Nuclear Electric Propulsion Technology: Response to NAS Questions

Presented to

NAS Space Nuclear Propulsion Committee

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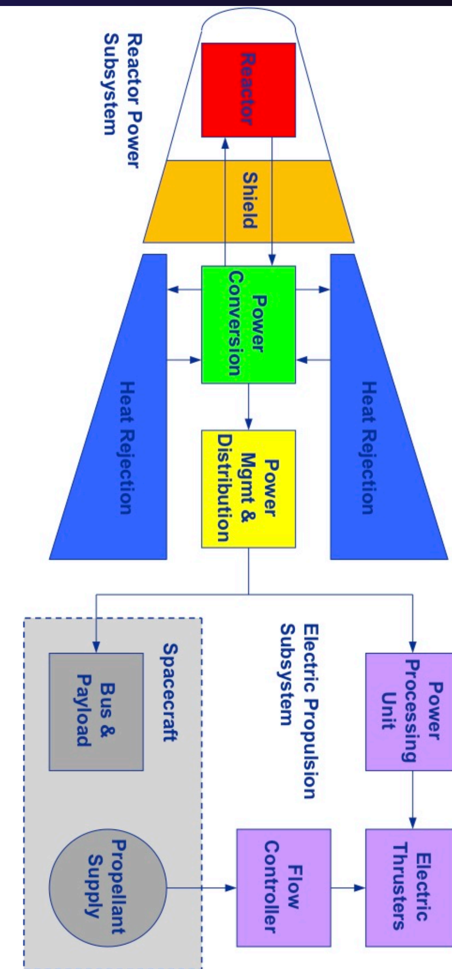
Presentation Outline

- Background
  - NEP Design ‘Requirements’
  - SP-100 derived system readiness to achieve NEP Mission
  - JIMO derived system readiness to achieve NEP Mission
- Findings related to current TRL of the NEP Reference Concept
- Recommendations for lowering technology risk
- Response to NAS Questions

NEP Operational Requirements

- NEP Reactor electric power requirement:
  - 1 to 1.5 MWe for the near term (2-3 Mwe in the future)
  - Within the power range of interest to microreactor vendors
- Specific weight: 14 to 20 (kgs of system mass/kWe)
  - Requires dynamic power conversion system operating at high temperature (1200-1350 K)
  - Present state-of the-art microreactor is 50-300 kg/kWe operating around 1000 – 1200 K
- Planned life time of 2 to 5 years at full power
  - Low burnup and service time relative to state-of-the-art
- Human rated control systems and directional shielding to support human transport
  - Lack of standards could have large mass impact

NASA (Mason et al)

