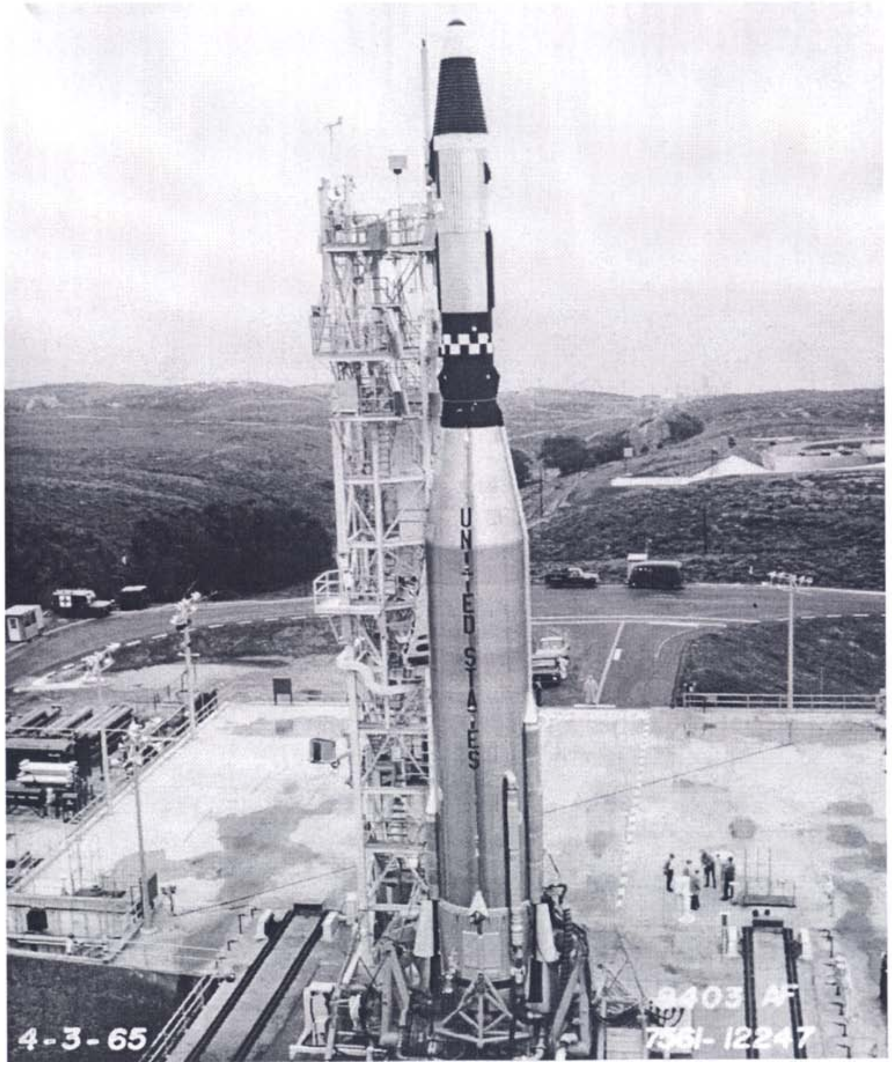


SNAPSHOT PRELAUNCH

SNAPSHOT LAUNCH

SNAPSHOT LAUNCH

SNAP OVERVIEW

General Background

By: Glen Schmidt

February 7, 2011

References:

94ETEC-DRF-1476

DCN: SP-100-XT-0002

SNAP Reactors Overview

- North American Aviation’s Atomic International Division (AI) was under contract with the Atomic Energy Commission (AEC) to perform R&D work on Systems for Nuclear Auxiliary Power (SNAP).
- A total of eight different SNAP reactors were built and tested at AI.

SNAP Nuclear Reactors

- Designs were typical for space power systems and included:

SER	SNAP-2 Experimental Reactor (Ground tested)
S2DR	SNAP-2 Developmental Reactor (Ground tested)
S10FS-1	SNAP-10A Flight Reactor (Failed acceptance test)
S10FS-3	SNAP-10A Flight Reactor (Ground tested)
S10FS-4	SNAP-10A Flight Reactor (Launch tested)
S10FS-5	SNAP-10A Flight Reactor (Spare - Stored)
S8ER	SNAP-8 Experimental Reactor (Ground tested)
S8DR	SNAP-8 Developmental Reactor (Ground tested)

SNAP 10A PROGRAM

<u>Mission Requirements</u>

- Power — 500+ watts
- Life — 1 year
- Weight — ~ 1000 lbs
- Spacecraft — Agena B modified with Atlas booster
- Orbit — 700 nm (north to south orbit)
- Safety — subcritical until launch startup
- Other — subcritical during re-entry, water/sand immersion, & ground accidents.

SNAP 10A PROGRAM

System Design Evolution

- **Concepts**

  Static thermoelectric-conduction heat transfer

  Static thermoelectric-liquid metal circulation heat transfer
- **Preliminary Design**

  Solid core with radial fins for waste heat rejection
- **Prototype Designs**

  Conical corrugated SST structure, 40 (10 mil) parallel tubes & manifolds, control drive motors located below reactor, TE pump located at base of structure
- **Final Flight Designs**

  Corrugated titanium structure, 40 (20 mil) parallel D-tubes, control drives and thermoelectric NaK pump located above the radiation shield, and instrumentation & controls located in a compartment below the structure

SNAP Nuclear Reactors

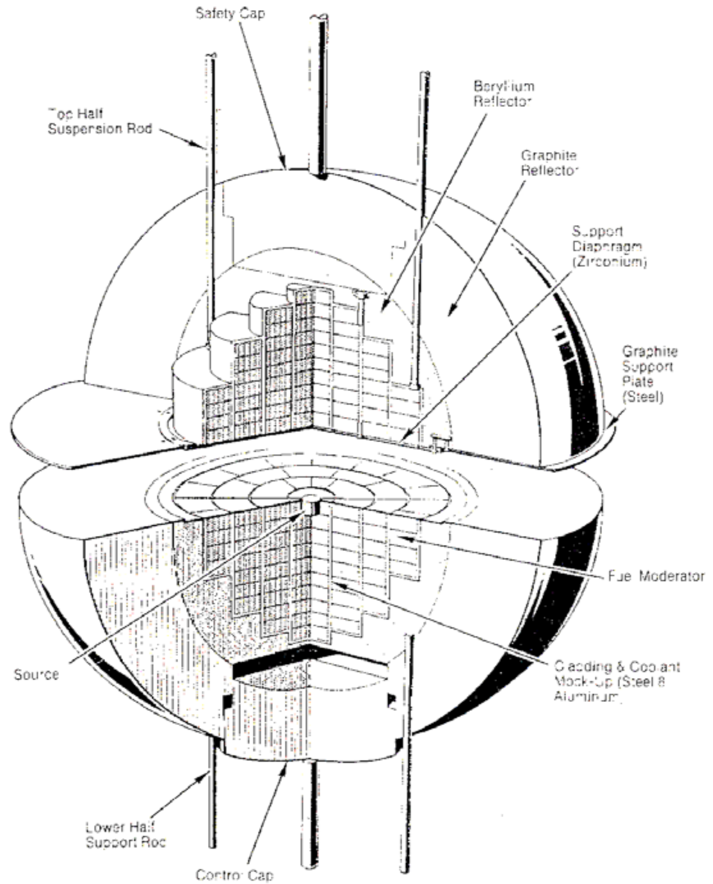


Figure 2. First SNAP Reactor Concept

SNAP 10 Reactor

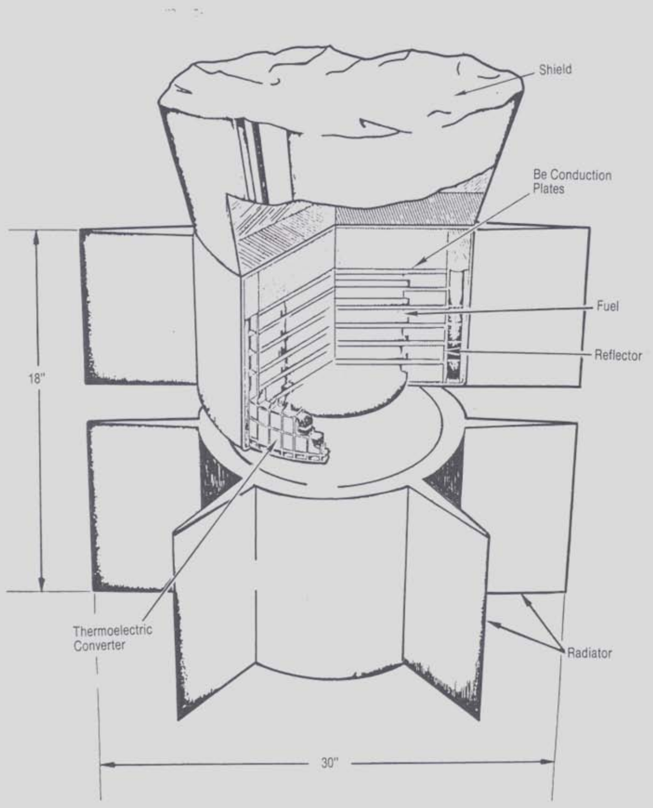


Figure 4. SNAP 10 (1100°F Hot Junction)

SNAP 10A Reactor

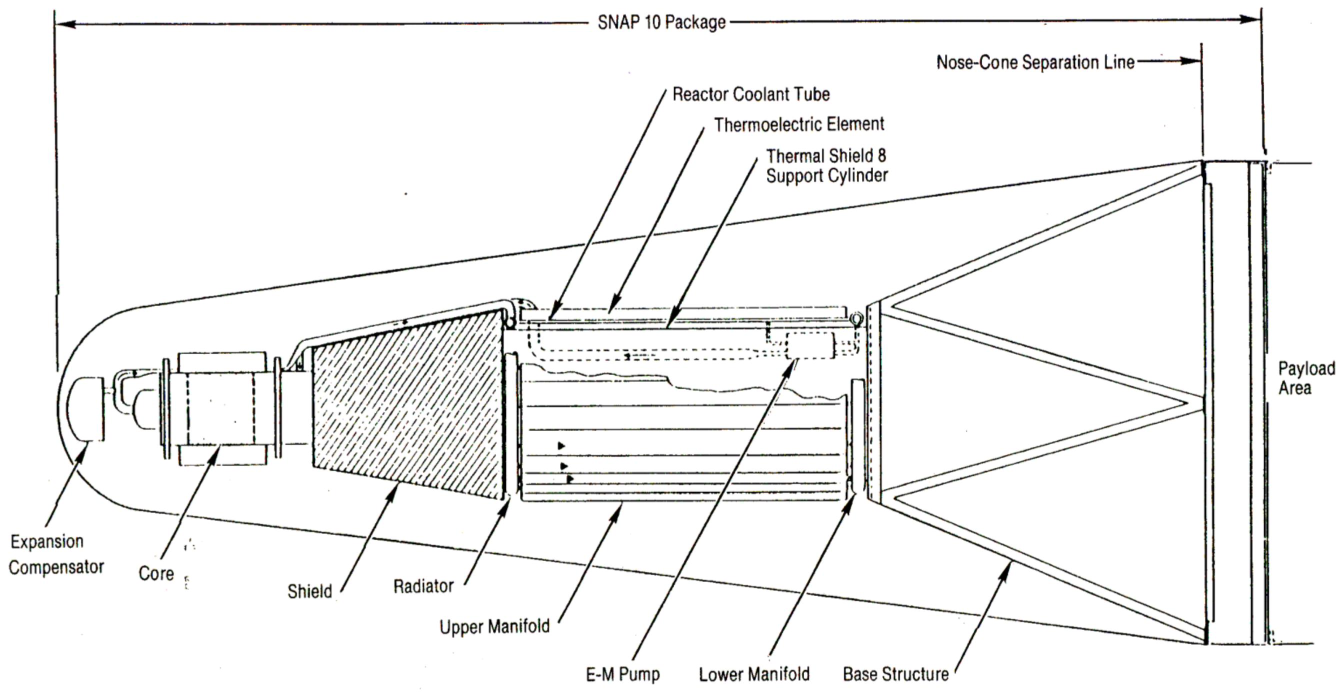


Figure 5. SNAP 10A Mark II (June 1960)

SNAP 10A Reactor

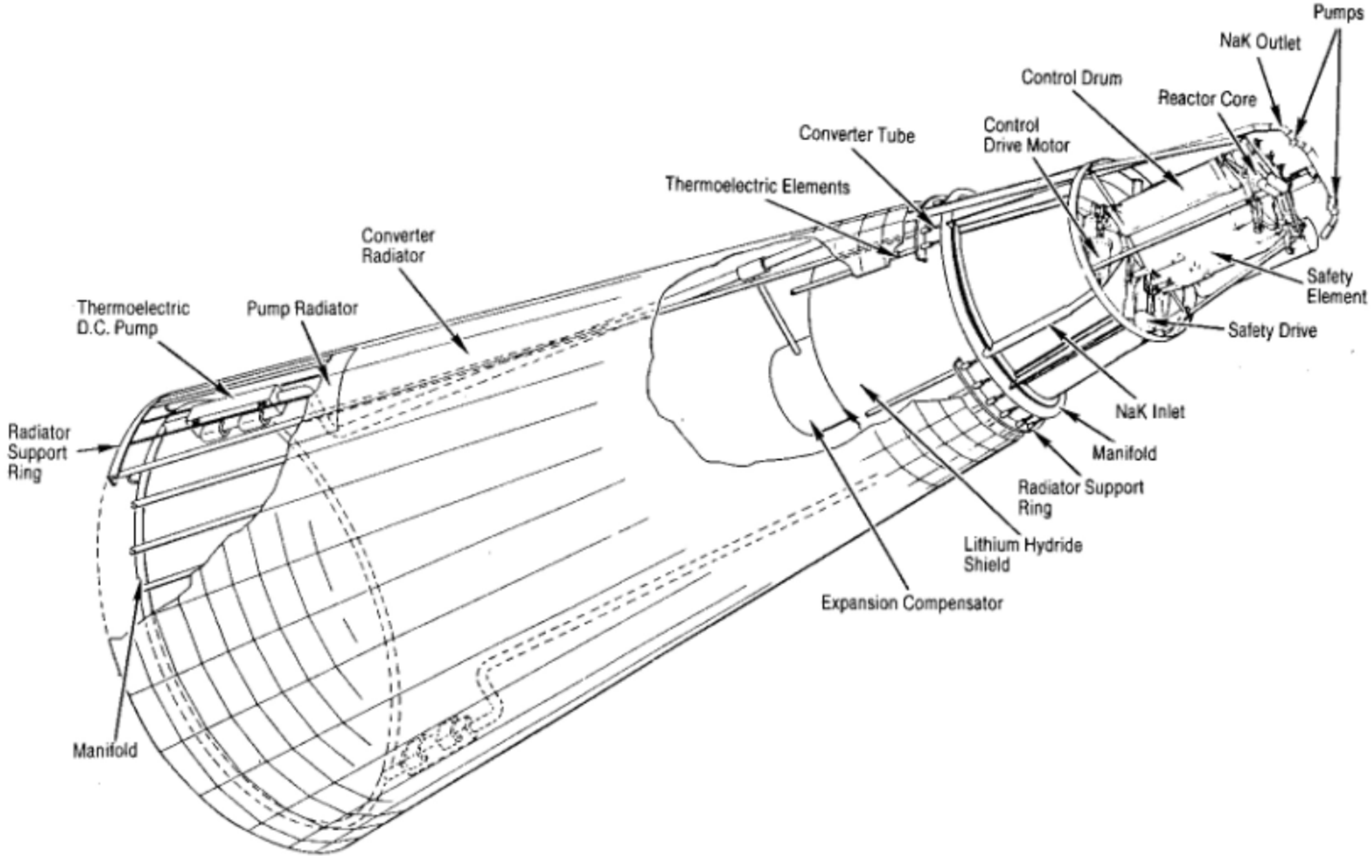


Figure 6. SNAP 10A System (June 1961)

