HISTORY OF FISSION PROPULSION

- **Leo Szilard- 1932**

" Only through the liberation of atomic energy could we obtain the means which would enable man not only to leave the Earth but also to leave the Solar System."

see P. 25 in " The Making of the Atomic Bomb", Richard Rhodes, Simon & Shuster, NY, 1986

'Traditional' Exploratory Work

- **R. Serber, July -1946**
  " The Use of Atomic Power For Rockets", Douglas Aircraft Co. Report, July 1946

- **H. S. Tsein - 1947**
  Lecture at MIT on H_2 cooled graphite cores

- ***See References - Appendix A for 1946 -55***

- ***April 1955 - Nuclear Propulsion Division established -LANL (AF/AEC)***

- ***See history on the nuclear rockets (R. J. Bohl et. al., P. 467 in <u>Space Nuclear Power Systems</u>, Ed. M. S. El Genk and M. D. Hoover, Orbit Books, Malabar, FL.,1988***

- ***See G. L. Bennett et. al., in "A Critical Review of Space Nuclear Power and Propulsion 1984-93" American Inst. Phys., New York (1994)***

APPENDIX A

Publications on Nuclear Rocket Propulsion in the 1946 to 1955 Era

The articles listed in this appendix were compiled by R. W. Bussard. Several of them are available at the Los Alamos National Laboratory Library. The list is included so that interested readers are aware of the articles. The list first appeared in LA-MS-2036 (Schreiber 1956).

1. *The Use of Atomic Power for Rockets*, R. Serber, Douglas Aircraft Company (5 July 1946).
2. *Nuclear Powered Flight*, APL/JHU-TG-20 (14 January 1947).
3. *Rocket Computations*, R. Cornog, NEPA-508 (3 August 1946).
4. *Controls for Nuclear Powered Aircraft*, L. A. Ohlinger, NEPA-511 (21 November 1946).
5. *Pilot Plant for Nuclear Powered Aircraft*, L. A. Ohlinger, NEPA-505 (13 August 1946).
6. *Rocket Performance Factors*, M. L. Lesser, NEPA-175 (21 March 1947).
7. *An Estimate of Nuclear Rocket Performance*, R. E. Adams, NEPA-283 (15 September 1947).
8. *Problems in the Application of Nuclear Energy to Rocket Propulsion*, H. S. Seifert and M. M. Mills, JPL-Memo-3–4 (23 January 1947).
9. *Feasibility of Nuclear Powered Rockets and Ramjets*, NA 47–15 (11 February 1947).
10. *A Preliminary Study on the Use of Nuclear Power in Rocket Missiles*, H. P. Yockey and T. F. Dixon, NA-46–574 (1 July 1946).
11. "Rockets and Other Thermal Jets Using Nuclear Energy, With a General Discussion on the Use of Porous Pile Materials," H. S. Tsien (1947), published in *The Science and Engineering of Nuclear Power*, Vol. II, edited by C. Goodman, Addison-Wesley Press (1949), p.177–195.
12. Pile Technology Lectures 31 and 32. "Nuclear Powered Rockets," N. M. Smith, Jr., M-3891, no date (about October 1947).
13. Preliminary Remarks on H. S. Tsien's Seminars, "Rockets ----------," W. K. Ergen, NEPA-544 (1 June 1948).
14. *Determination of Propellant Tank Weights and Optimum Pump Inlet Pressure for Orbiting Rocket*, A. N. MacDonald, NEPA-457 (10 March 1948).
15. *Program and Requirement of NEPA Project, Fiscal Year 1949*, NEPA-535 (1 May 1948).
16. *Nuclear-Powered Flight*, LEXP-1 (30 September 1948).
17. *The Feasibility of Nuclear-Powered Rockets*, E. M. Redding, LP-148 (8 September 1948).
18. "The Atomic Rocket I, II, III, and IV," A. V. Cleaver and L. R. Shepherd, *Journal of the British Interplanetary Society* (September 1948, November 1948, January 1949, and March 1949).
19. "Note on Shielding of Atomic Rockets," L. R. Shepherd, *Journal of the British Interplanetary Society* (July 1949).
20. *Monthly Progress Report MX-1589,*" CVAC-FW, CVAC-PR-1 (29 February 1952).
21. *Nuclear Rocket Study*, CVAC-FW, R. E. Adams, FZA-9–504 (1 March 1952).
22. *The Application of Nuclear Energy to Rocket Propulsion, A Literature Search*, E. P. Carter, ORNL, Y-931 (29 December 1952).
23. "Nuclear Energy for Rocket Propulsion," R. W. Bussard, ORNL, CF-53-6-6, July 2, 1953, later published in *Reactor Science and Technology*, TID-2011 (December 1953).
24. *A Survey of the Application of Nuclear Power for the Propulsion of Aircraft and Guided Missiles*, W. H. Thiel (CVAC-SD) ORNL, CF-53–8–223 (August 1953).
25. *Nuclear Propulsion of Missiles*, COPL-84 (8 February 1955).
26. *Conceptual Design of a Nuclear-Powered Ballistic Missile*, W. C. Cooley, GE-ANP, XDC-55–2–20 (February 1955).
27. *The Feasibility of Nuclear-Powered Long Range Ballistic Missiles*, LAMS-1870 (March 1955).
28. *Nuclear Rocket Propulsion*, Bussard, R. W., R. D. DeLauer, McGraw Hill, 1958.

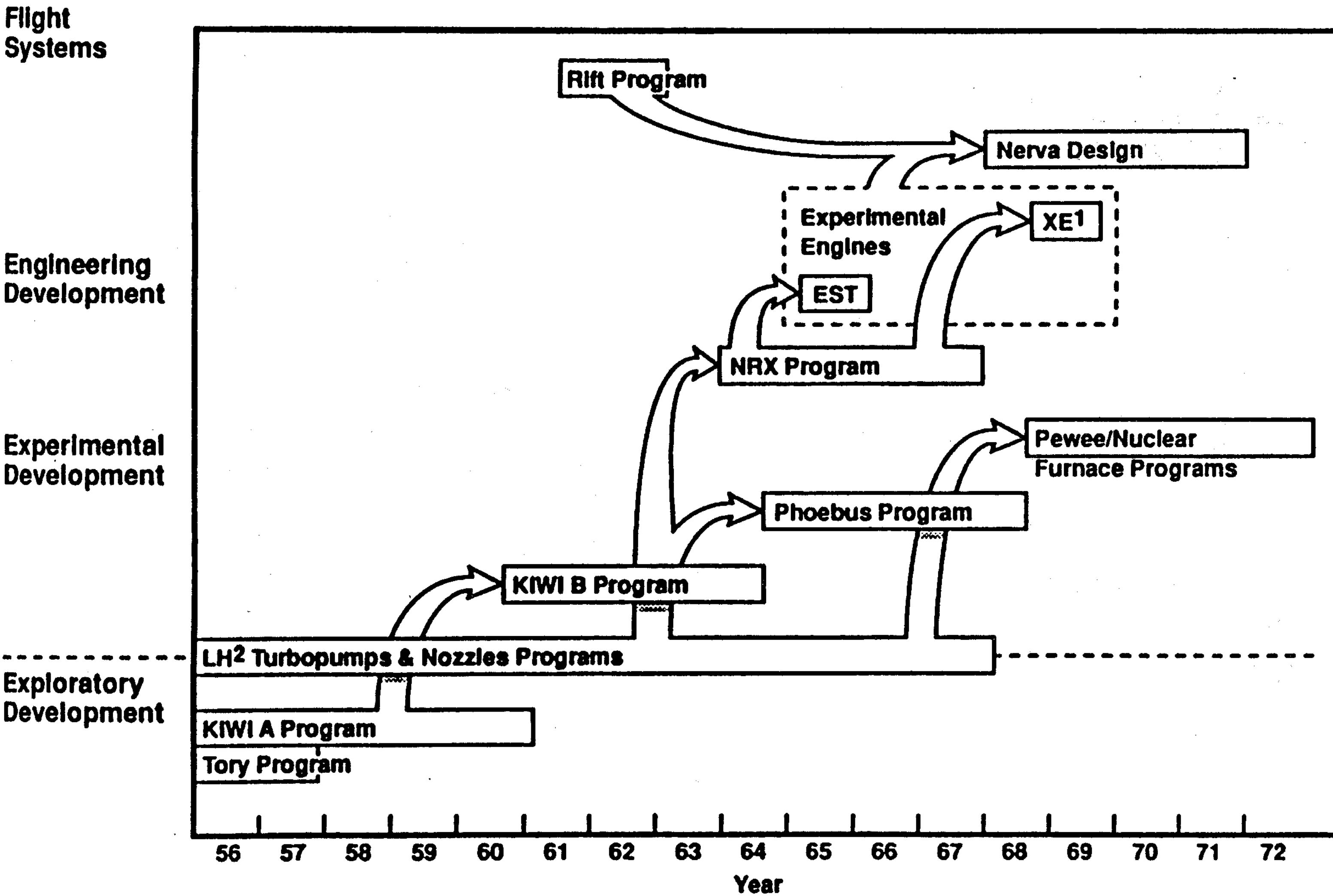


FIGURE 1. Chronological Overview of the Nuclear Rocket Program [Gunn 1989].

