thermonuclear rockets are ideal for in space applications which require large energy at moderate power levels.

Nuclear Rockets – Fundamentals of Fission Reactions

- Typical Fission Reaction:

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U^{*} \xrightarrow{200\,MeV} ^{147}_{57}La + ^{87}_{35}Br + 2\ ^{1}_{0}n$$



- There is a net gain of neutrons in the reaction
- Fission reaction products for uranium isotope is lanthanum and bromine
- Comparison of energies per reaction:
  - Chemical: 3-4 eV
  - Fusion: 3-18 Mev
  - Fission: ~200 Mev
  - Radioactivity: 1-5 Mev

Nuclear Rockets – Fundamentals of Fission Reactions

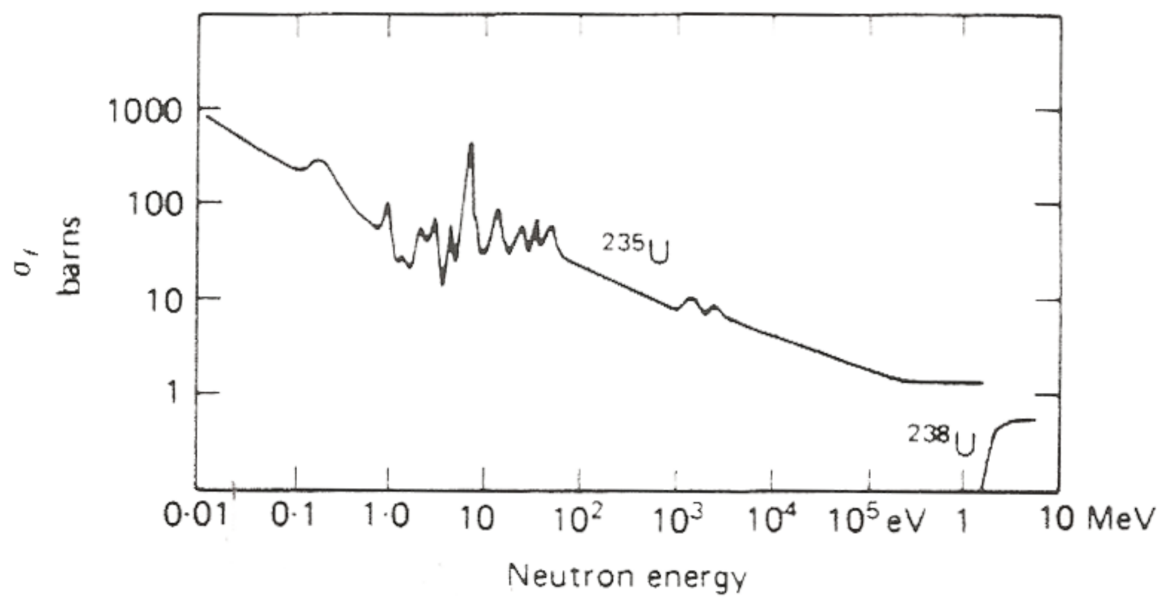
- Uranium is the most commonly used nuclear fuel.
- The natural uranium is a mixture of U235 (0.72% by mass) and U238.
- In nuclear reactors enriched uranium (with U235 concentration more than 0.72%) is used.
- Components of a nuclear reactor:
  - Fuel – Enriched uranium
  - Moderator – Water, Graphite, Beryllium
  - Coolant – Propellant in the case of nuclear rocket
  - Control Elements – Control the reaction rates
- Definition: Unified Mass Unit
  - 1 u = (Atomic mass of C12)/12
- Note that 1u=931 MeV (from $E=mc^2$)
- Nuclear reaction:

$$\Delta = z\, m_p + n\, m_n - m$$

- z: number of protons, n: number of neutrons, m: mass of nucleus before fission
- m_p: mass of a proton (1.007277 u) , m_n: mass of a neutron (1.008665 u)

Nuclear Rockets – Fundamentals of Fission Reactions

- Cross section for fission



- 1 barn: 10^{-24} cm^2
- Fission cross section decreases with neutron energy for U235.
- Thermal neutrons are more effective to propagate the fission reactions.
- Cross section for U238 is much smaller (zero for low energy neutrons).