SNAP 10A Reactor

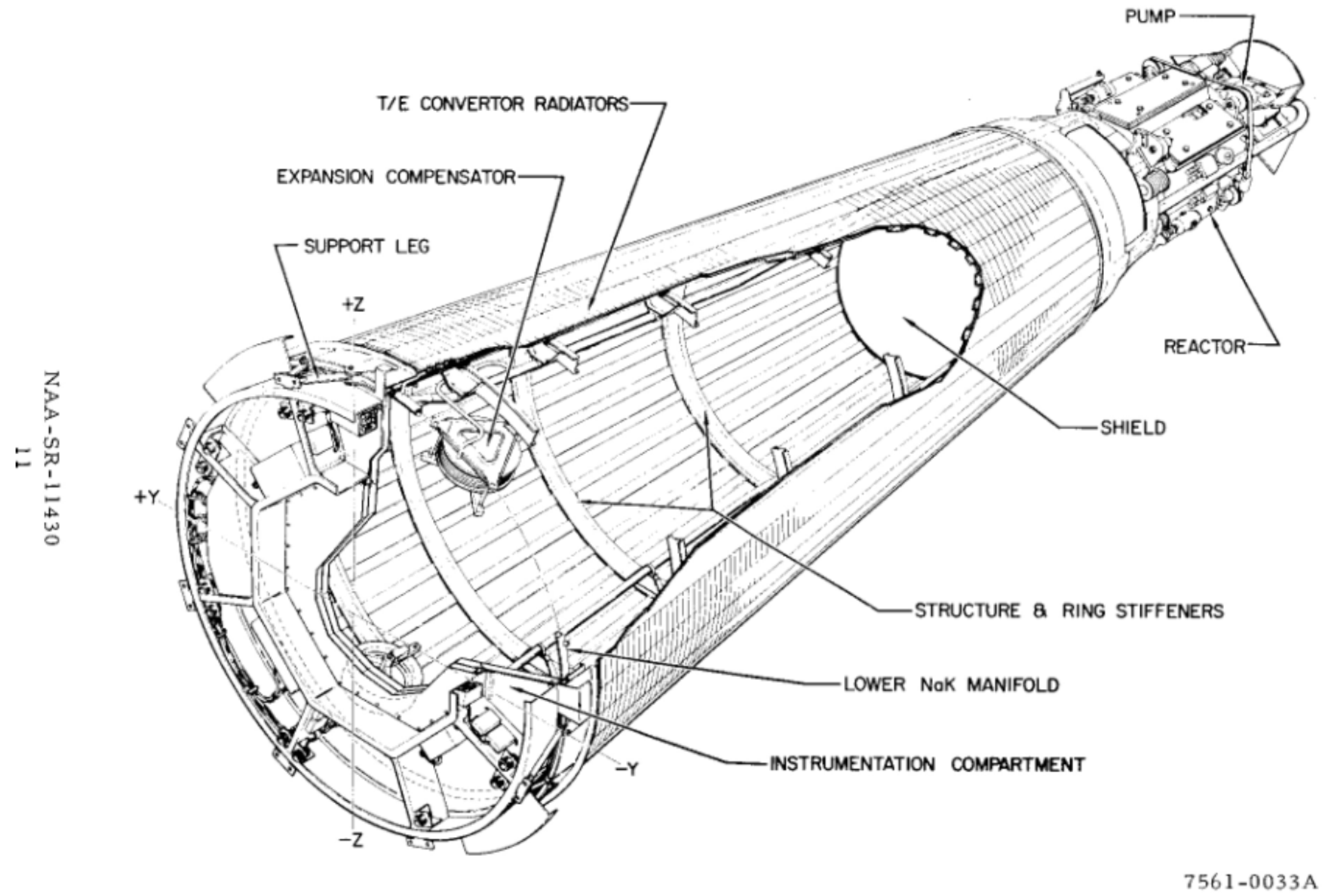


Figure 2. SNAP System 10A Schematic

SNAP 10A Reactors

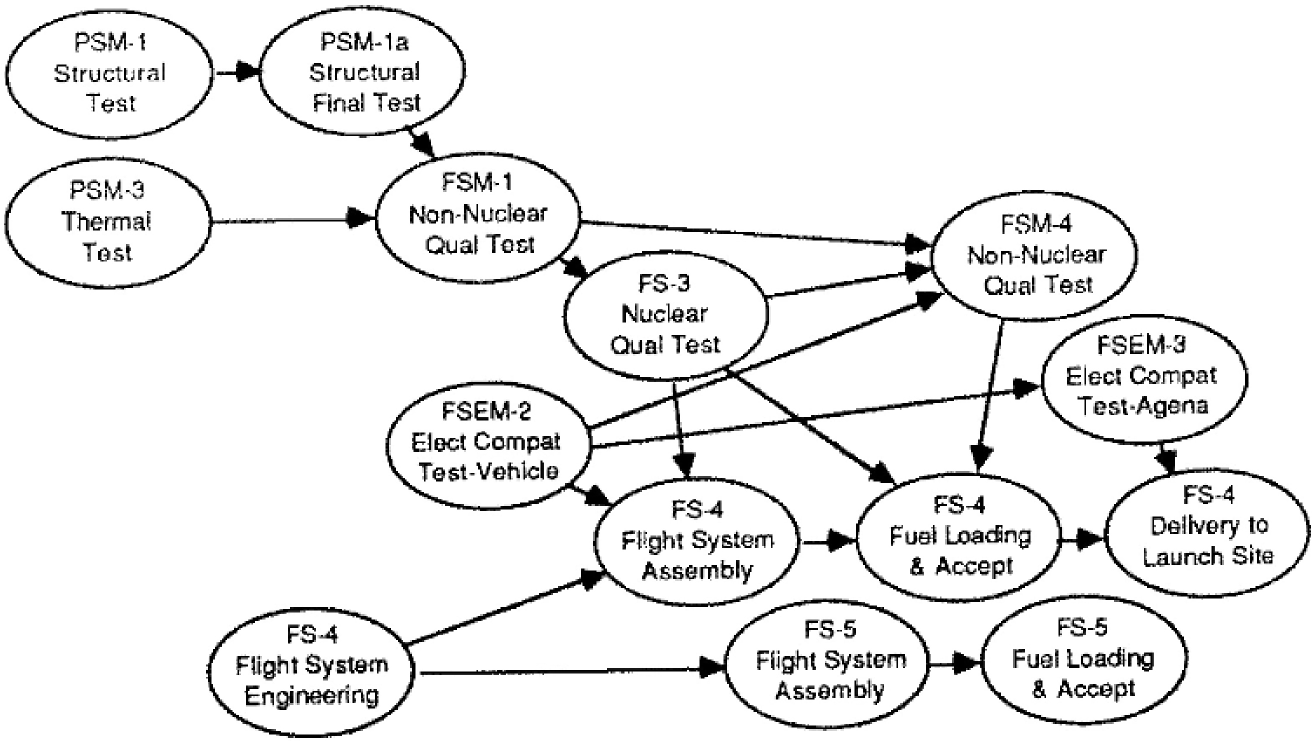


Figure 9. SNAP 10A System Development Sequence

SNAP 10A Development Schedule

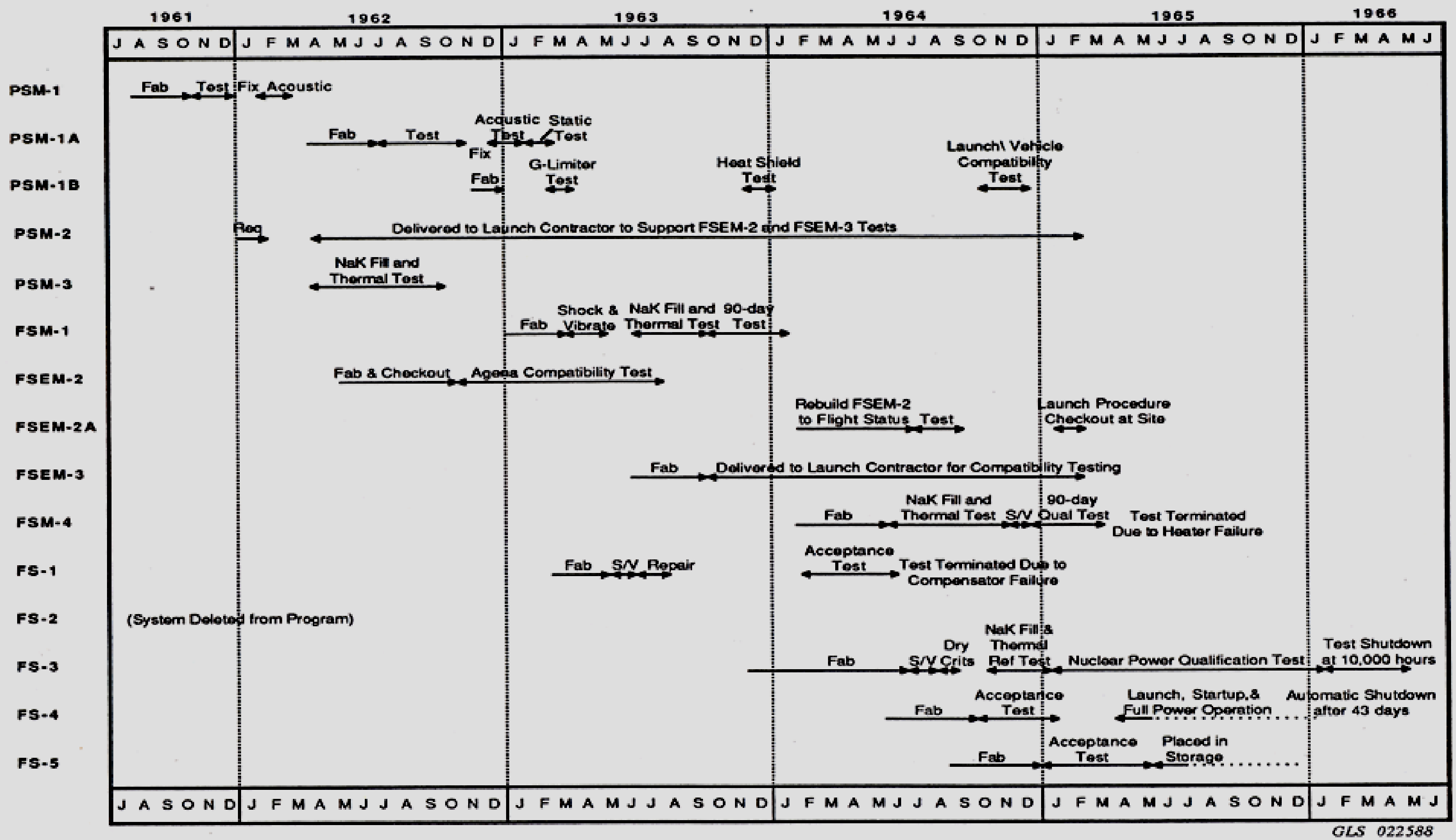


Figure 10. SNAP 10A Systems Fabrication and Testing Schedule

SNAP 10A Facility Schedule

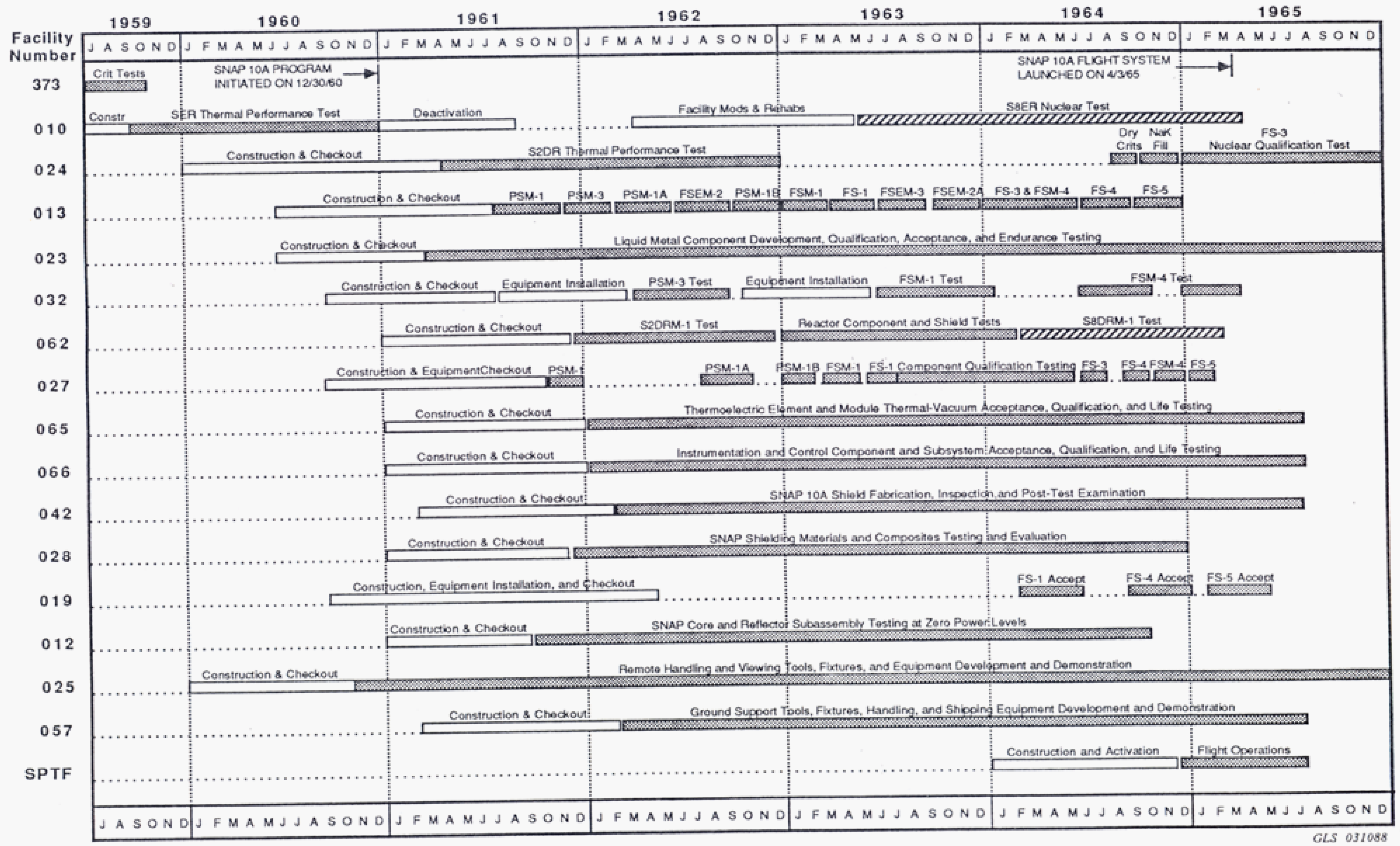
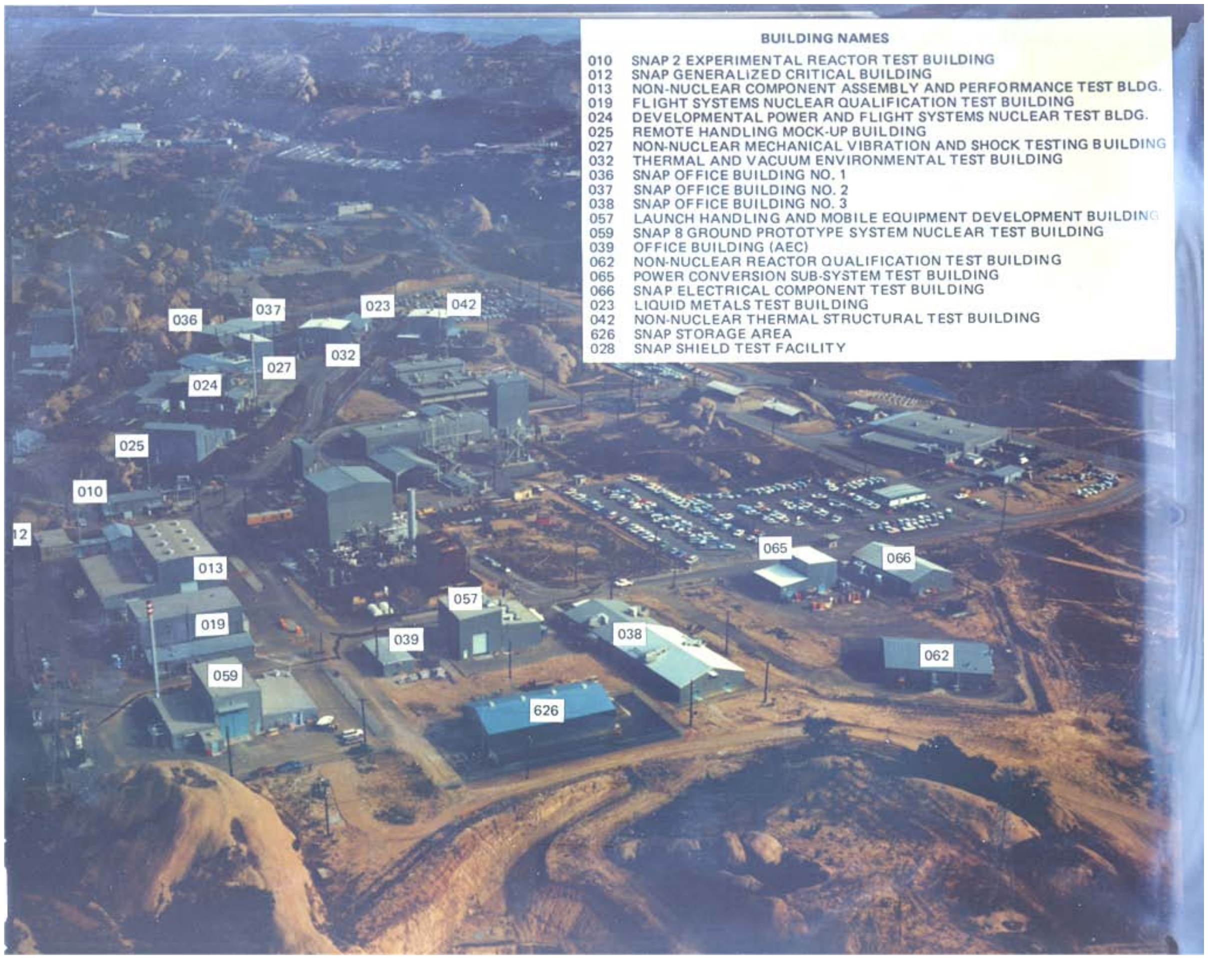


Figure 42. SNAP Facility Construction, Activation, and Utilization Schedule

SNAP Facilities-SSFL



SNAP 2 Experimental Reactor

- General Description:

Number of fuel elements	61
Date went critical:	September 19, 1959
First power operation:	November 5, 1959
Thermal power:	50 kWt
Thermal energy:	225,000 kWt-h
Time at power & temp	1900 h at 1200 F
	3300 h above 900 F
Final shutdown:	November 19, 1960

SNAP 2 Developmental Reactor

- General Description:

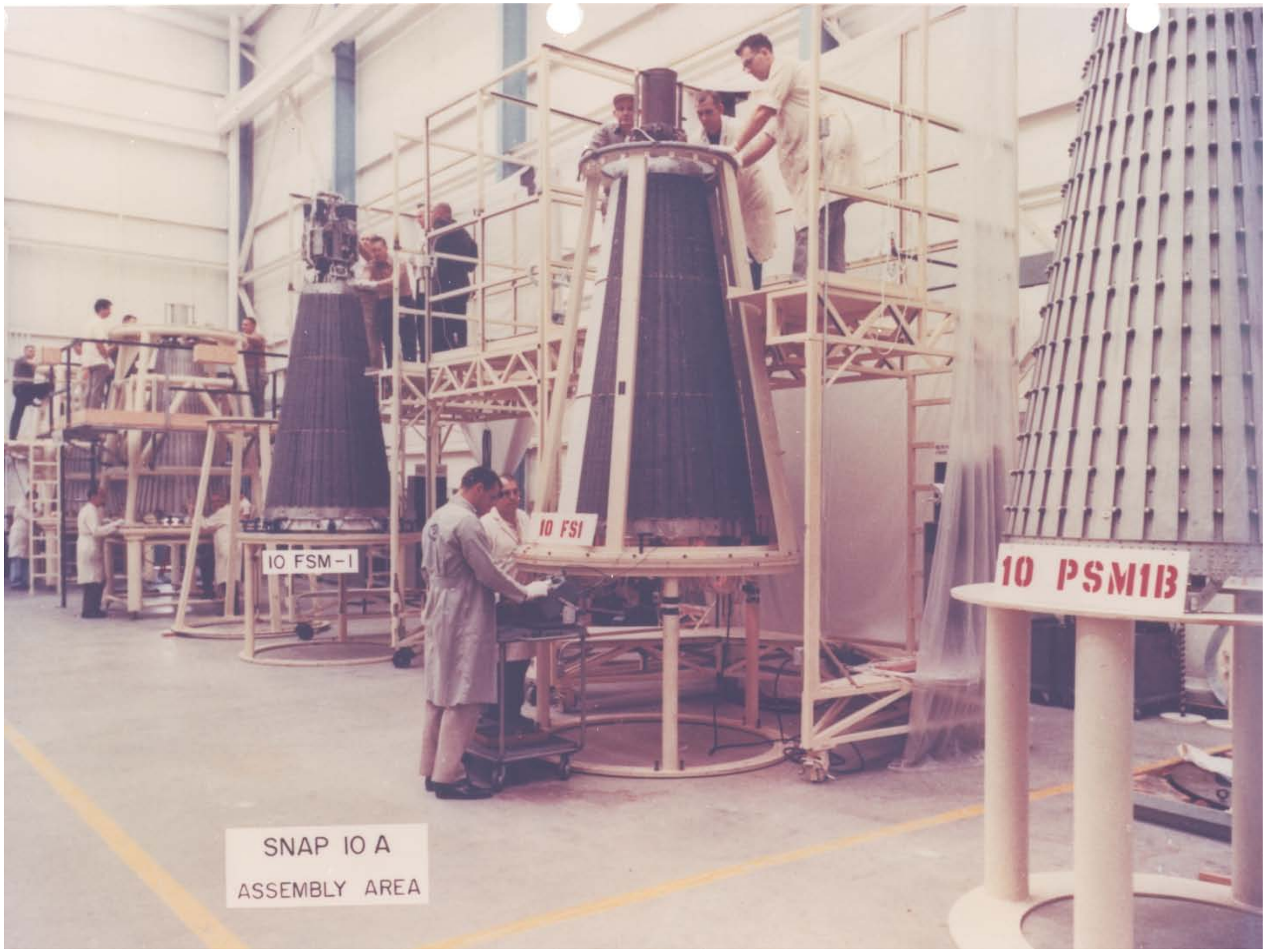
Number of fuel elements	37
Date went critical:	April 1961
First power operation:	November 5, 1959
Thermal power:	65 kWt
Thermal energy:	273,000 kWt-h
Time at power & temp	2800 h at 1200 F
	7700 h above 900 F
Final shutdown:	December 1962

