Structural Materials and Fuels for Space Power Plants

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INTRODUCTION

A fission reactor combined with Stirling convertor power generation is one promising candidate in on-going Fission Surface Power (FSP) studies for future lunar and Martian bases. There are many challenges for designing and qualifying space-rated nuclear power plants. In order to have an affordable and sustainable program, NASA and DOE designers want to build upon the extensive foundation in nuclear fuels and structural materials. This talk will outline the current Fission Surface Power program and outline baseline design options for a lunar power plant with an emphasis on materials challenges.

NASA first organized an Affordable Fission Surface Power System Study Team to establish a reference design that could be scrutinized for technical and fiscal feasibility. Previous papers and presentations have discussed this study process in detail. Considerations for the reference design included that no significant nuclear technology, fuels, or material development were required for near term use. The desire was to build upon terrestrial-derived reactor technology including conventional fuels and materials. Here we will present an overview of the reference design, Figure 1, and examine the materials choices. The system definition included analysis and recommendations for power level and life, plant configuration, shielding approach, reactor type, and power conversion type. It is important to note that this is just one concept undergoing refinement. The design team, however, understands that materials selection and improvement must be an integral part of the system development.

BASELINE MATERIAL SELECTIONS

Fuel selection is at the heart of the design process. UO_2, UN, U-Metal, and UZrH fuels were scrutinized for this reactor system. Selection issues included fuel availability, data availability, burn-up life, and containment. The structural material choices for the core and reactor vessel were considered a fundamental system design constraint. The Jupiter Icy Moons Orbiter was an ambitious NASA program to marry a high power reactor with electric propulsion. The cost of developing and qualifying higher temperature structural materials was one of the compelling reasons for mission deferment. Therefore designing a lunar system with a qualified material such as 316L stainless steel is a prerogative.

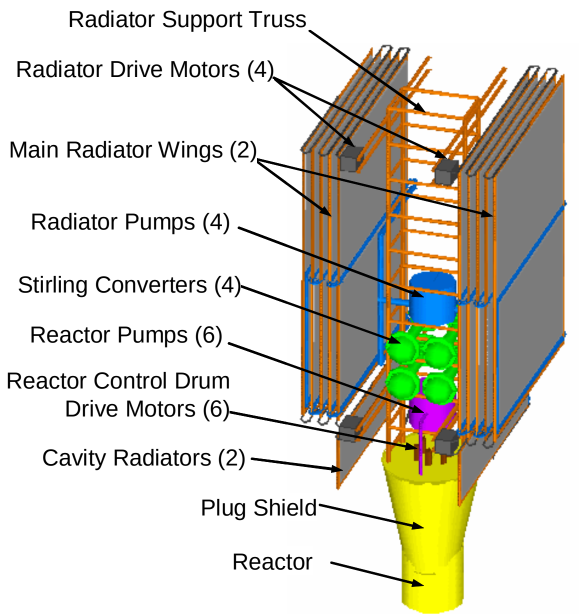

Fig. 1. Reference lunar power system in stowed configuration.

The primary shield between the reactor and the lunar outpost will be a combination of regolith and distance. Shielding will be required also between the reactor and the balance of plant. This shield design is an important balance between size and weight of the shield and the radiation tolerance of the power conversion components. One of the Fission Surface Power Risk Reductions Tasks is to establish a credible list of power conversion components and to determine if additional radiation testing is required. Dynamic power conversion based on a Stirling cycle is preferred for the power levels of interest. Stirling convertors are primarily composed of a variety of metallic alloys with typical radiation hardness. Therefore the emphasis for radiation tolerance is on the non-structural materials. This includes permanent and soft magnetic materials and a range of polymeric materials used in the alternator. Combinations of irradiation exposure and elevated temperature conditions are key to the survivability of these important component materials in the balance of plant.

