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REFERENCE REACTOR MODULE DESIGN FOR NASA'S LUNAR FISSION SURFACE POWER SYSTEM

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Abstract – *Surface fission power systems on the Moon and Mars may provide the first US application of fission reactor technology in space since 1965. The Affordable Fission Surface Power System (AFSPS) study was completed by NASA/DOE to determine the cost of a modest performance, low-technical risk surface power system. The AFSPS concept is now being further developed within the Fission Surface Power (FSP) Project, which is a near-term technology program to demonstrate system-level TRL-6 by 2013. This paper describes the reference FSP reactor module concept, which is designed to provide a net power of 40 kWe for 8 years on the lunar surface; note, the system has been designed with technologies that are fully compatible with a Martian surface application. The reactor concept uses stainless-steel based, UO_2-fueled, pumped-NaK fission reactor coupled to free-piston Stirling converters. The reactor shielding approach utilizes both in-situ and launched shielding to keep the dose to astronauts much lower than the natural background radiation on the lunar surface. The ultimate goal of this work is to provide a "workhorse" power system that NASA can utilize in near-term and future Lunar and Martian mission architectures, with the eventual capability to evolve to very high power, low mass systems, for either surface, deep space, and/or orbital missions.*

I. INTRODUCTION

NASA is evaluating options for human missions to the Moon and Mars. New and more capable power systems will be required to supply energy for sustained surface outposts. Lunar missions are expected to begin ~2020. Mars missions may occur later, possibly in the 2030s. Some potential surface power electrical loads include landers, habitats, in-situ resource utilization plants, mobility and construction equipment, and science experiments. Total power requirements could range from 10 kWe to more than 100 kWe.

Fission Surface Power (FSP) systems are well-suited to be the workhorse for this type of human exploration infrastructure. The power output of a workhorse system might be in the range of 20 to 50 kWe, with a lifetime of ~5 to 10 years. These power and lifetime levels allow near-term technology to be used to develop a relatively simple workhorse system. Furthermore, the step to higher powers and lifetimes in the future will be even smaller than the first; i.e. the step to develop and deploy the "simple" workhorse system.

II. CONCEPT AFFORDABILITY

One of the major challenges to the implementation of space fission power systems is development cost. In April 2006, NASA and DOE initiated the Affordable Fission Surface Power System Study (AFSPSS) to determine the design features and expected costs of a representative Fission Surface Power (FSP) system. A government study team with members from several NASA field centers and Department of Energy (DOE) laboratories evaluated technology options and design variables and selected a reference concept based on affordability and risk. The general design philosophy of the affordable study is contained in Poston and Marcille[1]. A high-level summary of the findings of this study is contained in Walz[2]. Numerous potential system concepts were evaluated and a handful were subsequently deemed to be good candidates for an affordable system. The selection of the NaK-cooled, SS/UO_2 concept as the reference system was made quickly to allow a quick transition to the more important task of costing an "affordable" system (development and flight). A summary of the comparison between potential AFSPS system concepts is provided in Mason[3]. A reactor technology comparison of some of the candidate affordable surface reactor concepts is provided in Poston[4].

The reference AFSPS concept that was used for costing was designed to provide a net power of 40 kWe for 8 years; a description of the overall power system is provided in Mason[5]. The concept uses a stainless-steel based, UO_2-fueled, NaK-cooled fission reactor coupled to free-piston Stirling converters. The concept was selected based on a preliminary assessment emphasizing affordability and low risk. The system is considered a low development risk based on the use of terrestrial-derived and flight-heritage reactor technology, high efficiency power conversion, and conventional materials. Low-risk approaches were favored over other options that might offer higher performance and/or lower mass. Low risk technologies are also essential for a system that is to last 8 years without maintenance; although there could be some opportunities for maintenance (planned or unplanned) depending on the infrastructure of the lunar outpost.

The affordable approach also requires a high emphasis on safety in the initial system design; not only because the safety program can be a substantial fraction of program cost for a nuclear system, but also because the uncertainty of the safety program cost is higher than any other component (because most of the forces that drive safety costs are non-technical and thus are hard to quantify). The reference reactor poses no significant radiological risk prior to reactor operation; therefore, the only nuclear safety issue is to avoid inadvertent criticality. The approach to preventing inadvertent criticality is to minimize voids in the core, which limits the reactivity insertion due to compaction, and to make the neutron reflector worth as much as possible, so that no other material besides the reflector material could cause criticality. Therefore, the only credible action that can cause criticality is the movement of the control elements into their operating position (which by definition must cause criticality, otherwise the system would not work).

