Nuclear Thermal Propulsion
Ground Test History

The Rover/NERVA Program

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Agenda

• Rover/NERVA Program

• Nuclear Rocket Development Station

• Rover/NERVA Engine Ground Tests

• Final Rover/NERVA Engine Designs
Many nuclear programs were under way in the early 1950’s
The Atomic Energy Commission (AEC) was before Department Of Energy (DOE)
1955 AEC assigned Lawrence Livermore labs Project Pluto (code name Tory) for nuclear ramjets and Los Alamos Project Rover for nuclear rockets
Project Orion (external thermonuclear blast push propulsion) was developed in parallel
The Nevada test site was selected in 1956 since it was close to both LLNL and LANL. Facility Construction began in 1957. [1]
August 31, 1960 the AEC-NASA office was formed and Harold Finger named Director.

2. September, 1960: Contracts with Convair, Douglas, Lockheed, Martin on flight testing nuclear rockets (RIFT).


The total would be $7.6B in FY13
President John F. Kennedy
Special Address to Congress On The Importance of Space, 25 May 1961

“… I therefore ask the Congress, above and beyond the increases I have earlier requested for space activities, to provide the funds which are needed to meet the following national goals:

“First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth…

“Secondly … accelerate development of the Rover nuclear rocket. This gives promise of some day providing a means for even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself.

“Third … accelerating the use of space satellites for world-wide communications.

Fifty two years later, it’s the only goal mentioned that remains unfulfilled-three down, one to go!
Kennedy visited NTS one week after KIWI-B4A failed. Kennedy shown the engine in MAD before it was disassembled [2]
Nuclear Rocket Evolution

Flight Systems

Engineering Development

Experimental Development

Exploratory Development

LH² Turbopumps & Nozzles Programs

KIWI A Program

KIWI B Program

Phoebus Program

Pewee/Nuclear Furnace Programs

EST

NRX Program

Experimental Engines

Nerva Design

Rift Program

[Year Scale: 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72]
Reactor In Flight Test (RIFT)

- Started 1960 and ended 1963
- Managed by MSFC
- Purpose - furnish the vehicles for the first flight tests of nuclear rocket engines and demonstrate the practicality of nuclear rocket propulsion for space vehicle applications
- Scope -
  - Design nuclear stage
  - R&D to qualify materials and components to withstand radiation
  - Fabrication and assembly of stages including NERVA engine
  - Static testing and flight demonstration
Nuclear Rocket Development Station (NRDS)
Nuclear Rocket Development Station (NRDS)- Nevada Test Site

Nevada National Security Site used to be called Nevada Test Site (NTS) during Rover/NERVA

NRDS
Engine Maintenance Assembly and Disassembly (E-MAD)

E-MAD, was used to assemble nuclear rocket engines for testing and to disassemble and inspect radioactive engines after testing. [1]
Test Cell “A”
Test Cell “C”
With two 500,000 gallon dewars of LH2
Engine Test Stand-1

- 77,000 gallon LH2 run tank
- Structure made of aluminum
- Engine surrounded by clamshell to provide high altitude simulation and reduce radiation effects on facility
NERVA nuclear reactor and controls were assembled at the Large, PA, Westinghouse Astronuclear Lab, made safe for travel and possible accidents with poison wires, and shipped as one unit to the Jackass Flats, Nevada Test Site (Aerospace America, June 1989).
Rover/NERVA Engine Ground Tests
### Chronology of Engine Tests

