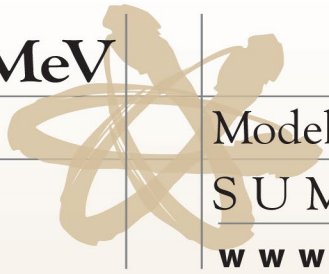


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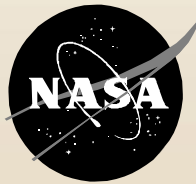


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Overview of Space Nuclear Technologies



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**Chief Engineer, Space Nuclear Propulsion Project
NASA – George C. Marshall Space Flight Center**

26 July 2022

13:00

Major NASA Space Nuclear Projects

- Fission Surface Power (FSP)
- Nuclear Thermal Propulsion (NTP)
- Nuclear Electric Propulsion (NEP)
 - Collectively, NTP and NEP are managed under the Space Nuclear Propulsion (SNP) Project

FSP and SNP both funded through NASA's Space Technology Mission Directorate (STMD)

FSP Project Overview

Managed by NASA-GRC: Todd Tofil (PM)

Collaborative Organizations: NASA GRC, DOE-NE, INL

Project's Big Picture

- Develop and deliver a space qualified fission surface power source flight unit to the launch site by 2029
- Scope includes the fission power system flight hardware and all development hardware
 - The scope does not include the Lander, Launch Vehicle, Cable Cart, or Rover/Transporter
 - The scope does not include integration with the lander, launch ops or lunar demonstration
 - The Project is a collaboration with DOE and their FFRDCs
 - Idaho National Laboratory managing the design and development contracts. Los Alamos providing reactor expertise.
- The Project, through flight hardware delivery, is funded entirely by STMD

Draft Project Goals

- #1:** Design a fission power source that supports Lunar and Mars surface exploration requirements
- #2:** Leverage Industry design capability and terrestrial power technology investments
- #3:** Build and ground test a flight-qualified, fully-integrated power system for Lunar demonstration

Key Performance Parameters

- 40 kW_e output at 120 VDC
- 6000 kg mass limit (must fit on a lander)
- 5 rem/year above background radiation limit at 1 km
- Transportable to locations away from the lander
- User loads from 0 to 100% power at the user interface

FSP Development and Acquisition Approach

- Two-phase acquisition strategy for development of the space-flight hardware
 - Phase 1 (7/2022)
 - Selected three contractors; will award three 12-month efforts for an initial design, \$5M each
 - **Lockheed Martin** – partnering with **BWXT** and **Creare**
 - **Westinghouse** – partnering with **Aerojet Rocketdyne**
 - **IX**, a joint venture of **Intuitive Machines** and **X-Energy** – partnering with **Maxar** and **Boeing**
 - Purpose is to show there are viable design options and inform the Phase 2 procurement
- Phase 2
 - An independent proposal solicitation, evaluation, and selection process to cover DDT&E, a separate nuclear ground test unit and payload delivery by December 2029

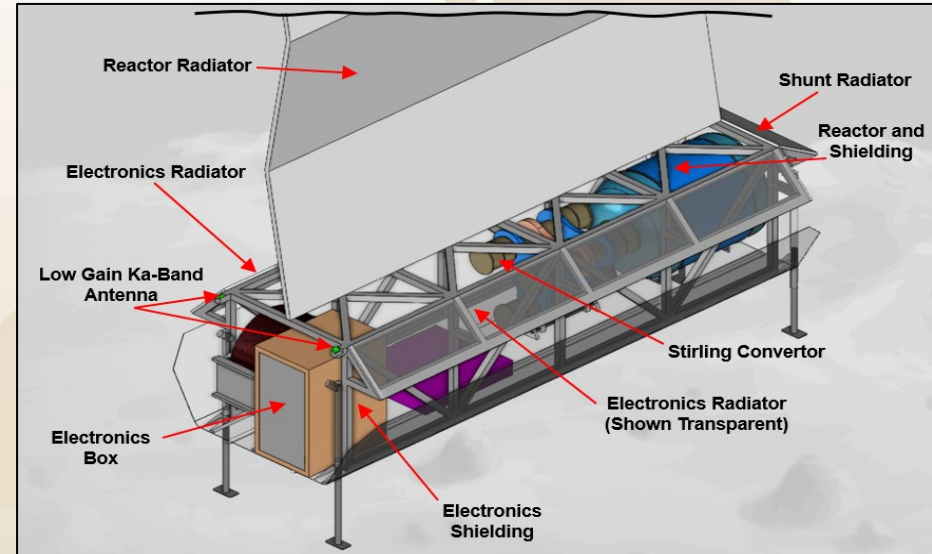
FSP Government Reference Technical Concept

