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EVOLUTION OF SPACE REACTOR QUALIFICATION METHODS AND A PATH FORWARD FOR NEW SPACE REACTORS UNDER CONSIDERATION

Changing the World's Energy Future

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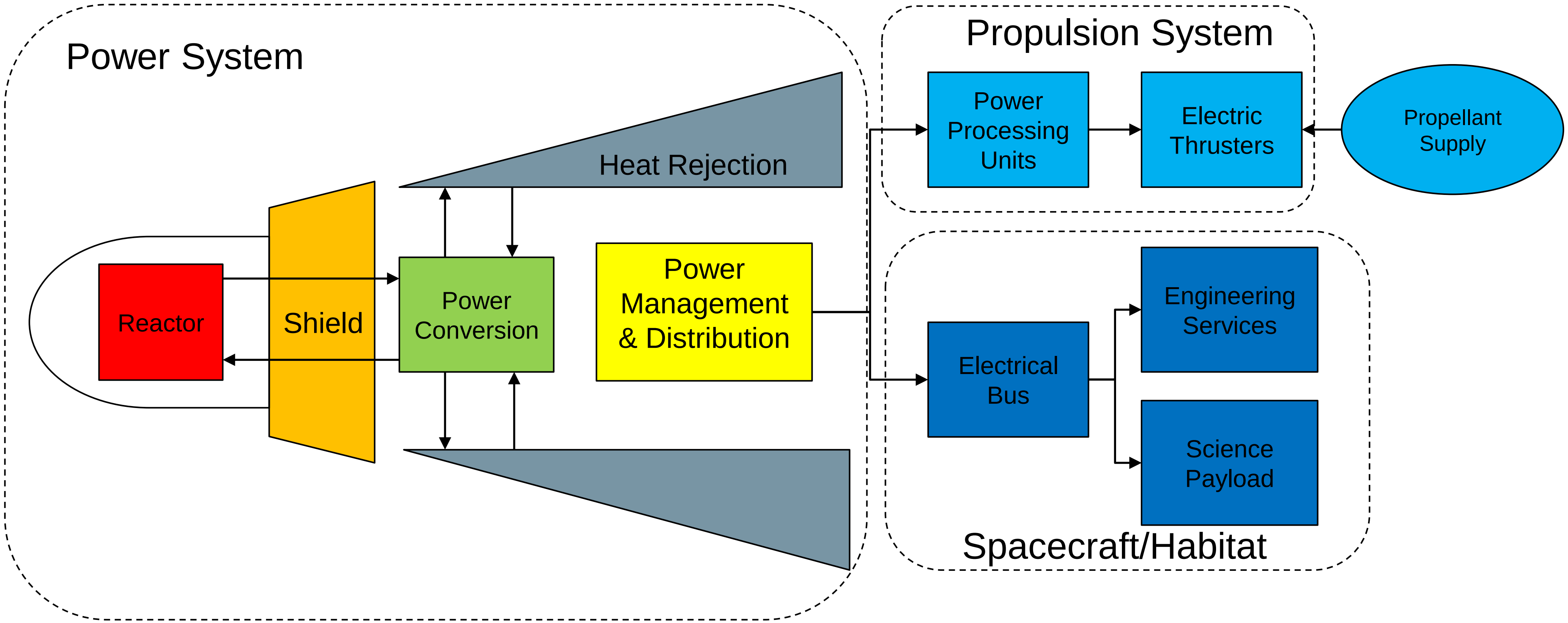
Overview

- General Space Reactor Systems
- Component and System Qualification
  - SNAP
  - SP-100
  - TOPAZ
  - Prometheus
- Presidential Memorandum
- Future Space Reactor Qualification

General Reactor System Components

- Reactor – generates thermal energy
- Shielding - reduces radiation exposure to equipment and personnel
- Primary heat transport system – transfers heat from the reactor to the power conversion system
- Power conversion system – converts heat to electricity
- Heat rejection system – rejects heat from the power conversion system to the environment
- Power management and distribution system – controls the distribution of power from the conversion system
- Control system – controls system power demand for the space reactor system