The success of the AFSPS effort has led to the NASA Fission Surface Power (FSP) project. The concept presented in this paper represents the reference FSP design at the time of publication. The purpose of creating and documenting this design is to a) show that a useful and credible FSP system can be designed with existing technology, b) provide a design point for current and future NASA lunar (and Mars) architecture studies, and c) serve as a guide to the multi-year FSP technology development program, of which a key component is an end-to-end non-nuclear system Technology Demonstration Unit (TDU). Note: the FSP reference concept does not reflect an official decision or downselection for flight system development.

III. REACTOR DEFINITION AND REQUIREMENTS

The FSP system is defined by four major subsystems: (1) Reactor, (2) Power Conversion, (3) Heat Rejection, and (4) Power Conditioning and Distribution (PCAD). Thermal power is transferred from the Reactor to the Power Conversion and from the Power Conversion to the Heat Rejection. Electrical power generated by the Power Conversion is processed through the PCAD to the User Loads. The PCAD provides power for Power Conversion startup and for auxiliary loads associated with the Reactor and Heat Rejection. The PCAD also provides the primary communications link for command, telemetry, and health monitoring of the FSP system.

This paper describes the reference reactor module subsystem (often simply referred to as the "reactor") for a 40-kWe Stirling-based FSP power system[3]. The reactor module consists of several subsystems: the core, reflector, instrumentation and control, shield, heat transport, and system thermal protection. The reactor begins and ends at the interface where the working fluid enters and exits the power conversion system (PCS). Shielding is highly dependent on the architecture of the deployed system, so it is not focused on in this report. Shielding options for the current reference FSP system is discussed in Poston[6]. Apart from shielding (and potentially a change in PCS from Stirling to Brayton power conversion), the remaining aspects of the reactor module concept are essentially independent of system architecture. The top-level reactor performance requirements for the reactor are shown in Table I.

TABLE I

FSP Reactor Top-Level Performance Requirements

Parameter	Value
Thermal Power	185 kWt
System Lifetime	8 years
Average gamma dose in local region above shield	5 MRad
Average fast neutron fluence above shield	2.5e14 nvt

The requirements for the dose above the shield represent the average dose integrated over 8 years within the open volume; if some components require a lower dose, then they can be spot shielded and/or placed in the locations within this region that have a lower than average dose. As mentioned previously, the dose limits to the outpost are architecture dependent, and are not listed here. Also, there is interdependency between the system and reactor requirements; e.g. the reactor thermal power assumes a certain pump efficiency, thus a change in reactor pump efficiency would change the reactor thermal power requirement.

There are several lower-level requirements under the top-level requirements in Table I. Some of the imposed criticality requirements are shown in Table II.

TABLE II

FSP Reactor Criticality Requirements

Configuration	k-eff
Drums out (BOL-EOL, Cold-Warm)	>1.020
One drum stuck in (BOL-EOL, Cold-Warm)	>1.005
Drums in (BOL-EOL, Cold-Warm)	<0.950
Credible Accident Scenarios	<0.985

The first requirement in Table II is to ensure there is sufficient margin in the FSP reactor to maintain criticality throughout lifetime, in both warm and cold temperature conditions. A margin of 2% (i.e. k-eff = 1.02) is meant to cover uncertainties in nuclear cross sections, computational/code uncertainties, material density/isotopic uncertainties and geometry uncertainties. These, or similar margins will need to remain in place until nuclear criticals testing is initiated. The second requirement is to allow some margin (0.5%) for criticality in all cases even when one control drum is stuck in its lowest reactivity (stowed) condition. This requirement is imposed due to the lack of design specifics and data that could ensure that each control drum within the radial reflector ("radref") will move after launch and emplacement. The third requirement is to ensure that the reactor can be safely shut down during all transport and storage scenarios during Assembly, Test, Launch Operations (ATLO).

For the final requirement in Table II, the definition of credible accident scenario includes almost any conceivable (let alone credible) combination of environments and configurations. The three environments evaluated are: a) reactor internal voids nominal, reactor external voids dry sand, b) reactor internal voids fresh water, reactor external voids water, resting on concrete, and c) reactor internal voids sea-water, reactor external voids wet-sand. Dry sand is pure quartz at 64% theoretical density. Wet sand is 64% quartz, 36% seawater with a composite density of 2.06 g/cc. In all cases the surrounding material is neutronically infinite. The two reflector configurations evaluated are: 1) radref/drums and all surrounding material stripped off (i.e. bare vessel), and 2) radref/drums intact (although possibly compacted), drums stowed.