SNAP 10A Non-Nuclear Systems

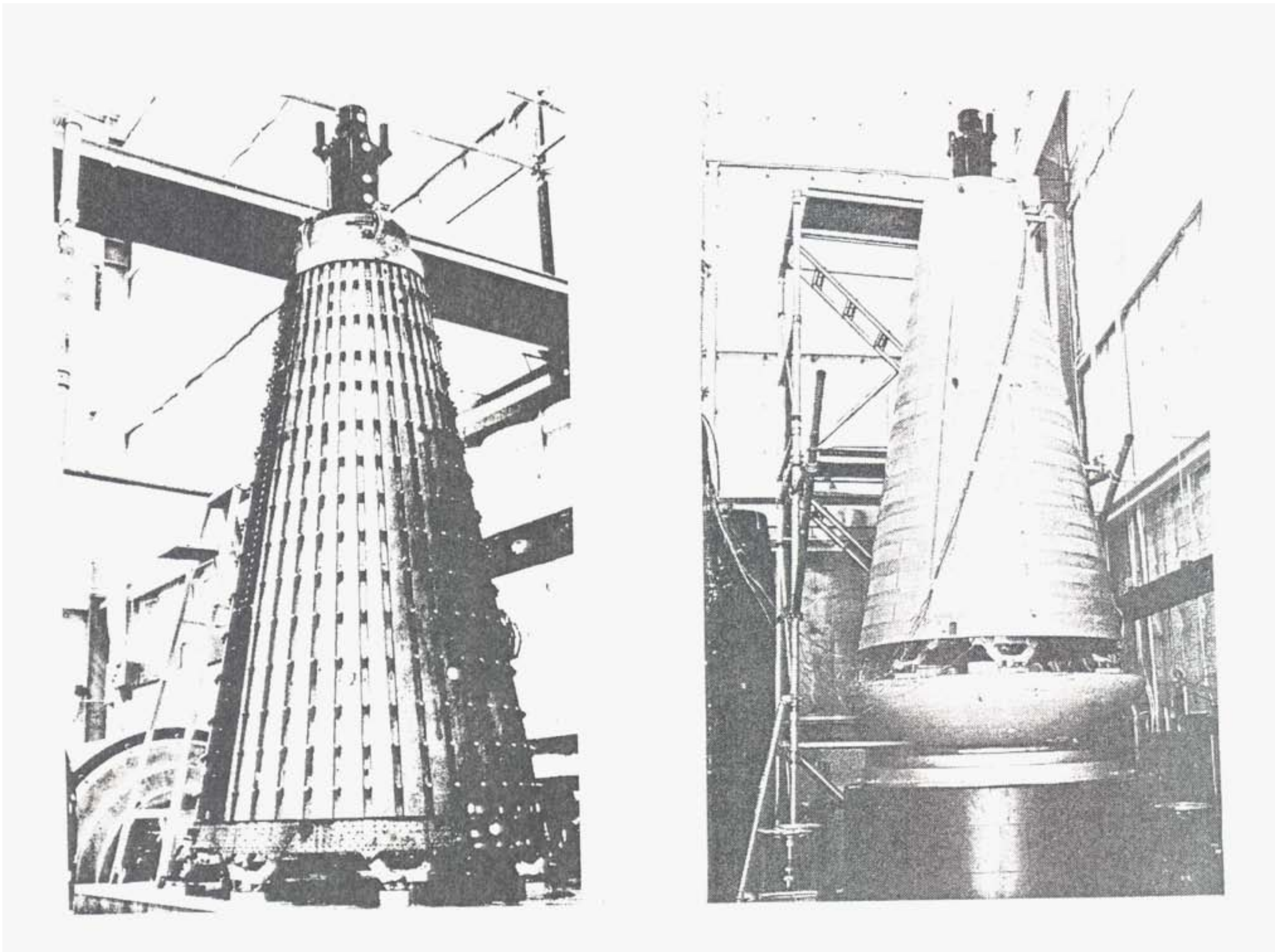
- Designs were prototypical mockups of space power systems and included:

PSM-1	Prototype system for structural testing
PSM-1A	Prototype system modified for structural testing
PSM-1B	Prototype system for heat shield/launch vehicle compatibility
PSM-3	Prototype system for NaK fill & thermal-vacuum tests
FSM-1	Flight system for shock/vibration & thermal vacuum tests
FSEM-2	Flight system for electrical testing & Agena compatibility tests
FSEM-2A	Flight system rebuilt for flight status & launch procedure tests
FSEM-3	Flight system for Launch Contractor compatibility testing
FSM-4	Flight system for non-nuclear qualification testing

SNAP 10A Reactor Assembly



SNAP 10A PSM-1 System



SNAP 10A PSM-3 System

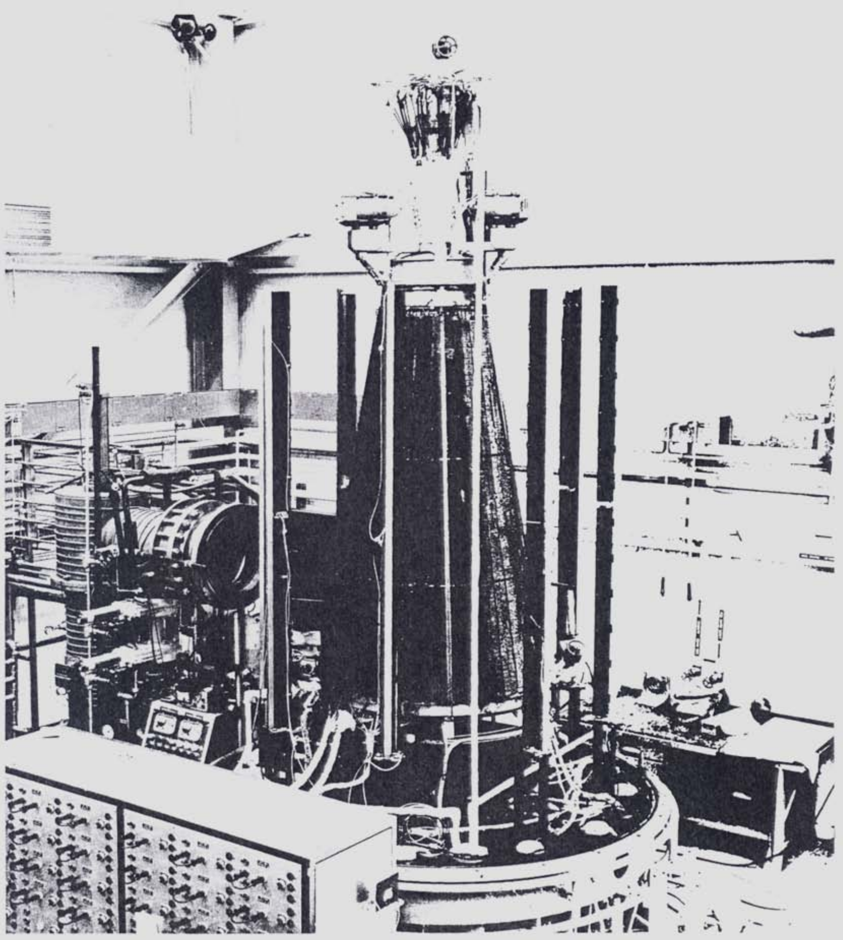


Figure 32. SNAP 10A Thermal-Hydraulic Performance Test Mockup (PSM-3)

SNAP 10A FSM-1 System

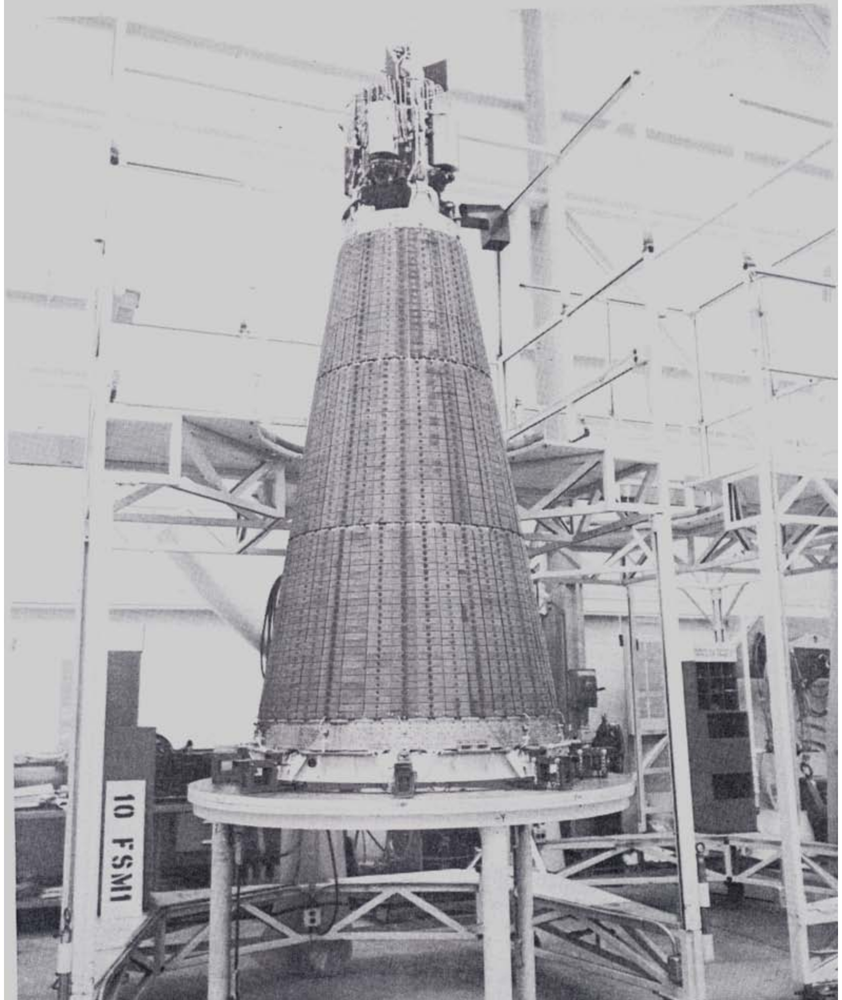
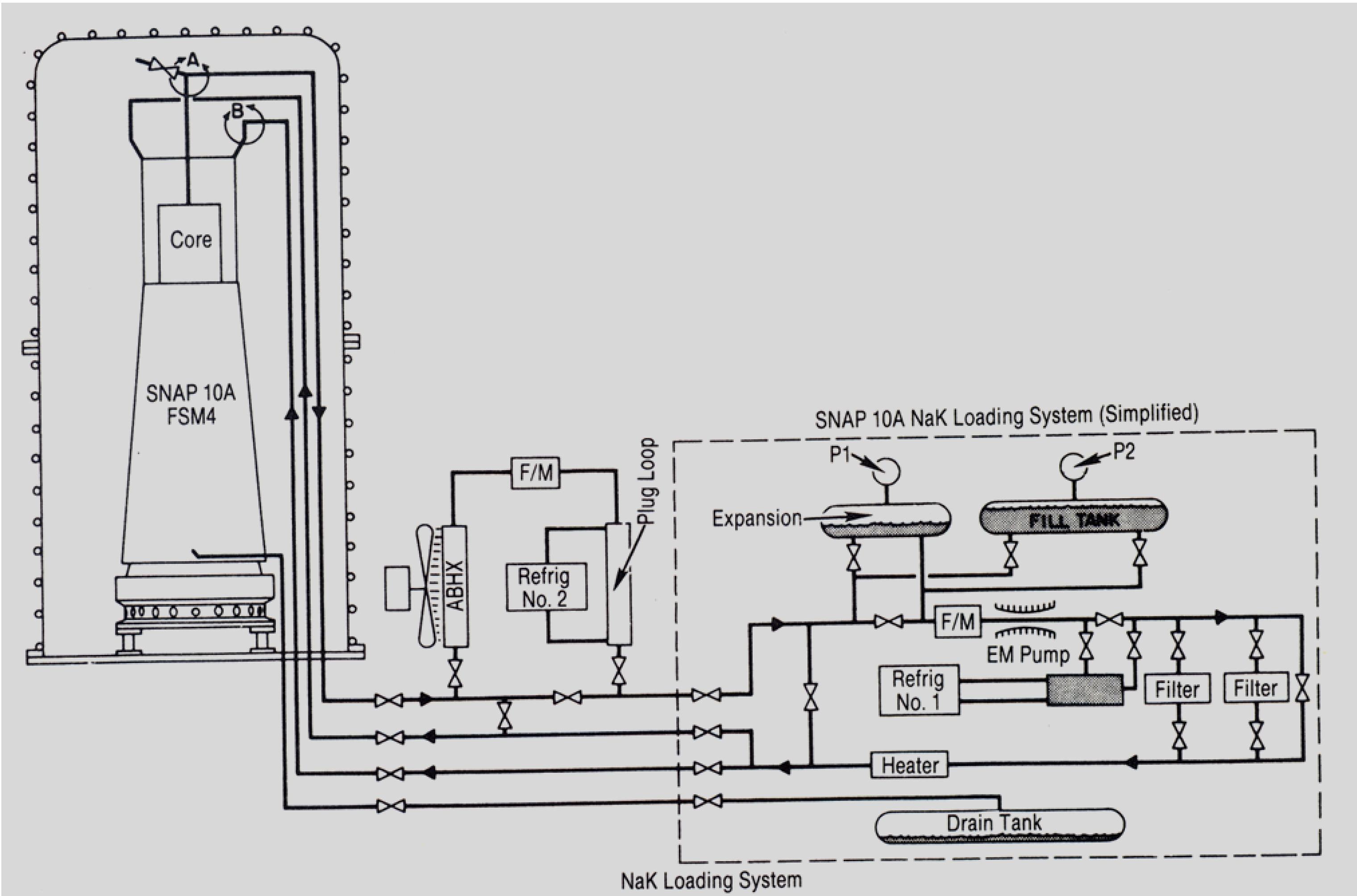
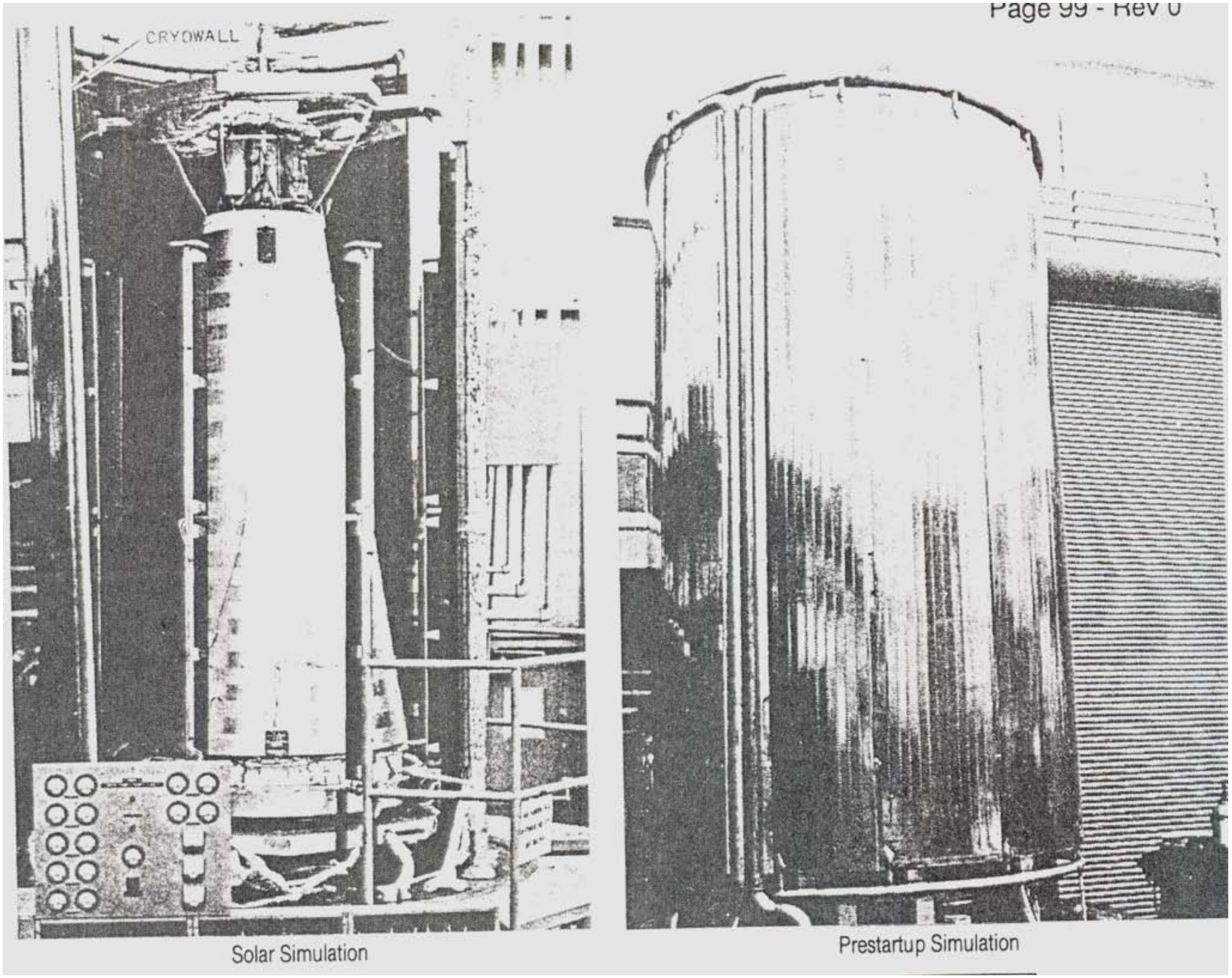


Figure 33. SNAP 10A Flight System Mockup (FSM-1)

