Sun, Aug 17, 12:00-13:00, rm 447-448**, 2025 Seattle WorldCon** Panel SPA20 **Nuclear Rockets - An Idea Whose Time Has Gone?:** "Development of the DRACO nuclear rocket is facing delays since testing an "open" nuclear reactor in Earth's atmosphere has become untenable. Are there any options?"

Manjula Menon (mod), **Bob Hranek**, **Charles J. Walther**, **Dan Dubrick**, **Mark Olson**

[My career began with 6 years of USAF Computer Programming plus 34 more years as an Aerospace Systems Engineer. Since I was a Defense Contractor for the Intelligence Community, I'm usually depicted as representing *the Dark Side* on panels. Hence my 'Protogen' name plate, which fans of ***The Expanse*** will understand. That being said, I do NOT speak for ANY of my employers! On this panel I'll add my aerospace experience in support of nuclear rockets. I OVERprepare for all my panels, so if you'd like my file regarding Nuclear Rockets, then just email me at BobHranek@gmail.com]

Nuclear Rocket Fundamentals:

1. The basic measures used to describe rockets are Thrust (T) and Specific Impulse (I_{sp}).
    a. Thrust (T) = fuel mass flow rate (M) times the velocity of the exhaust (V_e), or T = V_e x M/sec.
        i. T is only limited by the amount of fuel you can burn. Saturn V F-1's T = 6.9 million Newtons.
    b. Specific Impulse (I_{sp}) = how efficiently a rocket engine converts fuel into thrust measured in seconds (s).
        i. Change in momentum per unit of fuel used, I_{sp} = T/M x G_c), where G_c = 9.8 m/sec^2.
    c. Rockets with enormous thrust, like the Saturn V's F-1, had 263 I_{sp} at sea level & 304 I_{sp} in vacuum.
        i. Best conventional I_{sp} are New Glenn's BE-4's 340 I_{sp} at sea level & BE-3U's 445 I_{sp} in vacuum.
    d. All chemical reaction rockets have fundamental limits on how efficient they can be, requiring over 90% of launched mass to be the fuel needed to reach Earth's orbit.
2. Nuclear engines can be much more efficient, such as NERVA's 1964-1969 tests of up to 869 I_{sp} (3 times F-1's).
    a. Use the energy of nuclear reactions, both to superheat propellant & to generate electrical power.
3. Nuclear engines can be much more powerful than Chemical engines, just like nuclear bombs are MUCH more powerful than Chemical bombs.
4. **Manjula**'s James and Gregory Benford's Starship Century includes a nice summary of the need for nuclear rockets.
5. These are NOT Radioisotope Thermoelectric Generators (RTGs), which are just thermal batteries with decaying radioactive elements as the heat source. RTGs are heavy, always "on", & generally just used when solar is inefficient.
6. **ATOMIC ROCKETS** is a great site to get an overview of current, planned, & far-out engines for spacecraft of ALL sizes.

Nuclear Rocket History:

7. 1955-1964 **Project Orion** proposed using pulsed nuclear bombs to provide high thrust AND high I_{sp} for space travel.
    a. Fascinating theoretical technical specs of up to 6000 I_{sp} using fission bombs or 75000 I_{sp} using fusion bombs.
    b. 800x .35 kt bombs (1/second) might have propelled a 10000 kg craft to deliver 6100 kg to LEO, 5700 kg to soft landing on Moon, 5300 kg to Mars & back, or 1300 kg on a 3-year Saturn & back mission.
    c. 1963 Partial Nuclear Test Ban Treaty was part of reason for shutting down this project.
8. 1955-1973 **NERVA** (Nuclear Engine for Rocket Vehicle Applications)
    a. 1955/03, Mills committee authorized development for a nuclear rocket upper stage for an ICBM.
    b. Project Rover later designed to replace 3rd stage of Saturn V, or ~267,000 N thrust, with best test = 869 I_{sp}.
    c. 1968/06/22, Phoebus 2a , most powerful ever tested, operated for 32 minutes, 12 minutes at 4100 MW.
9. 1955-1972 Even-numbered Systems for Nuclear Auxiliary Power (SNAP) were compact nuclear reactors.
    a. 1965 SNAP-10A US fission reactor operated for 43 days in orbit, generating a maximum of 590 watts.
        i. Reactor 40 cm long x 22.4 cm diameter, 290 kg (unshielded), generating 30 kW heat.
10. 1973-1978 **Project Daedalus** proposed a Fusion rocket to reach Barnard's Star 5.9 light years away in 50 years.
    a. 2-stages 54,000,000 kg initial mass (50,000,000 kg fuel + 3,500,000 craft + 500,000 payload) in Earth orbit.
    b. 1st stage takes 2 years to reach 7.1% of light speed(*c*), detaches, & 2nd stage fire for 1.8 years to 12% *c*.
11. 1977-? **Variable Specific Impulse Magnetoplasma Rocket** (**VASIMR**) by varying the RF heating energy & plasma, VASIMR should be able to "shift gears" to provide low-thrust/high I_{sp}, high-thrust/low I_{sp}, or anything in between.
    a. 2015 Ad Astra's VX-200 engine provided 5 N thrust for 200 kW (40 kW/N).
        i. 2009 NEXT's conventional ion thruster produces 0.327 1.36 e-04N with only 7.7 kW, or 24 kW/N.
    b. 2023 Ad Astra Won 2 NASA Contracts For VASIMR Technology Development, promising, but not mature yet.