The environments and reflector states listed above lead to 6 evaluated cases (a1,a2,b1,b2,c1,c2) for every reactor configuration considered. There are 6 different off-design-basis core configurations analyzed: A) flood all internal pin gaps, including fission gas plena, B) compact radref to eliminate gap between vessel and radref, C) compact radref and vessel to force all pin/wire gaps to close, D) compact further to force pin/pin contact (P/D=1, wires crushed), E) compact further to crimp clad around fuel (eliminate fuel/clad gap), and F) compact further to eliminate all core void (pins deformed from cylinders to hexes). This provides 42 potential accident cases (i.e. Aa1, Aa2, Ab1, ..., Fc1, Fc2) that are evaluated for the design; in each of these cases k-eff <0.985, and in most cases k-eff <<0.985. The only cases that approach 0.985 are those with a flooded reactor and the radref/drums on. If necessary, k-eff can be lowered in these cases by increasing the thickness or arc-length of the B_4C poison layer in the drum. Note that each of the compactions assume symmetric radial compaction, while the ends of the core are constrained (thus preventing outward axial extrusion).

No requirements have been imposed on reactor feedback coefficients or nuclear kinetic parameters, but there are no serious issues anticipated in this area. The integral and major component reactivity feedback coefficients are simple and consistently negative for this class of reactor (a compact, fast spectrum system). Thermal-structural requirements are not formalized at this stage in the design process, beyond what might be considered standard engineering practice; e.g. primary stresses to 1/3 ultimate, 2/3 yield, creep limits of 1%, materials with at least 5% total elongation, temperature limits based on material/corrosion data, etc.

IV. FSP REACTOR TECHNOLOGIES

The most important factor to system affordability is the selection of the key materials and technologies for the reference system. The reference FSP system is a stainless-steel, UO_2, pumped-NaK cooled reactor with Stirling power conversion and pumped-water heat rejection. For this study, design decisions were heavily weighted towards safety. This is standard practice, but in the spirit of being affordable (at the "expense" of performance, e.g. power, mass, etc.) it is also a way to reduce both the magnitude and uncertainty of the safety program. The reference reactor poses no significant radiological risk prior to reactor operation; therefore, the only nuclear safety issue is to avoid inadvertent criticality. To simplify criticality safety, the system is designed such that there is no credible scenario that results in criticality other than the control elements moving into their operational positions. Beyond safety considerations, reactor design decisions were made to simplify development and lower cost (well-known materials, benign operation, simplified testing, etc.) as opposed to higher performance. The reasoning for several of the key reactor technology selections are given below.

IV.A. Nuclear Fuel Selection

The nuclear fuel (i.e. fissile material) is often the most important technology selection for a space reactor. The choice is highly dependent on the specific mass (kg/kW) and lifetime of the reactor. A strict specific-mass requirement leads to the selection of a high-temperature, high-uranium loading fuel that has good fission gas retention. Uranium-nitride (UN) has generally been the material of choice in this regime, although it still requires significant development and infrastructure cost. If specific mass is not a major driver, then UO_2 offers a significantly lower cost/risk solution. Uranium oxide is the most widely used reactor fuel material today. While commercial reactors incorporate this material in their fuel systems, the clad temperatures seldom exceed 600 K. However, in the past, tens of thousands of oxide rods were irradiated in the EBR-II and FFTF LMRs at clad temperatures of around 700 C.[7] In addition, low power (on the order of 100 to 200 kWt) and burnup (~1%) alleviates the need for UO_2 development, because factors such as thermal conductivity, fission gas retention, and swelling are much less important and are better understood (these issues become very important for a 1-MWt space reactor, but are relatively insignificant for a <200-kWt system).