Operations Approach:

- Lander: Provides transit and delivery to the Moon; deploys the FSP System to the lunar surface
- Rover/Transporter: Six-wheel Pressurized Rover chassis

Concept Results (GRC COMPASS Team and FSP Project):

- FSP System delivered in 3 pallets on one lander: Reactor, Controller, Voltage Down-Converter Pallets
 - **Reactor Pallet:** Reactor, power conversion, radiator, RF communication, start-up battery.
 - **Controller Pallet:** Stirling controllers, radiator, spool and 50 m cable.
 - **Voltage Down-Converter Pallet:** Converts high transmission voltage to 120 VDC at the user interface. Includes a radiator, spool and 1 km cable.

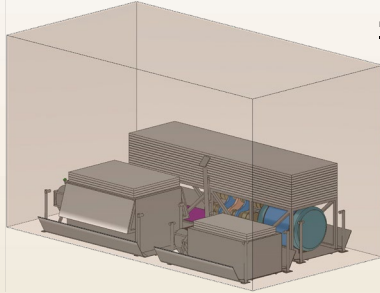


Reactor Pallet

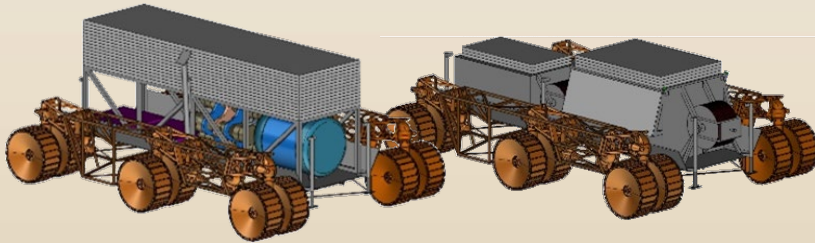
- A horizontal HALEU-fueled moderated reactor is the reference
 - Shielded controllers and sensors for the reactor
- Power conversion consists of four 6 kW_e Stirling pairs
- Deployable radiators are sized for polar operations
 - Equatorial radiators are much larger
- Shielded Ka-Band link for communications to Earth

FSP Reference Concept Design

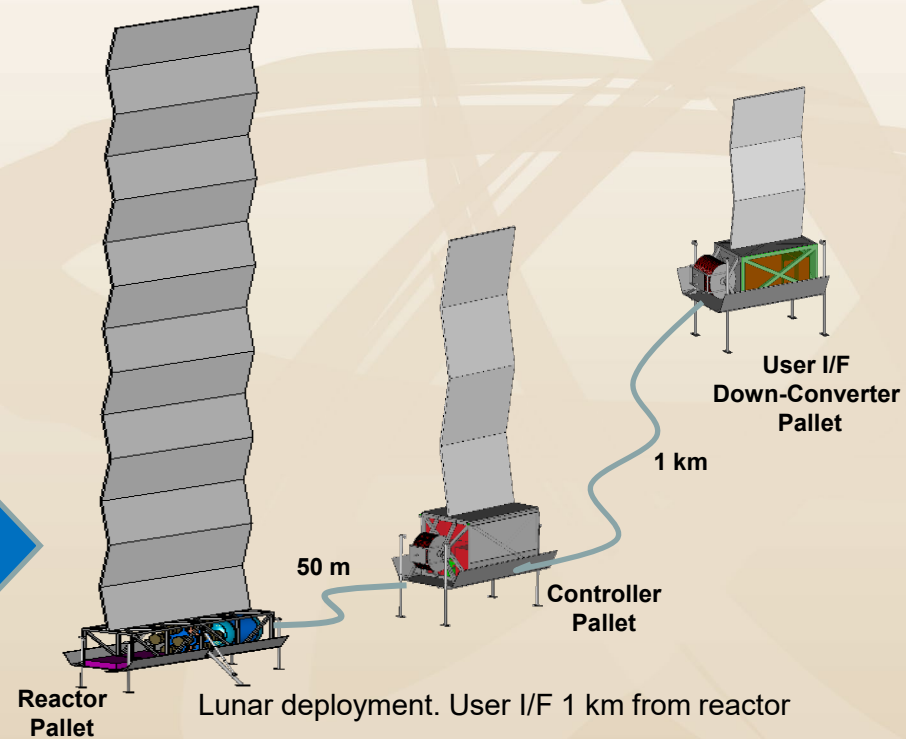
40 kW_e, Transportable Fission Power System