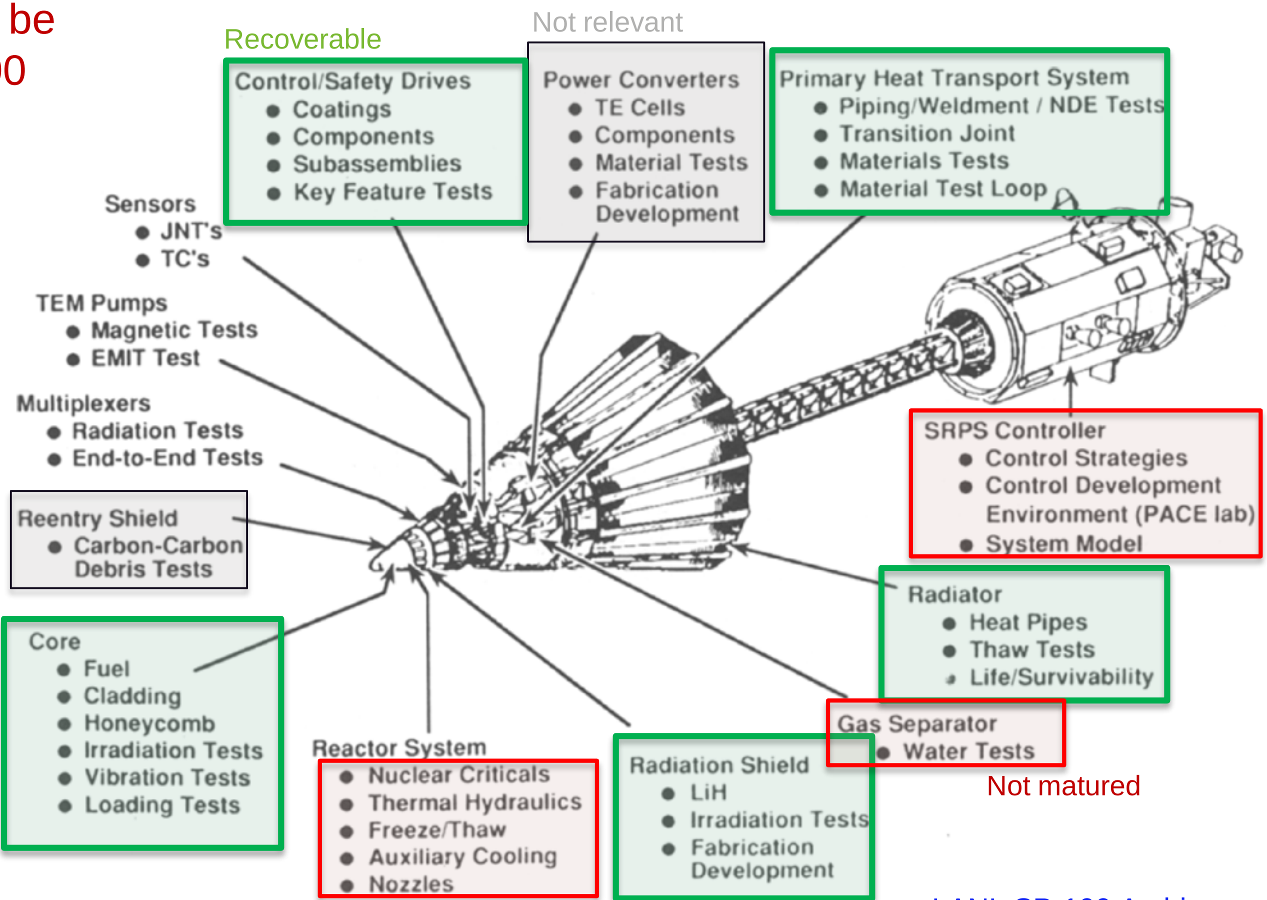


DOE did not participate in the requirements development process nor did DOE validate the requirements.

Reference Concept: Space Reactor Prototype (SP)-100 kWe (1983 to 1995) derived lithium cooled HEU fast reactor

Significant challenges must be overcome to mature SP-100 derived design to TRL 6

- Several systems and their qualification programs can be recovered (green)
- Some systems are not relevant (gray)
- Several key systems did not achieve TRL 3-4 status (red)
  - Freeze/Thaw
  - Thermal hydraulics
  - Nozzles
  - Gas separator
  - SRPS Controller
- Several systems are no longer available/manufacturable



LANL SP-100 Archive

Alternate concept: JIMO derived gas cooled HEU fast reactor

- No reference reactor core concept was chosen prior to project closeout. Preferred concept was gas cooled direct Brayton (Boeing and Northrup Grumman). Alternate was heatpipe reactor. No TRL assessments were completed and documented at the closeout.

