SOLID-STATE NUCLEAR POWER. Jeffrey A. George, EP/Propulsion and Power Division, NASA Johnson Space Center, Houston, TX 77058, jeffrey.a.george@nasa.gov.

Summary: A strategy for "Solid-State" Nuclear Power is proposed to guide development of technologies and systems into the second 50 years of nuclear spaceflight. The strategy emphasizes a simple and highly integrated system architecture with few moving parts or fluid loops; the leverage of modern advances in materials, manufacturing, semiconductors, microelectromechanical and nanotechnology devices; and the targeted advancement of high temperature nuclear fuels, materials and static power conversion to enable high performance from simple system topologies.

Background: The first 50 years of nuclear spaceflight dawned with numerous efforts advancing a broad portfolio of technologies and design approaches to space nuclear power and propulsion. Another surge of development occurred during the 1980's and early 90's to support the SP-100 Program and Strategic Defense Initiative. These efforts implemented the successful SNAP-10A and numerous RTG flights, and laid much of our current technology base [1], [2].

Challenges. Unfortunately, we face key challenges today. Our knowledge base is now decades old, capabilities are degraded or decommissioned, much of the workforce has retired, and both human exploration and space nuclear power have endured a series of boom/bust cycles. Additionally, we see aerospace developments becoming more and more complex, rising in cost and schedule, and facing threats or reality of cancellation (Examples: Constellation Program, MSL Rover, James Webb Space Telescope).

Complexity Kills. Rising complexity has been cited as an important contributor to the escalating cost, schedule and cancellations of aerospace developments [3], [4]. Manufacturing and service industries have also recognized the negative effects of complexity, and have adjusted to reduce costs and increase profit margins and competitiveness [5].

Technology is Best when it Simplifies. Advanced technologies are usually invoked to enhance performance or capability of a given aerospace mission or system. Often (if not usually) these advancements add functions, requirements, parts and subsystems to the system Product Breakdown Structure (PBS), thereby expanding the project Work Breakdown Structure (WBS), scope, workforce, number of unique developments, test and verifications, cost, schedule, and risk of overruns and cancelation. A better focus for technology insertion may be to simplify system topologies, thereby reducing project scope and risk.

Solid-State Strategy: A "Solid-State" strategy for nuclear power development may more robustly navigate the boom/bust cycles of space nuclear development, and would be based upon:

- "KISS" Simplified System Architecture with few moving parts or fluid loops, and Modular assemblies that can be replicated to configure larger systems and fail gracefully.
- Evolutionary development of a common design approach and technologies.
- Performance targets that are desirably *Useful* for early de-rated applications with large margin hold-back, and *Enabling* for farther term applications with fully matured technology and operating envelopes.
- Leveraged Technology Set drawing from the traditional "space nuclear" 1960's-90's state-of-art, as well as modern advances in the relevant fields of Materials, Manufacturing, Electronics, Microelectromechanical and Nano technologies.
- Targeted Advanced Development of high temperature nuclear fuels, materials, and power converters to enable a high level of performance from a simplified architecture.

Solid-State System Architecture: One example of a "Solid-State" nuclear system may feature:

- A tightly-coupled and largely thermally conductive topology wherein heat is conducted directly from the core, to the power converter, to the waste heat radiator. No or few moving parts or fluid loops would exist, eliminating a number of component developments, cost and failure modes. High temperature operation, fuels and materials are anticipated to compensate for the limitations of conduction and static power conversion.
- Reactor fuel and core capable of high temperature and burnup, such as a refractory cermet with tungsten or tantalum matrix and UN or UO_2 fuel.
- Static power conversion coupled directly in an "ex-core" (vs. in-core) geometry and requiring no fluids, pumps, plumbing, boilers or heat exchangers. Modest efficiency Thermoelectric converters would serve earlier and lower power systems. Higher efficiency Thermionic converters would (if successful) serve later and higher power systems.
- Radiators coupled directly to the cold shoes or collectors of the power converters. Highly conductive lightweight materials such as pyrolytic

graphite may be used to spread heat laterally across the radiator surface. Passive heat pipes or loops may be necessary at higher power levels.
- A "Bimodal" nuclear power/propulsion stage may be considered by adding propellant accommodations to the inherently high temperature system.