General Power Reactor Layout



SNAP 10A – Development and Flight Test Systems

- 11 systems were built for system development and flight testing
- PSM-1, 2, 3 – prototype system tests that provided early system design information that could be incorporated back into the system design
- FSM-1, 2, 3 – electrically heated qualification tests that allowed for practice in prelaunch operations, demonstrated component interoperability, and electrical compatibility with the upper stage
- FS-1 – nuclear qualification tests
- FS-2 – became FSM-4 non-nuclear qualification test using flight components
- FS-3, 4, 5 – flight systems

SNAP Program Ground Testing Facilities

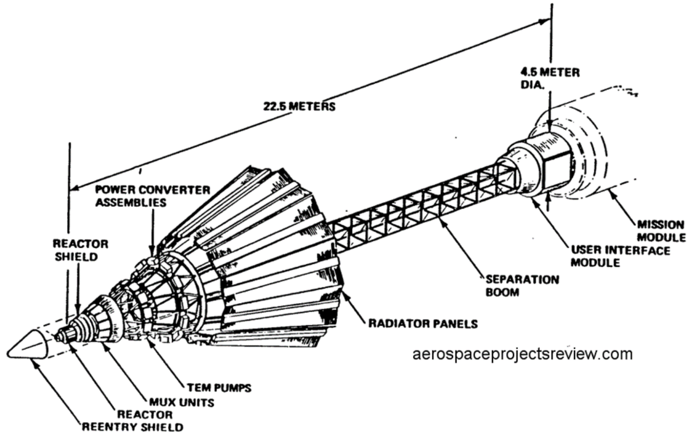
- Many facilities for component and system testing were located on the Energy Technology and Engineering (ETEC) site north of Los Angeles, CA
- ETEC facilities enabled concurrent engineering on development systems
- Additional testing was performed at the Idaho National Engineering Laboratory (INEL) and Oak Ridge National Laboratory (ORNL)
- ETEC Facilities included
  - Building 013 – hardware checkout
  - Building 025 – demonstration of remote handling tools
  - Building 023 – development, endurance testing, qualification, and acceptance testing of liquid metal components
  - Building 027 – component qualification testing and system checkout
  - Building 042 – shield fabrication and test
  - Building 057 – development and demonstration of hardware fixtures and ground support equipment
  - Building 065 – thermoelectric component life testing, qualification testing, and thermal vacuum chamber testing
  - Building 066 – control and instrumentation component life testing, qualification testing, and acceptance testing

SNAP Program Ground Testing Critical Facilities

- Component development and system tests were performed primarily at ETEC
  - Building 10 / 4010– criticality resting at low power levels
  - Building 012 /4012– core and reactor zero power level testing
  - Building 019 / 4012 – flight unit acceptance testing with underground thermal vacuum chamber
  - Building 024 / 4024 – nuclear tests in space environment chamber
  - Building 373 / 4373 – critical tests for ZrH fuel development

SP-100 Component System & Testing

- Materials Qualification
  - UN fuel irradiation at Fast Flux Test Facility (FFTF) and Experimental Breeder Reactor II (EBR II)
- Critical Facilities
  - Los Alamos Critical Experiment Facility (TA-18) was planned for benchmarking of nuclear cross sections
  - FFTF and EBR II were identified for fast neutron spectrum materials testing
- Ground Testing
  - Nuclear Assembly Test (NAT) facility at DOE Hanford site was to built inside the existing building 309 for prototype reactor assembly
  - Converter Pump Assembly Test (CPAT) in Valley Forge, PA was to perform electrically heated non-nuclear system tests