A low temperature surface application also invites the use of two other fuels that may not require much development and fabrication cost – UZrH and metal fuels (UZr and UMo). UZrH was used in the only reactor ever launched by the US (SNAP-10A) and is still used extensively as a research reactor fuel throughout the world. However, UZrH was not selected for the FSP concept because of unproven long life at high temperatures and the recapturing/developing of the hydrogen retention barrier technology. Metal fuels were considered a potentially attractive low-cost path because of current work going on to refuel research reactors, plus the majority of space reactors launched (Russian BUK) have used metal fuel. A thorough comparison was made between UO_2 and U-10Zr for the FSP reference system[8], based upon the fuel performance characteristics required for this reactor system (i.e. low fuel burnup, 8 yr operating life, low power densities, and low values of neutron fluence).

The following general conclusions were drawn when comparing oxide and metal fuels for FSP application. 1) In steady state conditions, oxide fuel has a slight advantage because it provides more design flexibility to the types of systems being that could be considered for FSP. 2) In transient conditions, oxide fuel has a slight advantage because metal fuel will experience a slightly higher peak cladding temperature due to the low specific heat characteristics of the fuel; however, most anticipated transients modeled (i.e. loss of radiator, loss of power conversion system, loss of pump flow) showed the peak transient temperatures to be below temperatures of concern. 3) In terms of fuel reliability, neither fuel was seen as having an overall advantage in this area. Metal fuel has the advantage of the Na between fuel and clad to mitigating potential fuel vibration damage during launch and has no potential for oxygen contamination with fuel pin failure. Oxide fuel has the advantage of less fuel swelling and fission gas release, and a larger burnup database. 4) In terms of system reliability, oxide fuel has an advantage because of the reduced need for significant reactivity control (due to fuel swelling) late in the operating lifetime and it provides a longer and more graceful reduction in power and temperature in the case of control element failures. 5) With respect to acquisition cost, metal fuel has a slight production cost advantage over oxide fuel, because the process is simpler and has a much smaller fabrication floor space footprint.

As a result of this assessment, oxide fuel was selected as the preferred fuel form for the FSP reactor system, recognizing that U-10Zr and UZrH could be affordable alternatives depending on the final requirements of the system. Note also that the fuel selection includes the specification of BeO pellets on each end of the fuel column to serve as axial neutron reflectors. More detail on the fuel fuel specification, performance, and test plan can be found in Porter[9].

IV.B. Structural Material Selection

Structural material selection (most notably the fuel clad) goes hand-in-hand with the fuel selection and development. In many cases it is better to speak of the fuel and clad in tandem as the "fuel system", but in this case it is discussed separately since it is highly desirable to have the fuel clad be the same material as the remainder of reactor structure (so that there are no dissimilar metals in contact with each other or the reactor coolant). The demands placed on a space reactor structural material are highly dependent on temperature, power, and lifetime. For a space reactor several attributes can be extremely important: yield/ultimate strength, creep strength, ductility (especially under irradiation), fracture toughness, chemical compatibility, density, neutronics, modulus of elasticity, ductile-to-brittle transition temperature (especially as it pertains to launch temperature), etc. These attributes, in combination with the availability, fabricability, weldability of the material, can be extremely challenging.

In previous space reactor programs, the system specific-mass requirement (as it translates to temperature) has often led to a refractory development program, which has led to high cost. A report by Zinkle and Wiffen[10] discusses many of the issues associated with using refractory metals; these materials do not lend themselves to a low-cost, low-risk reactor development program. In order to design an attractive surface reactor system, a structure temperature of at least 800 K is probably needed, which eliminates some of the simplest solutions; however, if the peak temperature can be kept <900 K, it allows for the use of well established stainless-steels (304 and 316), which are regularly produced and are fabricable into the types of parts and structures a surface reactor would need. The use of such a material would allow prototyping and testing to begin very quickly and at low cost, as has been demonstrated at the Early-Flight Fission Test Facility (EFF-TF) at the NASA Marshall Space-Flight Center (MSFC). If future requirements dictate that SS304 or SS316 are not found acceptable (perhaps because of ductility concerns near 900 K), then there are other options that may also not incur significant development cost: e.g. HT9, Hastalloy, Inconel.

Irradiation damage to the structural material is often one of the most important concerns of a space reactor program. If the displacements-per-atom (dpa) to the material in the FSP can be kept ~1 dpa (fast fluence on the order of 2e21 n/cm^2, depending on the material), then most steels or super-alloys will not experience a significant negative change in properties. Data from the "Nuclear Systems Materials Handbook"[11] indicates that SS-316 will retain adequate ductility at the calculated FSP peak fast fluence of ~5e21 n/cm^2. Thermal neutron irradiation can sometimes cause problems by producing gas (void swelling) in the metal, but this should be negligible for the FSP system as well (although if this does become an issue, then ferritic or super alloys may be desirable).