c. **ATOMIC ROCKETS** reported GOAL performance for 10000 kg VASIMIR engine with 5.9 MW thrust power are:
    i. High Gear= 29969 I_{sp}, 40 N thrust, mass flow 0.136 g/s, 0.000408 N thrust/kg.
    ii. Med Gear= 14985 I_{sp}, 80 N thrust, mass flow 0.544 g/s, 0.000815 N thrust/kg.
    iii. Low Gear= 2956 I_{sp}, 400 N thrust, mass flow 10 g/s, 0.00408 N thrust/kg.
    iv. ALL= 60% thermal & total efficiency, 19.6 MWe input, using liquid H_2, accelerated via magnetic nozzle.

12. 1983-1994 **SP-100** (Space reactor Prototype) successor to SNAP, but never advanced to flight hardware.
13. 1992-? **Antimatter-catalyzed nuclear pulse propulsion** invented at Penn State, antiproton-initiated fusion research performed at Lawrence Livermore in 2004. This remains a speculative technology for the foreseeable future.
    a. ~1 microgram of antihydrogen required per 1 kt yield.
    b. Estimated cost to produce 1 microgram of antihydrogen = $100 million.
    c. Presuming containment can be achieved, fueling a **Project Orion**-like craft above = $28 billion.
14. 2020-2025 **DRACO** (Demonstration Rocket for Agile Cislunar Operations) aimed to demonstrate a nuclear thermal rocket (NTR) engine using low-enriched uranium in orbit by 2027. (a.k.a., *ROAR* = "Reactor On A Rocket")
    a. 2023, $500 million project to demonstrate NTR with 10,000x greater thrust-to-mass ratio than electric propulsion and 2-5x greater than chemical propulsion in space.
    b. **DRACO**'s reactor startup time was as little as 60 seconds from zero to full power, much shorter relative to other space or terrestrial nuclear power reactors, which could be up to several hours.
    c. Technological, infrastructure, & regulatory challenges:
        i. High operating power density & reactor temperature necessary to heat propellant to 2700 K.
        ii. Need for long-term storage & management of cryogenic, liquid hydrogen (LH2) propellant.
        iii. **DRACO**'s startup & shutdown transients were still long relative to nearly instant chemical engines.
        iv. Expensive mods to launch vehicle, pad, & ground systems including support for unique missions.
    d. Why cancelled: the decreased cost of conventional launch (like SpaceX) & **DRACO** cost overruns.
    e. 2025/07/24 AWST, U.S. Grapples With Barriers To Rapid Space Maneuvering, at end of article: "Congress rejects NASA plans to defund nuclear propulsion research", "Senate Appropriations Committee included "no less than" $110 million for NASA to develop, produce and demonstrate NTP systems in its 2026 spending bill markup as well as $10 million to establish a national nuclear propulsion center of excellence."
    f. 2025/02/06 ESA's **Alumni** NTP engine may pick up where **DRACO** left off.
15. 2022, How to Solve Big Problems: Bespoke Versus Platform Strategies, informative 34-page study on why SpaceX was able to outperform NASA on cost, speed-to-market, schedule, and scalability.
16. 2024/12, Overview of **Space Nuclear Propulsion & Power** (**SNPP**)
    a. 16 slides that contain **excellent** summaries of the concepts, histories, & technologies intended for this panel.
    b. "U.S. DoD & civil & commercial space enterprises recognize the need for alternatives to traditional propulsion and power options that may enable novel missions or enhance mission-unique capabilities."
    c. **SNPP has become a viable consideration based on decades of advancements in**:
        i. Uranium fuel form development, enrichment, and processing
        ii. Reactor design and manufacturing (materials, additive manufacturing)
        iii. Nuclear industrial base growth (new companies, capabilities, facilities)
        iv. Interests in space applications across government and commercial communities
        v. High-assay low-enriched uranium (HALEU)—easier to obtain & nonweaponizable but less efficient
        vi. Advanced fuel forms: tristructural isotropic, accident tolerant, production history (terrestrial & naval)
        vii. Multiple core configurations—moderator block, tie rod, particle/pebble bed
        viii. High-temp materials & manufacturing methods: additive manufacturing, welding, ceramic composites
        ix. Validated physics modeling and design tools: reduces cost/risk, improves design
    d. General SNPP Challenges & Considerations: (CTE = Critical Technology Element)
        i. HALEU Processing - Significant investment needed to develop facilities for enrichment of low-enriched uranium to HALEU to meet prospective needs
        ii. Development of Very High-Temperature Materials and Assembly Processes

