9. NUCLEAR PROPULSION SYSTEMS

NEP SAFE 30 – An Example
AN END-TO-END TEST OF A SIMULATED
NUCLEAR ELECTRIC PROPULSION SYSTEM

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PRESENTATION OUTLINE

🌟 SUMMARY OF NEP OPTIONS
🌟 SAFE DEVELOPMENT PATH
🌟 OBJECTIVES
🌟 SAFE-30 POWERTRAIN
🌟 POWERTRAIN COMPONENTS
🌟 EXPERIMENT AT JPL
🌟 CONCLUDING REMARKS
**OVERVIEW - NEP OPTIONS**

- **Heat Transport from Reactor**
  - Heat Pipe
  - Pumped Liquid Metal
  - Direct Gas Cooled

- **Power Conversion**
  - Brayton
  - Stirling
  - Rankine
  - Thermoelectric
  - Thermionic

- **Heat Rejection**
  - Pumped Loop
  - Heat Pipes

- **PMAD**
  - AC or DC
  - Low or High Voltage

- **Electric Propulsion**
  - Ion Thruster
  - Hall Thruster
  - MPD, PIT

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**Reactor Power System**

- Reactor
- Shield
- Power Conversion
- Power Mgmt & Distribution
- Heat Rejection

**Electric Propulsion System**

- Power Processing Unit (PPU)
- Electric Thruster
- Propellant Feed System
- Propellant Tank

**Spacecraft Bus**

- Spacecraft Subsystems
  - C&DH
  - RCS
  - GN&C
  - TCS
  - RF
  - SW
- Science Payload
SAFE DEVELOPMENT PATH

Module Unfueled Thermal hydraulic Test (MUTT).
Refactory metal module

In-Space Fueling - safety
core fueling mechanism

30 kW Core
stainless steel full core

100/400 kW Cores
stainless steel full core
refractory metal full core

End-to-end system demonstrator
full core integrated with thruster

Full Propulsion System Demonstrator
core, in-space fueling mechanism, thruster, reflectors, radiators, etc…

Balance of Plant
thrusters, reflectors, radiators, shielding, energy conversion, bus design, etc…
OBJECTIVES

- Demonstrate operation of a resistance-heated simulated nuclear core and heat pipe system.
  - Validating existing computational models,
  - Demonstrate system flexibility (fast start-ups, multiple starts/shut-downs),
  - Simulate predictable failure modes,
  - Operating environments.

- Demonstrate integrated propulsion system consisting of core, conversion system and thruster.

- Identify and address integration issues:
  - Stirling operation/loading must be ensured at all times:
    - Response time of Stirling load share must be faster than thruster recycle event.
  - Heat coupling and exchange,
  - Vibration, balancing and damping in dynamic systems,
  - Electric interfaces:
    - Electrical connections to heaters,
    - Electric isolation between components (DC/DC converter, thruster power system)
    - EMI isolation and dynamics of cabling.
SAFE-30 POWER TRAIN

Thermal Energy ➔ Power Conversion ➔ Kinetic Energy

Q_{TH}

Diagram of Stirling engine control system with ion thruster power support system.
**SAFE 30 Core:**
- Core has hexagonal footprint comprised of 12 modules.
  - Zone One (3 modules): four SS tubes welded longitudinally to sodium-filled heat pipe.
  - Zone Two (9 modules): same as above where heat pipe substituted with blanked-off SS tube.
- Stainless steel tubes hold resistance heaters:
  - Graphite rods rated at 1.3 kW (0.34 Ω/1000 °C)
  - Operation: 750 W (1000 °C)

**Electric Power Input to Core:**
- Zone One:
  - HP PS: 100 A/100 VDC
  - String: four heaters in series
  - 3 strings in parallel
- Zone Two:
  - Linde PS: 400 A/200 VDC
  - String: two heaters in series
  - 18 strings in parallel
TEMPERATURE PROFILE

Graph showing temperature profile over elapsed time for HP7-core, HP8-core, HP9-core, HP7-us, HP8-us, HP9-us, HP7-ds, HP8-ds, and HP9-ds.
CONVERSION SYSTEM