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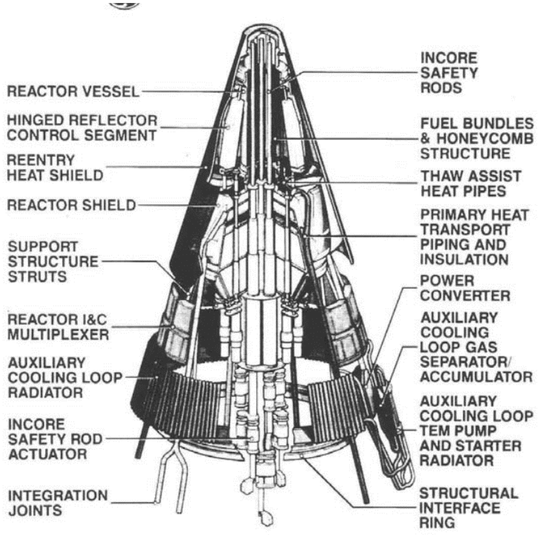


TOPAZ Component and System Qualification

- TOPAZ II system development began in 1969 in USSR and built 26 units
- Qualification test program in USSR included
  - Thermal management tests
  - Mechanical tests
  - Electrical heat source simulation
  - Ground nuclear tests
- US-Russian cooperative program began in late 1990’s to modify a TOPAZ II system for use in an electric propulsion system
  - Key changes were made to ensure that the core will remain subcritical on reentry

TOPAZ system qualification

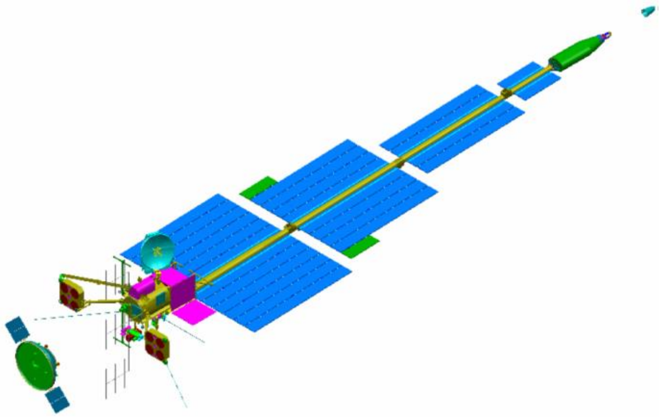
- Actual qualification on the TOPAZ II systems is classified
  - Process was likely similar to MIL-STD-1540B approach for U.S. spacecraft qualification
  - Russian approach tended to use qualification of similar hardware from production runs rather than actual flight hardware
  - Likely had significantly less environmental testing on flight units as compared to U.S. qualification processes
- Modifications identified during transition of the program to the U.S. included
  - Complete flight qualification
  - Replace forced convection cooling with radiative cooling
  - Replace control system with a U.S. microprocessor-based design
  - Change core loading to eliminate change of nuclear criticality when immersed in water

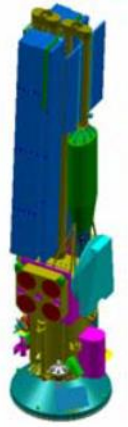
TOPAZ system qualification in U.S.

- Two units underwent non-nuclear testing at the Phillips Laboratory
- Testing included
  - Modal test to determine dynamic characteristics
  - Thermal vacuum tests from with electrical heaters to generate 0 to 95 kWth to create a performance baseline and demonstrate the NaK system loop’s integrity
  - Mechanical tests including mass properties (CG, MOI), load testing, vibration testing, and shock testing
  - Additional thermal vacuum test to demonstrate system durability and stable performance after mechanical testing

Prometheus Component and System Qualification

- Materials qualifications
  - JOYO facility in Japan for fast spectrum fuels and nuclear structure testing
  - Advanced Test Reactor (ATR) at INL and High Flux Isotope Reactor (HFIR) for thermal neutron irradiation and testing
- Component and System Qualification
  - Gas reactor had significant uncertainty early system models
  - System testing was identified as a high priority to identify a number of challenges
    - Control challenges
    - Minimization of system losses
    - Material incompatibilities
  - Plan was to begin at component level and work up to full system performance
  - Electrically heated system was planned to be used for a Thermal Test Module (TMM) for early stage thermal and an engineering model for early prototype testing