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Nuclear Rockets – Fission Reactor Design

- Cross sections for various materials used in nuclear reactors
- Purpose of the moderator is to quickly thermalize the neutrons and to prevent resonance capture in U238 nuclei

Fuels

	Density g/cm^3	σ_c barns	σ_f barns	σ_s barns	α	η
Natural uranium	18·9	3·4	4·2	8·3	—	1·32
^{235}U	18·7	101	579	10	2·44	2·08
^{238}U	18·9	2·72	0	8·3	—	—
^{239}Pu	19·6	266	742	9·6	2·90	2·12

Moderators

		Density g/cm^3	σ_c barns	σ_s barns	ξ	$\bar{D}$ cm	L^2 cm^2	$L_s^2(\tau)$ cm^2
Water	H_2O	1·0	0·66	~ 50	0·920	0·16	8·1	27
Heavy water	D_2O	1·1	0·001	10·6	0·509	0·87	30 000	131
Graphite	C	1·6	0·0045	4·7	0·158	0·84	2650	368
Beryllium	Be	1·85	0·0092	6·1	0·209	0·50	480	102

Structural, control and other materials

	Density g/cm^3	σ_c barns	σ_s barns
Boron	2·3	759	4
Nitrogen	gas	1·85	10
Oxygen	gas	0·0002	3·8
Sodium	0·97	0·53	4
Magnesium	1·74	0·063	4
Aluminium	2·7	0·232	1·4
Sulphur	2·07	0·52	1·1
Iron	7·87	2·56	11
Zirconium	6·8	0·182	8

Nuclear Rockets – Fission Reactor Design

- The power output of a fission reactor is dictated by the neutron flux in the core.
- Neutron flux is defined as

$$\phi \equiv n\,u \qquad neutrons/cm^2 - \sec$$

- *n*: number density of neutrons
- *u*: velocity of the neutrons
- The value of the neutron flux determined by the following
  - Number of neutrons that emerge from the fission of a nucleus
    - Fuel Utilization Factor: h
    - 2.44 in pure U235, 1.335 in natural uranium
  - Number of neutrons that cause fission in U238 – fast fission
    - Fast Fission Factor: e
    - Close to unity
  - Resonance capture of neutrons in U238
    - Resonance Escape Probability: *p*
    - *p*: 0.6-0.8
  - Absorption of thermal neutrons in nuclei other than fuel.
    - Thermal Utilization Factor: *f*
    - Depends on the mass fraction of the moderator

Nuclear Rockets – Fission Reactor Design

- Fission Chain
- Multiplication Factor:

$$k_\infty = \eta \varepsilon p f$$

- The multiplication factor determines the criticality of the chain reaction in an infinitely large domain:
  - Supercritical