In addition to irradiation damage to the material (by dpa, gas production, etc.), power and lifetime can put more demands on the clad. Increased fission gas production and release make ultimate and creep strength a major concern, increased fuel swelling can make clad ductility and fracture toughness a major concern, and increased thermal stress can make ductility and fatigue resistance very important. If the power and lifetime are kept within the range of the current FSP concept then almost all of these issues can be eliminated. In this case, the biggest material development cost could be associated with the operating environment – Lunar or Martian, in contact with regolith or not, etc. To some extent this development could be shared with the overarching mission/program, but temperatures of the reactor system may offer the biggest challenge (although if needed a lower temperature shroud could be used to minimize the temperature of the materials seeing the local environment).

As a result of this assessment, Stainless Steel 316L was selected as the preferred structural material for the FSP reactor system, recognizing that other steels or super alloys could be affordable alternatives depending on the final requirements of the system.

IV.C. Coolant Material Selection

The coolant for the reference design is NaK-78. This selection also goes hand-in-hand with the structural material selection of SS-316 (both in terms of chemistry and allowable operating temperature window of <900 K). NaK is baselined because there is considerable experience with this coolant, including all of the space reactor systems ever flown (SNAP-10A, BUK, and TOPAZ). The primary reason NaK is baselined (over Na or K) is its low freezing point of 262 K. All space reactor flight heritage has been to "launch-liquid, stay-liquid", and NaK makes this relatively simple. NaK is liquid at room temperature, and radiative heat losses at 262 K are small enough to require minimal heating (if needed) in cold space or shaded regions. The proposed system shroud cooled by H_2O heat pipes (see description in later paragraph) could be insulated to prevent freeze for a much longer time without any heating. The use of a coolant that is liquid at room temperature also simplifies testing operations because no freeze/thaw cycles are incurred when a test apparatus needs to be shut down (maintenance, change-outs, down-times, etc.).

One drawback of NaK as compared to potassium is coolant activation. Current calculations have shown that primary NaK coolant flow directly to the power conversion system should provide an acceptable dose to the PCS and other components (depending on configuration and requirements); however, since an intermediate pumped-loop is baselined, then coolant activation is even less of an issue. As compared to sodium, NaK has higher vapor pressure and lower specific heat, which result in a thicker vessel and higher pressure drop respectively, but these disadvantages will probably not outweigh the freeze-thaw advantage of NaK in this application (plus Na has a coolant activation 3 times that of NaK).

IV.D. Radial Reflector Material Selection

The radial reflector ("radref") material has a huge impact on the FSP system; i.e. a small, compact fast reactor. A very "high-worth" reflector is needed not only to keep system size small, but also to make launch safety accidents relatively easy to accommodate. The radref specified for most space and surface reactors is Be or BeO

– all other candidate materials do not have a reactivity worth high enough to allow launch accident criticality requirements to be met without internal safety rods.

Beryllium and BeO have rather complex behavior at high temperatures and neutron fluences. Fortunately, if design requirements can allow the radref temperature to be kept relatively low (~800 K) and the fluence to be kept low (<~1e20 n/cm^2, where E>100 keV) with shorter power and lifetime, then many concerns about operational Be and/or BeO performance can be alleviated (i.e., gas production, swelling, embrittlement). The current FSP system requirements appear to be within the envelope for which Be material performance should be acceptable[12]. The other advantage of a relatively low power, short lifetime is less chance of control elements bowing/sticking/failing (because of lower fluence and lower thermal stress).

The reference selection for the FSP concept is beryllium. Be is generally a heavier option than BeO (because of lower macroscopic scatter cross section), but Be is less susceptible to radiation/temperature induced swelling and cracking. Also, Be can maintain the thermal conductivity required to transport power out of the system; including power deposited directly into the radref and power radiated from the reactor vessel. One drawback of Be is that it produces more power peaking in the outer fuel pins (due to a more thermalized spectrum returning from the radref), but thermal-structural analysis has shown this peaking to be acceptable.

IV.E. Reactivity Control Mechanism Selection

The FSP reactor is rather unique in both its reactivity requirements and the options available to control reactivity. First, the flight system is not subject to reactivity requirements imposed on terrestrial systems (e.g. diverse and redundant shutdown), although ground test units will be subjected to the applicable terrestrial standards. Second, the FSP system is very amenable to external reactivity control, either via leakage or absorption, because of the high worth of the radref. Third, the lower power of the FSP system allows for a design that meets criticality requirements for all potential accident scenarios without an internal safety rod. Therefore, FSP reactor control can be accomplished with only one relatively simple form of external reactivity control.