- http://www.fas.org/nuke/space/links.htm

Nuclear Thermal Propulsion

- ***KIWI -A 7/59-Oct 1960, 3 tests up to 100 MW***

- ***KIWI -B, 12/61 –8/64, (5 tests up to 1020 MW)***

- ***KIWI-TNT, tested to destruction, Jan1965***

- ***Phoebus, 6/65-6/68 (3 tests up to 4100 MW)***

- ***Westinghouse and Aerojet started in 1960 to develop a flight version of KIWI into a Nuclear Engine for Rocket Vehicle Application (NERVA)***

- ***NERVA Reactor Experiments (NRX) , 9/64 –12/67 (5 Tests - 1200 MW for 60 mins)***

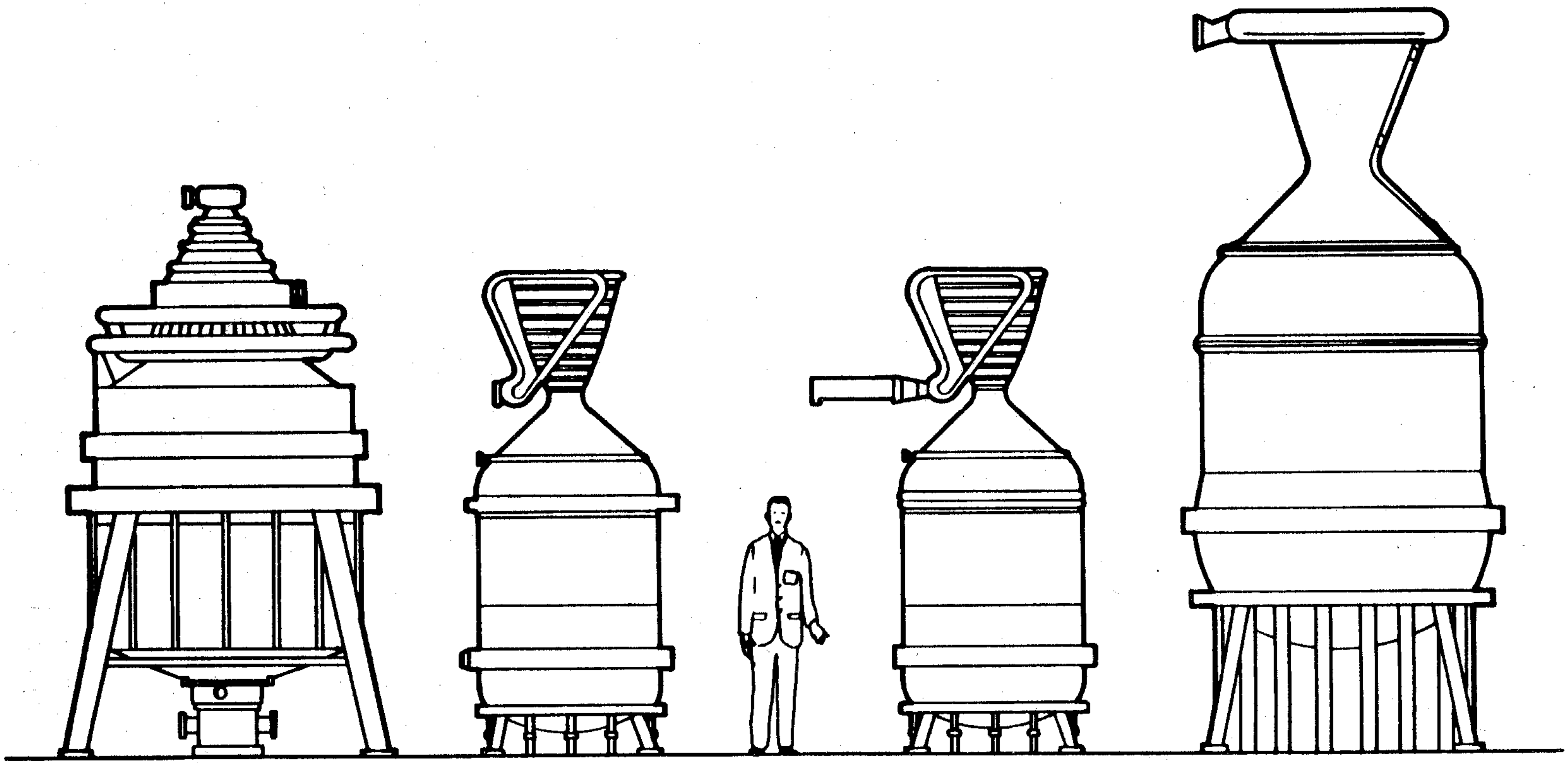
- ***Experimental Engine Test (XE) into vacuum, (28 starts and stops), March 1969***

- ***Pewee -I, Dec 1968, 500 MW, 40 min, test of Phoebus and NRX fuel elements***

- ***Final Fuel Element test, Nuclear Furnace, June 1972, 44 MW for 108 min***
Spent ≈ 1 $B over the period 1959-1972