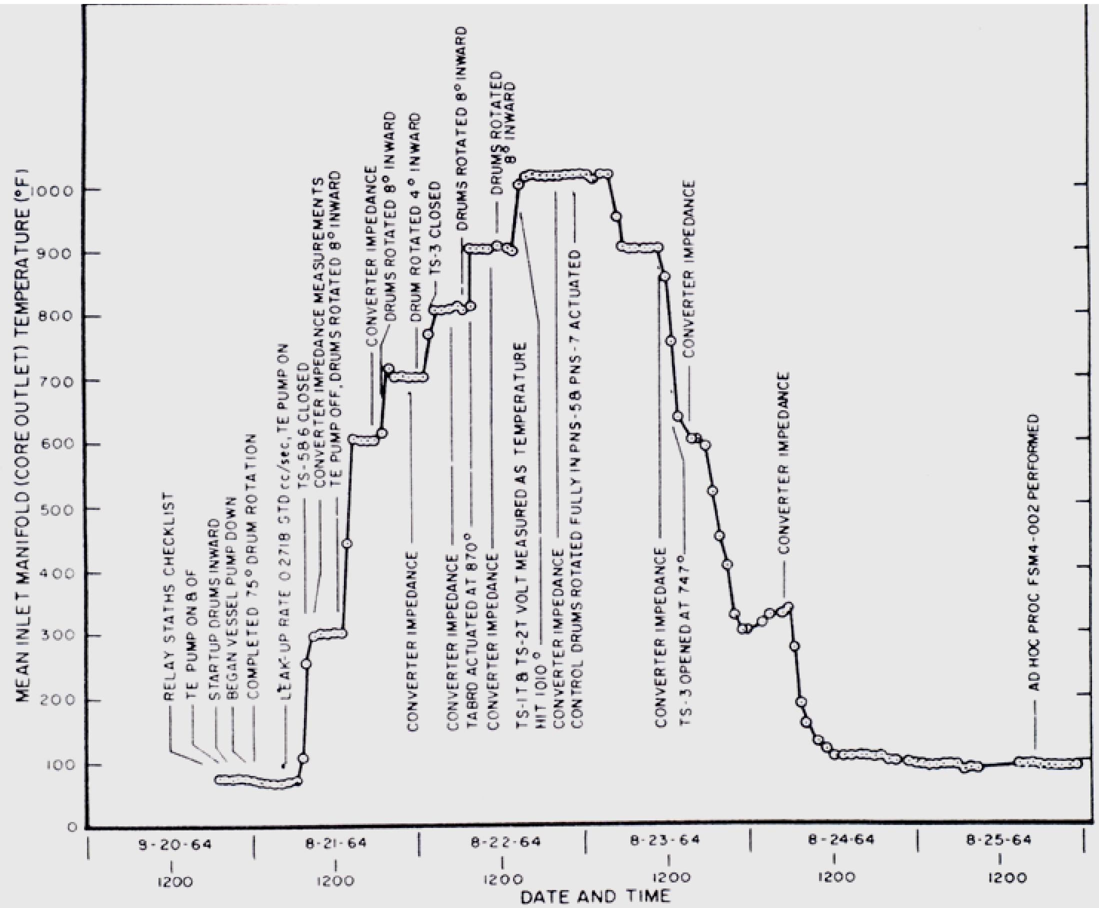
SNAP 10A FSM-1 TEST



SNAP 10A FSM-1 ORBIT TEST



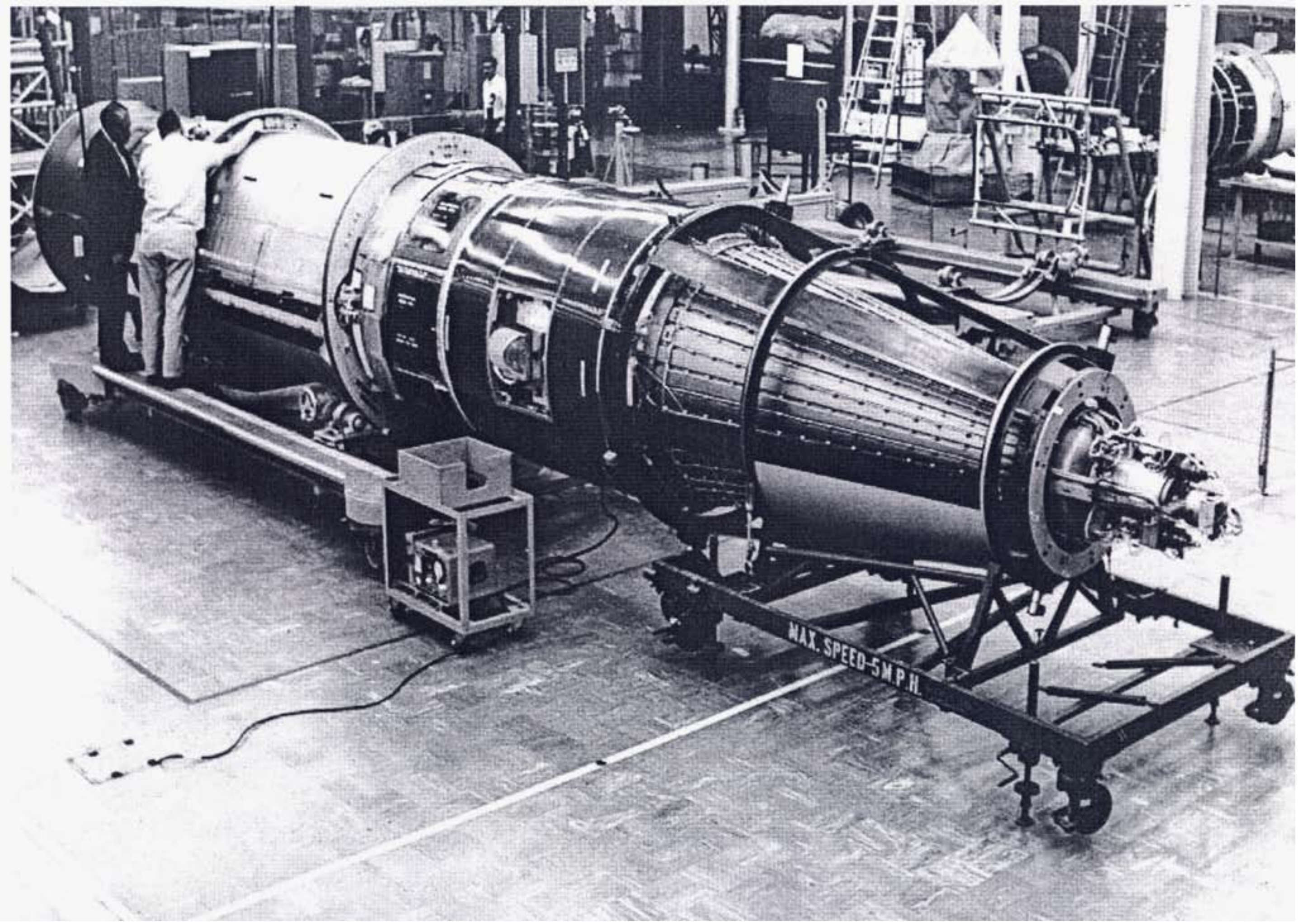
SNAP 10A FSM-1 TEST



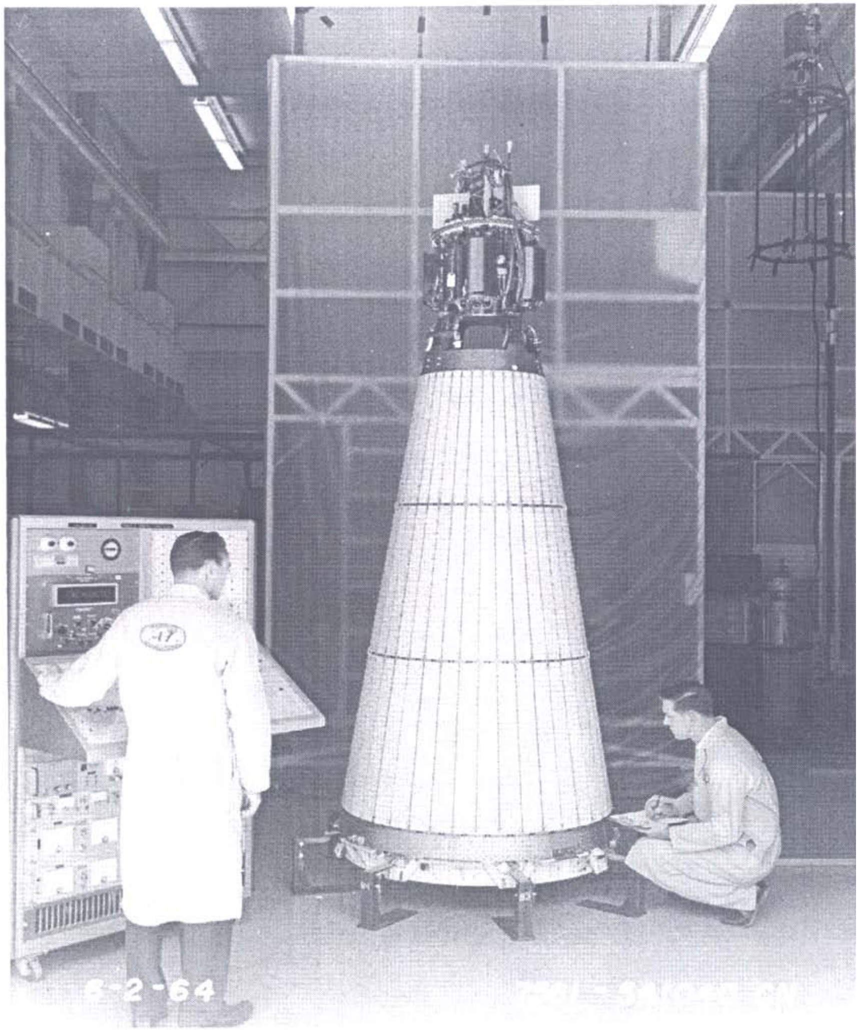
Thermal Reference Test Sequence

Figure 48. SNAP 10A Orbital Startup Simulation Systems and Thermal Reference Test Sequence

SNAP 10A FSEM-2 TEST



SNAP 10A FSM-4 System



SNAP 10A Nuclear Systems

- Designs were nuclear space power flight systems and included:

FS-1	Ground qualification system (failed in acceptance test)
FS-2	Reassigned to non-nuclear mock-up testing
FS-3	Ground thermal-vacuum qualification system
FS-4	Space flight system for launch & orbital demonstration
FS-5	Space flight system spare

SNAP 10A FS-1 Reactor

- General Description:

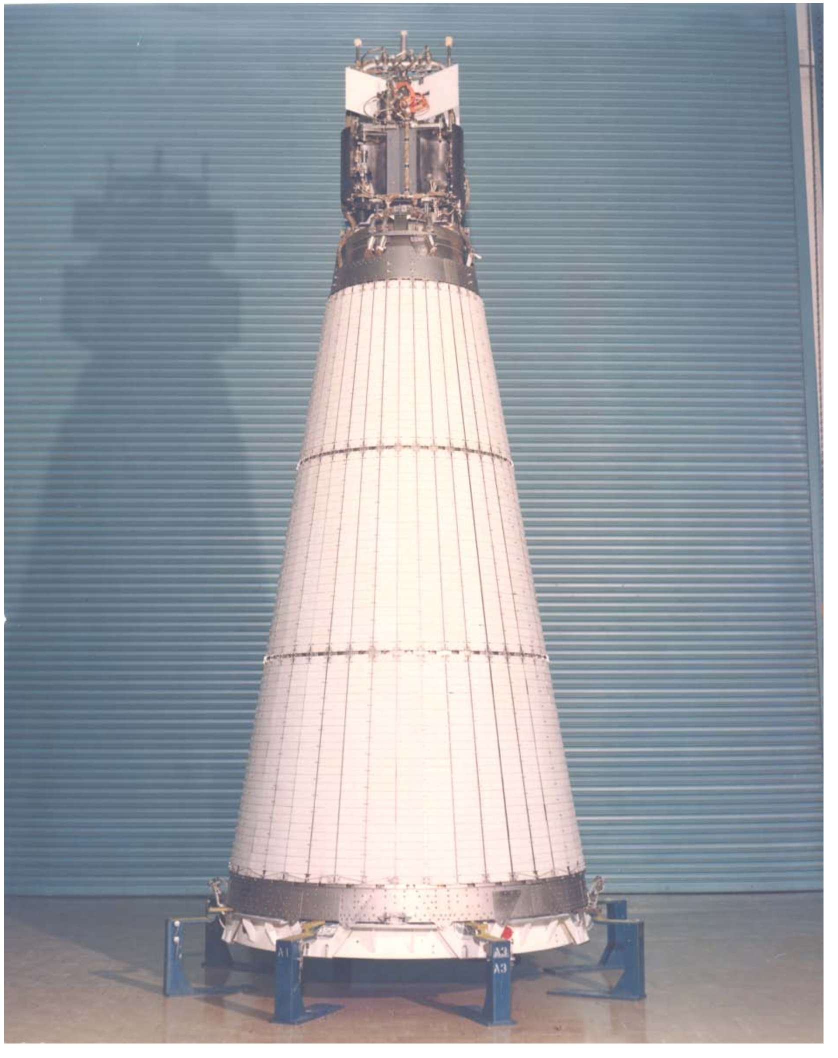
Number of fuel elements	37
Date went critical:	~May 1964
First power operation:	Failed acceptance
Thermal power:	0 kWt
Thermal energy:	0 kWt-h
Time at temperature	~ 50 h above 900 F
Accept test terminated:	June 1964
Post-test Disassembly	June 1964

SNAP 10A FS-3 Reactor

- General Description:

Number of fuel elements	37
Date went critical:	January 1965
First power operation:	January 1965
Thermal power:	41 to 37 kWt
Thermal energy:	382,944 kWt-h
Electrical power	402 Watts
Electrical energy	4028 kW-h
Time at power & temp	10005 h above 900 F
Final shutdown:	March 16, 1966

SNAP 10A FS-3 Reactor



SNAP 10A FS-3 Reactor

SNAP 10A FS-4 Reactor

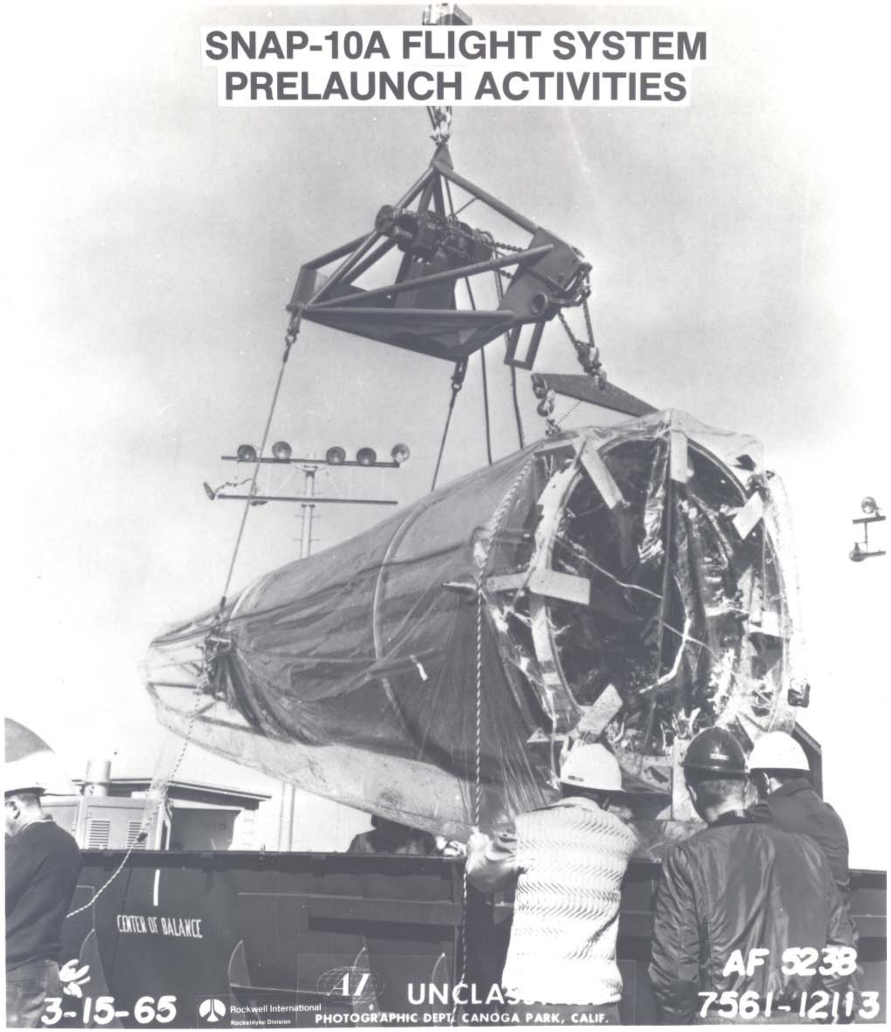
- General Description:

Number of fuel elements	37
Date launched:	April 3, 1965 (13:24PST)
First power operation:	April 4, 1965 (01:45PST)
Thermal power:	42+ to 39.4 kWt
Thermal energy:	41,349 kWt-h
Electrical power	600 to 530+ Watts
Electrical energy	573.6 kW-h
Time at power & temp	1000 h above 1013 F
Final shutdown:	May 16, 1965