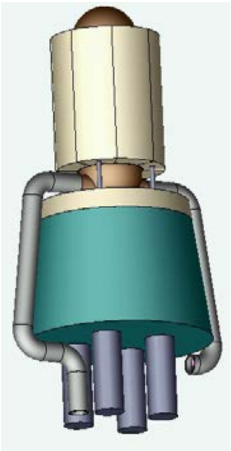
Relevant Insights from JIMO Closeout

- Trade studies performed on potential electric power distribution systems show a clear preference for Brayton cycle energy conversion due to the inherent ability of Brayton converters to produce high frequency AC power.
- Acknowledged that LM system may be preferred at higher power, provided technology risk is acceptable

Some of the JIMO development challenges align with recent industry interests

- High temperature (1200 K) cladding and structural materials (refractory/ceramic).
- High temperature (1200 K) superalloy based Brayton turbines and compressors

Boeing's Brayton Design for JIMO



LANL Archive

Naval Reactor proposed two ground nuclear demonstrations:

- To optimize the system I&C
- To demonstrate the final system

Summary of findings relevant to reference concept TRL

- Use of SP-100 derived system as the reference design considerably weakens the case for feasibility of the NEP system
- Major gaps exist in the current state of readiness of materials and technologies necessary to design, fabricate, test and operationalize the NEP reference design.
  - DOE and/or commercial industry will likely have to recapture lost expertise and infrastructure to enable the reference SP-100 derived design.
  - Selected components of SP-100 design can never be demonstrated fully before launch. These gravity-sensitive components include coupled TEM pump-helium bubble separator system, and freeze/thaw system.
- On going commercial microreactor designs, materials, technologies or timelines do not **directly** align with the reference design nor could they be **directly** applied to achieve low specific weight requirements (kg/kWe)
  - A reactor design and development program can be formulated that aligns better with the industrial priorities while achieving mission specific size, weight and power requirements.

Recommendations

- NEP requirements are ‘evolutionary’ or ‘incremental’ scale up from ongoing industry designs. It may be beneficial to reformulate the reference concept to better align with the ongoing microreactor R&D
  - Key components and technologies can be scaled-up (or evolved) from those being matured by the industry for terrestrial applications
  - Industry interest for Brayton is 1100 K which is extensible to NEP baseline of 1200 K
  - Industry is exploring fabrication of TZM and metalized ceramics for use as structural support and heat transfer equipment; extensible to NEP
  - Industry interest in radiation and temperature resistant embedded sensors and control systems to support remote operation is directly extensible to NEP
- Multi-scale component and system testability (up to and including full-scale nuclear demonstration) should be explicitly factored into the design down-select and program formulation
  - NEP again benefits from the fact that NRIC and microreactor demonstration projects are establishing infrastructure that is extensible to NEP

Response to NAS Questions

Note:
In the following pages slide titles are NAS questions (slightly edited to fit)

What is DOE's role in developing space nuclear propulsion systems for NASA?

- Historically DOE (through its laboratories) either directly supported NASA or oversaw industry's support to NASA during early stages of project planning related to:
  - Definition of design requirements, including reactor size, weight and power requirements and
  - Formulation of government reference design(s) and the development of defensible technology maturation/procurement strategies.
- DOE takes leading role in maturing underlying technologies to mission infusion stage (TRL-6). As necessary DOE integrates industry performers during this stage (e.g.)
  - Materials qualification (material properties, radiation damage, etc.)
  - Separate effects testing for nuclear and non-nuclear performance data (e.g., hydrogen loss from moderators, nuclear cross-sectional and irradiation performance data for unique alloys)
  - Integral testing of sub-scale assemblies (e.g., KRUSTY, TREAT, etc)
  - End-to-end concept design development and performance assessment
- DOE oversees industry-led design, fabrication, assembly, and qualification of nuclear systems.
  - Exact role varies depending on NASA's acquisition, and acceptance strategy.
- For the foreseeable future DOE solely possesses infrastructure and regulatory basis for performing full-scale (or near-scale) nuclear demonstrations

What are the major system elements and requirements for which DOE will have a role? Could they be achieved within schedule[1]?