1. Required for NTP where internal reactor temperatures can exceed 3,500 K (~6,000 °F)
2. Will also benefit SNP systems that have much longer operational lifetimes

iii. Reactor Ground Testing Not (Currently) Possible
1. No facilities exist in the U.S. that can support reactor ground testing (larger than KRUSTY)
2. NTP testing requires that engine exhaust be scrubbed of radiologics before release; could result in very large, prohibitively expensive facilities that take years to build & qualify
3. SNP systems require reactor testing with partially and/or fully integrated CTEs

iv. Complex System Engineering & Integration (SNP)
1. CTEs must auto-interact to ensure stability & control across the power-demand range
2. Must be packaged & qualified for space applications
3. Multiple, lengthy, expensive test/qualification programs

v. Commercial Launch Operator Must Obtain License to Launch Nuclear Material
1. SNPP asset must undergo several multi-agency reviews to assess safety assurance
2. FAA license application process can take 12–24 months
3. License might also cover debris and/or disposal, depending on mission

vi. Modifications to Launch Vehicle, Pad, and Ground Systems to Support SNPP
1. May require requalification, thus driving schedule and cost
2. May result in substantial investments for unique, infrequent, one-off missions

vii. Adopting SNPP systems will require careful consideration of their cost, development time, benefits, & challenges when performing mission-level comparisons to current systems

e. 2025/08/04, Duffy to announce lunar nuclear reactor, soliciting proposals for 100 kW reactor by 2030.

17. 2023/07/26, Pulsar's Nuclear Fusion Rocket, 1st half of 12-minute video exploring *possibility* of 2027 test in space.
    a. Proposed Direct Fusion Drive (DFD) has I_{sp} = 105 sec, but "uses so little fuel it can burn constantly" to allow ½ travel time to Mars, or 2-year travel time to Saturn!
18. 2024/05/22, Howe Industries' Pulsed Plasma Rocket (PPR) 1st 4 min of 12-min video using NASA's Pulsed Fission-Fusion (PuFF) Propulsion Concept of tiny nuclear bombs for propulsion for a 2-month mission to Mars.
    a. Thrust = 100,000 Newtons & 5000 I_{sp}. An extension of the old **Project Orion** concept.
19. 2024/06/02, Scott Manley's 22-minute **Nuclear Rocket** summary is great for new & experienced Aerospace fans.
20. 2025/06/30 AWST, p40, Isaacman claimed US States political support for pivoting NASA to nuclear-electric propulsion.
21. 2025/06/06 U.S. Unleashes Liquid Uranium Rocket to Conquer Mars with Unmatched Nuclear Speed, hyped-up title.
    a. IF this **Centrifugal Nuclear Thermal Rocket (CNTR)** can be implemented, it could deliver 1500 I_{sp}.
    b. 2023 NASA's **Centrifugal Nuclear Thermal Rocket Challenges & Potential** detailed technical paper for fast (<15 month) round-trip human Mars missions or high delta-V missions in cislunar space.
    c. **Neutronic Design of the Centrifugal Nuclear Thermal Rocket** for 420-day round-trip human Mars missions.
22. 2025/07/20, Eager Space's **Nuclear Electric Propulsion** 30-min video, EXHAUSTIVE details on getting rid of waste heat.
    a. Starlink V2 Ion Thruster Argon 2500 I_{sp}, 4.2 kW used to produce 170 mN (weight of 3 AAA batteries in 1 G).
    b. Need 240 MW to make an Ion engine with as much thrust as RL-10.
    c. X3 Hall Effect engine = 5.4 N each.
    d. MAT-100 engine = 1.4 N each.
    e. VASIMR VX-200 engine = 2.4 N.
    f. High-Power Brayton Nuclear Electric Propulsion for 2033 Mars Round-Trip Mission using two 5 MW Reactors, 4 Generators, 1361 m2 Reactor Radiators, 182 meters long, & 560 tons total. Liquid H2 5000 m3. Two 2.5 MW Plasma Thrusters, but the depicted heat radiators are WAY TOO SMALL.
23. 2025/07/14 AWST, p56-60, "Hidden Asset" details the Armstrong Test Facility (ATF) history in the development of **NERVA** & several other government & commercial high-energy Aerospace projects. ATF needs to be saved from short-sighted budget cuts if the use of nuclear power in space is going to progress in the U.S.
24. Chinese Nuclear-Powered Spacecraft Development
    a. 2024/03/20 China tests nuclear-powered engine for Mars spaceship in Scientia Sinica Technologica.