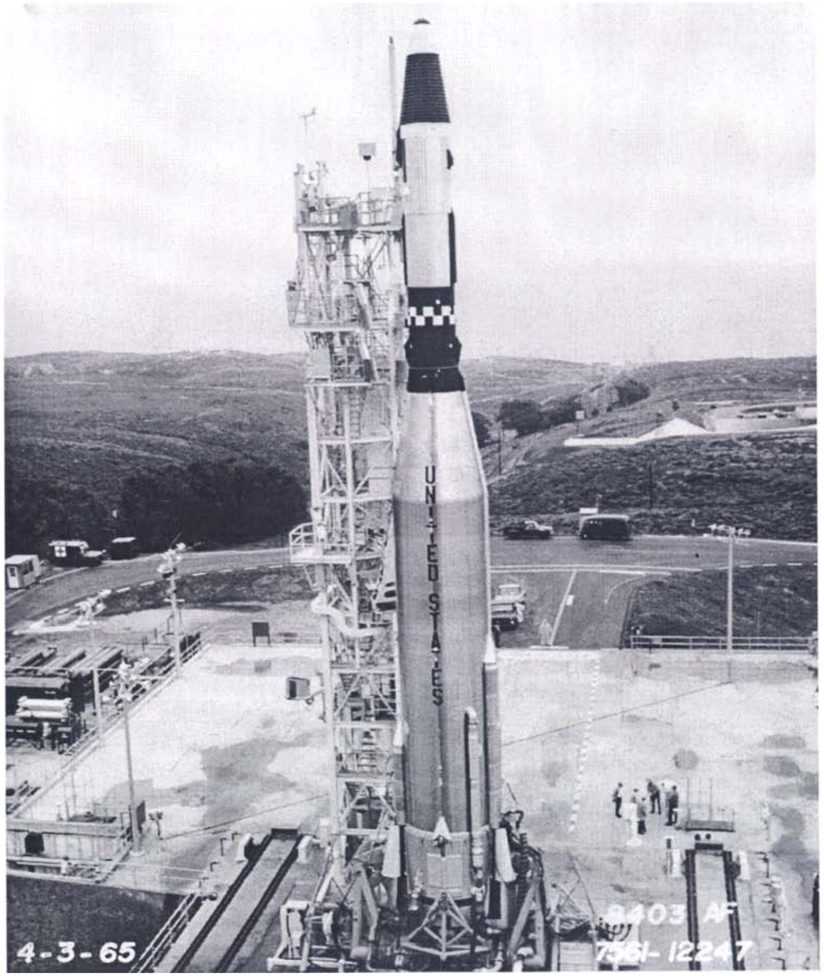
SNAP 10A FS-4 Reactor

Figure 51. SNAP 10A FS-4 Acceptance Test Facility

SNAP 10A FS-4 Reactor



SNAPSHOT LAUNCH

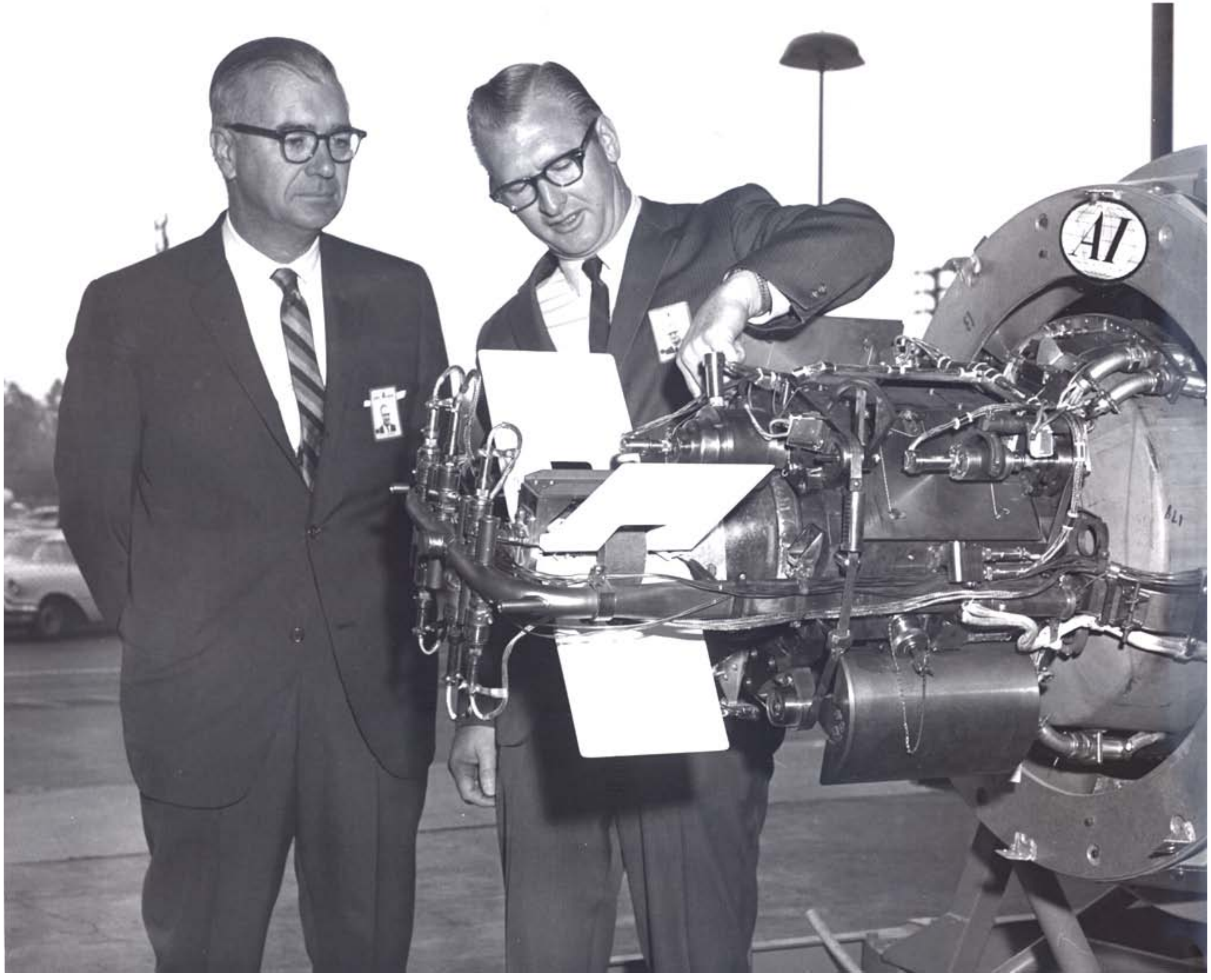


SNAP 10A FS-5 Reactor

- General Description:

Number of fuel elements	37
First thermal operation:	~ February 1966
Date went critical:	~ March 1996
Thermal power:	0 kWt
Thermal energy:	0 kWt-h
Time at temperature:	~40 h above 900 F
Accept test complete:	~May 1966
Placed in storage:	May 1966

SNAP 10A FS-5 Reactor



SNAP 10A FS-5 Reactor

SNAP 10A Components

General Background

By: Glen Schmidt

February 7, 2011

References:

94ETEC-DRF-1476

DCN: SP-100-XT-0002

SNAP 10A Reflector

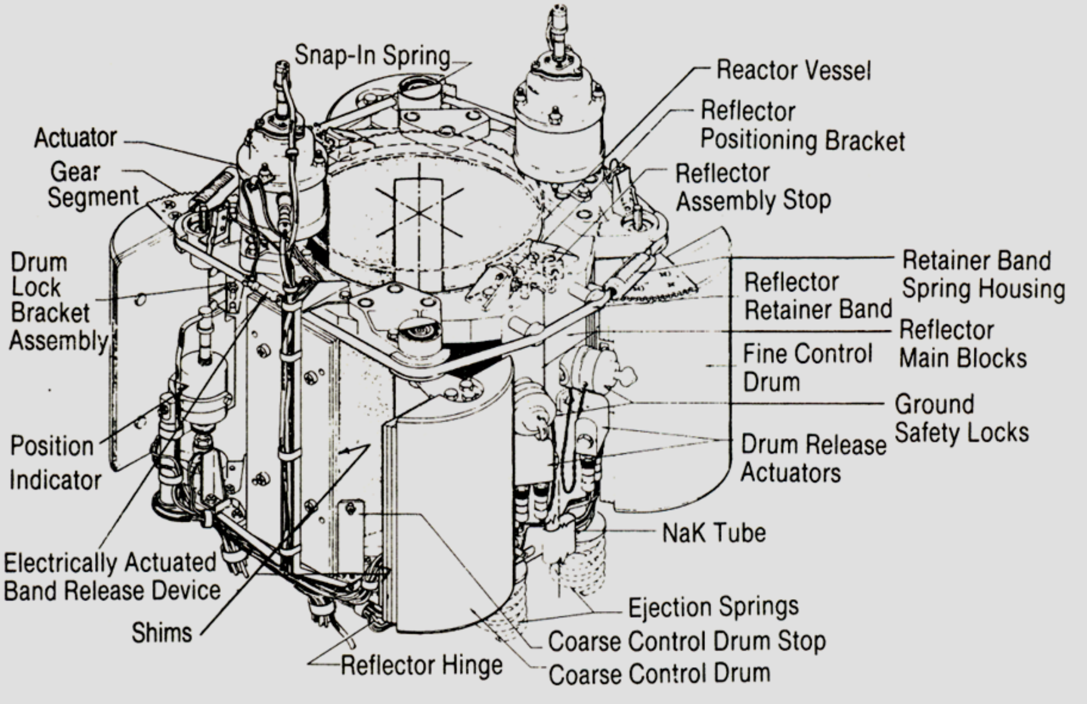


Figure 18. SNAP 10A Control and Reflector Assembly

SNAP 10A Reactor & Shield

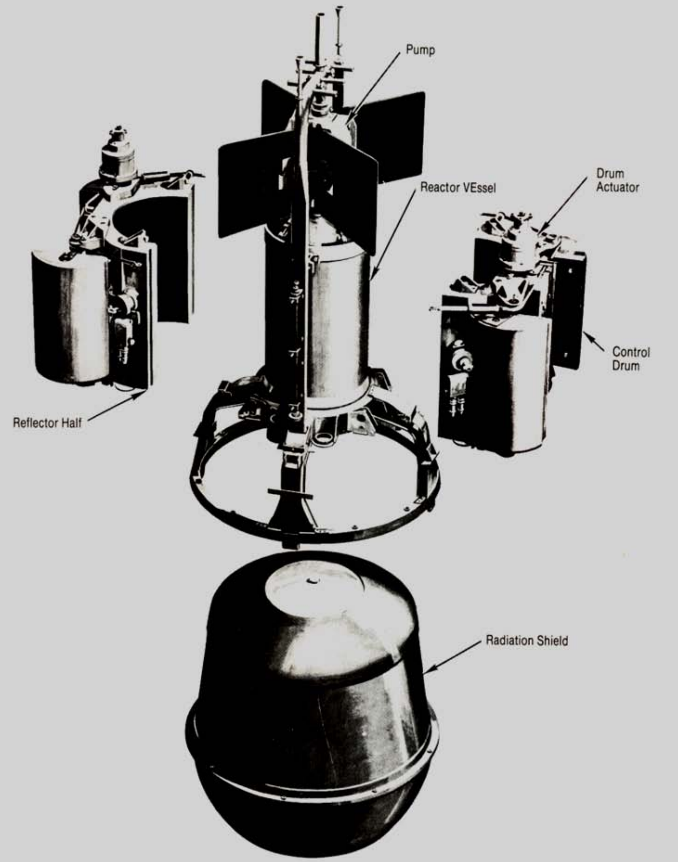


Figure 21. SNAP 10A Reactor and Shield (Exploded View)

SNAP 10A Thermodynamic

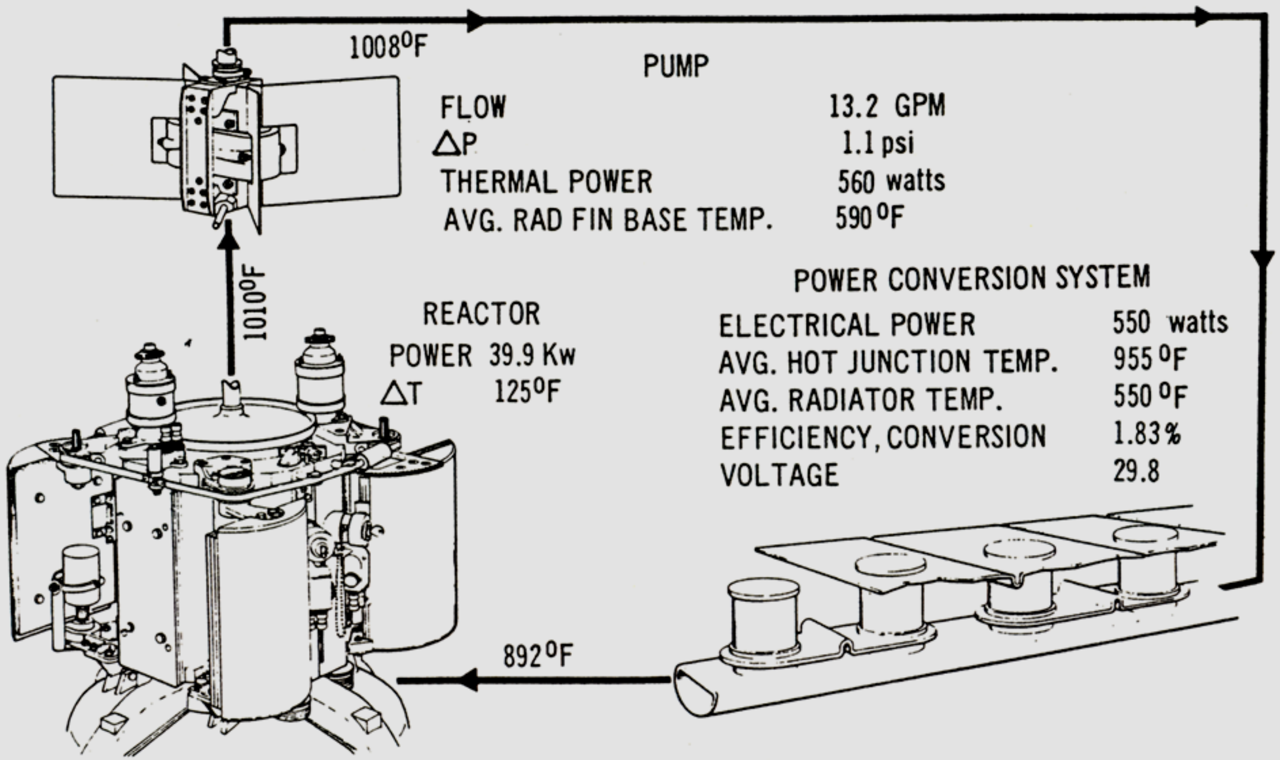


Figure 23. Thermodynamic Cycle

SNAP 10A TE Converter

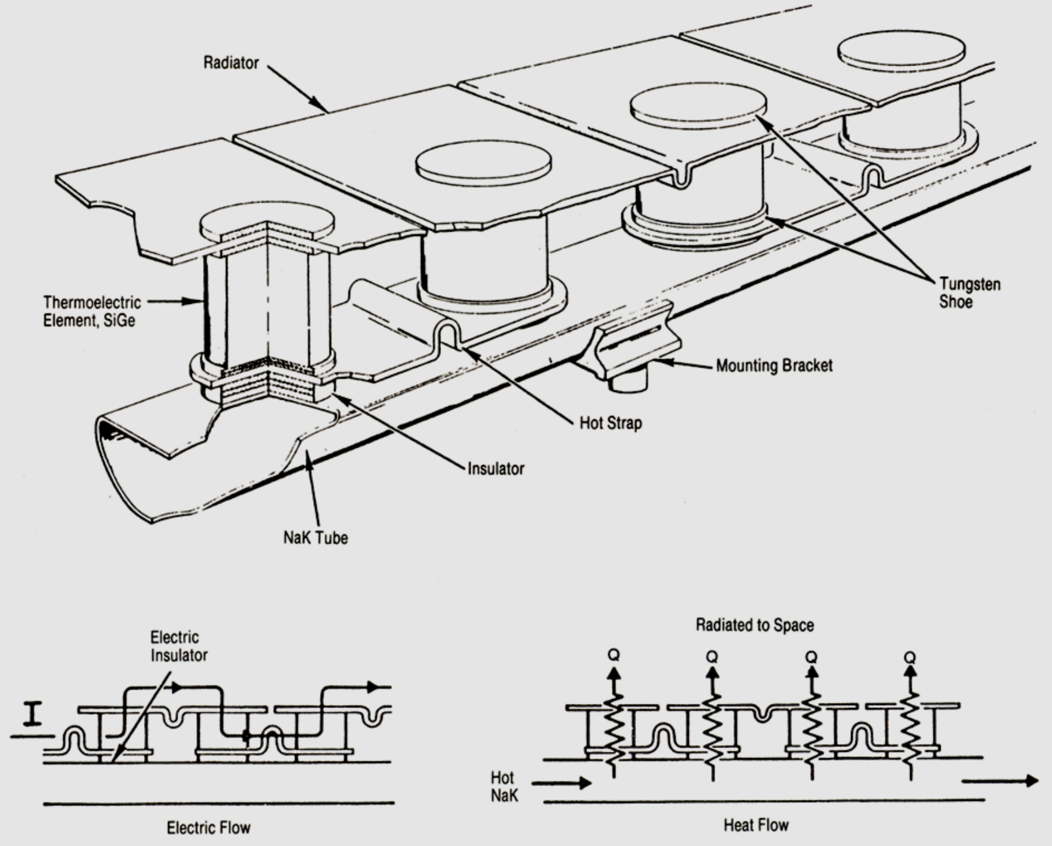
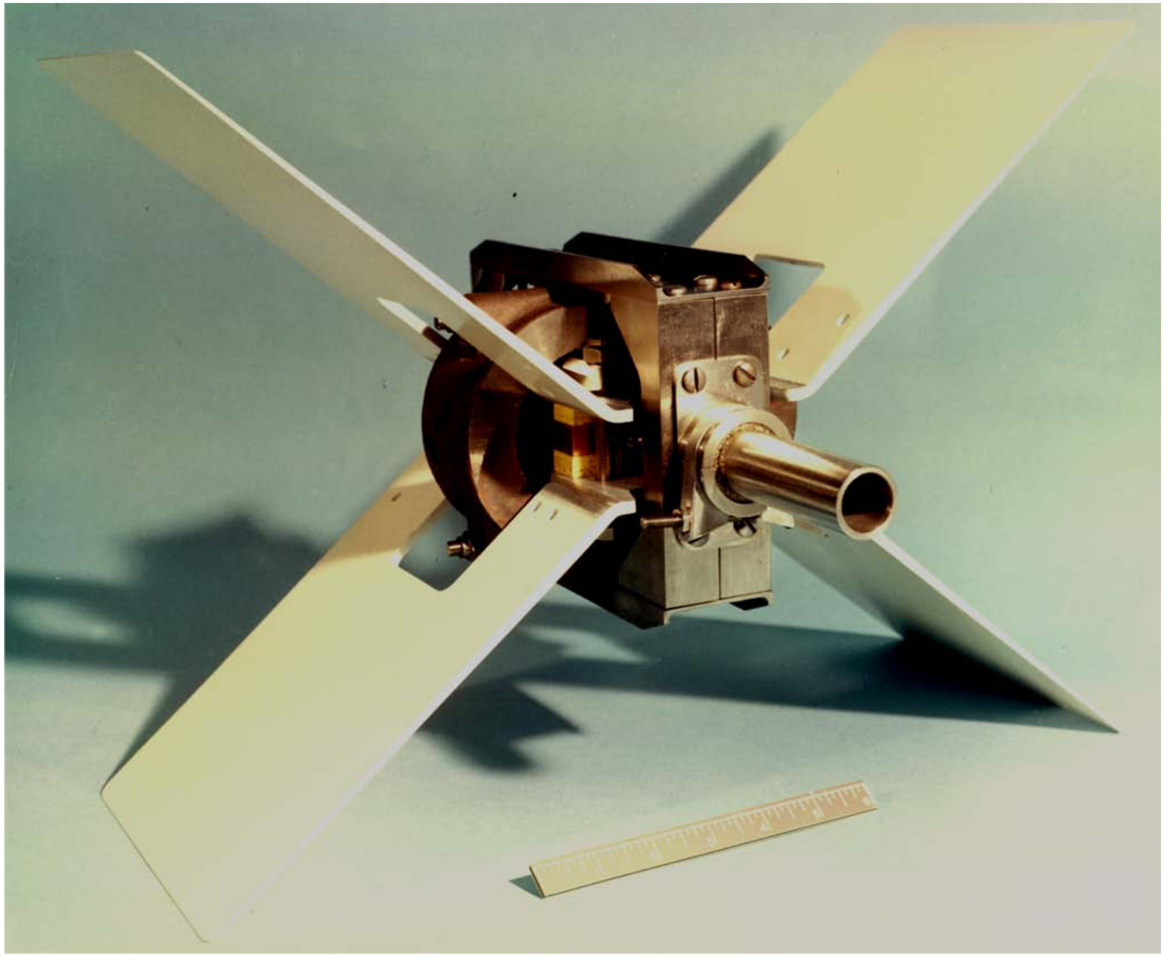
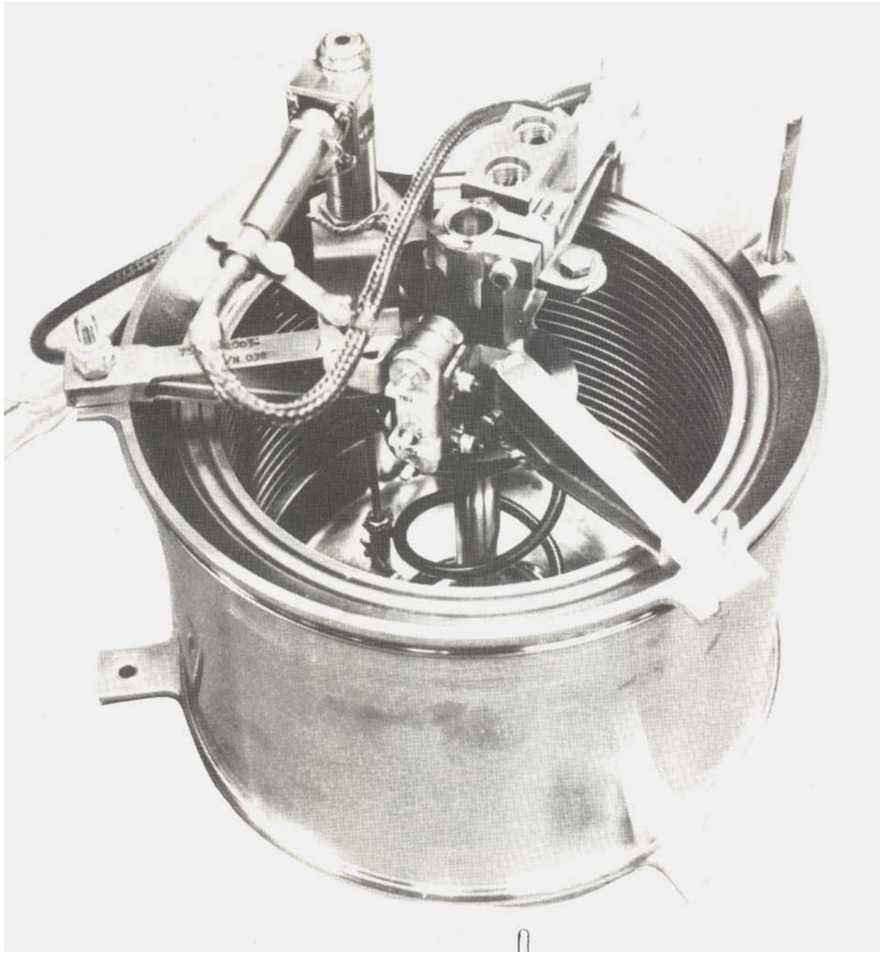