Stowed configuration on a lander



Stowed configuration for lunar transport (3 pallets)



Deployed configuration

FSP Key Technical Challenges

- Relatively low technology readiness level (TRL) of key some technologies/subsystems
 - Power conversion technologies: Stirling or Brayton
 - Moderator materials (though fast spectrum reactors may be used)
 - Shielding
 - Reactor instrumentation and controls
 - High voltage electronics (high transmission voltage over a kilometer)
 - Radiation-hardened electronics (10-year life, no maintenance)
- Interface definition for the lunar lander and lunar rover/transporter
- Transporting / deploying pallets
- Connecting pallets together

SNP (NTP & NEP) Project Overview

Managed by NASA-MSFC: Jason Turpin (PM)

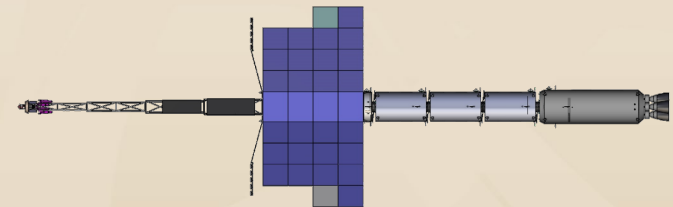
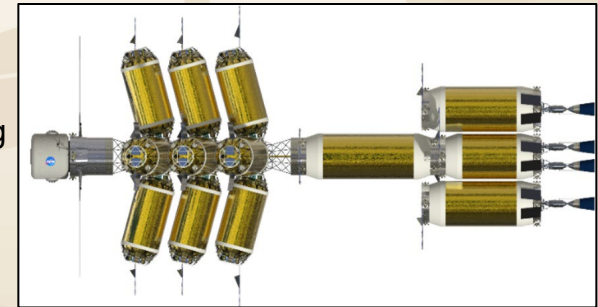
Collaborative Organizations: INL, NASA-GRC, many others

Project's Big Picture

- Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) for high Delta V (propulsively-challenging) missions
 - Greater payload delivery
 - Potentially* shorter trip time (less exposure to galactic cosmic radiation and zero-g) [* many caveats apply]
 - Nuclear allows mission robustness and potential abort scenarios
- Project aims to develop the nuclear propulsion technologies for propulsively-challenging missions (e.g., as human Mars exploration)
- Use of HALEU fuel
 - Directly reduce cost through savings related to safeguards and security
 - Indirectly (and more significantly) reduced cost through enabling use of an optimal development approach and team
 - Consistent with US policy. “The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.” (2012 White House “Fact Sheet”)
 - Space Policy Directive 6 (12/2020) also mandates use of LEU in most cases