☆ Stirling Engine by Stirling Technology Company
   - ‘Free-piston’ concept using thermal-mechanical oscillations to drive linear alternator.
   - Control Box: power processing and loading of engine
   - Balance Motor for Vibration Compensation
   - Operating Temperature: 650 °C
   - Working Fluid: Helium at 45-52 bar
   - Electric Output:
     - Stirling Engine: 350 W/175 VAC
     - Control Box: 350 W/123 VDC

☆ DC/DC Converter by Schaefer
   - Voltage Step-Up:
     - 123 VDC → 1000 VDC
     - 500 W, 90 %
   - Inrush-Current Limiting
   - Inhibit Switch
   - Current Limiting
**STIRLING ENGINE OPERATION**

- **Stirling Thermodynamic Heat Engine**
  - Free-Piston Stirling Engine integrated with linear alternator in common pressure vessel.

- **Thermal Input Supplied to Heater Head**
  - Isothermal Heat Addition (900-1000 K)
  - Regenerator Transfers Heat between $T_{\text{hot}}$ and $T_{\text{cold}}$
  - Oscillating flow of working fluid (Helium) causes linear motion of displacer

- **Pressure Forces from Displacer Cause Power Piston and Mover to Reciprocate in Cylinder**
  - Flexures or gas bearings
  - Linear Alternator
  - 60 to 80 Hz

- **Waste Heat Rejected to Space**
  - Separate cooling loop or heat pipes, moderate temperature radiator (350-500 K)

- **Electrical Controller**
  - Maintains proper piston stroke
  - Converts AC alternator output to usable form for loads
  - High voltage output is possible
STIRLING ENGINE
ION THRUSTER

* 15-cm Ion Engine
  - Slotted, Carbon-Carbon Grids
  - Power Input: 1.25 kW
  - Efficiency: 60% (± 5%)

![Graph showing Specific Impulse and Thrust as a Function of Input Power with Beam Current = 500 mA](image)
DS-1 SUCCESS STORY

NSTAR 30-cm Ion Thruster:

- Ground testing accumulated 23,800 hours with a propellant through-put of 192 kg!!

- Performance Characteristics:
  - Power Input: 0.5-2.3 kW
  - Thrust: 21-120 mN
  - Spec. Impulse: 2000-3200 s
  - Efficiency: 42%-62%
  - Propellant: Xenon

DEEP SPACE 1:
First use of Ion Thruster for Primary Propulsion

★ ~ 16,265 hours of Operation!
★ 72 kg of Propellant through-put!
★ DS1 successfully encountered the Comet Borrelly in September 2001.
★ Additional mission targets added.
★ The Ion Engine also provided pitch and yaw control even when thrusting is not required for the trajectory to save hydrazine.
VACUUM TEST FACILITY AT JPL
EXPERIMENTAL SET-UP AT JPL
EXPERIMENTAL SET-UP AT JPL
COPPER BLOCK DESIGNS
COPPER BLOCK REDESIGNS
ADDRESSED INTEGRATION ISSUES


 Thermal Interface:
   Resistance heaters, heat pipes, and core structure.
   Heat pipes, copper block, and heater head of Stirling engine.
    ⊡ Thermal conductively between heater head and copper block is crucial for Stirling engine operation, especially for high power operation.

 Electrical/Electronics Interface:
   Connection, isolation and proper grounding of 48 heaters and core support structure.
   Fast response times of Stirling engine and DC/DC converter to ensure recycle event of ion thruster.
   Proper loading of the Stirling engine during thruster start-up sequence, recycle event, or zero power demand.

 Structural Interface:
   Vibration, balancing and damping in dynamic systems.
STATUS

✶ Integration of powertrain components accomplished in phased approach.
✶ Integrated system performed well and had no problems.
CONCLUDING REMARKS

* Integration of powertrain components accomplished in phased approach.
* Integrated system performs well and has no problems.
* Stirling Engine overhaul and maintenance of all critical components currently underway at STC.
SUMMARY

✈ Successful demonstration of a simulated (resistance-heated) nuclear system, conversion system and electric propulsion system.

✈ The end-to-end system demonstration sets a precedent for ground testing of nuclear electric propulsion systems.

✈ The end-to-end system identified and addressed a number of integration issues.

✈ This demonstration was accomplished with commercially available components and advanced cutting-edge technology.