Achievements of the ROVER/NERVA Program

Biggest ••••Phoebus 2,
4086 elements,
4100 MW

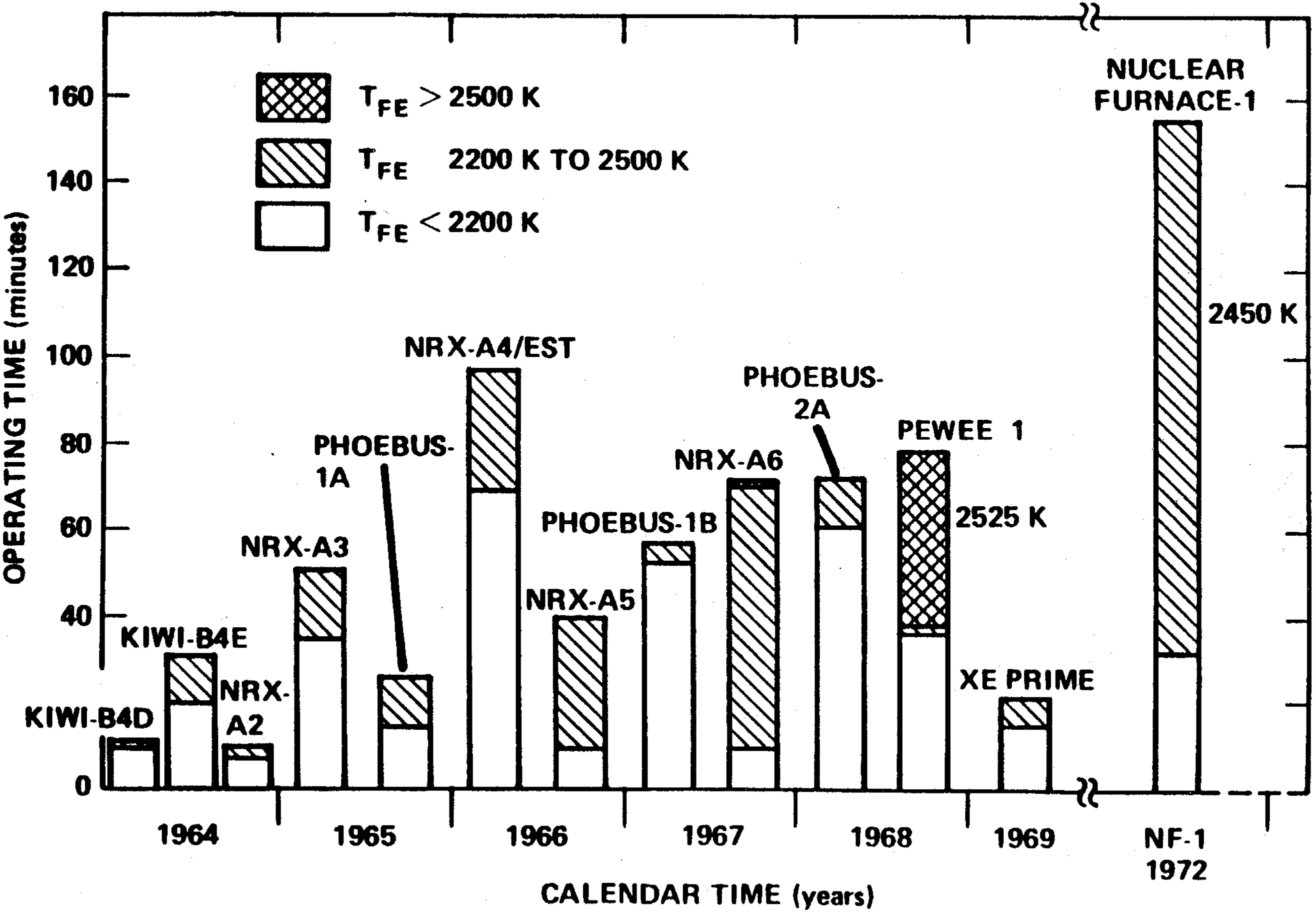


KIWI A
1958–60
100 MEGAWATTS
5000 lb THRUST

KIWI B
1961–64
1000 MEGAWATTS
50,000 lb THRUST

PHOEBUS 1/NRX
1965–66
1000 and 1500 MEGAWATTS
50,000 lb THRUST

PHOEBUS 2
1967
5000 MEGAWATTS
250,000 lb THRUST



$T_{FE} > 2500$ K
T_{FE} 2200 K TO 2500 K
$T_{FE} < 2200$ K
OPERATING TIME (minutes)
160
140
120
100
80
60
40
0
KIWI-B4D
KIWI-B4E
NRX-A2
NRX-A3
PHOEBUS-1A
NRX-A4/EST
NRX-A5
PHOEBUS-1B
NRX-A6
PHOEBUS-2A
PEWEE 1
2525 K
XE PRIME
NUCLEAR FURNACE-1
2450 K
1964
1965
1966
1967
1968
1969
NF-1 1972
CALENDAR TIME (years)

Highest Thrust••••Phoebus 2A
930 kN

H_2 Flow Rate••••Phoebus 2A
120 kg/s

Specific Impulse•••Pewee
≈ 838 s

Minimum Reactor •••Phoebus 2A
Specific Mass 2.3 kg/MW

Smallest •••• Nuclear Furnace
49 elements,
44 MW

Hottest•••• Pewee
2,550 ° K exit gas
2,750 °K fuel

Longest Lived ••••Nuclear Furnace
109 min

Highest Power Density •••• Pewee-
1.3 MW/ fuel element-5,200 MW/m^3*(fuel)*

Greatest Number of Restarts•••XE
28

Table 10.2 Performance of various Rover reactor systems.

	KIWI-4BE	NRX-A6	Phoebus-2A	Pewee-1
Reactor power (MW)	950	1,167	4,080	507
Flow rate (kg/s)	31.8	32.7	119.2	18.6
Fuel exit average temperature (K)	2,330	2,472	2,283	2,556
Chamber temperature (K)	1,980	2,342	2,256	1,837
Chamber pressure (MPa)	3.49	4.13	3.83	4.28
Core inlet temperature (K)	104	128	137	128
Core inlet pressure (MPa)	4.02	4.96	4.73	5.56
Reflector inlet temperature (K)	72	84	68	79
Reflector inlet pressure (MPa)	4.32	5.19	5.39	5.79
Periphery and structural flow (kg/s)	2.0	0.4	2.3	6.48