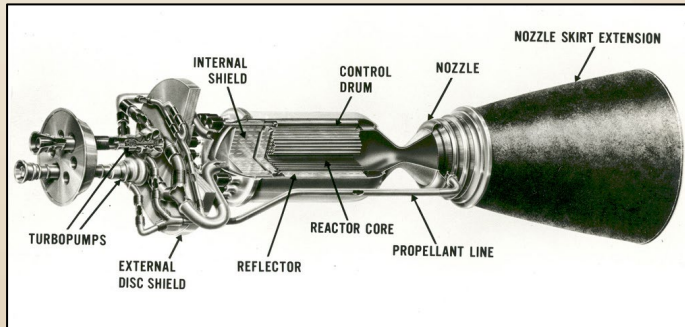
SNP Background

- Power source is decoupled from the propellant selection.
- HALEU designs (high-assay low enriched uranium (< 20% enrichment))
- **Nuclear Thermal Propulsion (NTP)**
 - Nuclear reactor replaces conventional chemical combustion process
 - Thermal power from the reactor is transferred to the propellant, heating the gas
 - Gas is expanded through a nozzle to yield directed kinetic energy, generating thrust
- **Nuclear Electric Propulsion (NEP)**
 - Nuclear reactor heat is converted to electricity through a thermodynamic power conversion cycle (e.g., closed-cycle Brayton)
 - Cycle cold side, large radiators reject heat to space
 - Generated electricity feeds electric thrusters
 - Thrusters accelerate charged particles through the application of electromagnetic body forces

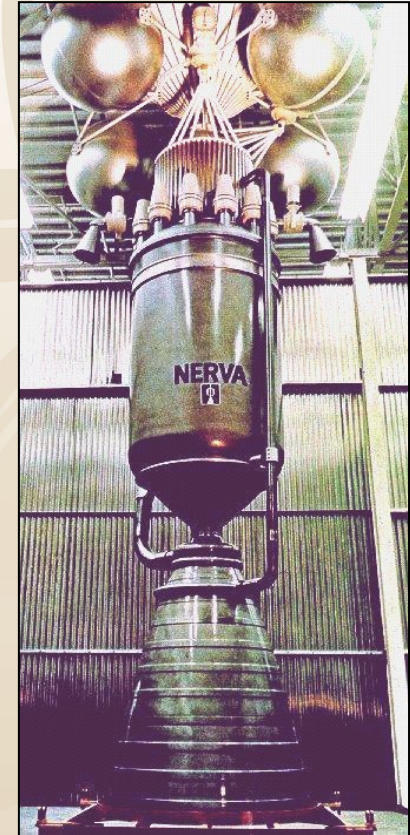


NTP Background – How it Works

- Expander cycle turbopumped engine
 - Propellant heated directly by reactor → gas thermally expanded through a nozzle
 - Thrust $\propto$ thermal power of reactor
 - $100,000 \text{ N (22.5 kbf)} \approx 450 \text{ MW}_{\text{th}}$ at $900 \text{ sec } I_{\text{sp}}^*$
 - I_{sp} directly related to exhaust temperature
 - $830 - 1000 \text{ sec (2300 - 3100 K)}$
 - Specific Impulse improvement over chemical rockets
 - Due to low molecular weight (H_2) NTP prop even though exhaust of $\text{O}_2\text{-H}_2$ combustion engine is much hotter ($I_{\text{sp}} \propto \sqrt{T_0/\text{MW}}$)
- * I_{sp} is thrust per unit weight flow of propellant (measure of momentum transfer capacity)



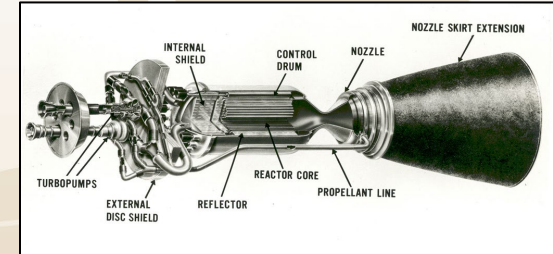
1960s Nuclear Engine for Rocket Vehicle Application (NERVA) program image



NERVA Nuclear Thermal Rocket Prototype

NTP Thermal and Materials Challenges

- For **$900 \text{ s } I_{sp}$** → propellant temperatures must be **$\geq 2700 \text{ K}$** (2427 deg C)
- Leads to required uranium fuel temperature **$\geq 2850 \text{ K}$**
 - Well beyond terrestrial power reactor temperatures
 - At or above melting point for some uranium alloys
 - Unlike combustion rocket, the propellant is not the hottest part of the system
 - Coatings / encapsulation layers in reactor fuel have different coefficients of thermal expansion and heat transfer
 - Further complicates heat transfer from nuclear fuel to the propellant
- Hot hydrogen chemically reactive/corrosive – difficult to keep away from reactor materials
- Neutron moderator material has significantly lower temperature limits than fuel
 - Can use propellant (to some extent) as moderator and reactor containment shell coolant
- Multiple restarts with operation for 30 minutes to several hours over 2 years for a human Mars opposition-class mission (plus flow during cool-down for decay heat removal)
 - Require low boil-off losses (cryogenic H_2 storage) – requires long-term CFM at the **20 K** level