    $$k_\infty > 1$$

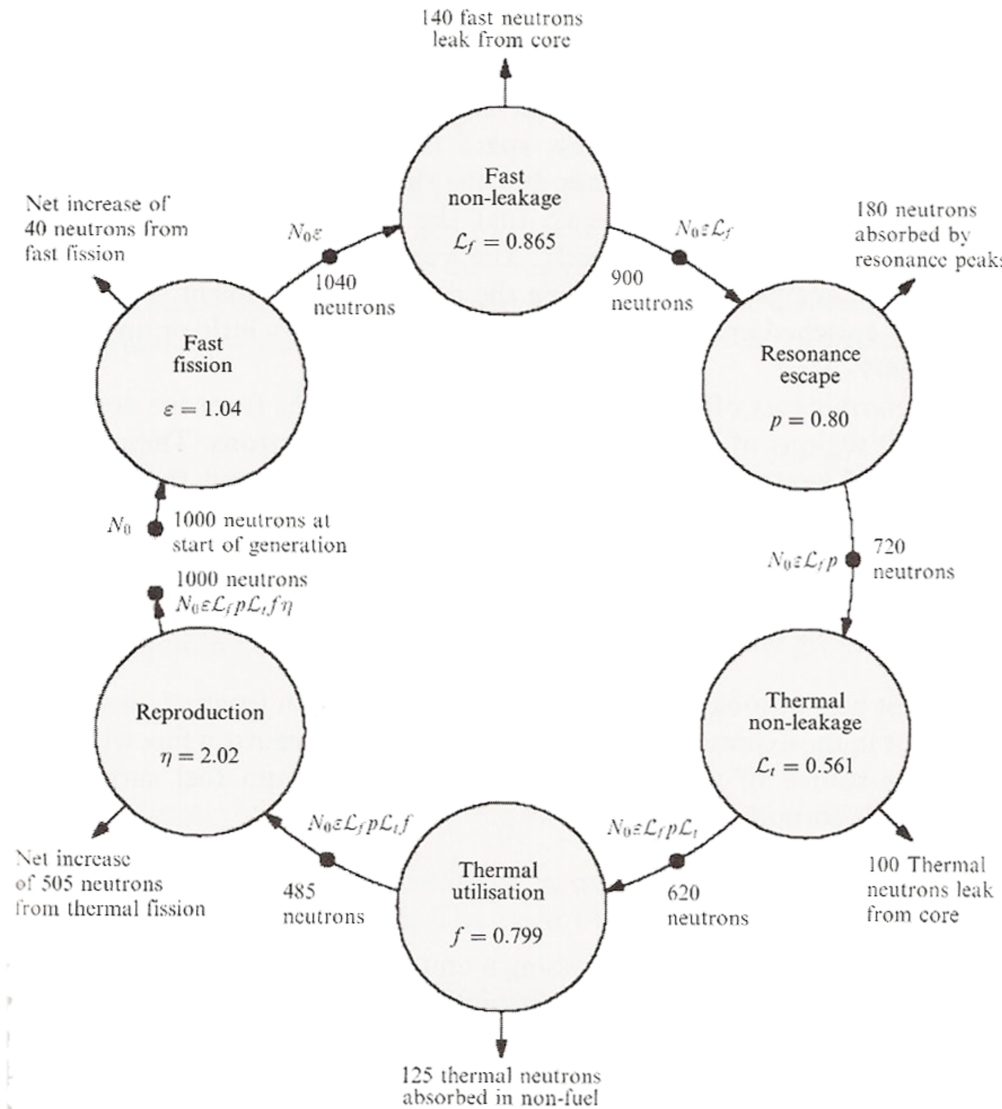
  - Subcritical:

    $$k_\infty < 1$$

  - Critical:

    $$k_\infty = 1$$

- In a reactor multiplication factor is actively controlled by control rods.



Nuclear Rockets – Fission Reactor Design

- In a finite domain one must consider the reactor equation (under steady-state):

$$\nabla^2 \phi + B^2 \phi = 0$$

- *B* is the buckling of the reactor:

$$B^2 = \frac{k_\infty - 1}{L_r^2 + L_s^2}$$

- L_r: Diffusion length after thermalization
- L_s: Diffusion length during slow down
- Free Surface Boundary Condition (for zero extrapolation distance):

$$\phi = 0$$

- Example: enriched U235/graphite reactor:

$$\varepsilon = 1, \quad p = 0.66, \quad f = 0.92, \quad \eta = 1.73$$

$$k_\infty = 1.055$$

$$L_s^2 = 368\, cm^2, \quad L_r^2 = 204\, cm^2, \quad B^2 = 0.94410^{-4}\, cm^{-2}$$

Nuclear Rockets – Fission Reactor Design

- Reactor Equation Solutions:
- Cube:

$$a = b = c = \frac{\pi\sqrt{3}}{B} \qquad V_{\min} = \frac{163}{B^3}$$

- Cylinder:

$$L = \frac{\pi\sqrt{3}}{B} \qquad R = 2.405\sqrt{\frac{3}{2}}\frac{1}{B} \qquad V_{\min} = \frac{148}{B^3}$$

- Sphere:

$$R = \frac{\pi}{B} \qquad V_{\min} = \frac{130}{B^3}$$

- Note that sphere is the most optimal geometry for the reactor in terms of minimum mass requirement.
- Practical considerations favor the cylindrical or rectangular reactors.
- Use of reflectors (pure moderators) reduces the minimum volume (or mass).