External reactivity control can be accommodated by changing the neutron leakage rate and/or absorption rate in the radref. Both options have been deployed on previous space reactors, generally the reason for using a leakage based system has been lower mass. For a surface fission system, leakage would significantly increase shielding mass (because some type of 4-pi shielding is needed), and leakage would not be worth quite as much neutronically because of back scatter off of other components. Leakage would also create thermal-balance and component irradiation issues that would be variable depending on the position of the control elements. Therefore, control via neutron leakage was not considered for FSP.

There were two options considered for FSP control elements – rotating control drums or sliding poison slats between the vessel and radref. Reactivity evaluations found that both methods were equally effective in providing the required reactivity control, so the trade was based on thermal, mechanical, reactivity feedback, and heritage issues. Each concept has unique thermal issues; a drum system requires some of the Be to run hotter because of the radiation gap between the drum and the radref, while the sliding poison presents unique thermal balance concerns because it serves as a 2-radiation-gap shutter, and the thermal design must account for any combination of shutter positions (i.e. various shutters ranging from fully open to fully closed). The B_4C poison in the sliding option also runs very hot when any poison is next to the core, which results in large temperature gradients and potential bowing of the thin, long element. A drum with the poison facing towards the core has similar issues, but has been found to be able to accommodate the thermal stresses very well. Each concept also has unique requirements with respect to bearings and mechanisms, but no net discriminator was identified in this area.

One discriminator that was identified was that sliding poison introduces additional reactivity feedback issues that could complicate operation and control. A heatup of the slider poison introduces a significant positive feedback coefficient because the reduced density of the B_4C will increase the core's view of the reflector. Also, positional changes of the slider due to thermal expansion could also be significant (in the operating position, the slider is worth ~30 cents/cm), and the nature of the feedback could be positive or negative depending on mechanical design. Finally, due to the high power deposition in the slider, these additional reactivity terms will be very sensitive to power.

Another discriminator between rotating drums and translating poison is flight heritage. Every successful space reactor has utilized rotating control elements. Technology was developed for sliding reflectors in the SP-100 program: however, the glide length was considerably shorter. A drum system does not require a mechanism to translate the rotational motion from a motor to the linear or angular motion of a reflector element. Also, a sliding system likely will require larger, higher-power motors because of the need to lift heavy elements (even more so in the higher gravity of ground testing).

As a result of this assessment, Be/B_4C control drums were selected as the reference control elements for the FSP reactor system, because of heritage, reactivity feedback, power peaking, and system integration concerns (for a 4-pi shielded system), recognizing that a sliding poison system could be made to work as well.

IV.F. Pump Selection

Given the specification of a pumped-liquid-metal system, the pump may be the most important reactor technology selection. At the highest level, two basic methods may be considered to circulate the liquid metal: mechanical and electromagnetic (EM) pumps. EM pumps have numerous advantages; there are no shaft seals and therefore may be totally sealed, they have no moving parts other than the liquid metal itself and therefore are free from wear and require no bearing lubrication. Because of these advantages, EM pumps have been selected for nearly all liquid metal pumping applications. Thus, mechanical pumps were omitted from consideration as it is desirable to avoid wear issues, mechanically induced vibrations, and sealing difficulties associated with incorporating reciprocating or rotating machinery into a liquid-metal flow system. The biggest drawback of EM pumps is electrical efficiency, but the performance gains of a mechanical pump do not justify the increased technical risk.

EM pump concepts may be divided into two categories: induction pumps and conduction pumps. The induction pump concepts may be further categorized by configuration: annular, flat and helical. The conduction pumps are either AC or DC powered, and the DC pumps are further divided into externally-powered and self-powered, i.e., thermoelectric, pumps. EM pumps in each of these categories and subcategories have been designed, built, and successfully operated to circulate liquid metals for broad ranges of applications. Of particular interest for this assessment are the Liquid Metal Fast Breeder Reactor (LMFBR) program pumps used to circulate Li, Na, and NaK. Based on prior experience and recent evaluations, an Annular Linear Induction Pump (ALIP) was selected as the FSP reference. The ALIP is also the lightest in weight of the induction pump family and has the simplest duct design. The design, fabrication, and testing of ALIPs is a major part of the current FSP technology program. More detail on the ALIP pump selection and development can be found in Werner[13].