- Fuel (including cladding, moderator). DOE will likely be involved through all stages of fuel supply, development, qualification and fabrication. **YES**
- Systems, structures and components related to reactor vessel, structural elements, primary heat transport, and heat exchanger. These ODS, refractory metal or metalized ceramic components need to be creep-resistant at normal and off-normal operating temperatures that may approach 1300 K and corrosive environments. DOE will likely be involved until the components reach sufficient maturity and transition to the industry for final fabrication and qualification. **YES**
- Reactor instrumentation and control systems. Design, qualification, testing and acceptance of human-rated instrumentation and controls are a challenge. DOE's microreactor program is maturing embedded sensors and control systems. Extremely likely that DOE will be the design and engineering authority on this system. **Likely**
- Power Conversion system, and Heat rejection. Typically, industrial base is stronger in this arena. Several ongoing Office of Nuclear Energy, DoD and ARPA-E projects are sponsoring industry led research into these components at relevant operating conditions. DOE will likely have oversight and integration role. **Unknown but likely**

[1] Lee, M., Presentation to NAS Space Nuclear Propulsion Committee (Backup slide)

What are the leading fuel forms and reactor design concepts, and what is their state of development?

- Uranium Nitride (UN) was the leading fuel choice coming out of the SP-100 and JIMO programs. JIMO performed a detailed analysis of alternates before down-selecting to UN
  - UN has significant but limited fuel data tailored especially for NEP operating conditions (note: the reference NEP design target burn up is 2-3 atom-% which is a third of the planned SP-100 burnup).

- Uranium Oxide could also be used, but it has less desirable uranium atom density and thermal conductivity.

- Both UO2 and UN fuels are currently being made in limited quantities at the required enrichment levels (>19.75%). Both could easily be ramped up to ~100 kg/yr.

What is the feasibility of using common fuels or reactors for NTP and NEP?

- Currently, NTP is leaning towards low density dispersed fuels such as modified TRISO UN fuel encapsulated in ZrC or UN-Mo Cermet. Though a structured design analysis was not carried out to examine suitability of those fuel forms for NEP, they are extremely unlikely to achieve low specific mass. At this stage it is neither recommended nor desirable to pursue a common fuel form – especially given that UN and/or UO_2 fuels are mature and easy to fabricate. Instead NASA's focus should be to plug a known national gap: lack of a national facility with a large capacity to fabricate HALEU ceramic fuels.
- Focus of NTP designs is to optimize features that allow for operation at extremely high temperatures for short periods. Focus of NEP design is to optimize moderately high temperature for several years where dominant failure mechanisms are swelling, creep, hydrogen loss and rotary systems reliability. Though a structured design analysis was not carried out to examine feasibility of using same design for NTP and NEP, it is extremely unlikely such a system would achieve required specific weight and service life

What are the prospects for reducing the mass-to-power ratio of a high-power NEP system?

- The most important way to reduce mass of an NEP system is to operate at temperatures in the range of 1150 – 1350 K (including normal and off-normal operating conditions).
  - This improves power conversion efficiency but even more importantly it reduces radiator area.
  - This requires use of refractory metal alloys (Nb1Zr or TZM) for cladding, reactor vessel and coolant boundary. Other metals such as superalloys and oxide dispersion steels may also be used in selected parts of the plant. Welding, diffusion bonding or other methods of joining these materials is difficult.
- Prospects are high that target specific weight could be achieved
  - SP-100 technology development demonstrated ability to fabricate system components with Nb1Zr. Industry already has ability to fabricate PCS systems using super alloy.
  - A key hurdle is joining of dissimilar metals with differing CTEs. 3-D printing might offer solutions

What are the prospects for fabricating qualified fuels including cladding and supports?

- UN fuel meets NEP needs. At least two national laboratories maintain capability to fabricate qualified UN fuel pellets. Scale up to fabricate 100's kgs per year is required but achievable. UN Fabrication risk is low.
- Developing necessary cladding and liners is straight forward for this application (compared to SP-100) because NEP's target service conditions are less demanding (lower temperatures, burnup and linear heat rate).
  - UN clad in high temperature materials, including ODS steel and SiC, are being pursued by at least two microreactor vendors.
- Fabrication and qualification of structural supports such as grid-plates is complicated by the lack of appropriate ANSI/ASTM standards.
  - An early task to develop engineering standards for structures constructed of refractory materials is recommended
- These tasks may become harder for moderated spectrum designs because many of the refractory materials are parasitic neutron absorbers.