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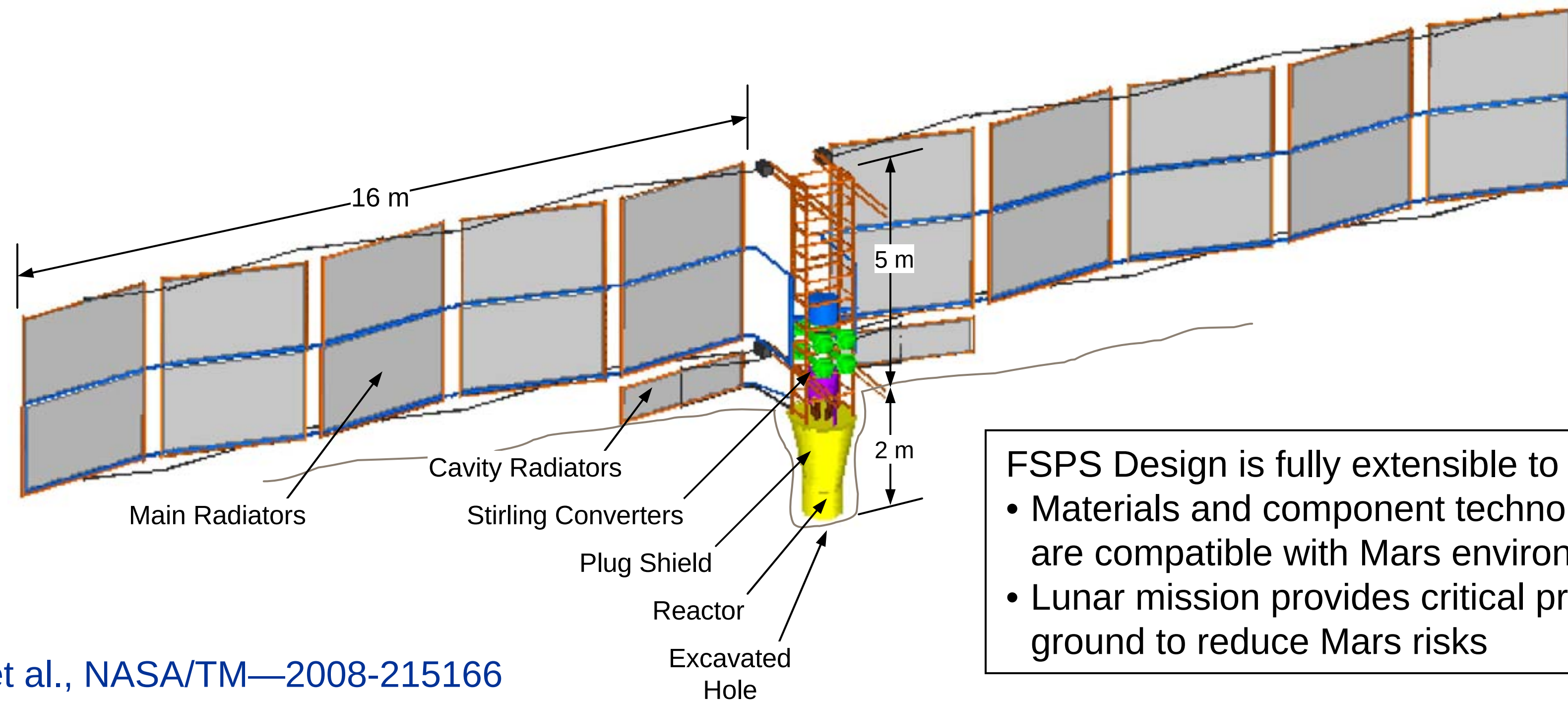
Affordable Fission Surface Power System Baseline

- Modular 40 kWe System with 8-Year Design Life suitable for (Global) Lunar and Mars Surface Applications
- Emplaced Configuration with Regolith Shielding Augmentation Permits Near-Outpost Siting (<5 rem/yr at 100 m Separation)
- Low Temperature, Low Development Risk Reactor



FSPS Design is fully extensible to Mars:
- Materials and component technologies are compatible with Mars environment
- Lunar mission provides critical proving ground to reduce Mars risks

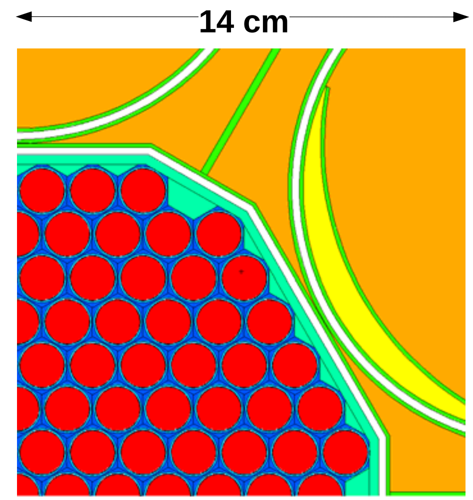
Mason et al., NASA/TM—2008-215166

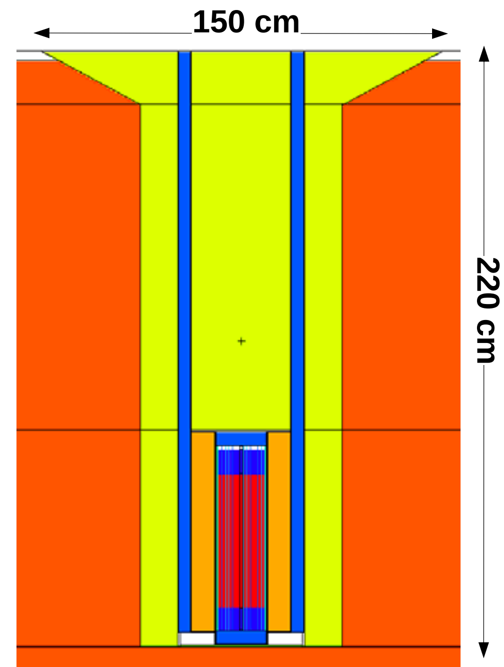
The “Affordable” Approach to Space Nuclear Power