✈ More extensive testing of the integrated system will be performed in the near future.
Non-Nuclear NEP System Testing

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\textbf{Abstract.} The Safe Affordable Fission Engine (SAFE) test series addresses Phase 1 Space Fission Systems issues in particular non-nuclear testing and system integration issues, leading to the testing and non-nuclear demonstration of a 400-kW\textsubscript{t} fully integrated flight unit. The first part of the SAFE 30 test series demonstrated operation of the simulated nuclear core and heat pipe system. Experimental data acquired in a number of different test scenarios will validate existing computational models, demonstrated system flexibility (fast start-ups, multiple start-ups/shut downs), simulate predictable failure modes and operating environments. The objective of the second part is to demonstrate an integrated propulsion system consisting of a core, a conversion system and a thruster where the system converts thermal energy into jet power. This end-to-end system demonstration sets a precedent for ground testing of nuclear electric propulsion systems. The paper describes the SAFE 30 end-to-end system demonstration and its subsystems.

\section*{INTRODUCTION}

Rapid access to any point in the solar system and beyond requires advanced propulsion concepts that can provide extremely high specific impulse, high specific power, and high thrust-to-power ratios. NASA’s vision for the 21\textsuperscript{st} century and beyond is challenging scientific and engineering communities to develop propulsion technologies which will enable ambitious exploration of the solar system and its interstellar neighborhood, commercialization of space, and eventual human colonization beyond Earth (Schmidt, 1998). Two technologies that synergistically offer tremendous potential for the immediate future are advanced electric propulsion and nuclear energy. Space nuclear systems have recently received a renewed interest due to their versatility, high-power density, and ability to support power-intensive missions (Borowski, 1998). The dualism of providing both propulsion and power, linked with the enormous energy available per unit mass of fission fuel, has significant benefits to future programs involving nuclear thermal rockets (Watson, 1994), efficient conversion systems, space-based nuclear reactors, and nuclear electric propulsion (NEP) (Allen, 1995).

To date, only a few electric propulsion concepts can support the high power requirements for future missions. Due to their specific impulse operating range, advanced ion and Hall thrusters (Sankovic, 1999) are the most likely candidates to be used in the near term for a wide variety of missions spanning from Low Earth Orbit to interstellar space. Depending on the mission scenario/profile, these efficient electric propulsion devices can be powered by solar or space nuclear power. Beyond the use of these very efficient systems, mid to far term solution might include propulsion concepts such as the MagnetoPlasmaDynamic (MPD) thruster (Polk, 1999, LaPointe, 2000) and the Pulsed Inductive Thruster (PIT) (Dailey, 1993).

Research in the field of electrostatic acceleration has been conducted since the late 1950s’ resulting in a number of different devices and ionization methods capable of supporting space propulsion. These devices use suitable grid electrodes for ion extraction/acceleration converting electric energy to kinetic energy. The most commonly used ion source is based on electron bombardment where plasma is generated by electrons colliding with neutral gas. Thrusters based on the Kaufman concept use weak magnetic fields for ion/electron separation. To date, the most successful ion thruster developed by NASA is the NSTAR engine, which currently flies on board the Deep Space 1 (DS 1) spacecraft.
NON-NUCLEAR TESTING PROGRAM

Power is the main constraint when exploring the design of a mission and its most probable scientific return. Compared with conventional approaches, nuclear electric propulsion (NEP) systems provide many additional options for exploration and sample return missions of the solar system. Nuclear systems provide power independent of distance from and position relative to the sun, and thus are suitable for deep space and planetary surface missions with high pay-off. Historically, development of such nuclear systems has been costly and time consuming. Figure 1 illustrates a basic schematic of a spacecraft based on NEP, while Table 1 summarizes possible options for the individual subsystem.