<table>
<thead>
<tr>
<th>Date</th>
<th>Test Article</th>
<th>NRDS Test Facility</th>
<th>Maximum Power</th>
<th>Time at Maximum Power</th>
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<tr>
<td>July 1, 1959</td>
<td>KIWI-A</td>
<td>A</td>
<td>70 MW</td>
<td>5 min</td>
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<td>KIWI-A1</td>
<td>A</td>
<td>85 MW</td>
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<td>October 10, 1960</td>
<td>KIWI-A3</td>
<td>A</td>
<td>100 MW</td>
<td>5 min</td>
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<td>December 7, 1961</td>
<td>KIWI-B1A</td>
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<td>300 MW</td>
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<td>KIWI-B1B</td>
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<td>900 MW</td>
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<td>November 30, 1962</td>
<td>KIWI-B4A</td>
<td>A</td>
<td>500 MW</td>
<td>Several sec</td>
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<tr>
<td>May 13, 1964</td>
<td>KIWI-B4D</td>
<td>C</td>
<td>1,000 MW</td>
<td>40 sec</td>
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<tr>
<td>July 28, 1964</td>
<td>KIWI-B4E</td>
<td>C</td>
<td>900 MW</td>
<td>8 min</td>
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<tr>
<td>September 10, 1964</td>
<td>KIWI-B4E</td>
<td>C</td>
<td>900 MW</td>
<td>2.5 min – restart</td>
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<td>September 24, 1964</td>
<td>NRX-A2</td>
<td>A</td>
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<td>NRX-A2</td>
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<td>1,165 MW</td>
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<td>NRX-A3</td>
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<td>1,122 MW</td>
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<td>NRX-A3</td>
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<td>≤500 MW</td>
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<tr>
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<td>June 25, 1965</td>
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<td>1,100 MW</td>
<td>1.5 min – 14.5 min – 8 min</td>
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<td>March 3, 16, 23, 1966</td>
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<td>1,140 MW</td>
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<td>NRX-A5</td>
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<td>Phoebus 1A</td>
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<td>December 13, 1967</td>
<td>Phoebus 1B</td>
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<td>June 26, 1968</td>
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<td>December 3–4, 1968</td>
<td>Phoebus 2A</td>
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<td>June 11, 1969</td>
<td>Pewee</td>
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<td>June 29—July 27, 1972</td>
<td>XE-Prime</td>
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<td>1,100 MW</td>
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<td>Nuclear Furnace</td>
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<td>44 MW</td>
<td>109 min (4 tests)</td>
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Note: Does not include TNT Test
Rover/NERVA Engines

20 NTP engines designed, built, and tested during Rover/NERVA
## Rover/NERVA Reactor System Test Sequence

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The KIWI A reactors demonstrated the following technologies: instrumentation and control, fuel element design and fabrication, structural design and testing techniques [7]
• The KIWI-B series was designed to achieve a 10-fold increase in power (1000MW) over the KIWI-A series while holding size constant [7]

• Regeneratively cooled nozzle

• Only operate for 36 seconds before stopping due to hydrogen fires near the nozzle flange area [8]
Tests were quickly turned off when the test started and flashes of light in the exhaust indicated core damage as power risen to ~450 MW. Fuel elements broke down due to severe vibrations [8]
• Harold Finger halted further hot fire testing until vibration problem resolved. Dr Norris Bradbury (LANL Director) said stopping hot fire testing would kill the program. [2]
• Cold Flow test run with nitrogen and non-fissioning reactor and well instrumented. Vibration caused by interstitial flow. Problem resolved with better bundling of the core and seals. Final cold flow tests showed no vibration[2]
• Dr. Norris Bradbury wrote Harold Finger and said “**insistence on a repeat KIWI B-4A cold flow test resulted in a damned interesting experiment! Perhaps we have all learned something!”**[2]
Cold flow test in early 1964. Hot fire test run was curtailed during the test after 40 seconds due to leak in the nozzle which led to a failure. No evidence of any core vibration or fuel element ejection. [8]
Tested a few months after KIWI B4-D. The engine was the first redesign tested after the intense investigation of KIWI B4-A. No significant problems noticed during disassembly. The design jumped up into the NERVA NRX
• Intentional (control drum speed 4000 deg/sec) reactor destruction to partly examine engine disposal in space[8]
• Can’t happen with slow control drum actuators (45 deg/sec)!
• ~200-300 lbs gunpowder equivalent. Explosion mechanical not nuclear[1]
• Done 700’ from test cell C
NRX reactor series was developed to prove that the KIWI-B4 series reactor structure could withstand vibration and shock environments, and that reactor controls could handle rapid exhaust temperature variations (100R per sec)[7]
NRX/EST (Engine System Test)