Figure 22. Direct Radiating TE Module

SNAP 10A TE Pump



SNAP 10A Expansion Comp



SNAP 10A Support Structure

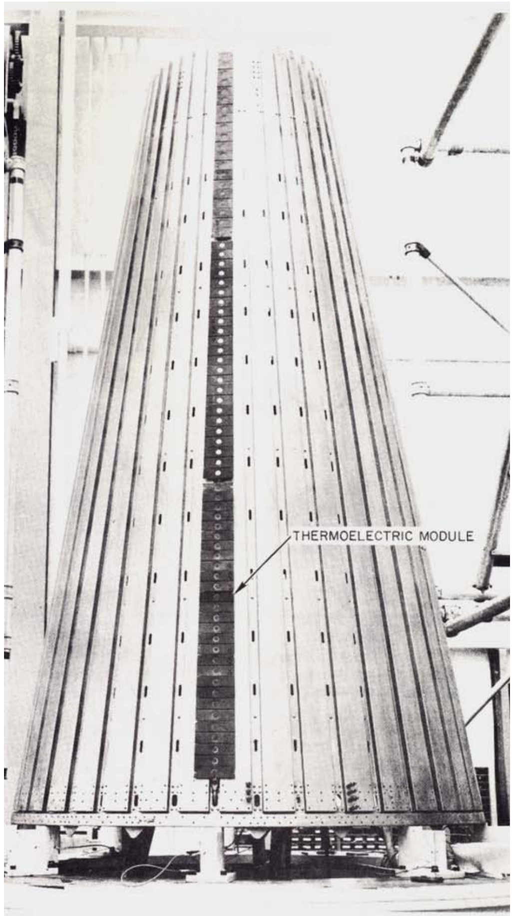


Figure 26. SNAP 10A Conical Structure

SNAP Fuels-General

- Fuel -A Homogenous Mixture of ^{235}U & ZrH_x

  For ZrH_x temperatures of 1400 to 1500 F, material retains an N_H near that of cold water.

- Fuel Element -An unsegmented fuel rod enclosed in a Type 347 SS or Hastelloy N metal tube with end caps.

  Entire inside cladding surface, including end caps, was coated with a glass-ceramic mixture.

SNAP Fuel Rod

- Produced alloy by multiple consumable arc meltings of reactor-grade enriched uranium metal & crystal bar zirconium.
- Produced alloy rods by extrusions of the alloy.
- Produced $UZrH_X$ & rods by diffusion of H_2 at high temperatures (isothermal at 1600 F peak).
- Note: Yield of acceptable fuel rods was greatly increased with simultaneous improvements in microstructure by adding ~0.15 w% of ZrC to the melt.

SNAP 10A Fuel Rods

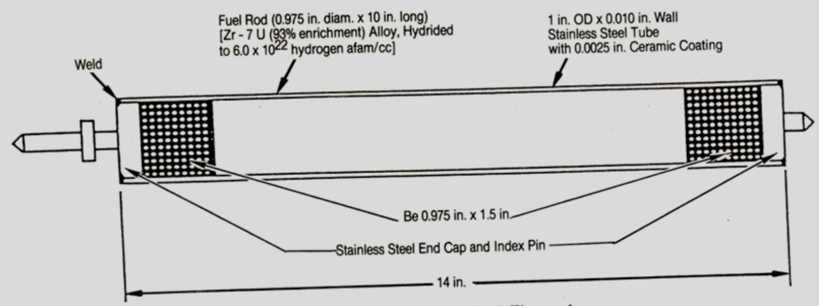


Figure 14. SER Fuel Element

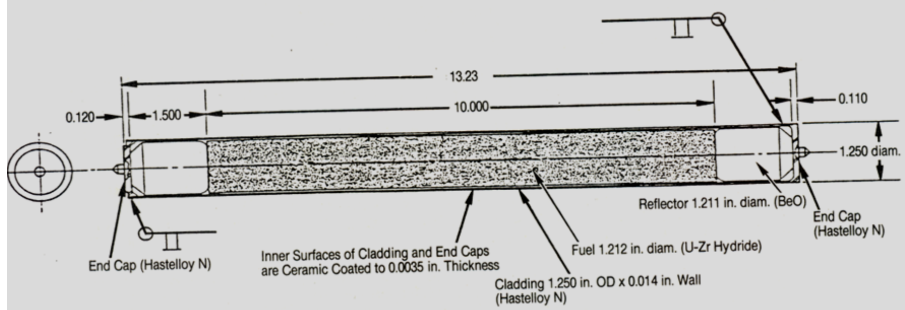


Figure 15. S2DR Fuel Element

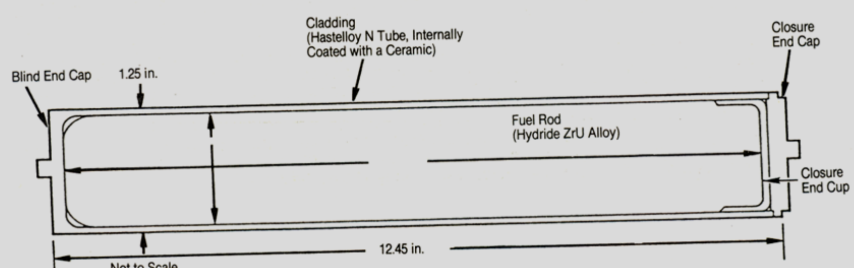


Figure 16. SNAP 10A Fuel Element

SNAP Fuel Microstructure

- Fuels consist of uranium-rich particles & ZrC particles in a matrix of substoichiometric ZrH_2 .
- Uranium does not hydride and remains in micron-size particles in the $UZrH_x$ matrix.
- $UZrH_x$ undergoes a series of phase changes as the H/Zr ratio increases during the hydriding process.
- Phase changes are accompanied by volume changes that must be considered during the hydriding process.

SNAP Fuel H_2 Barrier

- <u>H_2 retention:</u> Improved by lining the inside of the cladding & end caps with a silicate composition.
- <u>Barrier Application</u>: Separate layers were applied to permit a burnable poison (SM_2O_3) to be incorporated in the last layer.

SNAP Fuel Element Assy

- Tube cladding & one end closure were welded
- Internal H_2 barrier layers applied
- Fuel rod inserted
- Coating on cladding fused to pre-coated plug
- Separate uncoated end cap welded to seal fuel element
- Element tested to determine H_2 permeation rate

SNAP Reactor Fuel Operation

- Each fuel element in core,depending on its location, is a closed individual system.
- Initial uniform (H/Zr) profiles in fuel elements change because of axial and radial temperature gradients. They are not in equilibrium.
- The bottoms of fuel rods, at cooler locations, had higher H/Zr than as-fabricated values.
- Note: Overall, the 37 fuel rods in 10AFS-3 showed very good H_2 retention.

SNAP Fuel Structural Effects

- Microstructural effects of fission products and neutrons appeared to be relatively slight.
- Fuel material is brittle and strong.
- Tensile strength increases with temperature.
- Swelling was observed due to accumulated fission products and showed small micron size of the uranium particles.

SNAPSHOT SPACE TEST

General Background

By: Glen Schmidt

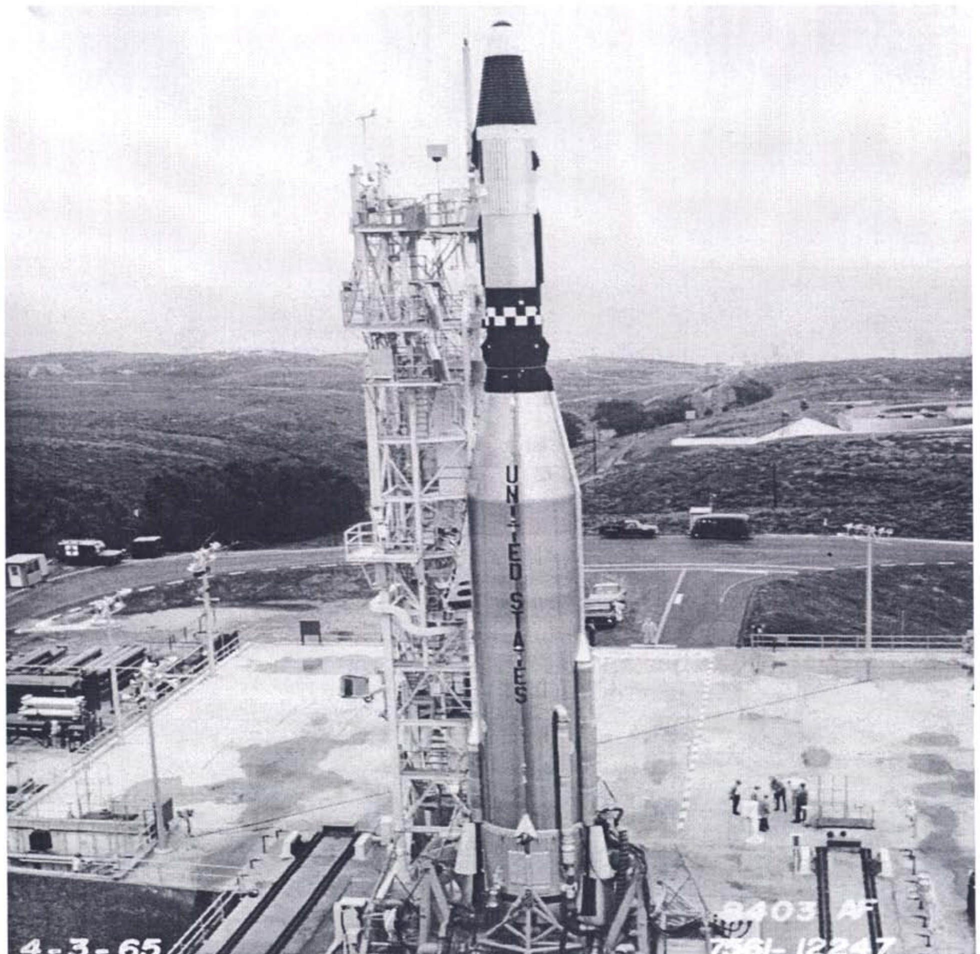
February 7, 2011

SNAPSHOT SPACE TEST

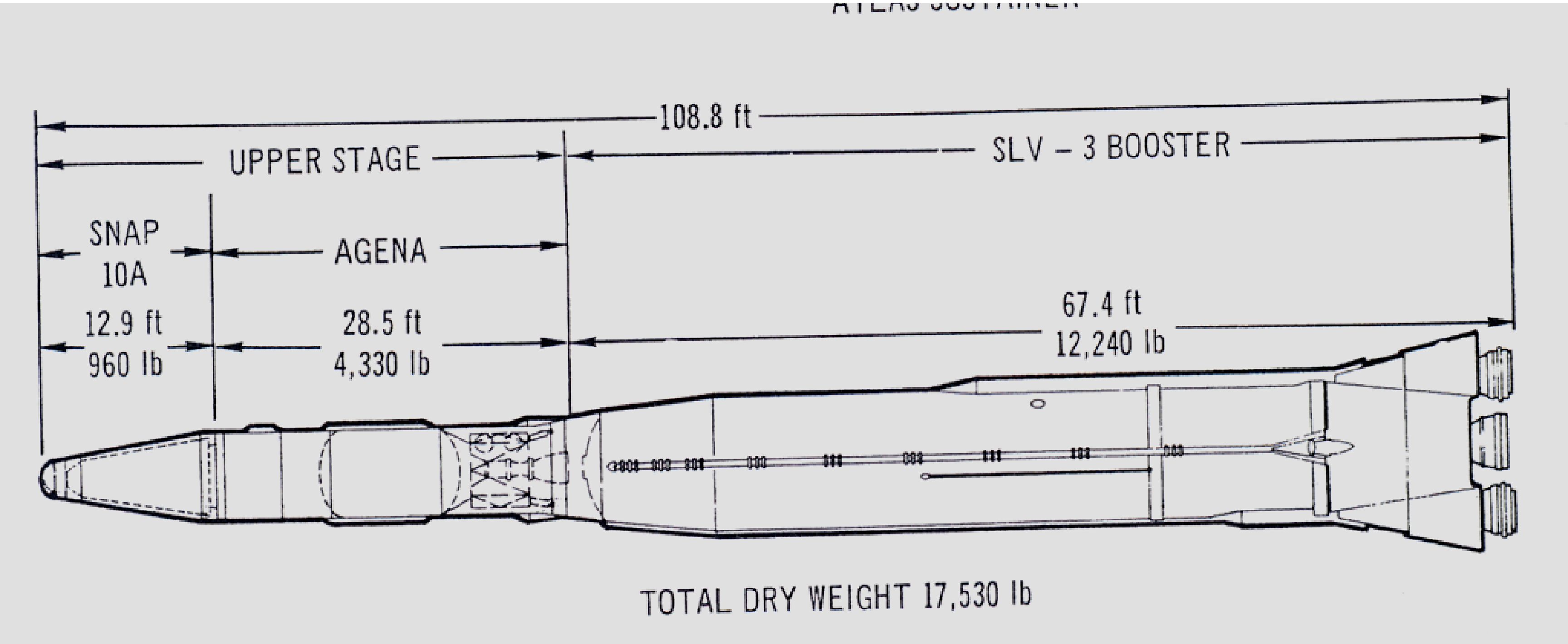
Major Milestones:

1. Spacecraft launched
2. Reactor startup
3. Criticality & heat shield ejection
4. Full-power operation
5. Failure/surge battery switched off
6. Secondary payloads power check
7. Ion engine operation
8. Passive attitude control
9. Temperature switch override
10. Controller off
11. First indication of failure