Development of nuclear fuel that can survive at temperature while exposed to hot hydrogen and effectively transfer heat to the hydrogen propellant has been the #1 challenge for NTP since its inception

SNP NTP Development Strategy

Pursue multiple parallel options to develop a subscale nuclear engine that demonstrates a viable NTP propulsion system that is scalable to Mars mission engine needs

- Three reactor design teams (phase 1 contracts): **BWXT, Ultra Safe Nuclear Technologies, General Atomics**
1. Develop a HALEU fuel form that can provide reactor propellant exit temperatures ≥ 2700 K (corresponds to ≥ 900 s I_{sp})
 2. Design a reactor capable of being scaled to support Mars mission engine needs (future scaling to be an engineering solution rather than further tech development)
 3. Design and develop a demo-scale engine (key attribute goals: 12.5 klb_f thrust, ≥ 900 s I_{sp})
 4. Determine demonstration option (ground test and/or flight demonstration)
 5. Identify testing and launch regulatory requirements and mitigate issues
 6. Work with cryogenic fluid management (CFM) project for future passive and active CFM systems that will support long-duration NTP missions

Buy down future mission risk through technology development leading to the demonstration of an NTP engine.

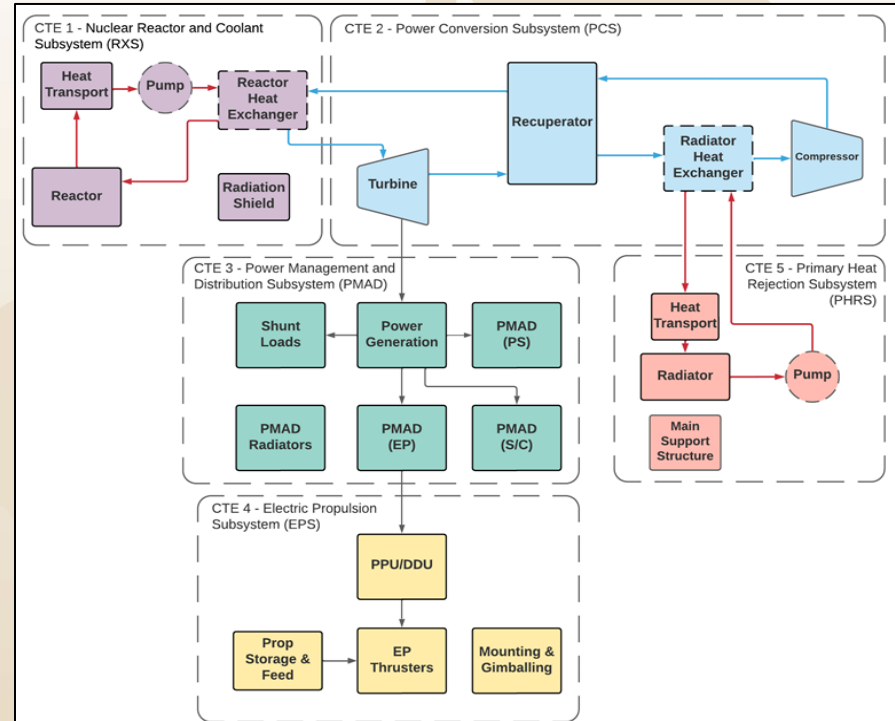


NTP 25K Engine

NEP System – Critical Technology Elements (CTEs)

- Nuclear Reactor and Coolant Subsystem (RXS)
- Power Conversion Subsystem (PCS)
- Power Management and Distribution Subsystem (PMAD)
- Electric Propulsion Subsystem (EPS)
- Primary Heat Rejection Subsystem (PHRS)
- Cryogenic Storage of Propellants*
- Chemical Prop System*
- For a human Mars mission
 - Multi-MW of electric power, 2000-7000 s I_{sp} , 2-3 years of continuous operation

* Possible if a hybrid NEP/Chem system is employed / challenges not discussed in this presentation