- Judicious Concept Selection
  - Benign requirements and operating conditions
  - Selection of well established reactor concept
  - Significant terrestrial and some space experience
  - Large fabrication experience (low cost)
  - Large operational database
  - Handle operating-transients with thermal inertia
  - Robust control system
- Maintain a Focused Development Program
  - Build on existing database
  - Minimize nuclear testing
  - Non-nuclear tests provide systems interaction data

Affordable Fission Surface Power Baseline Reactor

- Pumped NaK-Coolant
  - Used in all successful space reactor programs (SNAP-10A, BUK, TOPAZ).
  - NaK mitigates freeze/thaw issues during testing, deployment and operation.
- Closely-Packed, Relatively Large-Pin, Open-Lattice Flow Geometry
  - Allows criticality requirements to be met without internal safety rods
- SS/Be/B4C Reflector and Control Drums
  - Most established space reactor technology option
  - Fluence and temperature of Be keeps swelling <1%
- B4C neutron shielding and SS316 gamma shielding
  - Lowest cost/risk (in development/reliability)





Poston et al., STAIF—2008

Fission Surface Power System Materials Selection

Fuels

- Fuel Candidate Selection
- Concept Feasibility
- Fuel Qualification and Demonstration

Structural Materials

Balance of Plant Materials

FSPS Fuel Candidate Selection

Fuel Burnup, max	1.2 at. %
Peak Cladding Temperature, Steady-State	627 °C
Peak Cladding Temperature, Transient	725 °C
Average Linear Heat Generation Rate	2.80 kW/m
Duration of Operation	8 years
Peak Neutron Fluence	$7x10^{21}$ n/cm^2
Gas Release, %	<1%
Fuel Swelling, areal %	< 2 %
Run-Beyond Cladding Breach/reaction with coolant	Self Arresting – no breach propagation to other pins by mechanical load or flow blockage.

Highly enriched UO_2 selected based on:

- Reliability under steady state & transient conditions
- Previous experience under similar operating conditions

U-10Zr was also considered capable of meeting design requirements, however the expected axial swelling would lead to excessive reactivity loss in the small FSPS core design

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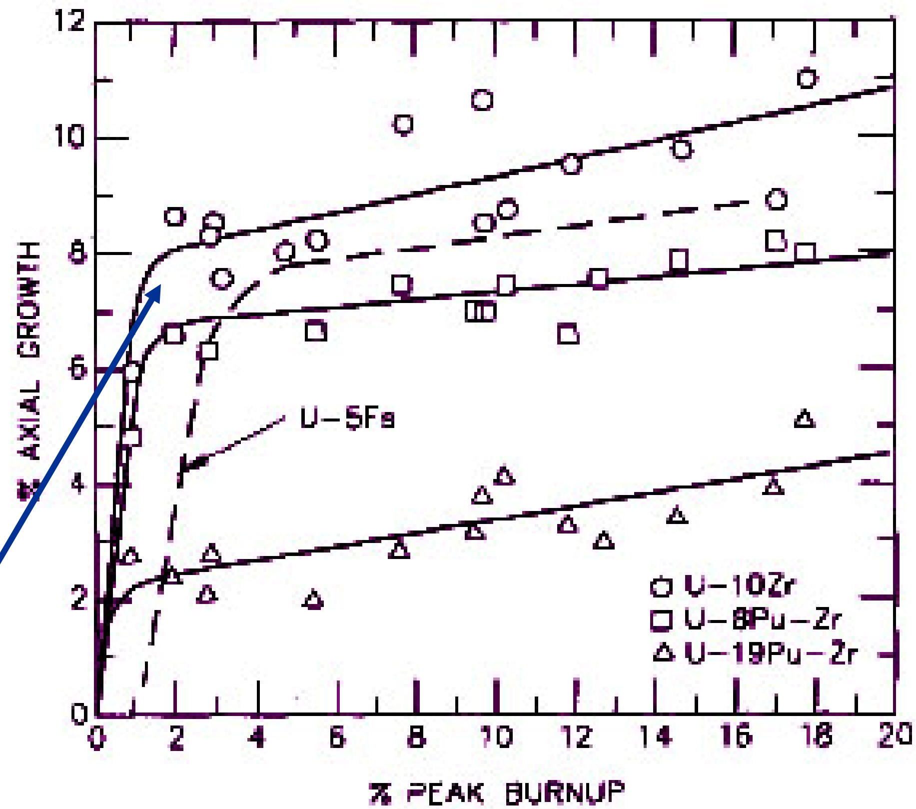
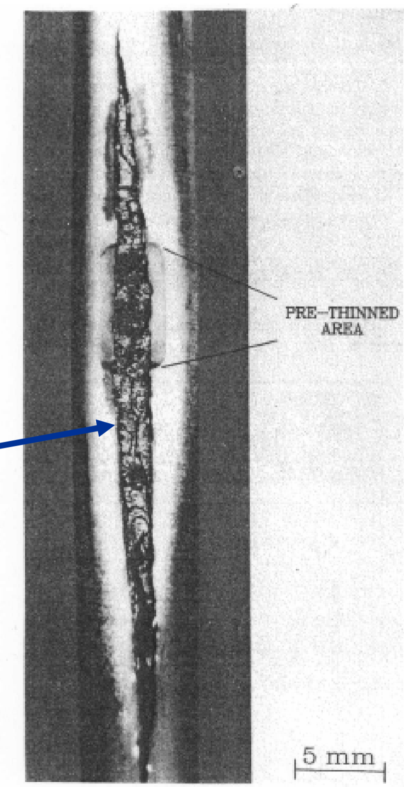