- First rocket engine “breadboard” using flight functional relationship.
- Hot bleed bootstrap principle was demonstrated.
- Operated with 11 start-ups and final run for 13.7 minutes. [8]
• Engine run continuously for 62 minutes and 2220K at test cell C
• LN₂ pulse cooling was completed after 75.3 hours[8]
• Reduction of 75-80% fuel element time rate of corrosion compared to NRX/EST and NRX-A5[8]
Phoebus-1A

- Prototype of new class of reactors to increase specific impulse, power density and power level. [8]
- Run for 10.5 minutes before running out of propellant.
- Intense radiation environment caused capacitance gauges to produce erroneous LH$_2$ tank measurements and supply was became empty. [8]
- Double 500,000 gallon LH$_2$ dewars were not yet installed.
Phoebus-1B

- Phoebus-1B is rated at 1500 MW with total test duration of 46 minutes.
- External coatings of NbC reduce corrosion to .7g/element compared to uncoated.
- Mid range erosion noticeable.
Phoebus-2A

- 5 GW Reactor Core
- 805 seconds Isp space EQUIV.
- 250,000 lbf Thrust
- Ran for 32 minutes with 12 min above 4 GW
- Excellent mechanical and thermal performance
• 55430 lbs thrust
• 1140 MW power using NRX-A5 type fuel
• Hot-bleed-cycle in flight type configuration
• 28 restarts in 1969
• 11 minutes at full power
• Optimum startup and shutdown sequence demonstrated [8]
Pewee

- Pewee set records in power density and temperature. Operated at 503 MW for 40 minutes at 2550K with a peak to 2750K
- ~25k lbf of thrust
- Tested both NbC and ZrC coated fuel elements. ZrC outperformed NbC in reducing corrosion.
Nuclear Furnace NF-1

- 44 MW in size and ran on GH₂, 4500-5000 MW/m³ power density
- NF-1 test started in Summer 1972 and last reactor test done before program canceled
- Six runs were made. Final two runs completed without incident
- Exit gas temperature above 4000R for 121 minutes and above 4400R for 109 minutes total
- Only Rover/NERVA reactor test with filtered exhaust before burning hydrogen in flare stack
- Composite fuel achieved better corrosion performance, while carbide fuel had cracked extensively near center of reactor
Mid-band Corrosion in NERVA Fuel Elements

Fuel element Axial Profile

- Mass loss is greatest where fuel temperatures are only half of the maximum
- NF-1 had 8-50 grams mass loss per fuel element from ~90 minute run
Feasibility of Engine Clustering

- Two reactors. One was KIWI B4, the other was PARKA zero power reactor.
- One reactor stationary, while the other moved to distances of 16’, 9’, and 6’.
- Data showed neutron coupling had marginal effects, which were negligible.
Hot Gas Test Rig
- Fuel Elements Resistively heated with DC current
- Changes in fuel element composition during a test affected electrical conductivity

Reactor Critical Assembly
- Nuclear data obtained at low neutron flux levels or essentially zero power
Final Rover/NERVA Engine Designs
“Small Engine” Nuclear Rocket Design

16,125 lbf
367 MW

This engine design was the last reactor design based on lessons learned from past engines.
NERVA Flight Engine

- Thrust 75,000 lbf
- Isp 825sec
- Chamber Pressure 450 psi
- 60 startups
- Minimum 10hr at rated temperature
- Design specs ready to go before program canceled
NERVA Start-up and Shut-down

Based on NERVA Flight Design
- Startup to steady state can take ~1-2 minutes for conditioning, 30 sec for thrust buildup
- Shut down time depends on steady state duration. 5 min run, I=.5min, M=16.5 hours. 20 minute run time, I=3 minutes, M=49 hours
The Rover/NERVA program was canceled before a prototype flight was achieved, but achieved a TRL 6 for the design requirements set in the 1960’s and 1970’s.

Many lessons learned from the entire Rover/NERVA program will help the current NTP program develop faster and at a lower cost back up to TRL 6.
References

2. Finger, H. B., “Managing the Rover/NERVA Program”, ANS/ENS International Meeting, 2000, slide 2, 8, 9,10 page 6, 7