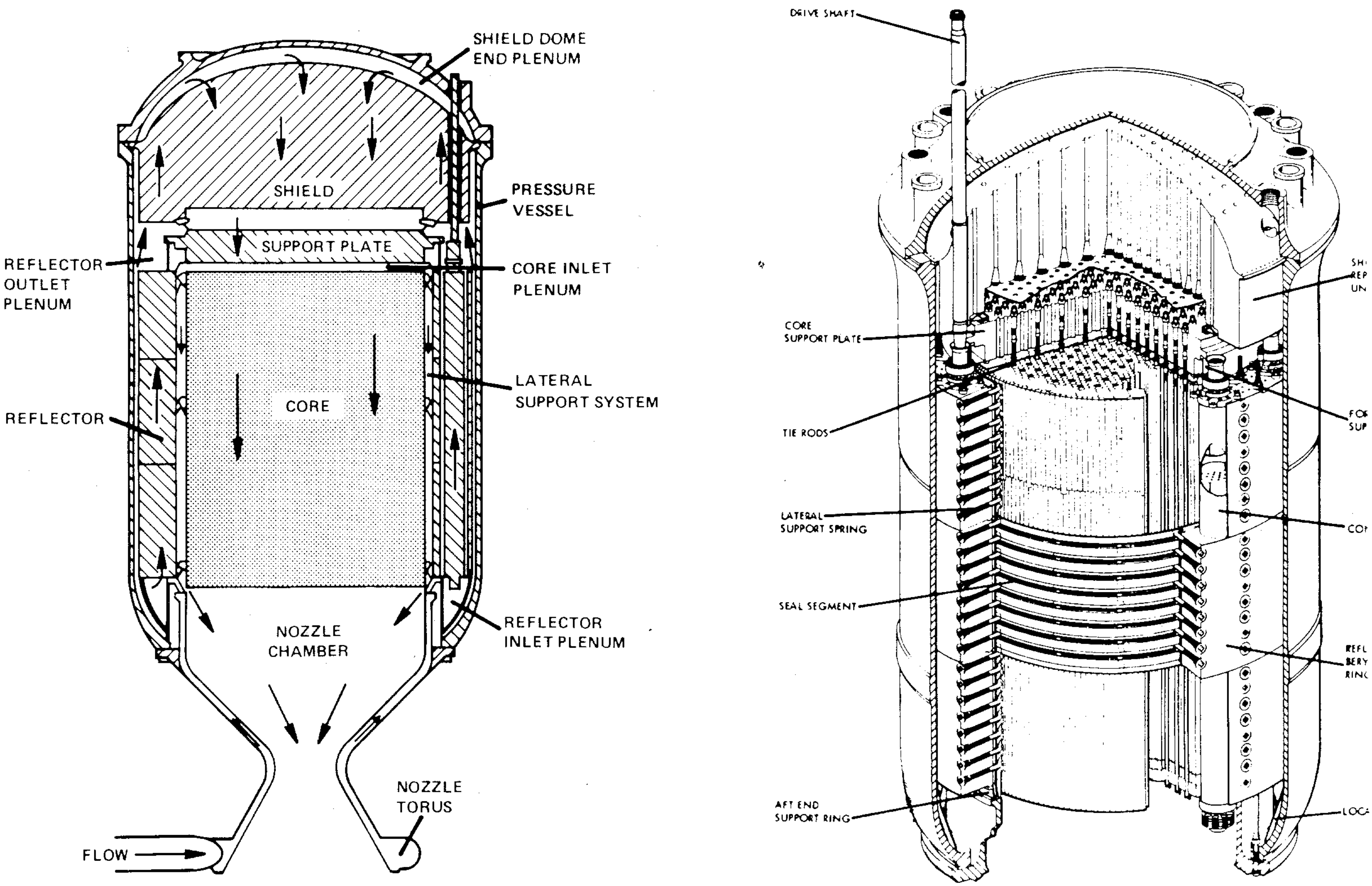


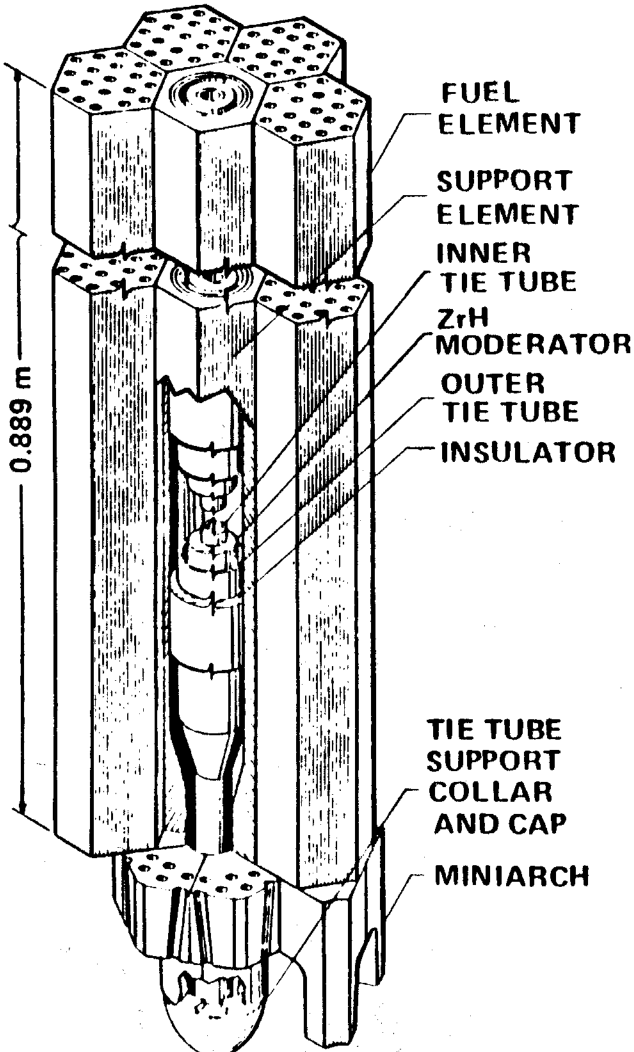
Fig. 10.8 Schematic (left) and cutaway (right) views of Rover nuclear rocket reactor. *From Westinghouse Astronuclear Lab "NRX-A6 Test Predictions," WANL-TME-1613, November 1967.*

ROVER/NERVA

REACTOR DESIGN FEATURES

- EPI-THERMAL, GRAPHITE-MODERATED, HYDROGEN-COOLED REACTOR
- USED ENRICHED 93.15% URANIUM -235 AS FUEL
- CORE INLET ORIFICES ADJUSTED FOR FLOW DISTRIBUTION
- POWER FLATTENING BY VARYING FUEL LOADING AND FLOW DISTRIBUTION
- CORE SUPPORTED BY COLD-END SUPPORT PLATE AND STRUCTURAL TUBE ARRANGEMENT
- REACTIVITY CONTROL BY ROTATING DRUMS IN REFLECTOR CONTAINING NEUTRON ABSORBER

DESCRIPTION OF "SMALL ENGINE" FUEL MODULES



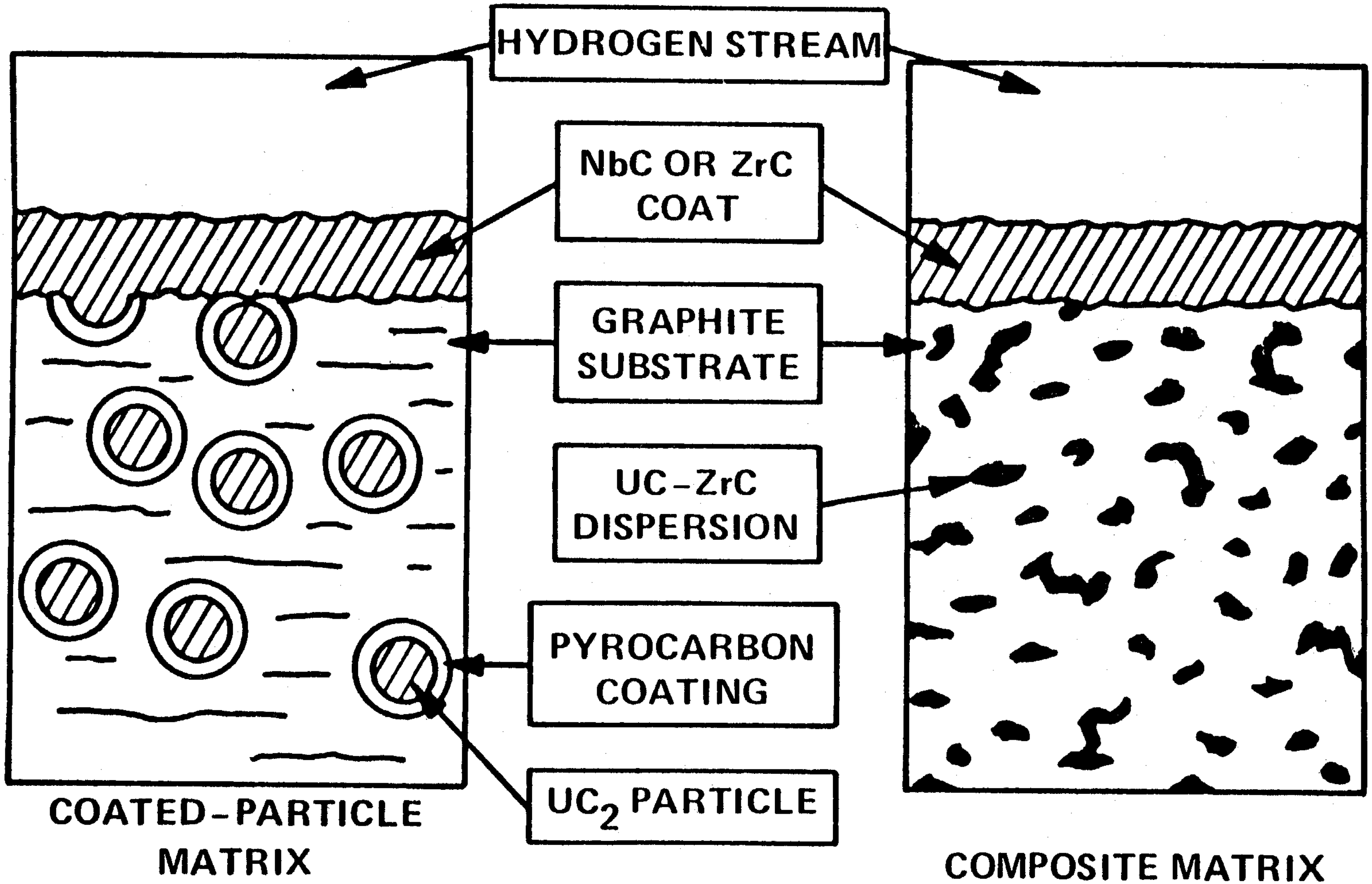
FUEL

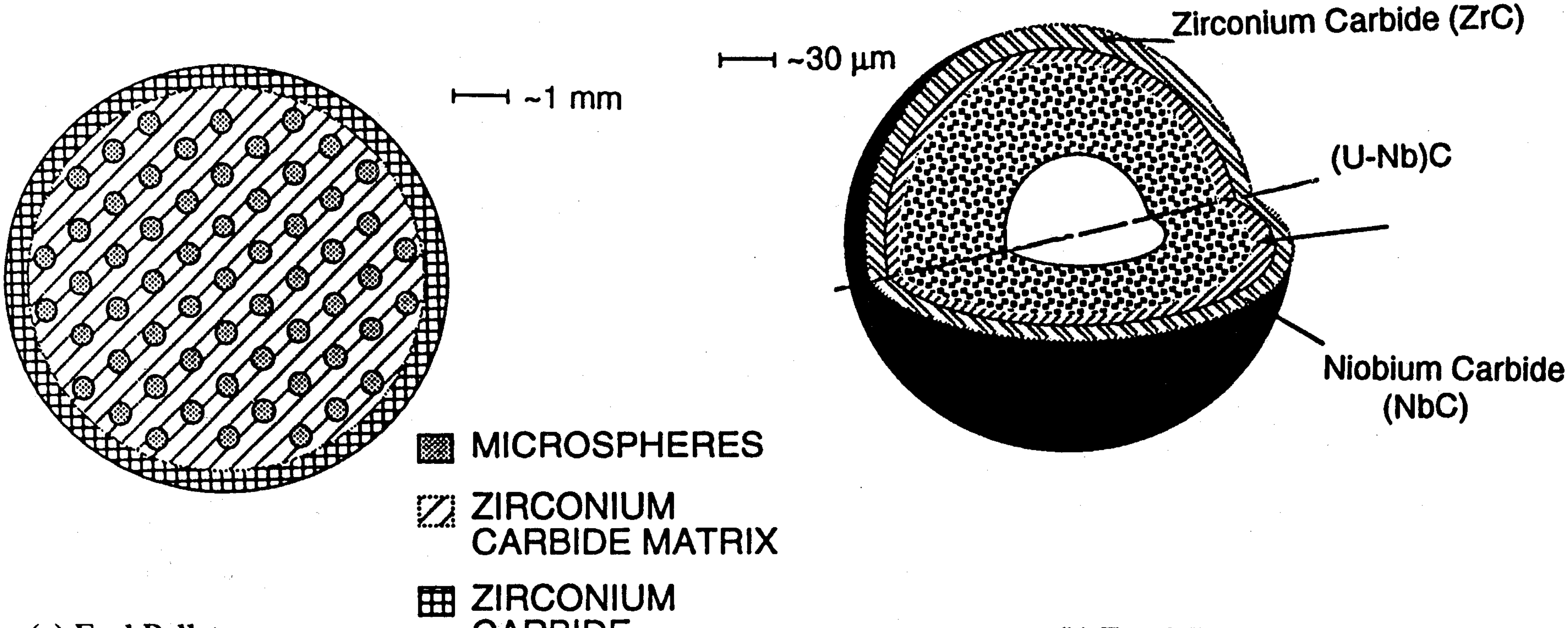
- **FUNCTION**
  - PROVIDED ENERGY FOR HEATING HYDROGEN PROPELLANT
  - PROVIDED HEAT TRANSFER SURFACE
- **DESCRIPTION**
  - ^{235}U IN A COMPOSITE MATRIX OF UC-ZrC SOLID SOLUTION AND C
  - CHANNELS COATED WITH ZrC TO PROTECT AGAINST H_2 REACTIONS