Fast Reactor Metal Fuel Axial Growth (from Hofman, et al, 1997)

FSPS Fuel Concept Feasibility

- Steady-state operation of UO_2 demonstrated in LWR, fast reactor driver, fast reactor blanket, and other special testing fuels
- Several successful programs with similar or more aggressive reactor conditions: BN350, BN600, Fast Flux Test Facility (FFTF), Phenix, Materials Test Reactor (MTR), TOPAZ I & II, (ORNL in early 1970s, SNAP?)
- No UO_2-NaK interaction experience available, but Na-MOX fuel interactions show breaches are self-limiting or self arresting (Fuel loss is limited after initial crack extension caused by Na-MOX interaction).
- Codes for steady-state gas release low fission densities and low operating temperatures (LIFE4) and experiments simulating transient heating using PWR fuel pins suggest minimal gas build release under projected FSPS conditions.



Typical breach extension in induced midlife failure, EBR-II K2B test.
(from Lambert, et al, 1990)

No outstanding performance issues have been identified for the use of UO_2 in the expected Fission Surface Power System design.

FSPS Fuel Qualification and Demonstration

- Demonstrate engineering-scale or full-scale fuel production in conformance with the Fuel Specification (i.e., qualify the fabrication process)
  - Domestic vendors do not have current fabrication experience therefore a production line must be initiated and qualified
- Confirm acceptable fuel behavior under prototypic, worst-case conditions
- Possible post-irradiation testing might include
  - Determination of gas plenum pressure and gas release
  - Diametral profilometry to assess cladding strain
  - Confirmation of expected NaK-UO_2 interaction