NEP Background & Development Strategy

- Electric propulsion systems fly, but only up to 10 kW_e
- Development electric thrusters of $\geq 100 \text{ kW}_e$ have only operated for short durations (100s of hours)
- Majority of critical NEP/Chem subsystems are relatively immature¹
- Many decades of intermittent effort that has not realized significant maturation for high power applications
- Developing MW_e -class NEP systems requires orders of magnitude power increases relative to any technology demonstrations completed to date²
- Subscale in-space flight testing of NEP systems cannot address many of the risks. Recommends modular subsystem ground tests **at relevant scales and power levels** with accompanying modeling and simulation²



Project Prometheus Jupiter Icy Moons Orbiter NEP concept vehicle

SNP plan uses milestone-based hardware development and testing supported by modeling and simulation

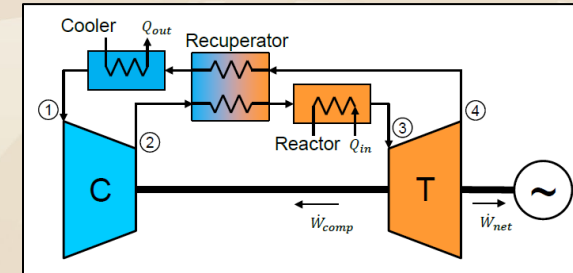
- Work at the sizes and scales necessary to mature all key NEP technologies (selected $8\text{-}10 \text{ MW}_{th}$ reactor & 1 MW_e for all other subsystems)
 - Large step increase from current state of the art flight or laboratory systems demonstrating any endurance
 - Building blocks large enough for credible, straightforward scaling into the $1\text{-}10 \text{ MW}_e$ range by

¹ "Independent Assessment of the Technical Maturity of Nuclear Electric Propulsion (NEP) and Nuclear Thermal Propulsion (NTP) Systems," NASA Engineering & Safety Center, 2020.

² "Space Nuclear Propulsion for Human Mars Exploration," National Academies of Sciences, Engineering, and Medicine, 2021.

NEP Development Challenges

- NEP reactor temperatures beyond those for terrestrial power reactors ($\sim 1200\text{-}1400\text{ K}$)
 - Well below NTP temperatures
 - Typical designs have employed either liquid metal (Na or Li) heat pipes, gas-cooled (He-Xe mixture) passages, or pumped liquid metal (Li) through the core to extract heat
 - No LH_2 cooling capability available
- Power conversion inlet temperature limited by materials capabilities
 - High T refractories/ceramics to meet inlet requirements?
 - Typically does not use active means to cool turbine and turbine inlet ducting
 - Power conversion subsystem designed for space never tested at the power levels needed
 - Size is well below terrestrial generator output levels
 - Closed-cycle system with only radiation for heat rejection to space, unlike terrestrial application



Closed Brayton Cycle Power Generation System

NEP Development Challenges

- Radiator mass often drives power system mass
 - Heat rejection to space $P = \epsilon \sigma A (T_{rad}^4 - T_{background}^4)$
 - Want T_{rad} high, but it is not that hot (not glowing – ‘low quality’ heat at 300-600 K – hard to reject to space)
 - High emissivity ϵ low degradation coatings
 - Area (and radiator mass) high for a multi-MW_e system
- Electric propulsion system
 - Size is well outside of current SOA for power and demonstrated endurance
 - Questionable and (potentially) propellant dependent ability to ground test propulsion system at 1 MW_e
 - Survivability of materials in very high-power discharges for long duration operation
 - Availability of electrical/electronics components for control, current/voltage/frequency conversion, and isolation at these power levels

Conclusions

- The operating points and modes of operation for FSP, NTP, and NEP each present unique challenges
 - FSP – Advancement of nuclear reactor and power generation technologies to support 10s of kW_e power generation that must land on a surface and then be deployed/connected prior to use
 - NTP – Advancement of nuclear reactor materials to support very high temperature, high power density (100s of MW_{th} during operation), short duration operation to heat a potentially corrosive propellant (H_2), replacing the traditional combustion process.
 - NEP – Advancement of a host of technologies that must all be integrated to support power generation and electric propulsion operation at the multi- MW_e level, which is well beyond the current experience base for either flight or an appreciable long-term ground testing.