**TABLE 1. Subsystem Options of Nuclear Electric Propulsion Systems**

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Radiators</th>
<th>Power Conversion</th>
<th>PMAD</th>
<th>Electric Propulsion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Pipe</td>
<td>Heat Pipe</td>
<td>Rankin</td>
<td>AC or DC</td>
<td>Ion Thruster</td>
</tr>
<tr>
<td>Pumped Liquid Metal</td>
<td>Pumped Loop</td>
<td>Brayton</td>
<td>Low or High Voltage</td>
<td>Hall Thruster</td>
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<tr>
<td>Direct Gas Cooled</td>
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Proposed for most early flight demonstration missions, the reactor thermal power level is less than 400 kWt. At these power levels, systems can be designed such that most potential issues are thermal or stress related, with nuclear effects being secondary. More specifically, the reactors can be designed such that fuel burnup is within demonstrated capability, and designed such that the fast neutron fluence seen by reactor materials and components is well below the level where significant radiation damage would occur. If these design criteria are met, realistic and valuable testing can be performed using non-nuclear heaters to closely mimic heat from fission. Phase 1 Space Fission Systems (SFS) (van Dyke, 2002) are targeted for, but are not limited to, space science missions extending from planetary orbiters and landers to interstellar precursor probes. The Safe Affordable Fission Engine (SAFE) test series addresses some system issues of Phase 1 SFS, in particular non-nuclear testing and system integration issues leading to the testing and non-nuclear demonstration of a 400-kW, fully integrated flight unit. The SAFE test program (van Dyke, 2001) has a phased structure/approach, which started with module testing (MUTT) (van Dyke 2000) and will be completed with a full propulsion system demonstrator including core, thruster, reflectors, radiators, etc.

Development, integration and testing must be affordable, realistic, and timely to ensure success and ultimately deployment of NEP systems in space. Non-nuclear testing schemes can deliver a high degree of system maturity resolving integration, fabrication and testing issues. In addition, causes of component and system failures can be quickly and accurately identified. Even particular failure modes can be purposely induced to analyze, characterize and identify system behavior and shortfalls of the system. Hardware work performed at NASA Marshall Space Flight Center’s Propulsion Research Center focuses on development of fabrication and test capabilities necessary for rapidly building and testing potential near-term space fission systems. To support this non-nuclear approach, some of the unique capabilities include the high power propulsion thermal simulator (HPPTS), advanced manufacturing, high purity alkali metal handling machine, heater development and testing (van Dyke, 2003).
SAFE-30 POWERTRAIN

The purpose of the end-to-end tests is to showcase the nuclear electric propulsion (NEP) concept by a simulated approach with inexpensive off-the-shelf materials in a relevant environment. An appropriate powertrain converts thermal energy mimicked by resistance heaters into kinetic energy. The end-to-end system demonstration consists of the SAFE-30 simulated core, 350-W Stirling engine, DC/DC converter and 15-cm ion thruster with slotted carbon-carbon grids.

30-kW$_t$ Simulated Reactor Core

The SAFE-30 is a full core test designed for a power input of 30 kW$_t$ using resistance heating to simulate the thermal energy from a fission reactor. As illustrated in Figure 2, the core has a hexagonal footprint of 48 stainless steel tubes and 12 stainless steel sodium filled heat pipes. It is assembled in a modular fashion where a module consists of 4 stainless steel tubes and one heat pipe welded together longitudinally. The heat pipes are 119 cm and the tubes are 43 cm long, while the diameter of both is 2.54 cm. Resistance heaters, which are inserted into the stainless steel tubes, are made from graphite rods and are rated for up to 1.3 kW$_e$ (Pedersen, 2001). The heaters generate thermal energy closely simulating the thermal profile of an actual nuclear (fission) system. The heat pipes embedded in the core remove the heat out of the core where the maximum isothermal operating temperature for the heat pipes is about 750 °C.

For the end-to-end system demonstration, the SAFE-30 core is assembled in its modular manner and consists of two heating zones each powered by a separate power supply. Zone One encompasses three modules containing heat pipes (Figure 2). There are three strings of heaters wired in parallel where each string contains four heaters in series. These twelve heaters are powered by a Hewlett Packard power supply providing 100 A at 100 VDC. The remaining nine modules comprise Zone Two which is provided with heating power by a 400-A, 200-VDC Linde power supply. A module in this zone has four stainless steel tubes welded to a blanked-off pipe of the same dimensions as the heat pipe. The heaters are wired in 18 parallel strings where each string contains two heaters in series.