Fission Surface Power System Materials Selection

Fuels

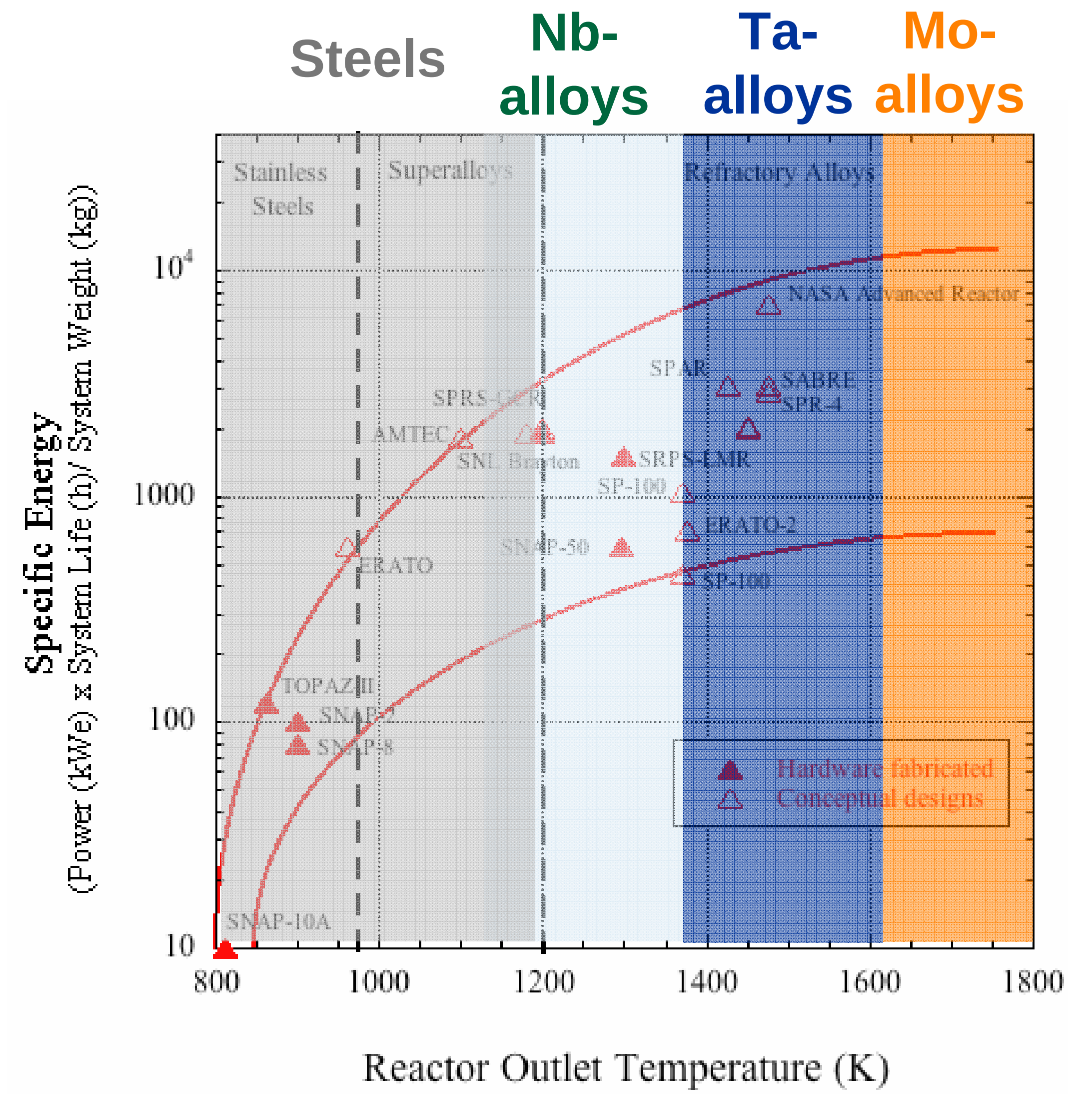
Structural Materials

- Core Candidate Selection
- Concept Feasibility
- Qualification and Demonstration

Balance of Plant Materials

Alloys for space fission reactor applications

- Reactor temperature is a key factor in space reactor design.
- Temperature will often determine materials that can be used in a reactor design.
- Many different material systems have been examined for past space reactors.
- The rest of this presentation will highlight advantages and disadvantages of these material systems.



Structural material requirements

- To enable the FSPS mission, reactor structural materials must have the right properties.
- A number of considerations will help determine the most appropriate materials
  - Mechanical properties (tensile and creep)
  - Long-term stability (must last mission lifetime)
  - Improved thermal properties (thermal expansion and conductivity)
  - Tolerance of environment (coolant and irradiation)
  - Availability
  - Cost (raw material, joining, and QA costs)
  - Joining and fabrication
  - Neutronics
  - Weight/density is also important for space systems
- A balance of all these factors will yield optimum performance.
- Stainless steel provides the best combination of maturity and performance for FSPS applications.

FSPS Core Structural Material Selection

- Austenitic Stainless Steel is mature, well characterized, and suitable for reactor temperatures less than 650°C

	Austenitic SS	Ni Superalloys	Nb Alloys
Physical Properties			
Fabrication			
Joining			
Thermal Stability			
Mechanical Properties			
Coolant Compatibility			
Fuel Compatibility			
Irradiation Performance			
Technological Maturity			
Reactor Heritage			

FSPS Core Material Concept Feasibility

- Austenitic stainless steels have mature industrial infrastructure and extensive heritage in reactor designs
- Microstructural evolution can be an issue at temperatures above 600°C, selection of low carbon grades (e.g. SS316L) will minimize second phase precipitation
- Creep strength will limit application stress, but acceptable for a low pressure design
- Past corrosion studies indicate modest corrosion rate (microns/year); contaminate control very important
- Stainless steels have been used with oxide fuels with creep rather than fuel interaction limiting temperature
- Low dose will limit irradiation-induced precipitation and creep
- High temperature will limit irradiation-induced hardening

No outstanding performance issues have been identified for the use of SS316L in the expected Fission Surface Power System design.