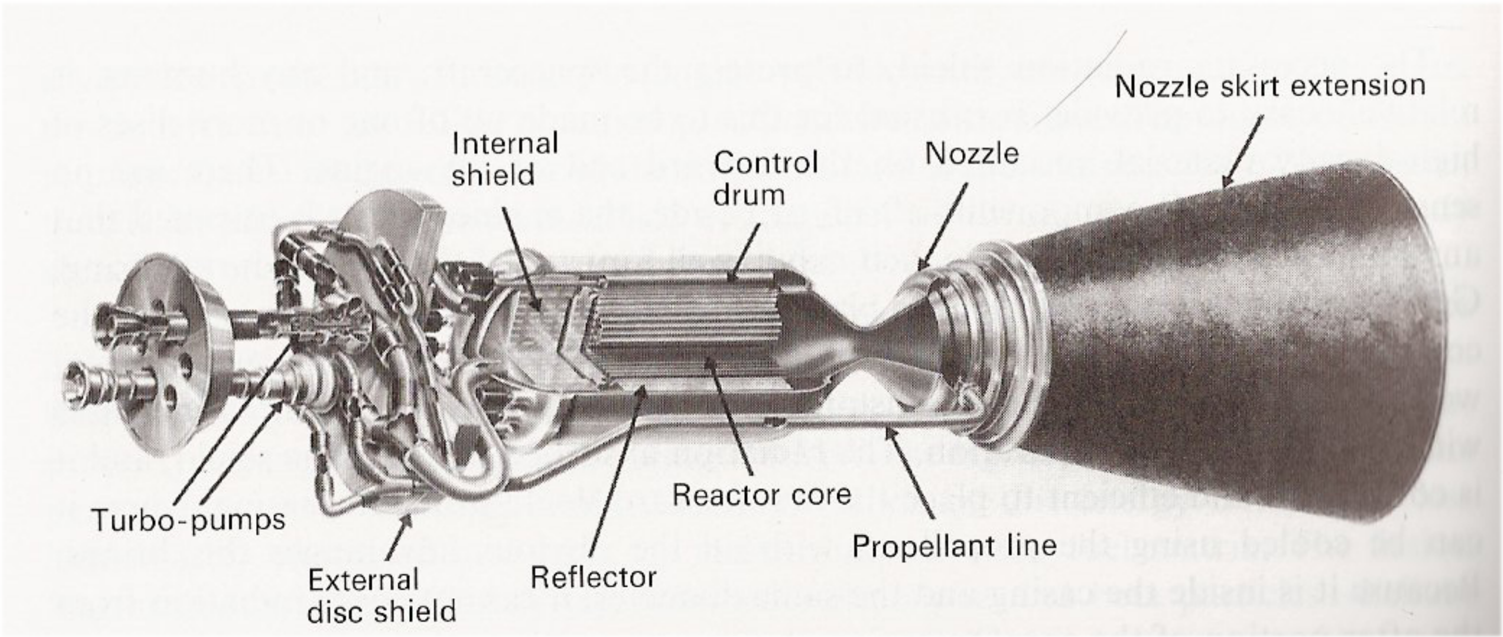
Nuclear Rockets – Fuel Melting Temperatures

- Melting and sublimation temperatures for nuclear reactor fuels, refractory metals and non-metals.

Type of material	Material	Temperature (K
Fuel metal	Uranium (U)	1,400
Fuel compounds	Uranium nitride (UN)	3,160
	Uranium dioxide (UO_2)	3,075
	Uranium carbide (UC_2)	2,670
Refractory metals	Tungsten (W)	3,650
	Rhenium (Re)	3,440
	Tantalum (Ta)	3,270
	Molybdenum (Mo)	2,870
Refractory non-metals	Carbon (C)	3,990 (sublimati
	Hafnium carbide (HfC)	4,160
	Tantalum carbide (TaC)	4,150
	Niobium carbide (NbC)	3,770
	Zirconium carbide (ZrC)	3,450