TIE TUBES

- **FUNCTION**
  - TRANSMIT CORE AXIAL PRESSURE LOAD FROM THE HOT END OF THE FUEL ELEMENTS TO THE CORE SUPPORT PLATE
  - ENERGY SOURCE FOR TURBOPUMP
  - CONTAIN AND COOL ZrC MODERATOR SLEEVES
- **DESCRIPTION**
  - COUNTER FLOW HEAT EXCHANGER OF INCONEL 718
  - ZrH MODERATOR
  - ZrC INSULATION SLEEVES

COMPARISON OF FUEL ELEMENTS

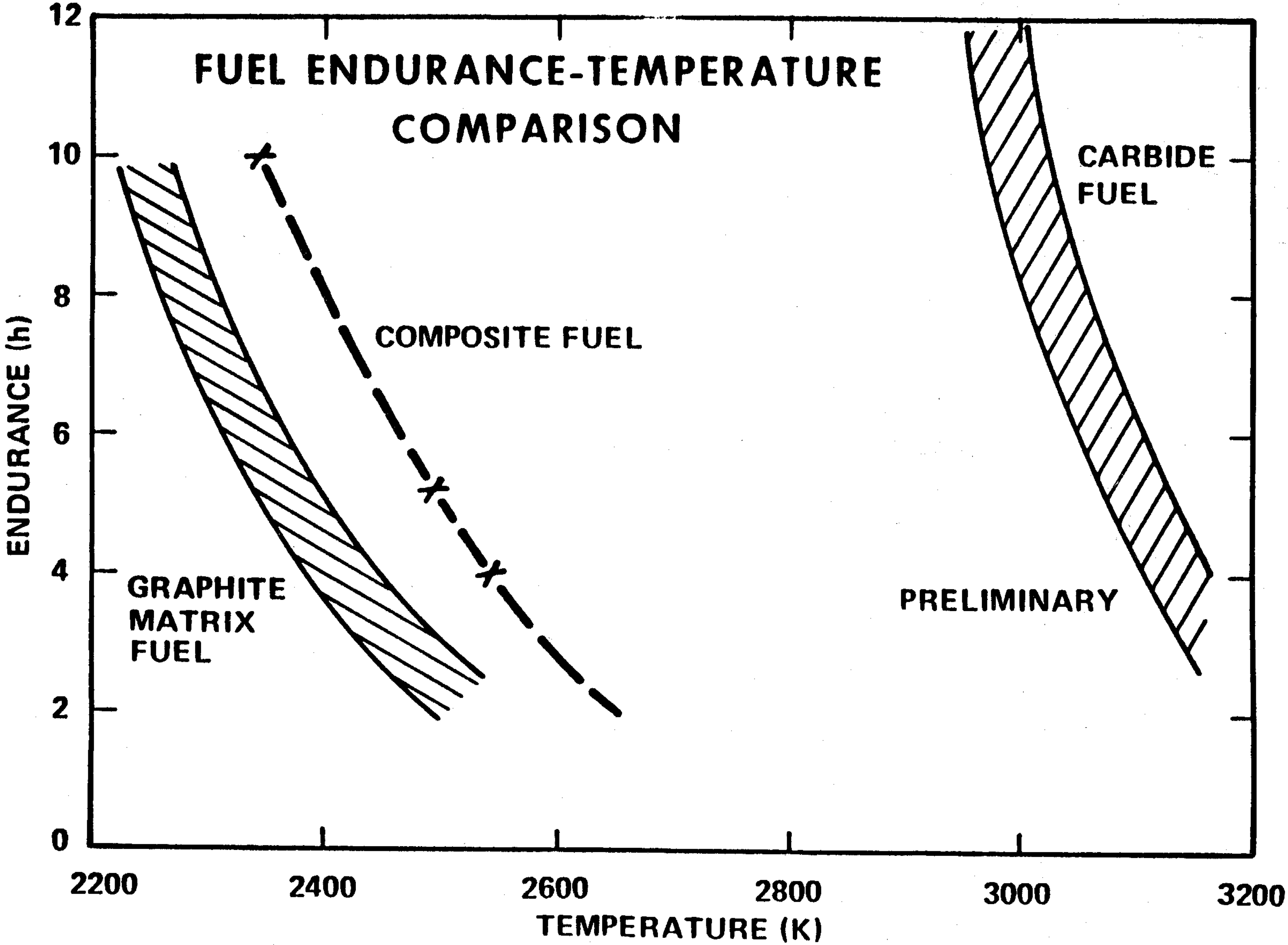




(a) Fuel Pellet

(b) Fuel Microsphere

FIGURE 3. Radial Cross-Sectional Views of the Fuel Pellet and Fuel Microspheres in the PeBR for NTP Applications.



FUEL ENDURANCE-TEMPERATURE COMPARISON
ENDURANCE (h)
TEMPERATURE (K)
0
2
4
6
8
10
12
2200
2400
2600
2800
3000
3200
GRAPHITE MATRIX FUEL
COMPOSITE FUEL
CARBIDE FUEL
PRELIMINARY

ZIRCONIUM CARBIDE LOSS RATES

Measured in 1 atmosphere flowing hydrogen

TEMPERATURE K	LOSS RATE MILS/HR	TIME FOR 2 MIL (51μ) ZrC COATING TO ERODE AWAY hr
3200	5.5	0.4
3100	2.4	0.8
3000	1.4	1.5
2900	0.6	3.2