Helium Embrittlement at Conditions Relevant to FSPS

0 MPa

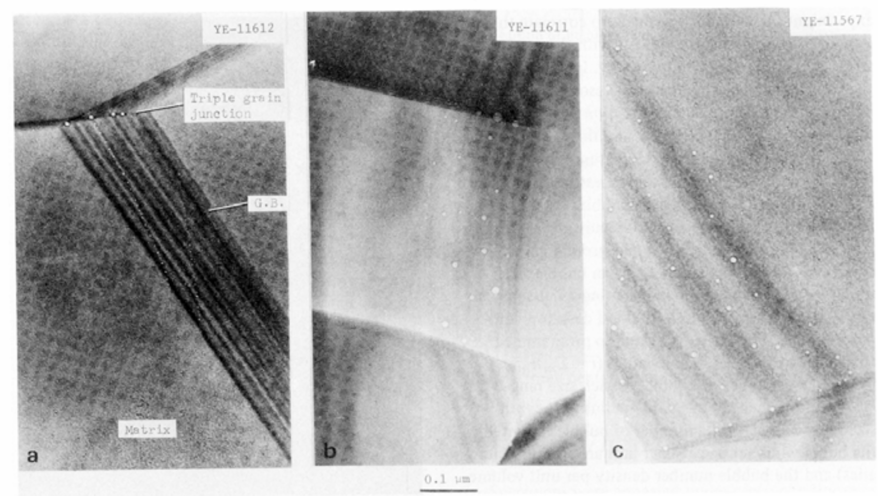
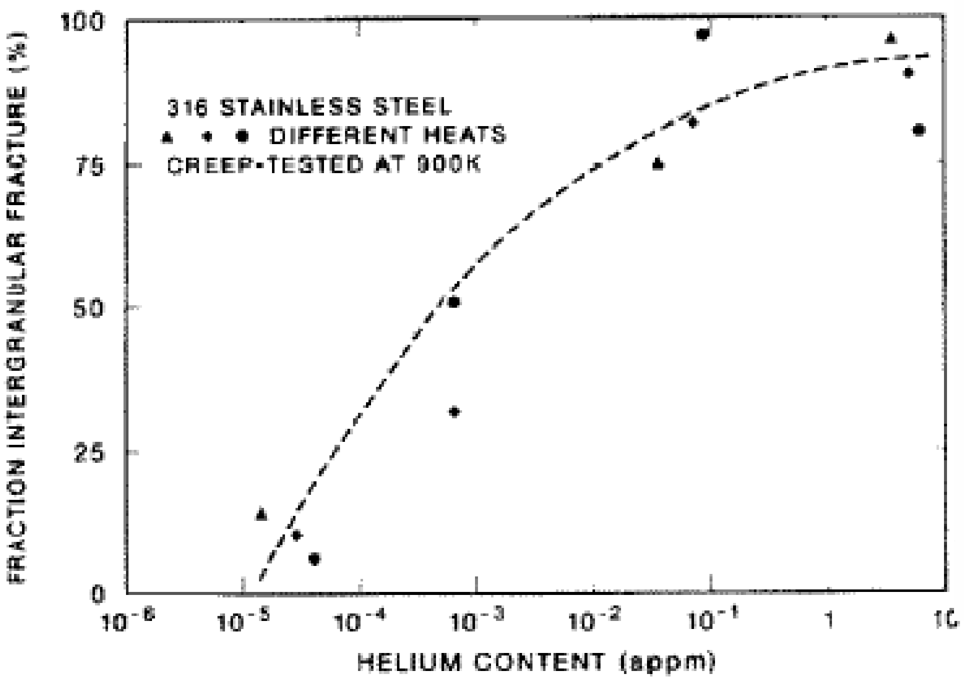
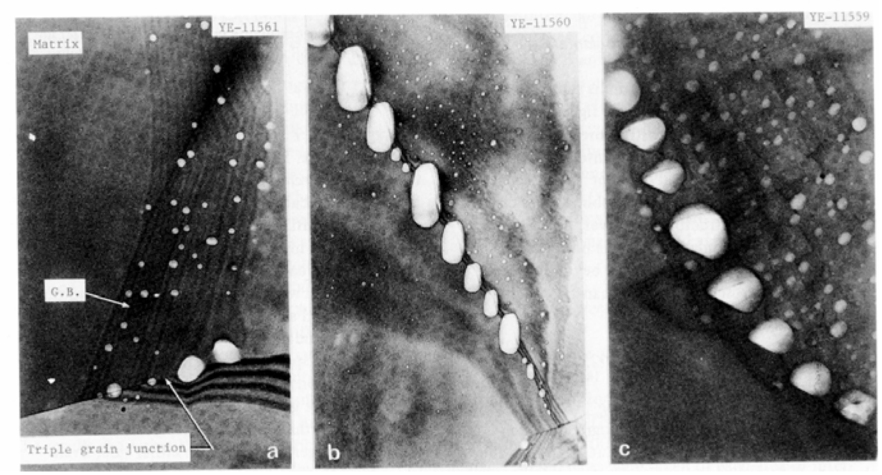


Fig. 2. Growth of helium bubbles in unstressed Fe–17 Cr–17 Ni specimens after annealing at 1023 K for (a) 2.88×10^4 s, (b) 6.48×10^4 s and (c) 21.60×10^4 s.

Embrittlement via Intergranular fracture is dependent on helium content, temperature, and strain rate

van der Schaaf & Marshall, 1983





19.6 MPa

Stainless Steel Qualification and Demonstration

- Desirable to generate SS316L-NaK corrosion data at reference design conditions, especially for welded joints
- Demonstrate capabilities to properly fabricate and operate NaK systems including ability to measure and control impurity levels
- Minimize He production by specifying nuclear grade 316L with very low B content
- Desirable to generate additional data on He embrittlement of grain boundaries at reference design conditions

Fission Surface Power System Materials Selection

Fuels

Structural Materials

Balance of Plant Materials

- Candidate Materials for Free-Piston Stirling
- Combined Irradiation and Temperature Effects in Sensitive Materials