- UO_2 and UC_2 are commonly used in nuclear propulsion.
- The maximum temperature capability of the fuel limits the performance in nuclear engines. – 2,300-2,500 K (liquid and gas core nuclear reactors can be used for better performance)

Nuclear Rockets – NERVA Engine

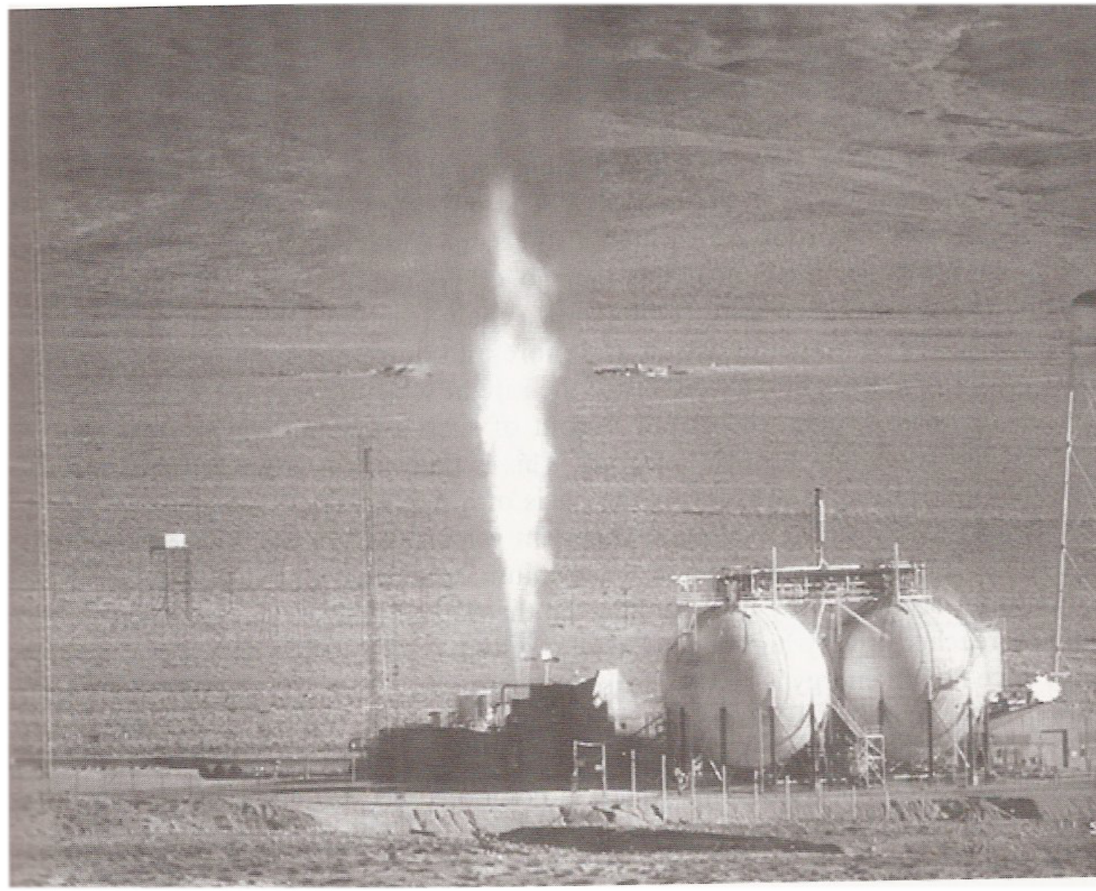


- Thrust: 75,000 lb
- Weight: 14,000 lb
- Chamber Temperature: 2,500 K
- Chamber Pressure: 450 psi
- Specific Impulse: 825 s

- Fuel: Enriched Uranium
- Moderator: Graphite
- Propellant: H_2
- Duration: 50 minutes

Nuclear Rockets – Challenges

- Nuclear propulsion has high potential in space propulsion due to its high Isp performance and very high specific energy capability.
- The safety and environmental issues are the biggest challenge:
  - Testing
  - Launch system failures during launching into LEO
- Increase in the launch system reliability would help.



Nuclear rocket engine test (NERVA program), Jackass flats, Nevada