Ion Thruster

Ion thrusters have been developed and tested since the 1950’s accumulating an extensive laboratory and flight history. They electrostatically accelerate positively charge particles at continuous, low to moderate power levels. The end-to-end system demonstration uses the 15-cm, carbon-carbon grid ion engine designed for a maximum input power (to the power processing unit) of 1.25 kW$_e$. Performance characteristics with carbon-based grid materials are comparable, although in general performance values are slightly lower. However, carbon-based grids supersede with extremely low erosion rate and superior sputter resistance (Mueller, 1993). These properties are key to
significantly extend the lifetime of ion thrusters. Preliminary performance evaluation for molybdenum and graphite grids indicates a total thruster efficiency of about 52 to 66 % with an uncertainty of up to 10% (Brophy, 1993). Figure 3 shows the 15-cm, slotted carbon-carbon grid ion thruster as it is mounted to the door of the vacuum chamber at the JPL facilities.

During normal operation of ion thrusters, the thruster will recycle to clear apparent shorts in the accelerator system. During a recycle event the high-voltage is turned off, the discharge current is throttled back (to decrease ion production), the high-voltage is then turned back on, and the discharge current is returned to its normal operating point. During a recycle event the Stirling engine and DC-DC converter system must redirect the power normally going to the thruster to a resistive load during the high-voltage off time and then redirect the power back to the thruster when required. Therefore the controller for the Stirling engine and DC-DC converter must respond faster than the controller of the ion engine.

**Power Conversion System**

The power conversion system converts thermal energy into usable electric power. The three main elements of this system are a heat exchanger, Stirling engine, and a DC/DC converter. The heat exchanger transfers heat from the heat pipes (HP) to the heater head (HH) of the Stirling engine. The Stirling engine then converts the thermal energy into electric power, while the DC/DC converter steps up the output voltage of the Stirling engine to the operating voltage of the ion thruster.

Heat Exchanger – The heat exchanger must take into account the thermal interface at the heat pipes and the heater head. Two heat exchangers were fabricated out of copper. The main objectives of the different designs were to explore thermal flux and assembly/disassembly efficiency. Figures 4 and 5 highlight the different attachments around the heater head. Heat exchanger design 1 (HED-1) consists of three copper pieces, which clamp around the heater head and heat pipes. Stainless steel clamps provided a uniform force during high temperature operation, since the thermal expansion of stainless steel is much smaller than copper. The second design (HED-2) consists of two parts. Part One attaches to the heat pipes, while Part Two clamps around the heater head. Four cylinder sections are placed around the heater head and the stub, while two sets of stainless steel clamps fasten around the whole assembly. Both designs used 0.127-mm thick Grafoil for all interfaces between heater head and heat exchanger. Compressing the Grafoil ensured maximum heat transfer and prevented voids from forming, which could occur due to material expansion at high temperature operation.

Stirling Engine – The Stirling engine is an off-the-shelf device manufactured by Stirling Technology Company (STC), Kennewick, WA. The Stirling engine converts thermal energy into electric energy based on the thermodynamic process described by the Stirling cycle (Schreiber, 2001). This engine is based on the ‘free-piston’ power conversion concept using thermal-mechanical oscillations to drive a linear alternator. The active heat exchange zone on the heater head is about 4.5 cm wide operating at a nominal temperature of 650 °C. The heat
exchanger clamps precisely over that region to ensure proper heat input to the heater head (HH) of the Stirling engine. The Stirling engine is equipped with a balance motor compensating for vibrations generated by the engine during the entire operation sequence (initial start-up, power generation, shut-down). The working fluid of the engine is Helium at a pressure of 45 to 52 bar, while the alternator generates 350 W at 175 VAC. The Stirling engine controller processes the generated power and provides logistics to the Stirling engine depending on operating conditions and power demand (load). The control board algorithm manages the proper loading of the Stirling engine. Sensing circuitry monitors power demand at the output and accordingly the control board ties in or removes stages of a resistive load array. The AC power generated by the Stirling engine is processed by rectifier circuitry and converted to an output of about 123 VDC and 3 A. Thermocouples on the top and the bottom of the heater head (HH-top, HH-bot) monitor the temperature during operation. Figure 6 shows the Stirling engine mounted to the heat exchanger. A fiberglass/aluminum foil blanket thermally insulates the heat exchanger.