Prometheus Component and System Qualification

- Nuclear System Qualification
  - Broken into three phases
    - Benchmark tests for initial information and cross section information on critical assemblies
    - Mock-up tests to qualify design methods
    - Ground test reactor to test various operating modes and improving computational models
- Critical Facilities
  - Early in the program a lack of U.S. facilities for mockup and criticality experiments was identified as a program risk
  - Potential international facilities that were identified included
    - JOYO reactor in Japan for materials testing
    - Fast Critical Assembly (FCA) in Japan for criticality experiments
    - BOR-60 reactor in Russia for materials testing
    - PHENIX reactor in France for materials testing
  - Prototype Ground Test Reactor (GTR) facility was considered but would introduce siting and construction schedule risk
  - Lack of existing domestic critical facilities led some to push for designs to be effectively tested in non-nuclear tests

Presidential Memorandum

- Recent presidential memorandum helps to clarify the process of launching space nuclear systems
- Tier 2 approval consists of the head of the sponsoring agency for federal projects or the secretary of transportation for commercial projects and LEU
- Tier 3 approval consists of the President or Director of OSTP for approval of federal launches that use a non-LEU fission system
- Safety Analysis Report (SAR) requires
  - Launch, staging, flyby, and reentry accident scenarios that may expose the public or environment to radiological effects
  - Analysis of consequences of a maximally exposed member of the public
  - If possible, make use of previous mission reviews and experience

Presidential Memorandum Tier Descriptions

1	<100,000 times total A2 Table 2 value in IAEC SSR-6	Head of Sponsoring Agency	Secretary of Transportation
2	>100,000 times total A2 Table 2 value in IAEC SSR-6	Head of Sponsoring Agency	Secretary of Transportation
2	Tier 1 with 1:1,000,000 probability of a member of public receiving 5 to 25 rem TED	Head of Sponsoring Agency	Secretary of Transportation
2	Any launch of LEU fission systems with additional safety review	Head of Sponsoring Agency	Secretary of Transportation
3	1:1,000,000 probability of a member public recieving >25 rem TED	President or OSTP Director	Secretary of Transportation
3	Any launch of non-LEU fission system with additional safety review	President or OSTP Director	Secretary of Transportation

Future Reactor Qualification

- Prototypic non-nuclear tests and an increased number of tests can improve system reliability
- Electrically heated non-nuclear tests can help to increase system reliability
  - Quantifies component behavior
  - Identifies potentially unknown system interactions
- Materials qualification
  - Thermal or epithermal designs can use ATR or HIFR reactors
  - TREAT reactor can provide rapid power transients