FOR HIGHER HYDROGEN PRESSURES SHORTER LIFETIMES ARE ANTICIPATED

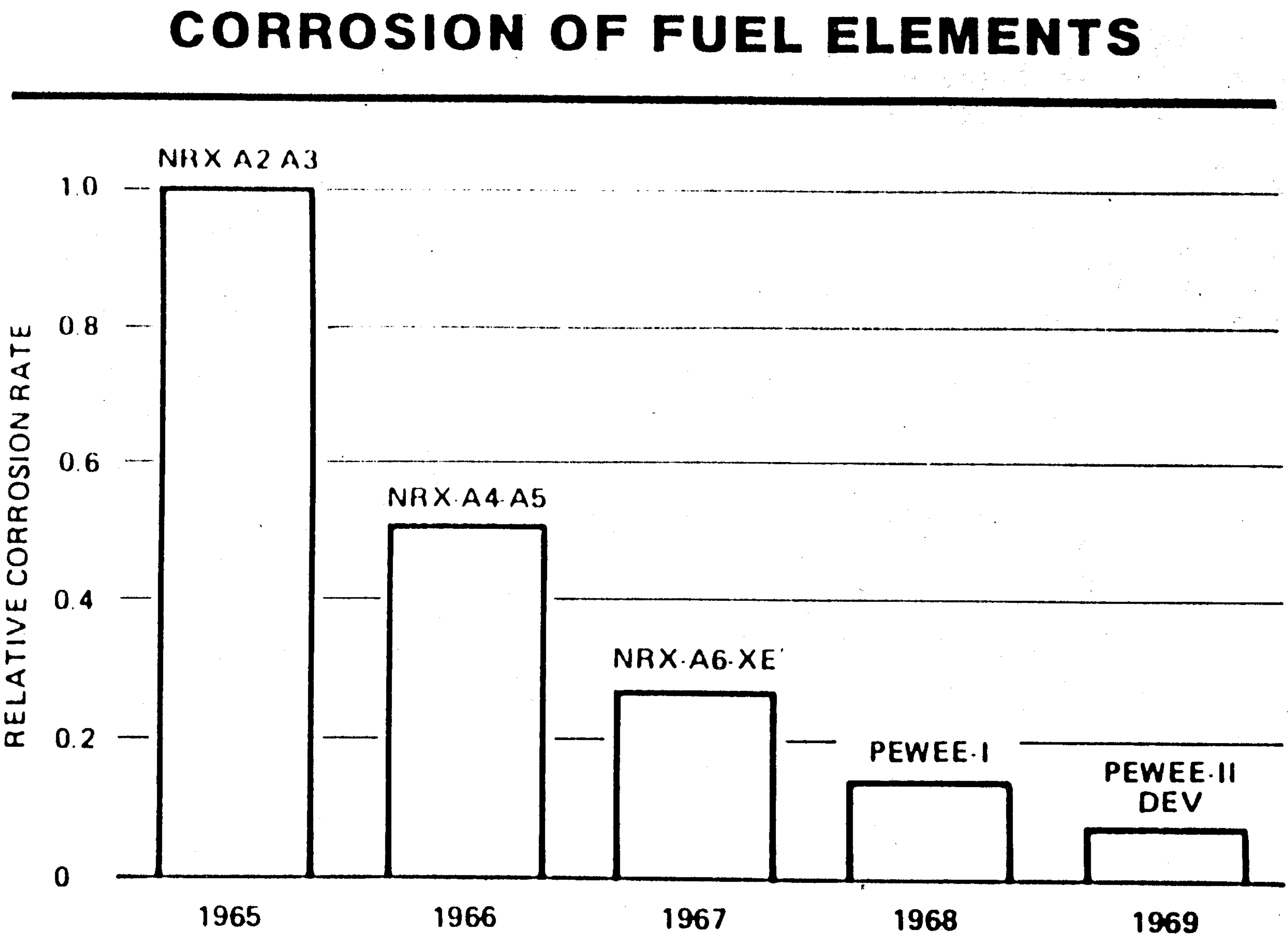
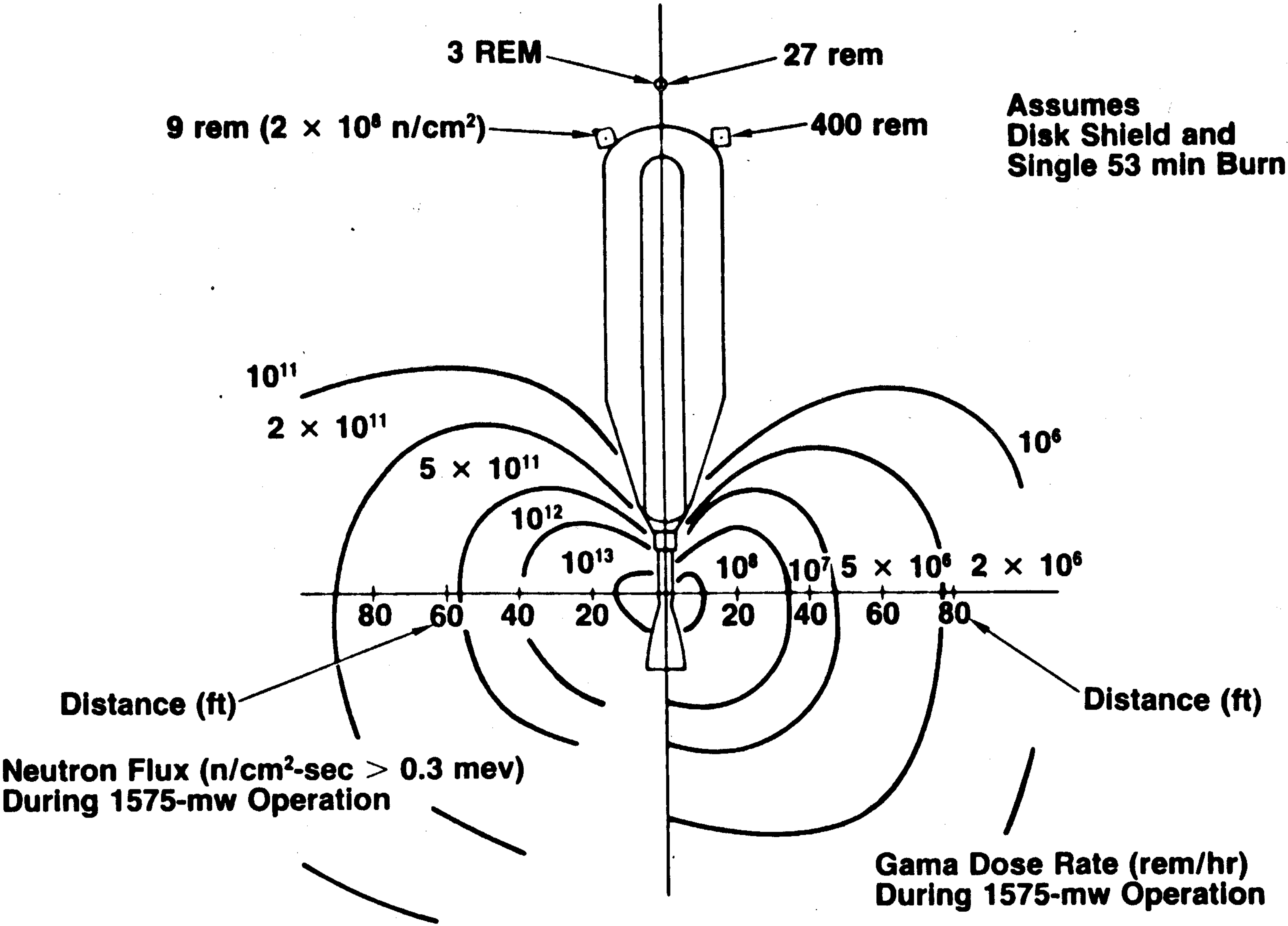
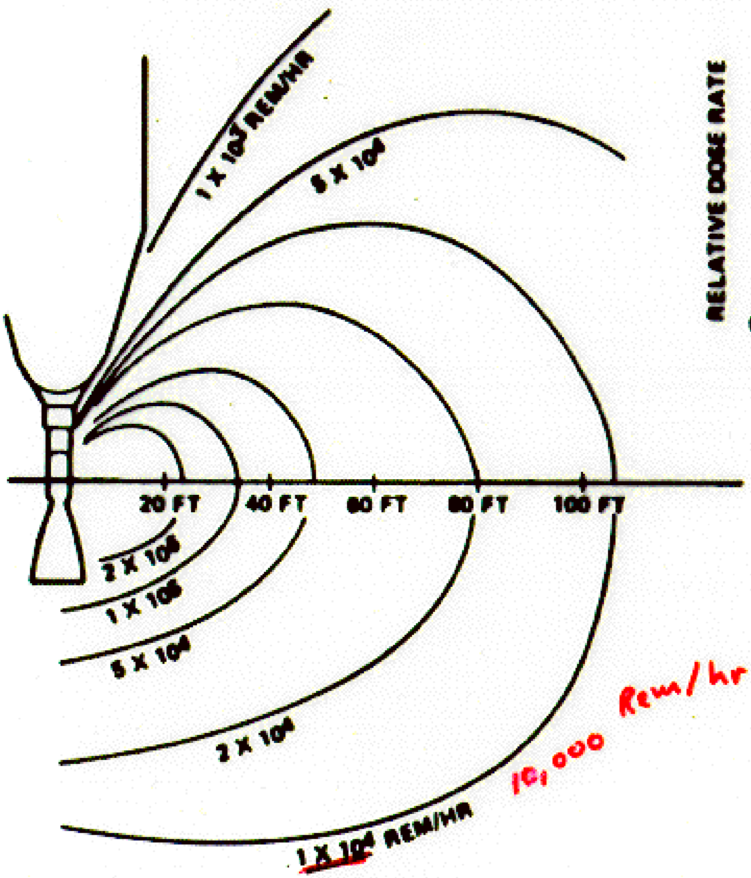


Fig. 10.13 Progress in reducing hydrogen corrosion of fuel elements. *Courtesy of Los Alamos National Laboratory and Westinghouse Astronuclear Laboratory.*