What are the prospects for improving reactor designs?

- Reformulating the designs to better align with DOE/NASA/DoD sponsored and industry-led initiatives relative to fission surface power, microreactors would broaden the supply chain and lower development risk
  - The reference designs are the derivatives of SP-100 and JIMO designs. Though selected components possess high TRL, the reference designs as a whole possess low technology readiness level (TRL 2/3).
  - Inclusion of industry and national laboratory teams to formulate alternate designs would improve the prospects
- NEP operating conditions are incrementally more demanding than designs sought by the industry
  - NEP program can leverage some of technologies being developed by the commercial microreactor programs, such as heat exchangers, piping, structural elements and power conversion systems.
  - Instrumentation and control systems are being modernized to support remote operation of microreactors. Embedded fiber-optic nuclear sensors and radiation tolerant FPGA’s offer innovative options for simplifying control strategies

What is the prospect for testing and qualification of components and integrated systems without need for refurbishment of existing facilities and construction of new facilities?

- Testing and qualification of all parts can be done at DOE national laboratories in existing facilities with minor modifications.
  - Separate effects testing of fuel, flow loops, power conversion and heat removal would be required for early testing.
  - Integral testing/demonstration of a full-scale non-nuclear system is possible and recommended.
  - INL is establishing a microreactor test bed which can be leveraged to perform NEP engineering demonstration unit testing.
- Depending on materials choices, a select number of nuclear measurements and criticality testing may be needed.
  - NNSS facilities may be used with no modification
- Confirmatory nuclear qualification may be necessary.
  - Burnup and neutron fluxes can be tailored in HFIR

From a DOE perspective, what are the options for full-scale system-level ground demonstration testing?

- A full-scale NEP reactor could be tested at INL through NRIC. Such testing regime aligns with NRIC charter. NNSA's NNSS could be considered as an alternate. Significant modifications to facilities and authorization basis may be necessary. If LEU is used as a fuel then the range of available facilities increases. Both sites have the necessary nuclear infrastructure that includes:
  - Certified reactor operators
  - Radiation safety program and technicians
  - Criticality safety program and technicians
  - Waste handling
  - Regulatory framework and safety engineers
  - NEPA that allows for testing (INL is currently pursuing a flexible NEPA to support a multitude of planned reactor demonstrations)

What are the technical and programmatic considerations (e.g., performance, mass and lifetime) associated with selecting HEU rather than HALEU as the fissile material

- For NEP, the use of HALEU will be a modest penalty on system weight of approximately 10%.
- Reactor lifetime will not be impacted.

How well equipped is the Department of Energy to develop the key subsystem technologies to readiness for mission infusion (i.e., to technology readiness level 6)?

- NEP reactor system requirements are only incrementally more difficult relative to the state-of-the-art
  - Advanced fabrication methods for refractory materials, specialized steels and metalized ceramics are being investigated for fusion and solar thermal applications
- DOE national laboratories are establishing capabilities necessary for carrying out near full-scale end-to-end non-nuclear demonstration of microreactors
- High temperature Brayton PCS are being pursued by national laboratories in collaboration with industry (CRADAs)

What regulatory challenges does the Department of Energy foresee for developing NEP?

- NEP reactor system, if designed appropriately, is normal by microreactor standards.
  - Reactor would be done under current regulations which should not pose a barrier to development
  - Reactor demonstration does not generate waste streams or waste forms that are unique

Backup slide

Preliminary NEP Development Schedule

Ref: NEP Technology Review: Presentation to SNP Committee by L. Mason