Future Reactor Qualification

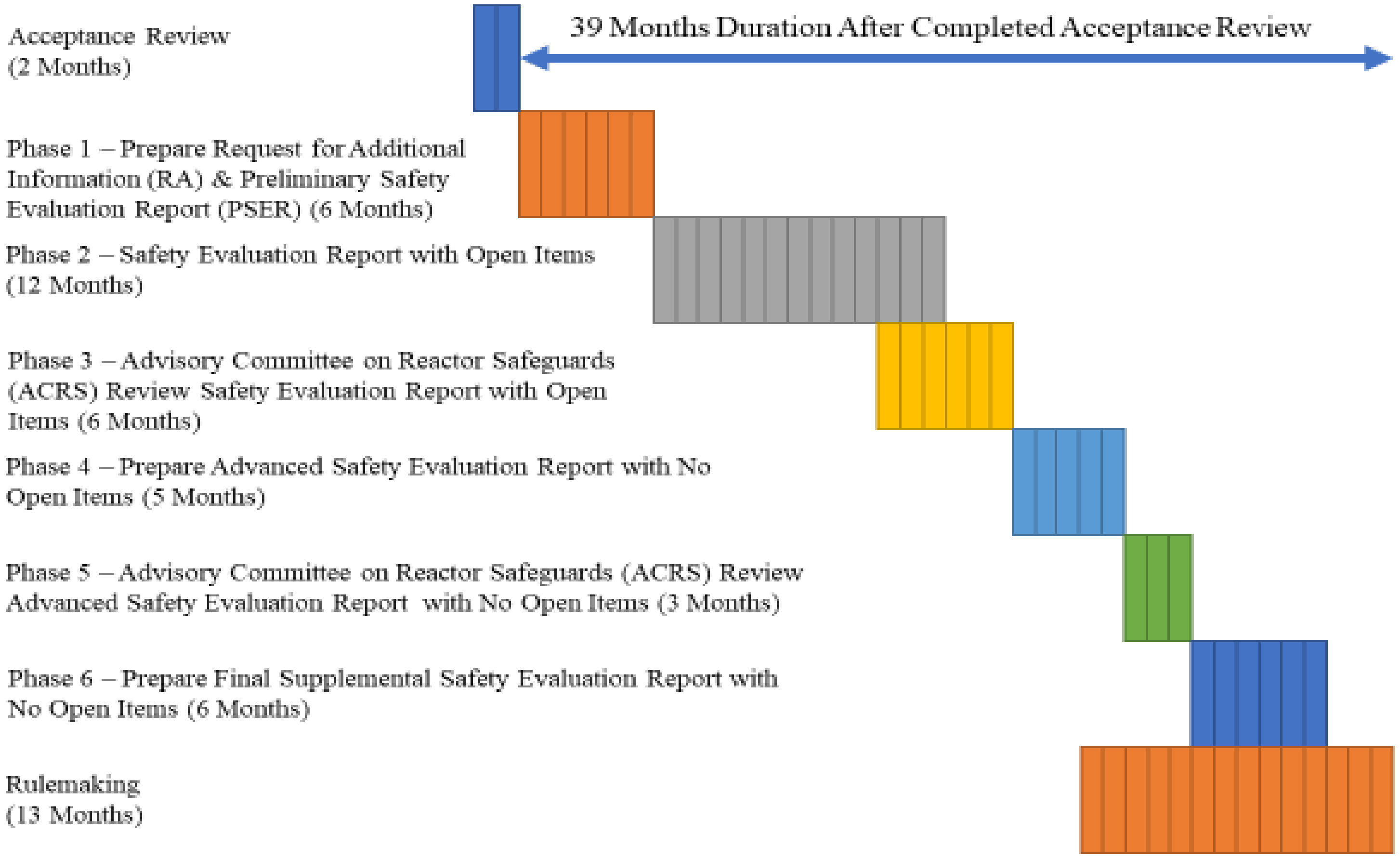
- Security and Transportation
  - Type of fuel used can be a significant driver in costs
  - HEU can create higher security risks and costs during manufacture and transport
- Component Testing
  - Standalone component testing is recommended prior to larger system integration
    - Characterize component performance, failure modes, and reliability
    - Reduce likelihood of system performance shortfalls
- Ground Testing
  - Using electrically heated systems and nuclear ground test is likely the most cost and schedule effective path to certify a system
  - Electrically heated units help to verify concept of operations (CONOPS), off nominal operational modes, and system lifetime
  - Nuclear tests help to verify final system configurations and provide a ‘ground twin’ for the launched reactor system

Future Reactor Qualification

- SAR Creation
  - Ideally would cover all potential missions
  - Cost and schedule constraints may not allow every case to be covered
  - System SAR may cover near term or highly likely cases rather than all encompassing cases
  - Is a living document that should be updated regularly
- Environmental and Safety Reviews
  - Preparation and review of space reactor environmental and safety reviews can be extrapolated from the NRC reviews for small modular reactors and isotope facilities
  - Lack of mature space reactor designs creates some uncertainty

Future Space Reactor Qualification

- NRC's licensing process of Small Modular Reactors is expected to take at least 39 months
- Space reactor is expected to take a minimum of 36 months and likely 48 months due to current lack of design fidelity



Conclusions

- Space reactor development has historically been a hardware and test intensive
- Current development paths focus more on computation analysis and non-nuclear testing
- Facility needs and availability early in program lifecycle will help to minimize development surprises
- Development of a realistic cost and schedule should identify key task including
  - Required existing fabrication and test facilities
  - Required new fabrication and test facilities
  - Safety and environmental applications
  - Component and system design
  - Launch permitting
  - Component and system ground test