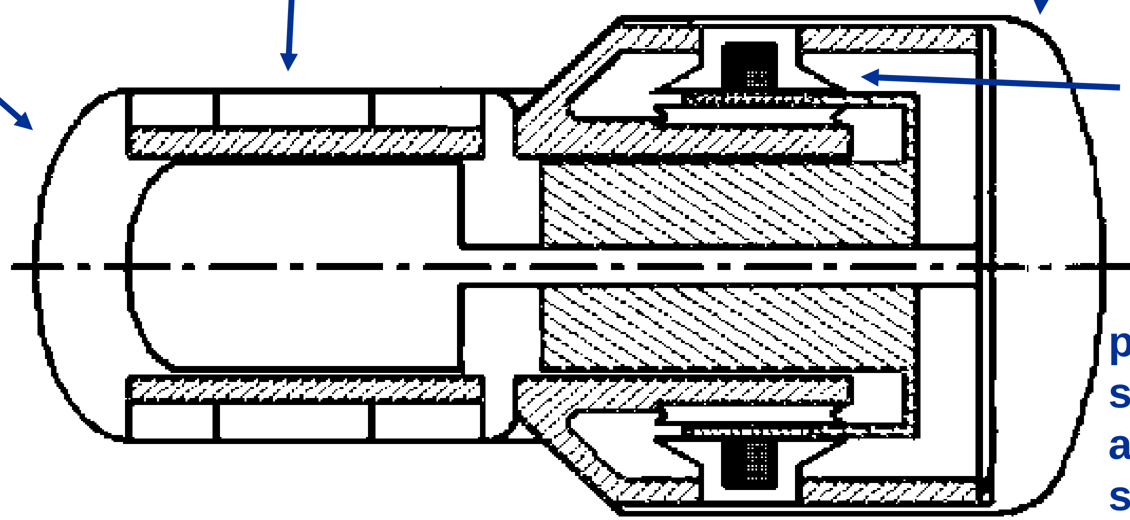
General Materials in a Free-Piston Stirling Engine

Polymeric and Magnetic Materials have lowest radiation tolerance

hot end pressure boundary, usually superalloy

porous metal regenerator

alternator pressure boundary, usually stainless steel



hard and soft magnetic materials, Cu wire, polyimide insulation

piston, rod & supports, Ti alloy and stainless steels

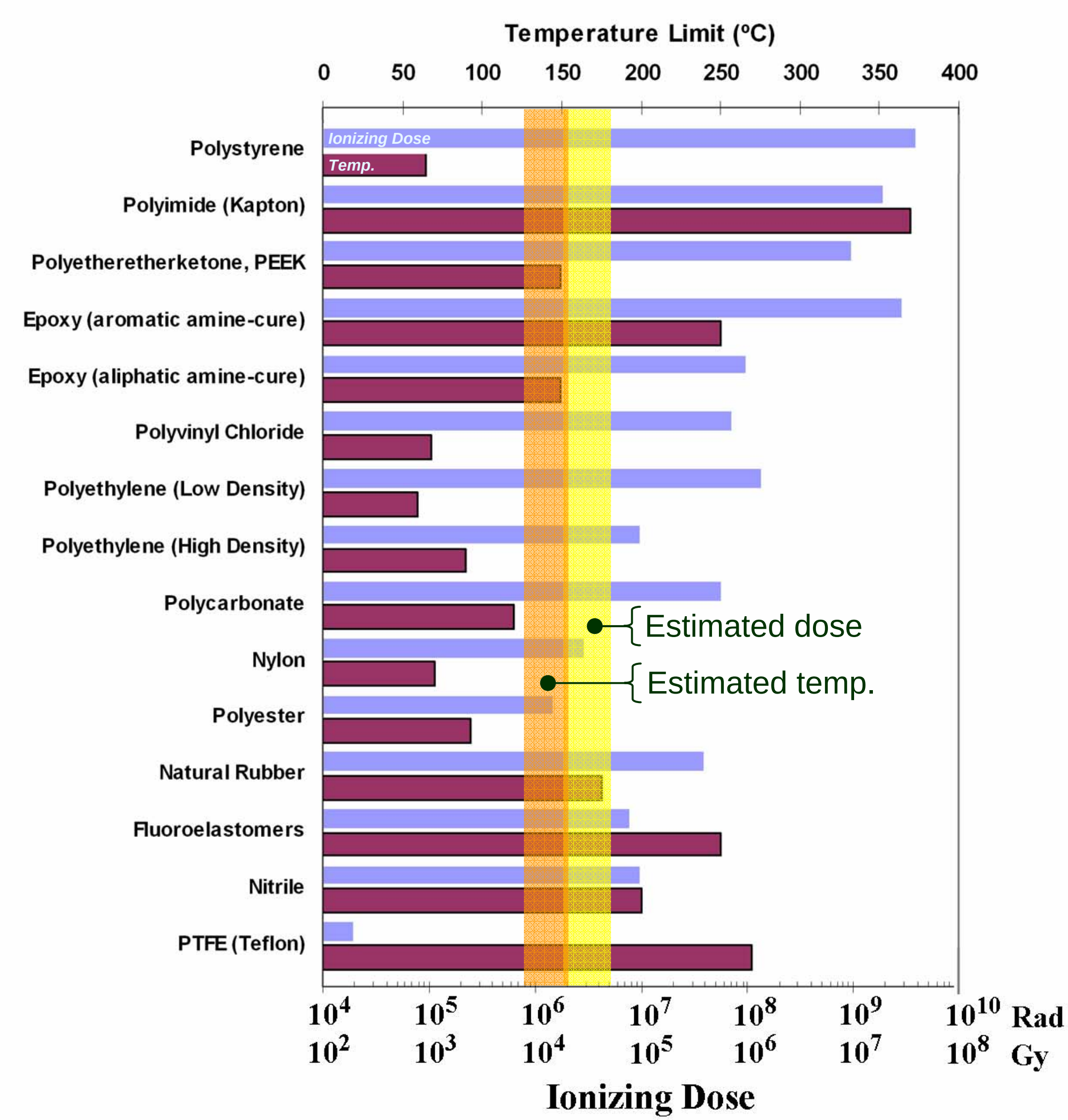
solid lubricants on displacer and piston shafts