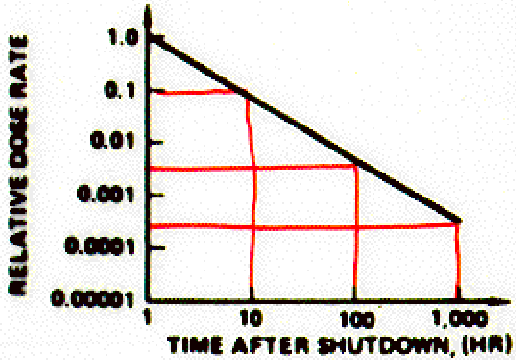
RADIATION MAP

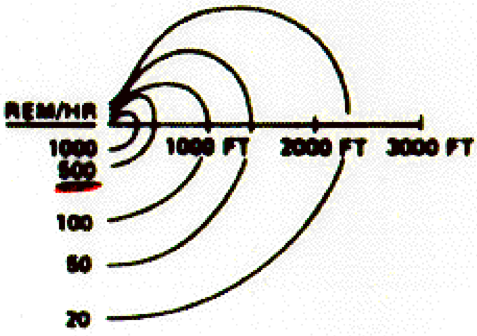


DOSE RATE AFTER SHUTDOWN



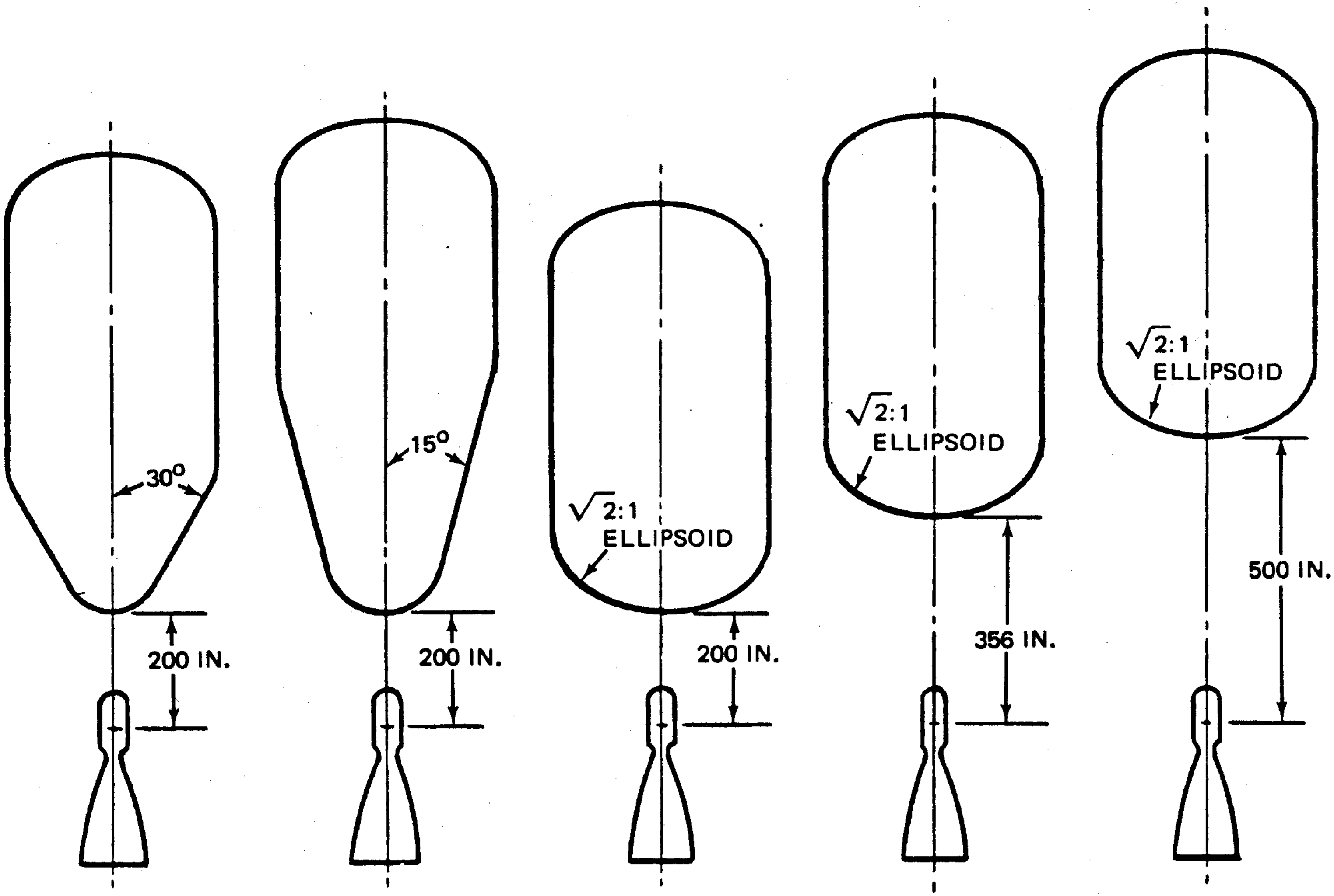
FISSION PRODUCT DOSE RATE
1 HR AFTER 0.5-HR OPERATION AT 1,575-MW



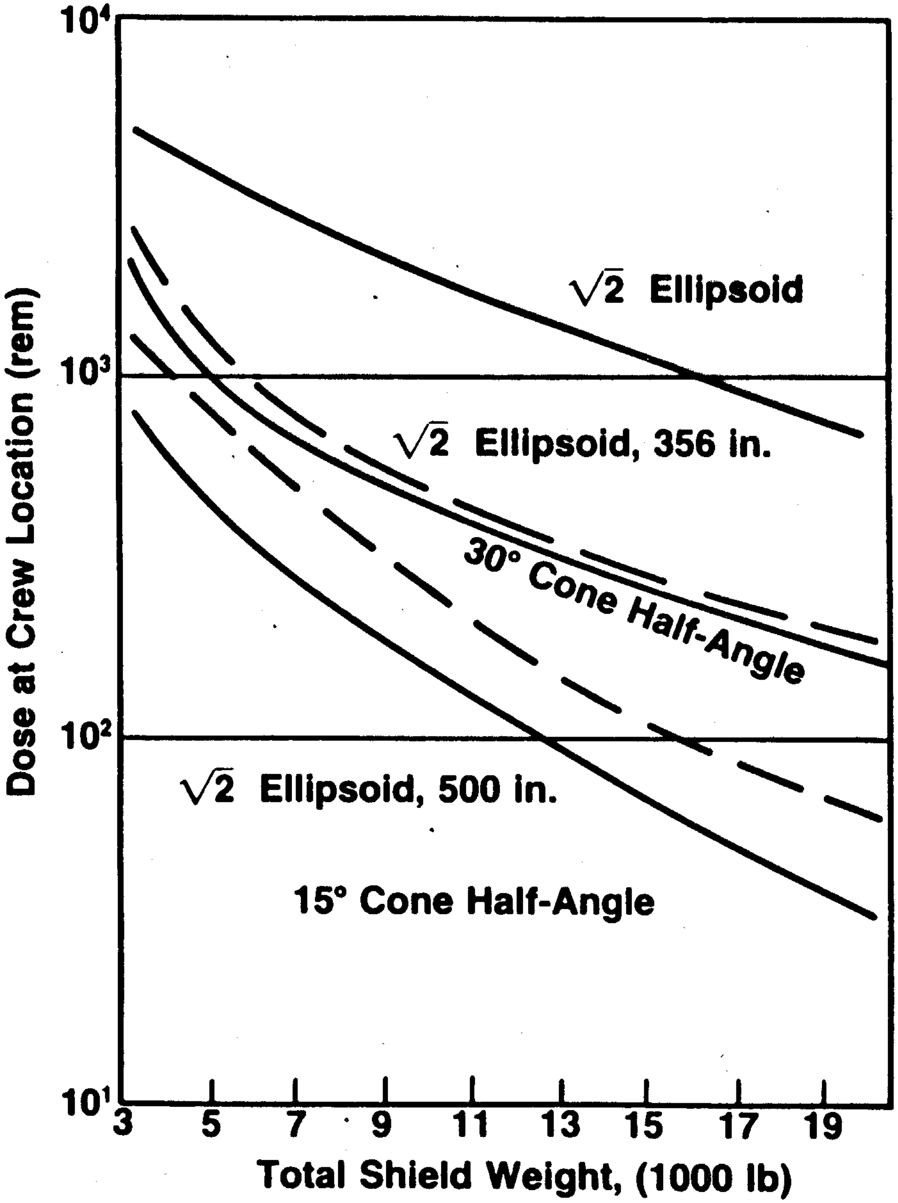


FISSION PRODUCT DOSE RATE 1 HR
AFTER 0.5-HR, 1,575-MW OPERATION

CONVENTIONAL TANK CONFIGURATION



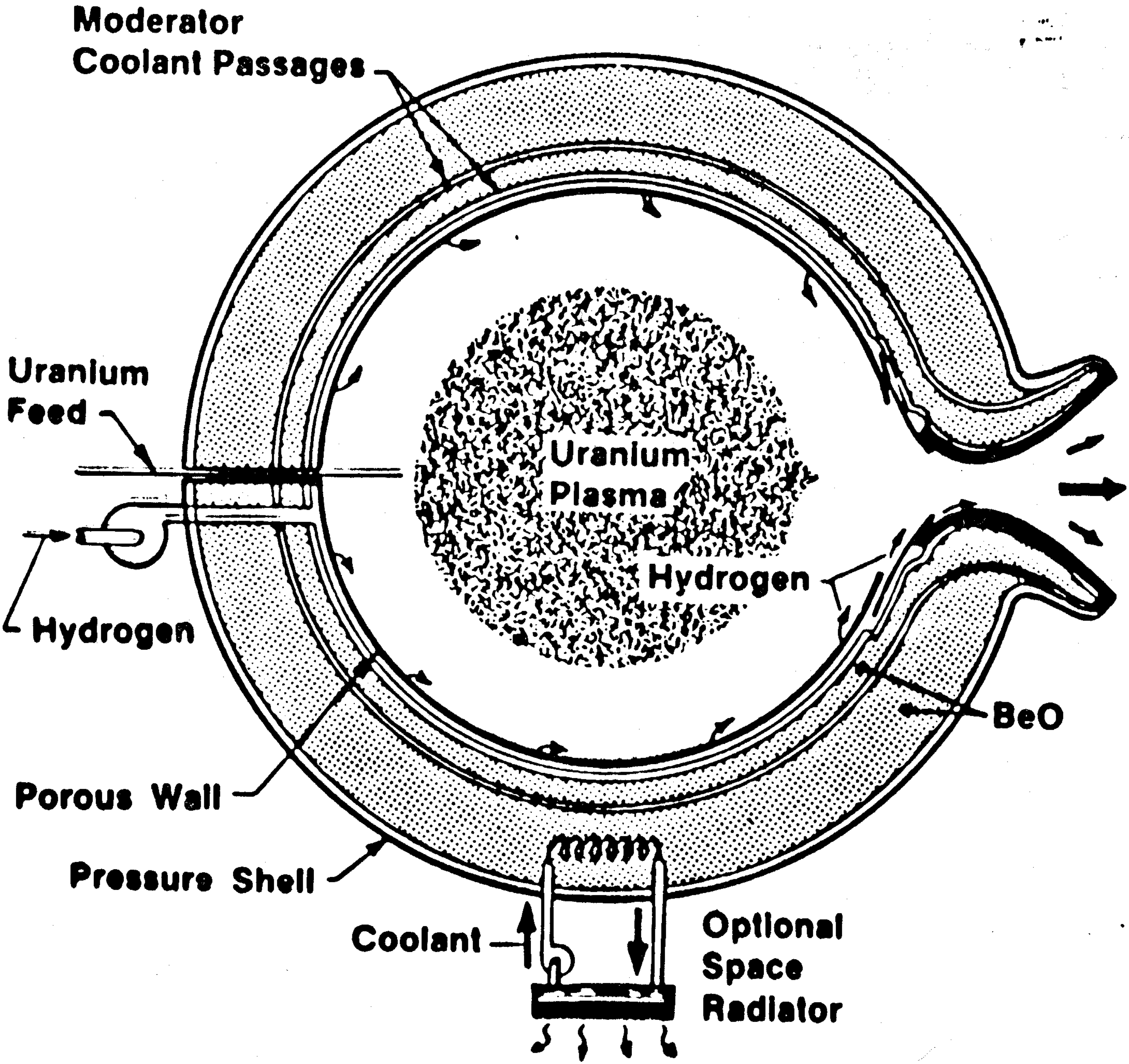
SHIELD WEIGHT REQUIREMENTS FOR CONVENTIONAL TANK CONFIGURATIONS



300,000 LH_2 Capacity