   b. Chinese systems integration is currently the best, they have consistent & reliable funding once they decide on a goal, & they will take the best of all the technologies we've discussed & actually implement them.

Panel Agenda: (The answers listed here are Bob's opinions, and do not reflect the entire panel's POV.)

25. Why did nuclear propulsion fail before?
    a. Nuclear LAUNCH is a non-starter due to public fears until we're VERY experienced with matured versions.
    b. Technilogical Readiness Levels (TRL) of too many required systems were too low to warrant development.
    c. Long-lead-times of nuclear propulsion proposals made use of chemical propulsion more cost-effective.
    d. There was insufficient need for deep-space operation to warrant the investment in nuclear propulsion.
26. What must be done to make it succeed next time?
    a. Develop nuclear space propulsion for operations where it outshines solar & chemical implementations.
        i. Deep-space missions, such as people to Mars, where high thrust & I_{sp} are required to minimize crew radiation exposure by getting them there more quickly & with more radiation protection, such as thicker water belts, which is too heavy for cost-effective chemical propulsion.
        ii. Military operations in Cislunar space, where maneuver & observability requirements make nuclear propulsion more desirable than chemical & solar options.
27. Where beyond Earth is nuclear power better than solar?
    a. Lunar surface, where 354 hours of night make having a continuous source of power better than storing 354 hours of solar power in batteries. If base is completely underground, then no risk due to solar panel damage.
        i. This applies to Mars as well, since dust storms there can severely limit solar power.
    b. For any spacecraft that needs to limit its observable size, if nuclear heat dissipation is < solar panel size.
    c. Depending on the cost-effectiveness of the solar panels, then missions operating around 400,000,000 km from sun (asteroid belt) & beyond.
28. What technologies do we have now that might make nuclear useful?
    a. Continuing **DRACO**, **SNPP**, **CNTR**, and other projects to implement nuclear propulsion in space ASAP.
29. What can we reasonably foresee coming in the next, say, thirty years?
    a. My crystal ball has been fractured by living in the stupidest timeline, but I expect the Chinese to develop cislunar space (including Lunar colonization) before the rest of the world can stop its infighting to catch up.
    b. A few limited commercial ventures will start asteroid mining & nuclear propulsion could be used for that.
    c. Once 1 country or corporation uses nuclear propulsion practically, then several will follow within a decade.
30. IF small fusion reactors (no ITER in space, please!) come to fruition, might this be a better power source than fission?
    a. Obvious answer is "YES!", but there are longevity issues with current ITER that would be hard to overcome.
    b. Fusion power outshines fission, just like fission is always inherently more powerful than chemical energy.
31. One of the biggest issues for exploring space is developing affordable technologies to sustain funding for exploration, even without financial return. How can nuclear propulsion help?
    a. Nuclear propulsion can help by dramatically shortening human exposure to radiation during interplanetary missions by decreasing the travel time & allowing more radiation-absorbing water to be transported.
32. Any timelines for when we'll have a nuclear rocket?
    a. In the 'West', the main obstacle is funding. Unless a return-on-investment can be shown, nothing gets done.
    b. In the U.S., cutting through bureaucratic barriers may be the next most difficult hurdle. There's still a HUGE irrational stigma against anything with the word 'nuclear' included, so educating people is key.
    c. Next will be building the infrastructure to build & test these technologies at full power, which don't exist.
    d. Your best bet may be to follow the Chinese Space Program, since they're the only group actually thinking long-term AND funding long-term space development in a reliable & efficient manner.
        i. 2025/07/20 China Reveals 12,400 MPH Propulsion Tech That Can Orbit the Planet in Under 2 Hours is an example of how far ahead the Chinese are in hypersonic technology.
33. What is possible in this context?
    a. What is "possible" is only limited by our imaginations. What gets funded is whatever ideas can actually persuade scientifically-illiterate politicians.
34. What is likely to remain science fiction?
    a. **Project Orion**, because no one (except maybe the crazy Russians?) is comfortable with that many nukes being made and distributed as a source of propulsion. Way too easy to be used as weapons too.