SNAPSHOT LAUNCH



SNAPSHOT SPACECRAFT



SNAPSHOT SPACECRAFT

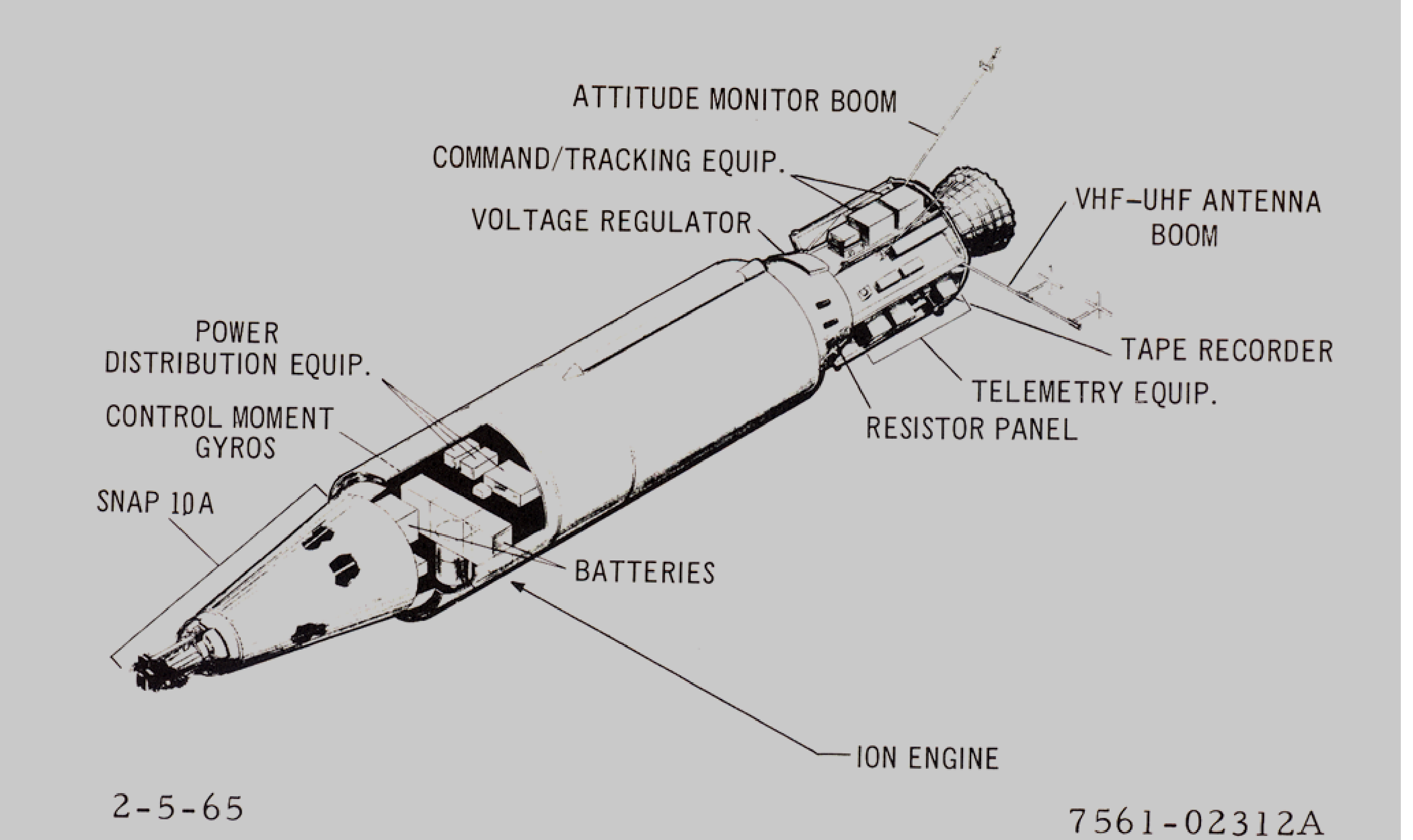


Figure 5. Spacecraft Configuration

SNAPSHOT LAUNCH

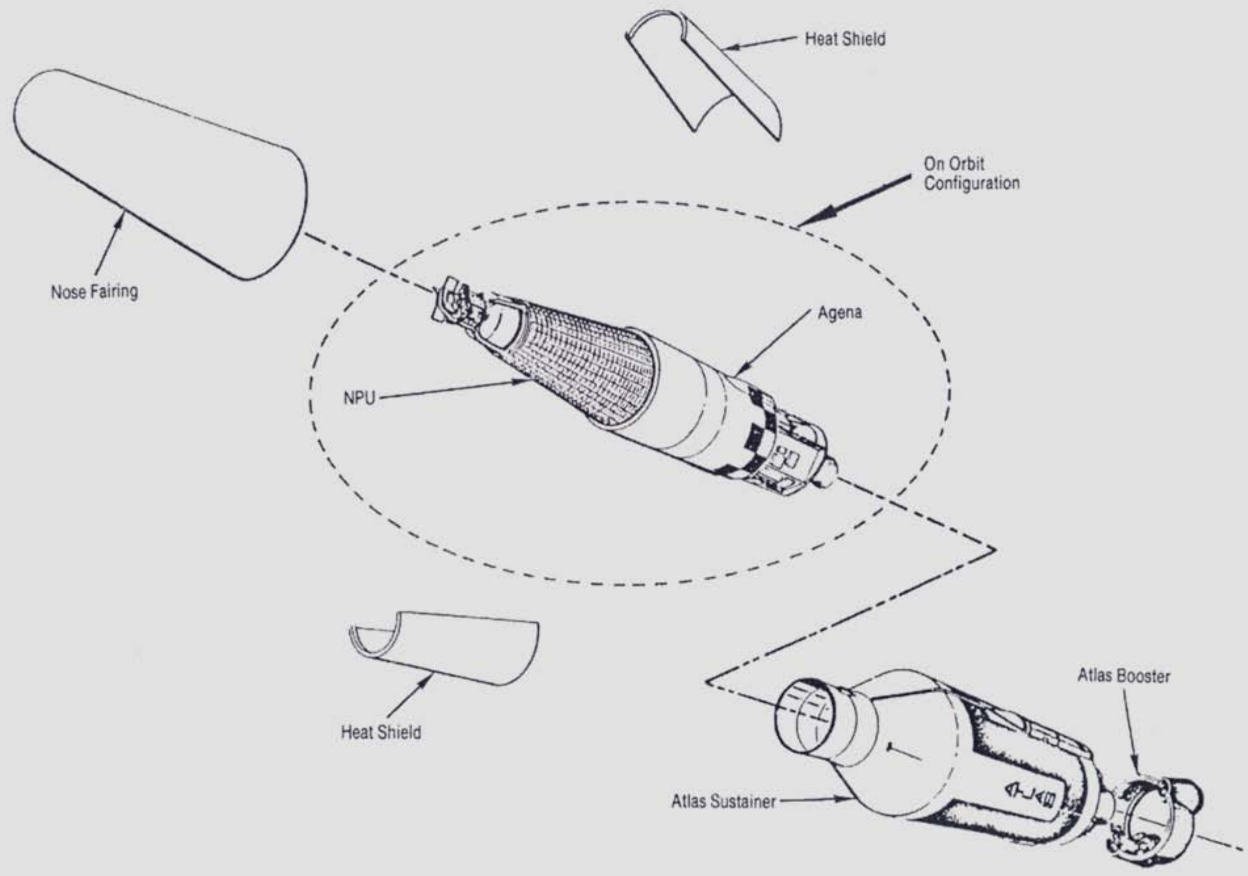


Figure 27. SNAP 10A Heat Shield Ejection Sequence

SNAPSHOT SPACE TEST

1. **Spacecraft launched**
- Liftoff from VAFB on Saturday, April 3,1965 at 13:24 PST
- Ascent was normal-Atlas booster, sustainer, vernier engine cutoffs occurred at specified times.
- Nose-cone separation and ignition of Agena first-burn verified.
- Second Agena burn occurred & indicated nominal orbit was achieved.
- Apogee of 705 nmi & perigee of 695 nmi and with an orbital period of 111.4 min. Long-lived orbit was achieved.
- Reactor startup was authorized by AEC.

2. **Reactor startup**
- Startup command verified on Rev 2 at 17:05 PST, April 3, 1965.
- Receipt of startup command verified by squibs being energized, coarse drums snapping to full-in position, and both control drums stepping in at a period of 150 sec,

SNAPSHOT SPACE TEST

3. **Criticality and heat shield ejection**
- Observed increased reactor outlet temperature and verification that heat shield were ejected at beginning of Rev 6.

4. **Full power operation**
- Initial controller deactivation and reflector full power operation observed during data acquisition on Rev 7 (outlet temperature of 1015 F and converter power in excess of 500 w).

5. **Failure battery/surge battery switching**
- Failure batteeries used to support pre-startup batteries were switched “off” and surge was switched “on” on Rev 8.
- Secondary payload groups were sequentially operated to obtain a power loading profile.

SNAPSHOT SPACE TEST

6. **<u>Secondary payloads power check</u>**
- Within the first 24-hours of reactor full-power operation, the ion engine was turned “on”.

7. **<u>Ion engine operation</u>**
- After ion engine warm-up, spurious data occurred with widely fluctuating control drum position readings.
- Other instruments were observed to be equally noisy.
- During the following, Rev 9, the ion engine had been turned “off” by its own timer.
- All reactor parameters were again indicating normally.

SNAPSHOT SPACE TEST

8. <u>Passive attitude control</u>

- After several days, active attitude control was turned “off” because control gas was gradually being depleted.
- Stability of spacecraft in nose-up attitude was maintained by gravity gradient effect and assisted passively by damping effects of control moment gyros.

9. <u>Temperature switch override</u>

- The planned nominal sequence required reactor malfunction and failure sensing system to be turned “on” on Rev 55. It was not turned “on”.
- A revised sequence was followed because of uncertain ion engine operation.

SNAPSHOT SPACE TEST

10. <u>Controller off</u>

- On April 9, 1965 (six days and four hours after reactor startup), two additional control drum steps were inserted by ground command to provide extrapolated power level of more than 500 w after end of 90 days.
- Reactor power level increased to 590 w.
- Reactor controller was turned “off”.

11. <u>First indication of failure</u>

- On May 16, 1965 after 43 days of operation, the spacecraft did not respond to ground command or interrogation of Rev 555.
- Later data indicated the reflectors had ejected, the controller was stepping the control drums, and the electrical power was zero.
- Failure was caused by the bus voltage regulator located in the Agena spacecraft.

SNAPSHOT ORBIT

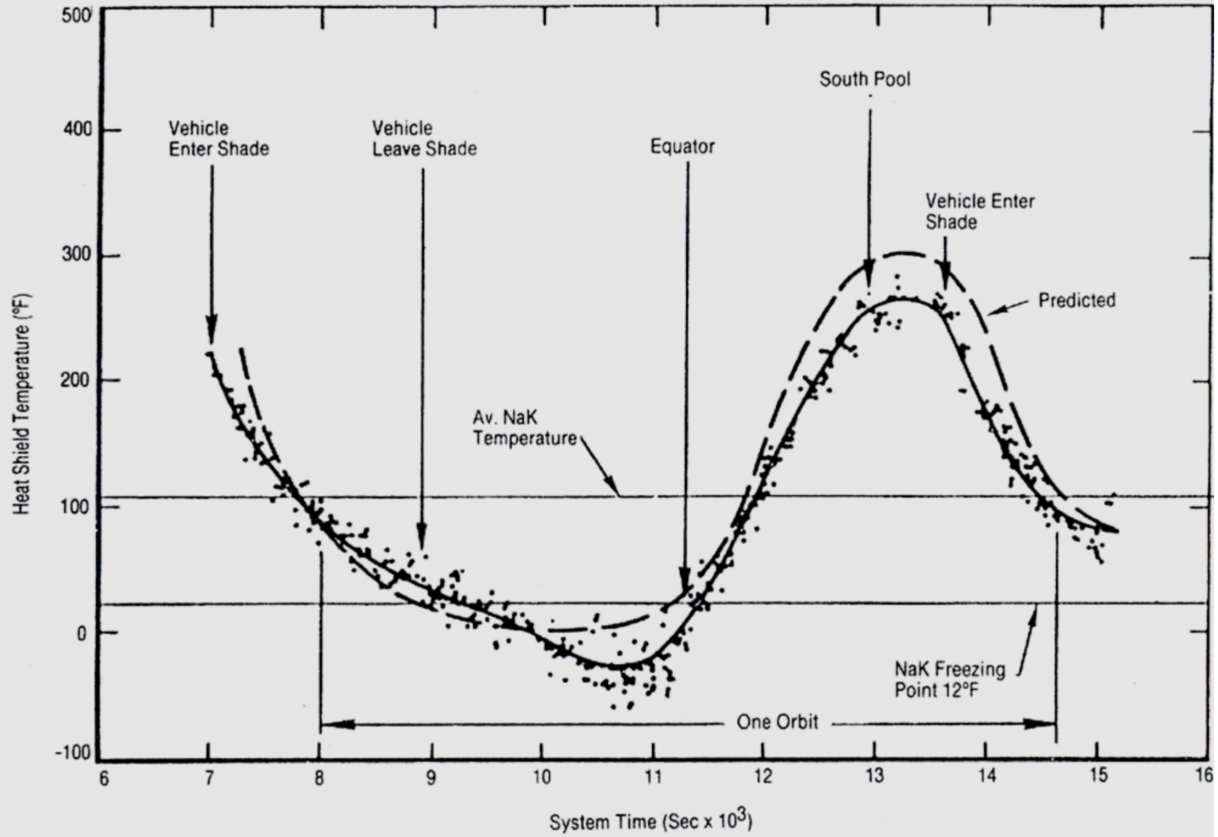
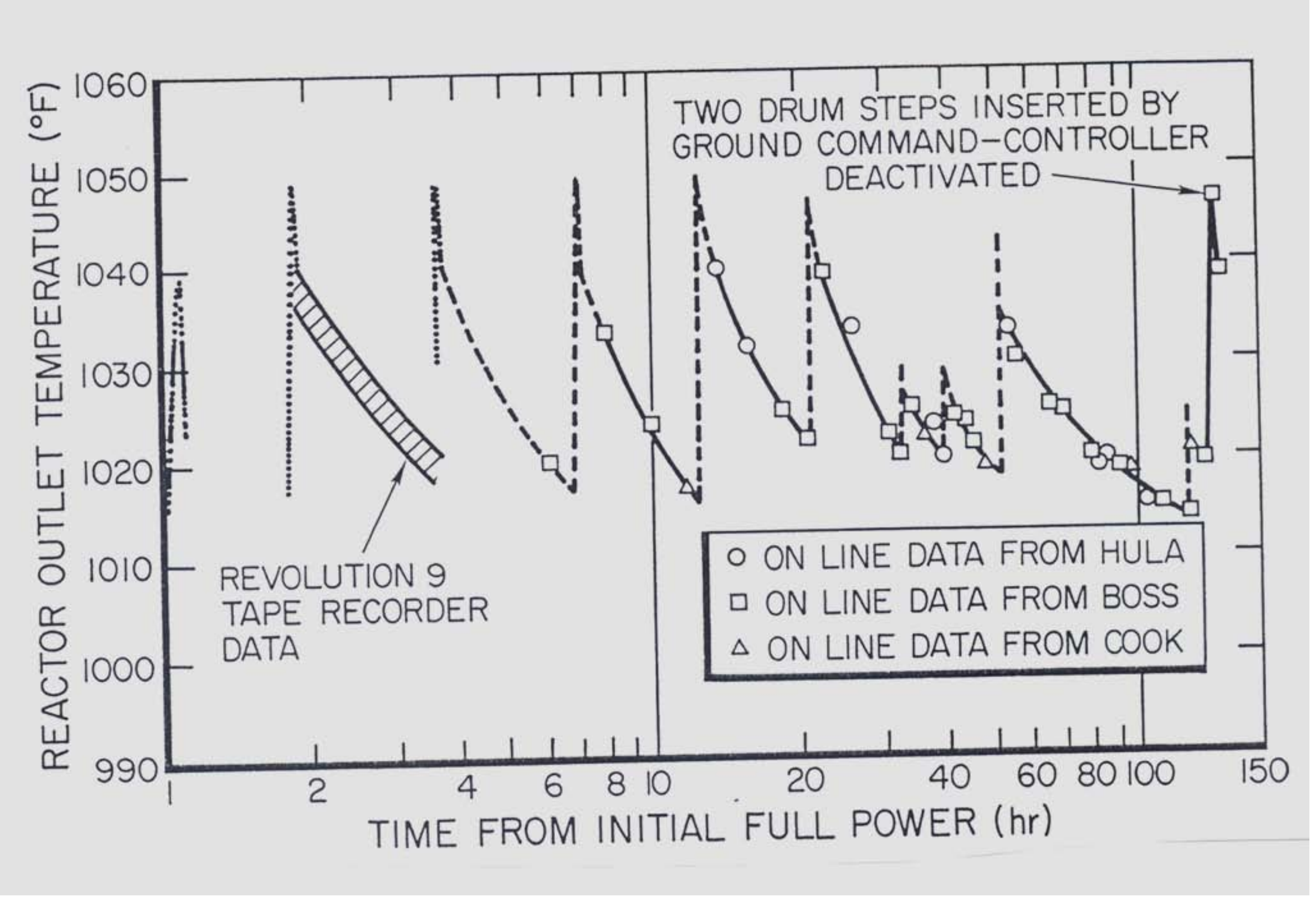
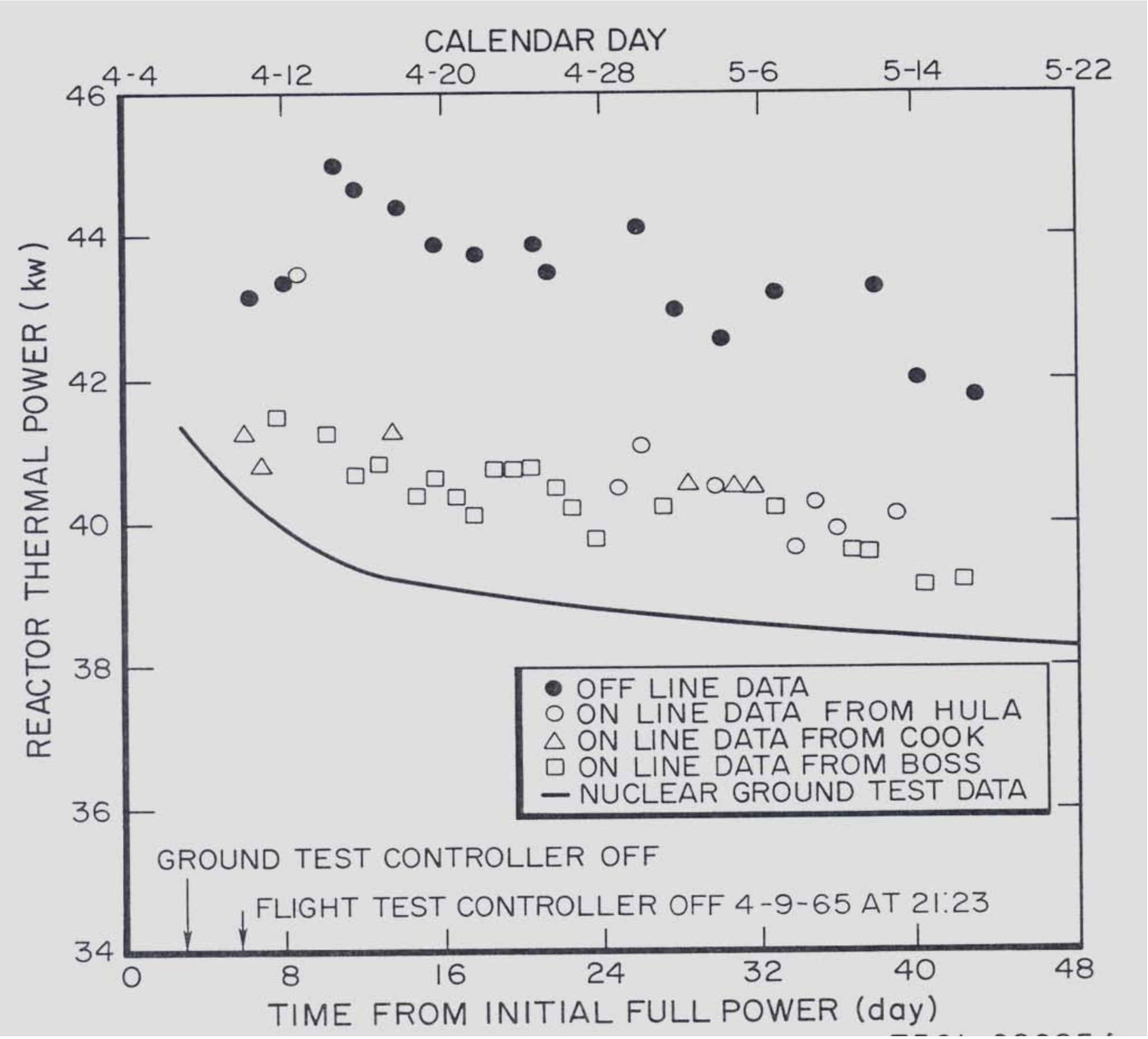


Figure 28. SNAP 10A Heat Shield Temperature (Prior to Ejection)