3300-lb Internal Shield
7500-lb LH_2 Residual
3-Zone Disk Shield
All Sources in May 1969 Cram Rpt
200-in. Engine Tank Separation
(Unless Otherwise Noted)

***Table 1** Lifetime of Parking Orbits.*

Altitude (Nautical Miles)	Expected Time In Orbit (Days)
85	1/2
100	3
150	35
200	200
300	4000


Moderator
Coolant Passages
Uranium
Feed
Hydrogen
Uranium
Plasma
Hydrogen
BeO
Porous Wall
Pressure Shell
Coolant
Optional
Space
Radiator

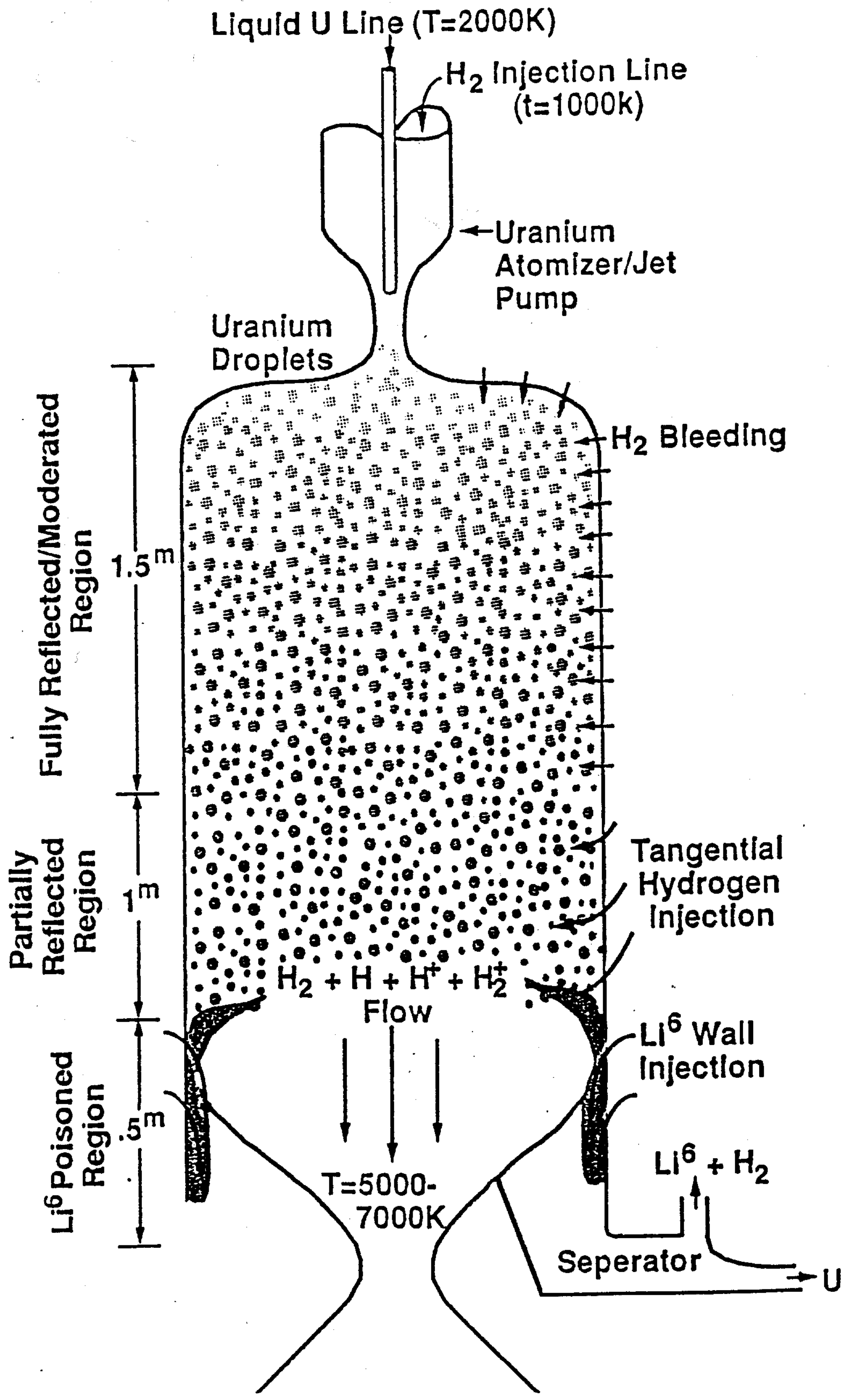


Figure 8. Droplet Core Nuclear Rocket (DCNR).