b. **Antimatter-catalyzed nuclear pulse propulsion**, because of the extreme cost of creating antimatter, the extreme technical challenges of **100%** containment, and the extreme danger of weaponization.

c. I LOVE everything about **The Expanse** TV series & Books (I've got 14-pages of notes for it!), but their SUPER efficient Epstein Drive that makes interplanetary travel so easy will likely always remain science fiction.

   i. **ATOMIC ROCKETS** lists the performance of Epstein's fusion-drive yacht as:

      1. Thrust: 1,000,000 N
      2. Specific Impulse (i_{sp}): 1,100,000 seconds
      3. Exhaust Velocity (v_e): 11,000,000 m/second (~3.7% of light speed)
      4. Mass Flow Rate ($\dot{m}$): 0.09 kg/second
      5. Thrust Power: 5.5 Terawatt
      6. Engine's Thrust to Weight Ratio: ~140 [*Citation needed*]
      7. Propellant mass fraction (yacht's mass fueled / mass empty): ~4

   ii. Alternative set of performance statistics has been suggested by the Tough SF website, based on the performance of the *Rocinante* (main ship of the show) on-screen:

      1. Thrust: 6,370,000 N
      2. Specific Impulse (i_{sp}): 1,927,000 seconds
      3. Exhaust Velocity (v_e): 18,900,000 m/second (6.8% of light speed)
      4. Mass Flow Rate: 2.2 kg/second
      5. Thrust Power: 60.2 Terawatt
      6. Total power output: 96.8 Terawatt
      7. Engine's Thrust to Weight Ratio: Presumably over 3 (*Roci* has a dry TWR of 2.6)
      8. Fusion type: D-He3 (1:2 mixture ratio)
      9. Fusion pulse rate: "*[what we see] can be achieved with as few as 10 pulses per sec, or hundreds if possible*"

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Seattle Worldcon 2025

Pannelists

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NERVA
Nuclear Engine for Rocket Vehicle Applications

Overview
1945 Studies begin to develop nuclear propulsion in aircraft and missiles

1955 The U.S. Atomic Energy Commission (AEC) initiated Project Rover at the Los Alamos National Laboratory in New Mexico, aiming to develop nuclear rocket propulsion.

1958 NASA was established and joined the AEC in Project Rover, which marked the beginning of what would later be named the NERVA program.

1959-1964 The Kiwi series of nuclear reactors were designed and tested. These reactors were not meant for flight but were required for ground testing and proving the feasibility of a nuclear rocket engine.

1961The NERVA program was officially named and launched. It combined the resources of the AEC's Project Rover and NASA's Nuclear Engine Program.

1964-1969 Development and testing of the Phoebus series of nuclear reactors took place. These were the most powerful reactors developed during the NERVA program, achieving power outputs of up to 5000 MW.

1968 The NERVA NRX/XE, an experimental nuclear thermal rocket engine, achieved a full-power run of 60 minutes during a test on December 3rd.

1969-1972 Research and development continued. During this time, significant focus was placed on improving the efficiency, safety, and reliability of the engines. Project Canceled 1973