**DC/DC Converter** – The power support system for the ion thruster consists of four separate power supplies providing power to the subsystems of the thruster. However, the power generated by the Stirling engine replaces the conventional beam supply. All other subsystems of the thruster will be maintained and controlled by the power support system as depicted in the block diagram of Figure 7. The DC/DC converter conditions the power for the beam supply of the ion thruster. The major functions of this device are voltage step-up, current and inrush current limitation, and power enable/inhibit control. The DC/DC converter steps up the input voltage of about 123 VDC to 1000 VDC with appropriate transformer circuitry. In addition, the device limits the inrush current during the start-up sequence of the ion thruster. Without appropriate protection circuitry during this period, the current drawn by the system could be very high, damaging all crucial components of the powertrain. This circuit (consisting of an IGBT and capacitor array) monitors the input current to the converter. In the case that the rate of rise is too high, the IGBTs are switched on and off at high frequency allowing the capacitor bank to charge in increments using the current drawn during the pulses. The inhibit switch is another important part of the converter, which is controlled by the power support system of the ion thruster. The switch terminates the high voltage provided by the converter to the thruster in case of malfunction or system failure. The power support system provides a signal of 5 VDC to engage the inhibit mode of the switch and a 0-VDC signal to disengage the mode. Another feature of the converter is the external programming, which sets the maximum output current by a signal provided by an external power supply. The input signal is between 0 and 5 V, where the output current is 0 A at 0 V and 500 mA at 5 V. Any desired output current within this limit follows a linear relationship depending on the input voltage. The DC/DC converter is rated for a power input of 500 W and its efficiency is about 90%.

**FIGURE 6.** Stirling Engine mounted to Heat Pipes.  
**FIGURE 7.** Block Diagram of DC/DC Converter and Power Support System of Ion Thruster.
RESULTS

The end-to-end system demonstrator was operated and tested successfully at the JPL facilities in Pasadena, CA. All components were successfully integrated, including the SAFE-30 core, heat pipes, heat exchanger, Stirling engine, DC/DC converter and ion thruster. Modification reviews with the manufacturers, subsystem testing and a phased integration approach of major components resolved thermal, electrical and structural issues. Using Grafoil solved thermal conduction problems at the main heat exchange interfaces when operating at high temperature and in vacuum. Thermal conductivity between heater head and heat exchanger is crucial for the operation of the Stirling engine especially for high power operation. Modifying and adjusting the control circuitry of the DC/DC converter addressed electrical issues necessary to operate an ion thruster. In addition, the control logistics of the Stirling engine was adjusted to properly account for the fast response times required by the recycle events of ion thruster operation. This ensured flawless operation of the ion thruster and the Stirling engine during thruster start-up sequence, recycle event and zero-power demand. Employing a balance motor addressed vibration and damping problems, thus minimizing any material fatigue issues, which might result in a dynamic system.

Overall the end-to-end system demonstrator performed well in all the tests and no significant problems occurred. The beam power of the thruster ranged between 50 to 150 W. Thrust measurement was not available at the facility where the end-to-end system demonstrator was installed. In the final phase of the test program, a simulated load substituted the thruster, since the thruster entered an unrelated test project and was not available for further testing. Figures 8 and 9 depict the performance of the two heat exchanger designs. Both diagrams show the power generated by the Stirling engine (Stirling Power) as a function of the electrical power (Core Power) provided to the SAFE-30 core. In addition, they also show the temperatures of heat pipe #8 (Figure 2), the heat exchanger (Cu Block) and heater head (HH) as a function of Core Power. The electrical power to the heaters was reduced keeping the experiment at lower temperatures during breaks (gray shaded area). HED-1 provides a higher heat flux when compared to HED-2, since the temperature of the heat pipes, the heat exchanger, and the heater head are within approximately 10% of each other. The temperature drop for HED-2, which occurs between the heat pipes and the heater head, is about 30%. A significant higher power input to the core is needed to achieve the same power output of the Stirling engine. The relative thin profile of the cylinder sections of HED-2 significantly reduces heat conductivity. A significant advantage of HED-2 over HED-1 is the installation of the heat exchanger.

CONCLUSIONS

The end-to-end system demonstration sets a precedent for ground testing of nuclear electric propulsion systems. Simulating the thermal energy released by a nuclear core with resistance heaters is inexpensive and can be performed in a timely manner. More importantly, integration issues, system behavior/failure and component matters are quickly identified and accurately analyzed. The success of this program led by NASA MSFC is shared and
depends on the collaboration with NASA centers, other government agencies, industry and academia. The combination of long life, low specific mass, and high specific impulse is unique among electric propulsion systems, making NEP systems well suited for the challenging missions envisioned by NASA.

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