SNAPSHOT ORBIT



SNAPSHOT ORBIT



SNAPSHOT ORBIT

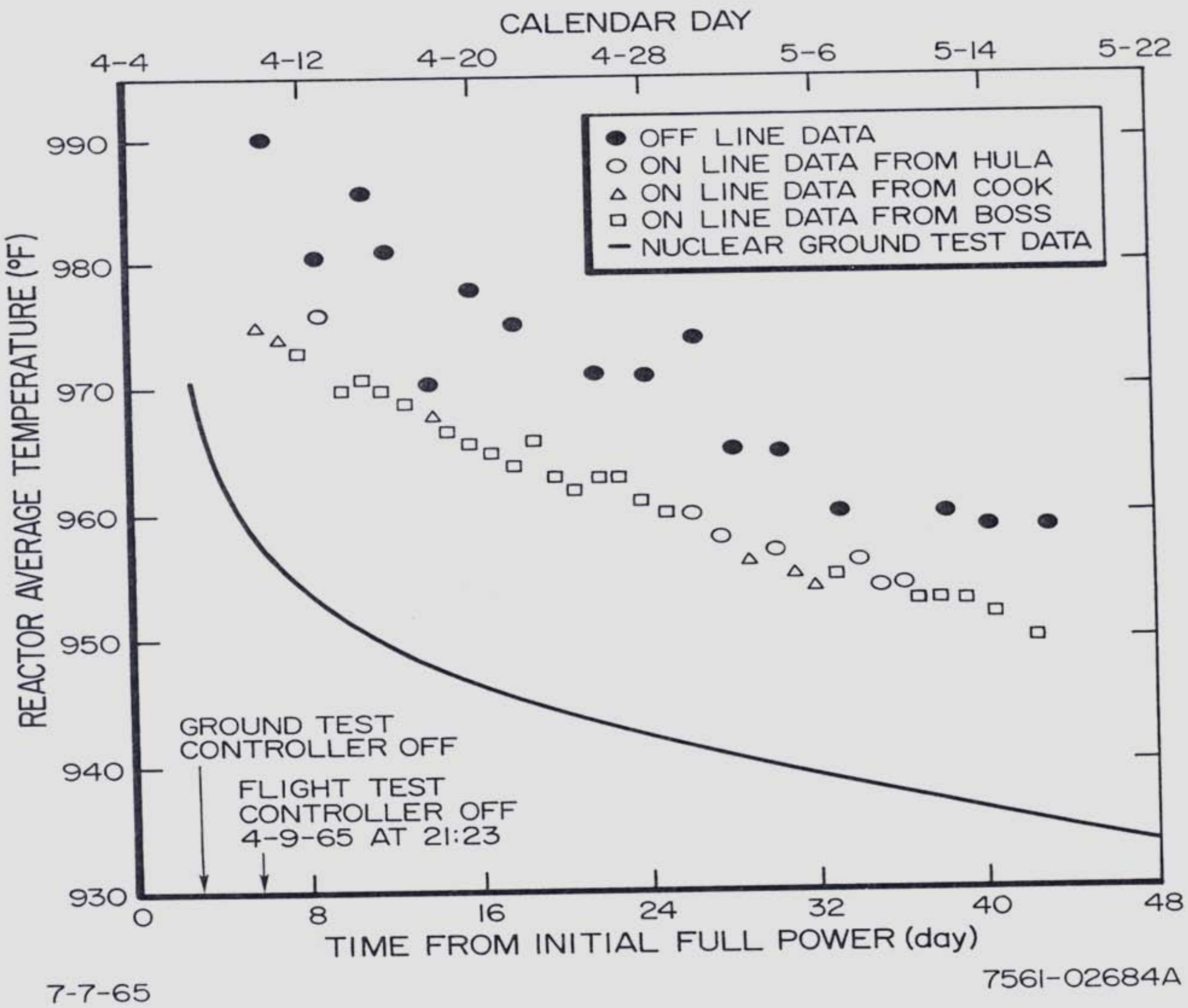
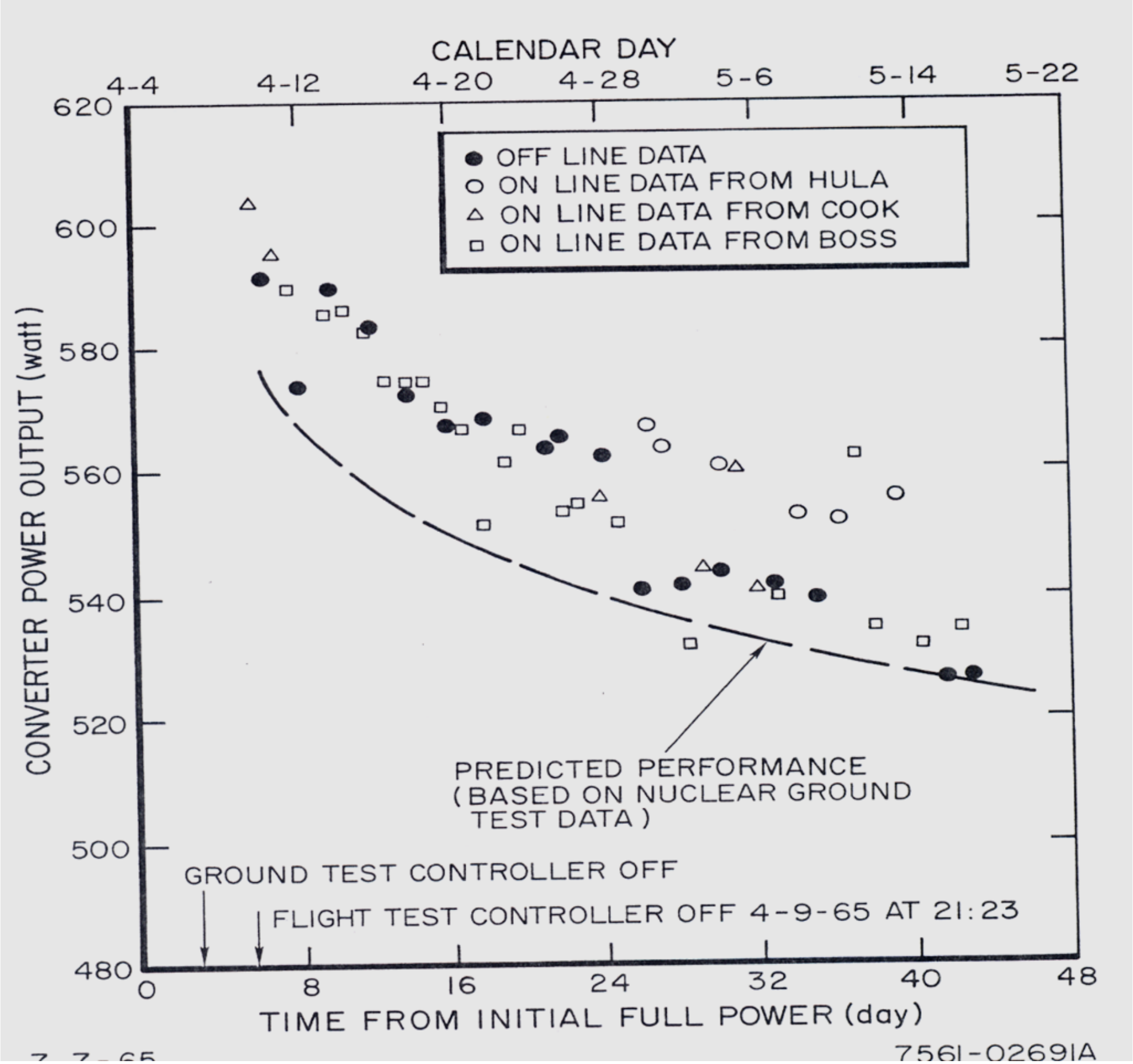


Figure 25. Reactor Average Coolant Temperature

SNAPSHOT ORBIT



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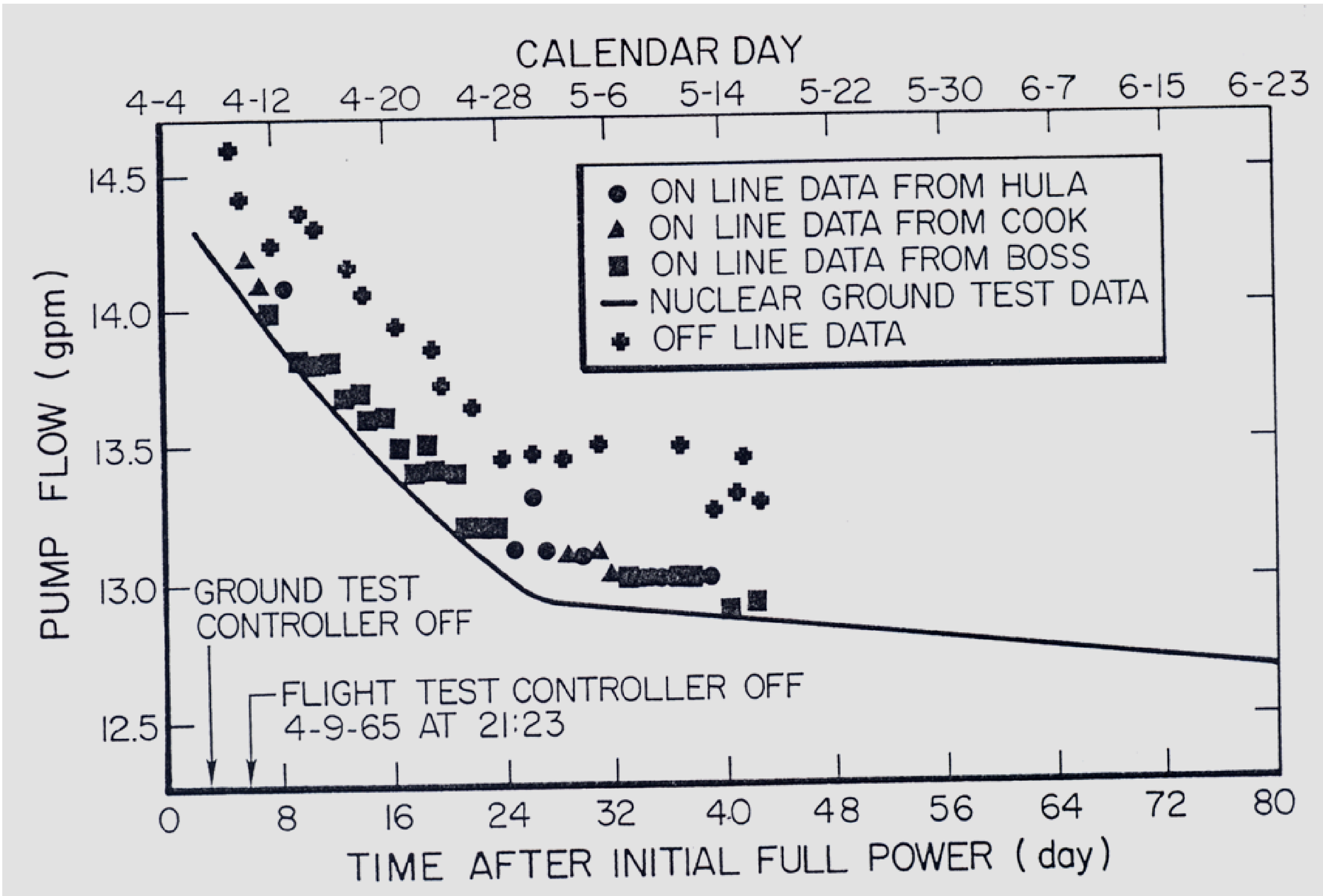
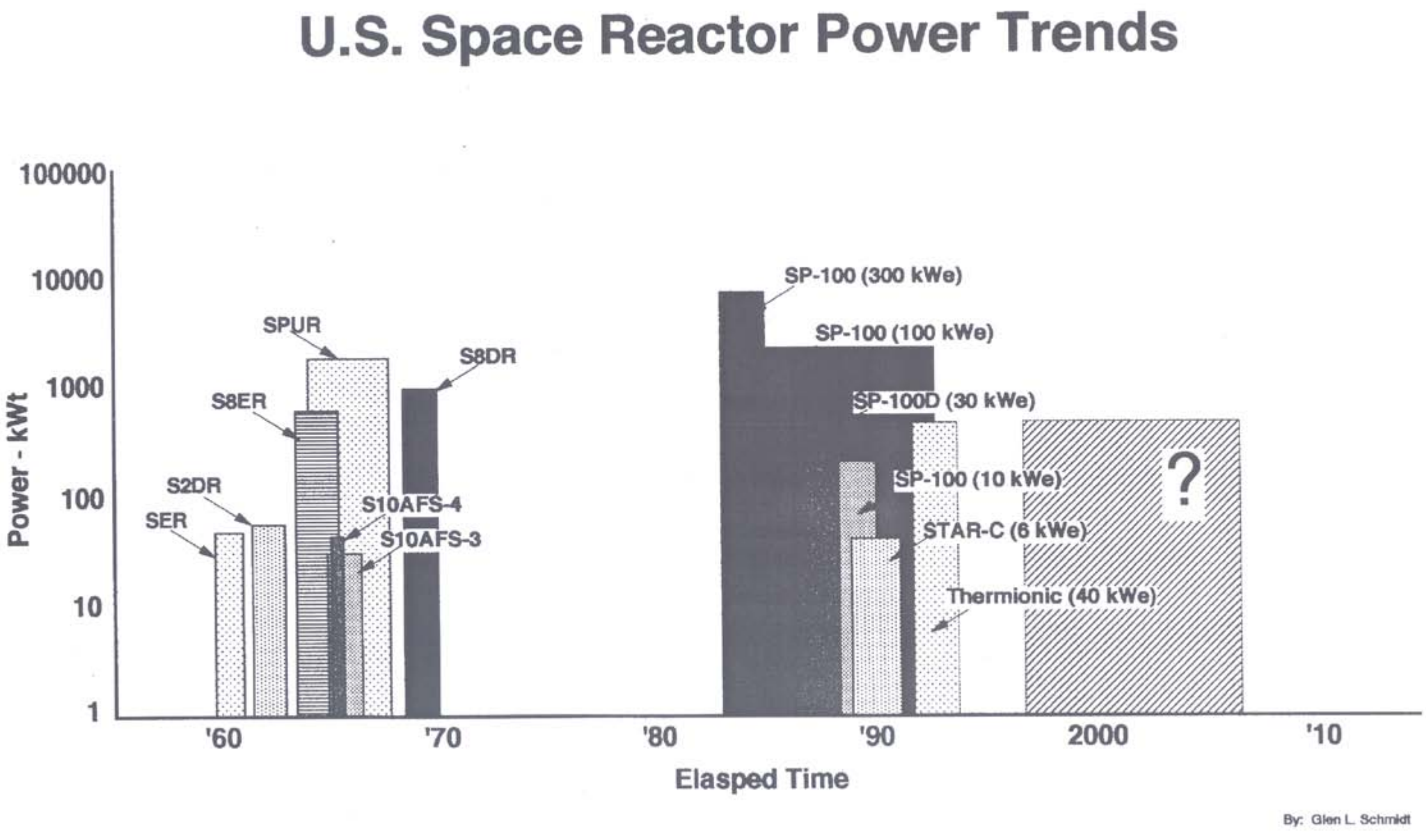


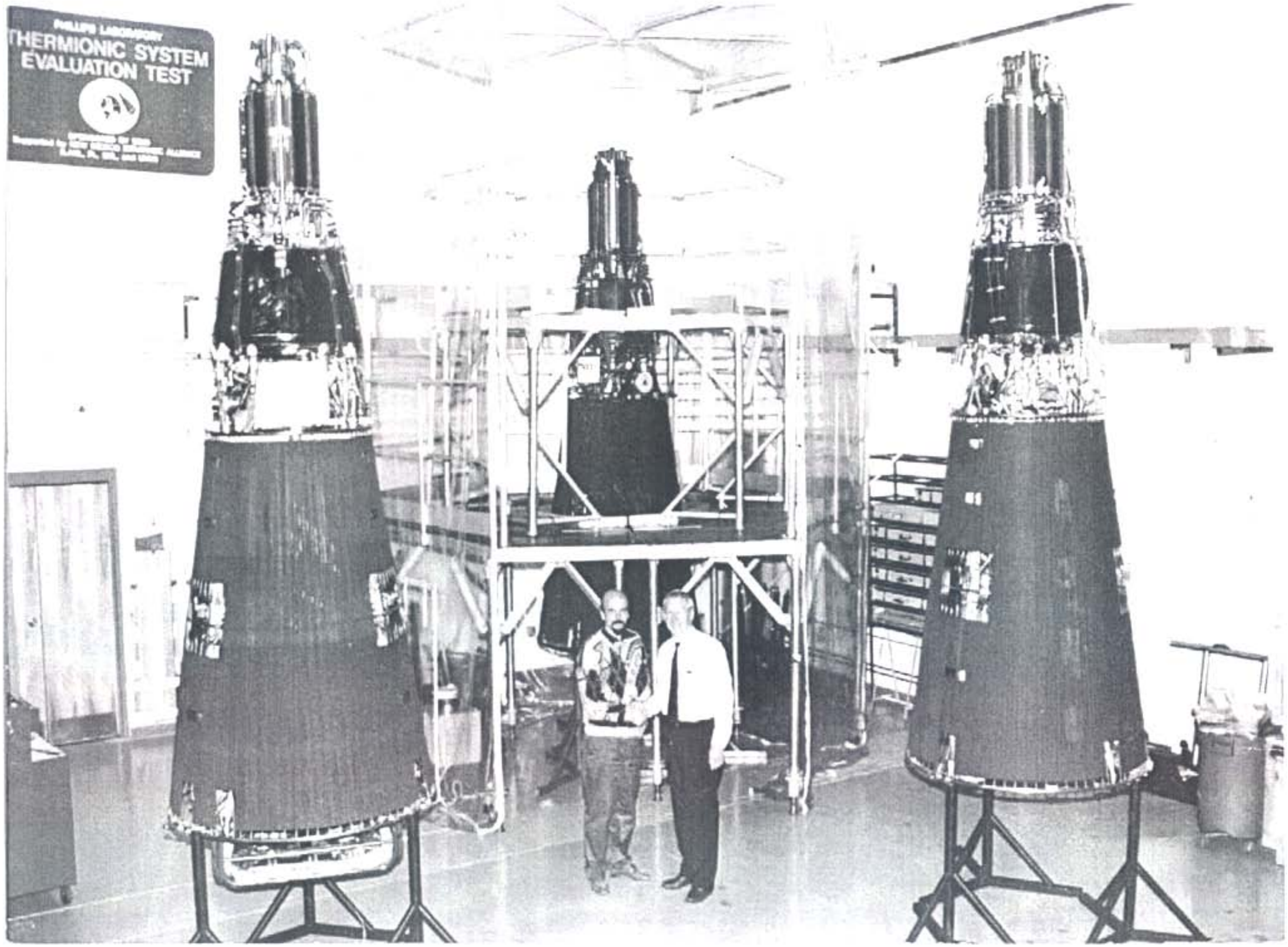
SNAP 10A Lessons Learned

- Development of processing and production control techniques and equipment to provide predictable, consistent, and acceptable fuel elements for more than one core loading required additional planning and effort than anticipated.
- Revisions in the design of fuel elements between the experimental and development reactor tests required improvements in the processing and production control techniques.
- The final configuration of a compact space reactor required consideration of many competing factors to accommodate the assembly, nuclear qualification and acceptance test, and launch sequence and were not anticipated prior to design and testing of the experimental reactor.
- Two nuclear reactor tests and a non-nuclear reactor mockup test were required to assure that design of reactor fuel elements, core vessel internals, and reflector subassemblies were ready for nuclear qualification and flight demonstration. Each test was required to verify design improvements, provided new information and was different than previous tests.
- The experimental reactor test must be followed by a development reactor test and be completed before final design of the flight system. A non-nuclear mockup of the flight design containing flight components must be tested prior to start of the nuclear qualification test.

SNAP Reactors Overview



TOPAZ II Space Power Systems



HY-LIFE Test Setup