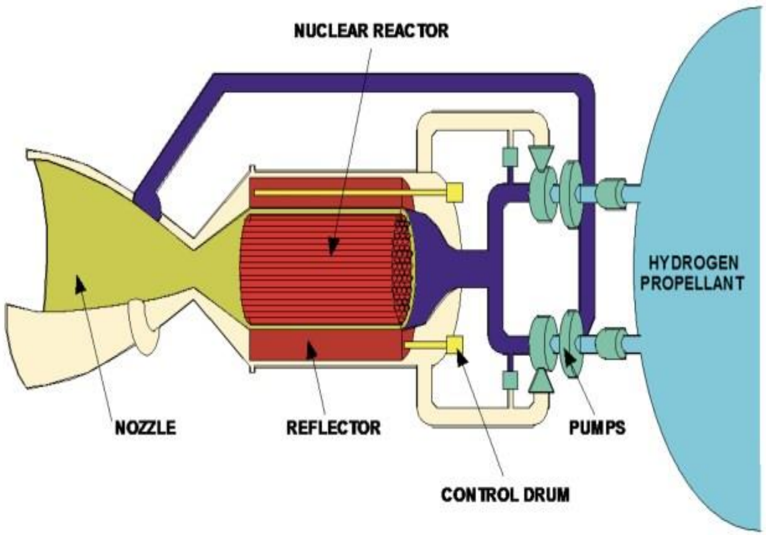
Theory of Operation

Liquid Hydrogen at -420F (-251C) is heated to 3000F (1650C) and expelled through a nozzle to produce thrust estimated at 50,000 pounds in test engine

Some Liquid Hydrogen is first pumped through the nozzle to cool it to prevent melting

Nuclear fuel was contained in a moderator of graphite to hold the nuclear material in place despite the high temperature

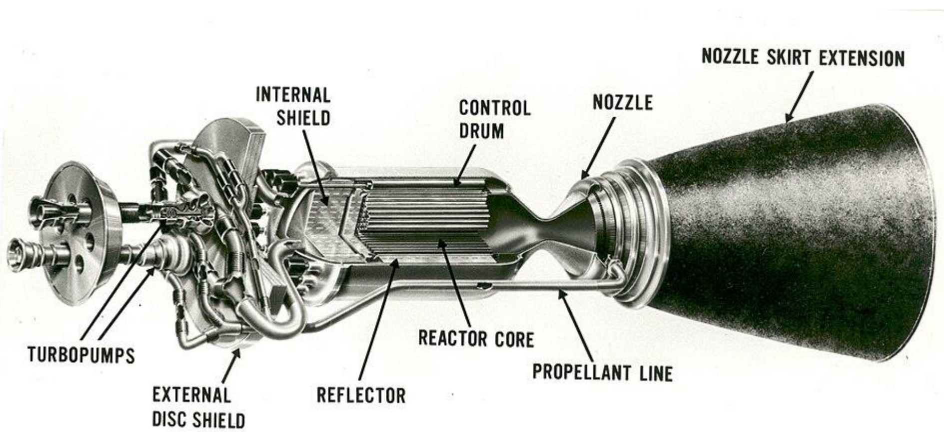
Reactor was surrounded by a beryllium reflector and control drums to control fission rate and reflect neutrons back into the reactor



Major Elements of a Nuclear Thermal Rocket

Specific Impulse was estimated to be higher that chemical engines (rated at 300 sec). Late tests showed Specific Impulse of NERVA greater than 800 sec

NERVA Engine Tests



1. NERVA mounted on outside Test Stand
2. NERVA on Test Stand
3. Detail illustration of test engine

Major Reactor and Engine Tests

Summary

Reactor	Test date	Starts	Average full power (MW)	Time at full power (s)	Propellant temperature (chamber) (K)	Propellant temperature (exit) (K)	Chamber pressure (kPa)	Flow rate (kg/s)	Vacuum specific impulse (s)
NERVA A2	September 1964	2	1096	40	2119	2229	4006	34.3	811
NERVA A3	April 1965	3	1093	990	2189	>2400	3930	33.3	>841
NRX EST	February 1966	11	1144	830	2292	>2400	4047	39.3	>841
NRX A5	June 1966	2	1120	580	2287	>2400	4047	32.6	>841
NRX A6	November 1967	2	1199	3623	2406	2558	4151	32.7	869
XE PRIME	March 1969	28	1137	1680	2267	>2400	3806	32.8	>841

These values correspond to a thrust of approximately 60,000 lbf in vacuum

UNTILIZATION & CANCELLATION

Engine was to become a “Space Tug” to take payloads from Low Earth Orbit (LEO) to higher orbit to Tran Lunar orbits

As a third stage to a Saturn V rocket the engine could raise payloads to LEO from 270,000 lb (122,500 kg) to 340,000 lb (150,000 kg)

President Johnson support NERVA, and initially so did President Nixon, but budget cuts were made citing higher priorities.

The Office of Management and Budget wanted to cancel the program as early as 1970, but funding remain at lower levels until 1973.

Money was instead given to the Space Shuttle and other projects.

Project Cancelled in early 1973. Project staff were stunned at the decision, but were immediately let go.

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Nuclear Rocket Engine, Wikimedia Commons

Wikipedia NERVA