epoxy adhesives holding magnets in place

various adhesives, feed through potting

elastomeric seal to minimize leakage between chambers

Combined Radiation/Temperature Environment Challenging for Polymeric Materials



Typical literature data based on tensile property changes for materials irradiated at room temperature, oxygen environment

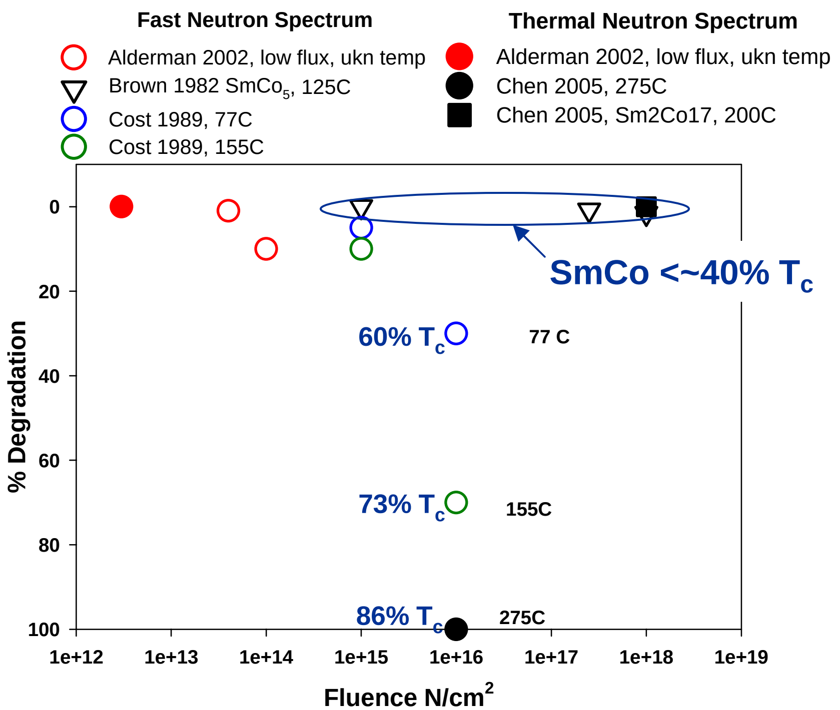
FSP environment is ~150°C and He gas

Properties will vary based on:

- Irradiation temperature
- Environment (air, vacuum, inert gas)
- Irradiation source
- Exposure duration
- Polymer chemistry including addition of stabilizers and fillers

Combined Radiation/Temperature Environment Affects Magnetic Permanance

- Studies suggest that localized thermal spiking combined with global elevated temperature can accelerate thermal-induced loss of magnetic permanance
- SmCo-type magnets have higher Curie Temperatures than NdFeB-type magnets and retain magnetic properties at higher absolute temperatures
- No outstanding performance issues have been identified for the use of SmCo in the expected Fission Surface Power System design



FSPS Reactor Material Selection Summary

UO_2 Fuel

- Extensive infrastructure and experience
- Low linear heat rate, temperature (~1000 K) and burnup (~1%) alleviates the need for UO_2 development, because factors such as thermal conductivity, fission gas retention, and swelling are low and well understood.

SS-316 Clad/Structure

- Extensive infrastructure and experience (peak temperatures <900 K))
- No significant irradiation damage: peak fast fluence of ~4e21 n/cm2 (retain ductility) and low thermal flux (void swelling)
- Biggest Downside – minimal system growth potential due to of temperature limitations.

UO_2/SS fuel pins used in similar environment in past reactors

- Tens of thousands of oxide rods were irradiated in the EBR-II and FFTF LMRs, in addition to all of the UO_2 infrastructure and experience in the LWR industry and NR.

FSPS Balance of Plant Material Selection Summary

- **Material radiation sensitivity assessment performed based on previous fission (SP100) and radioisotope convertor designs.**
- **Dose limiting components are polymeric and permanent magnetic materials in the alternator section of the Stirling convertors.**
- **Pre-existing data for polymeric materials suggest dose limits on the order of 10's of Mrad. Confirmatory testing underway.**
- **Pre-existing data indicate dose limits exceeds 10^{18} n/cm^2 for some SmCo-type permanent magnets**

Questions?