Precedents & Analogies: This strategy is informed by a number of preceding developments. Static power conversion has been solely employed by every US and Russian nuclear flight, including RTG's, SNAP-10A [1], BUK and TOPAZ 1 [6]. Conductively coupled systems have been demonstrated or proposed by RTG's [1], the original SNAP-10 (vs. "A"), ROMASHKA [6], and STAR-C [7]. Relevant Bimodal systems were proposed for STAR-C, ROMASHKA, and NEBA [8].

Key Technologies: Significant technical challenges must be overcome in order to achieve reasonable performance from low-complexity systems. The following are representative:
- Cermet or other high temperature Nuclear Fuels.
- Refractories and other high temperature materials.
- Additive and other Advanced Manufacturing.
- Micro-Electro-Mechanical and Nanotechnology.
- Advanced Semiconductors.
- Thermoelectric Power Converters.
- Thermionic Power Converters.

Evolving Missions & Applications: The strategy, system architecture, and core technology set may accommodate the following applications:
- Advanced RTGs with augmented performance or reduced plutonium need (100's We).
- Low-Power Reactor Systems to replace plutonium RTGs (100's We – 1's kWe).
- Medium-Power Reactor Systems for Moon, Mars and Deep Space (10's kWe).
- Higher-Power Systems to support Human Exploration Power and Propulsion needs.
- Terrestrial applications.

Development: A common strategy, system architecture and core technology set would provide continuity across developments. Earlier robotic flights would build confidence in similar or related systems for use in later human missions. Each successive development would evolve and "stand on the shoulders" of the prior. Earlier systems would incorporate "higher tech" materials and technologies than explicitly necessary, and then back well off from design limits to incorporate large operating margins. Subsequent systems could then improve performance by incrementally releasing now-proven margins. Specifics of geometry and performance would of course evolve, along with perhaps infrequent materials substitutions. A planned power conversion upgrade would transition from thermoelectric converters to (presumably successful) higher efficiency thermionic converters at higher power levels.

Benefits & Summary: Assuming successful technology development prior to need, greatly reduced programmatic scope, cost, schedule and risk may be realized by reduced complexity systems with fewer unique "parts" to be designed, developed, integrated and tested. Evolutionary deployment and validation build confidence for later missions and promote long term cost efficiencies. System reliability is likely enhanced by static operation and the graceful degradation of modular power converters.

Finally, though it may seem counter-intuitive to emphasize technologies beyond a minimal "floor" set, or even space nuclear technologies at all – now is the time (literally) to do it. Once the next exploration mission is green-lighted and a launch date penciled-in, it will once again be too late to advance technology. Risk-averse project managers will gravitate to lower levels of technology. These levels may or may not enable a "desirable" mission performance, putting continued funding at risk. Injection of immature technologies to boost mission performance may lead to schedule slips and cost overruns, further risking cancellation. Laying a solid foundation now is the best chance to allow future nuclear missions and developments a chance to overcome the boom/bust cycle that has marked much of the first 50 years of nuclear spaceflight.

References: [1] Angelo J. A. and Buden D. (1985) *Space Nuclear Power*. [2] El-Genk M. S. et al. (1994) *A Critical Review of Space Nuclear Power and Propulsion 1984-1993*. [3] Bearden D. (2008) *Perspectives on NASA Mission Cost and Schedule Performance Trends*. [4] Deloitte Consulting LLC Whitepaper (2008) *Can We Afford Our Own Future?*. [5] Wilson S. A. and Perumal A. (2009) *Waging War on Complexity Costs*. [6] Ponomarev-Stepnoi N. et al. (2003) *Russian Space Nuclear Power*. [7] Begg L. L. (1992) *STAR-C Thermionic Space Nuclear Power System*. [8] Jacox M. et al. (1995) Conceptual Design Review USAF/DOE Bimodal Power and Propulsion Program.