IV.G. Other Technologies

This section has focused on some of the reactor technology selections that strongly impact development risk and cost; however, there are many other FSP technologies that have been evaluated and/or selected. Many of these technologies are discussed later in the reactor design description section. The status of some FSP technologies that are not part of the reactor module, e.g. power conversion and heat rejection, can be found in Mason[14].

V. REACTOR DESIGN METHODOLOGY

The primary design tool for the FSP reference reactor is MRPLOW[15]. MRPLOW creates several MCNPX[16] input files to perform nuclear analyses and generate power depositions for use in the thermal analysis. A spreadsheet-based tool then examines the heat transfer, thermal-hydraulics, and fuel-pin structural performance. Iterations are performed with MRPLOW to arrive at final convergence between the nuclear and thermal-mechanical design.

The nuclear design of the reactor core is initially focused on meeting the requirements in Table II (i.e. maintaining sufficient criticality throughout life as well as having sufficient shutdown margin to ensure subcriticality prior to deployment). MONTEBURNS[17] depletion calculations are run to evaluate the burnup reactivity and confirm the as-designed end-of-life reactivity margin. The temperature defect and reactivity coefficients are calculated with MCNPX using multiple temperature dependent input decks created by MRPLOW. Reactivity coefficients for FSP-type concepts are consistently negative and essentially constant over the FSP operating temperature range. The primary contributors to loss of reactivity with temperature are (1) thermal expansion of the fuel, reflector and structures (i.e. increased leakage), (2) Doppler broadening of parasitic absorption cross sections (i.e. increased absorption relative to fission). The nuclear design of the system also includes shielding design and analysis. MRPLOW creates shield geometries and compositions based on user input, which includes the configuration of the system on the surface (e.g. buried in regolith with radiator deployed above system).

Thermal-mechanical design is performed primarily with a spreadsheet-based surface reactor engineering tool.[18] These calculations size the fuel pin based on the input cold-BOL and warm-EOL gap requirements, in conjunction with design requirements such as thermal power, lifetime and temperature. Thermal expansion and irradiated material property data for UO_2 and SS316 are incorporated to evaluate the generated fuel system stresses and clad strain. The strain calculation includes the effects of both thermal and irradiation stresses on the clad, as well as hoop stress due to internal pressure from accumulating fission gases within the free volume of the pin. A fission gas release correlation is used to determine the molar gas quantity produced as a function of peak pellet burnup, temperature, and time. The design tool adjusts the fuel pellet/clad gap, fission gas plenum height, and/or clad thickness to preclude pellet/clad interaction at EOL and maintain the clad below specified stress and strain limits. For the FSP reactor, the fuel system performance is extremely benign compared to conventional power reactors. The spreadsheet also contains macros that perform core thermal-hydraulic analysis based on the power peaking factors received from MRPLOW. In addition, detailed thermal and structural analysis is performed with commercial codes on individual components and system structure as needed (e.g. a detailed thermal-structural analysis has been performed for the radref and drum assembly).

The design methodology also includes a simple system thermal-balance and transient analysis. MCNPX provides heating rates and reactivity coefficients that are used by FRINK[19] to evaluate system temperatures during steady-state and simple bounding transients. In steady-state, the key parameters generated by FRINK are the radref temperatures and the overall power balance of the system. Transient analyses investigate how the system responds to reactivity insertion, loss of heat sink, and loss of flow. These analyses provide confidence (or lack thereof) that the system can be designed to meet any anticipated design basis event in a simple and robust manner. A more sophisticated transient model will be discussed later which has been developed to evaluate complete system transients.

VI. REACTOR DESIGN DESCRIPTION

The FSP reference reactor is designed to provide ~185 kWt to the PCS via pumped NaK coolant, and is designed for a full-power lifetime of 8 years. As stated above, this system has not been selected or determined to be the best choice for an FSP flight system; furthermore, the concept has not been optimized or been applied to an adequate design basis. For this reason, the description of the concept is kept at a relatively high level, although in most areas more detailed work has been completed.

Many of the design choices for the reference system were made to simplify core neutronics and dynamic response, because it can simplify control as well as the types and level of testing that is required. The neutron spectrum in the core is very hard, which can eliminate

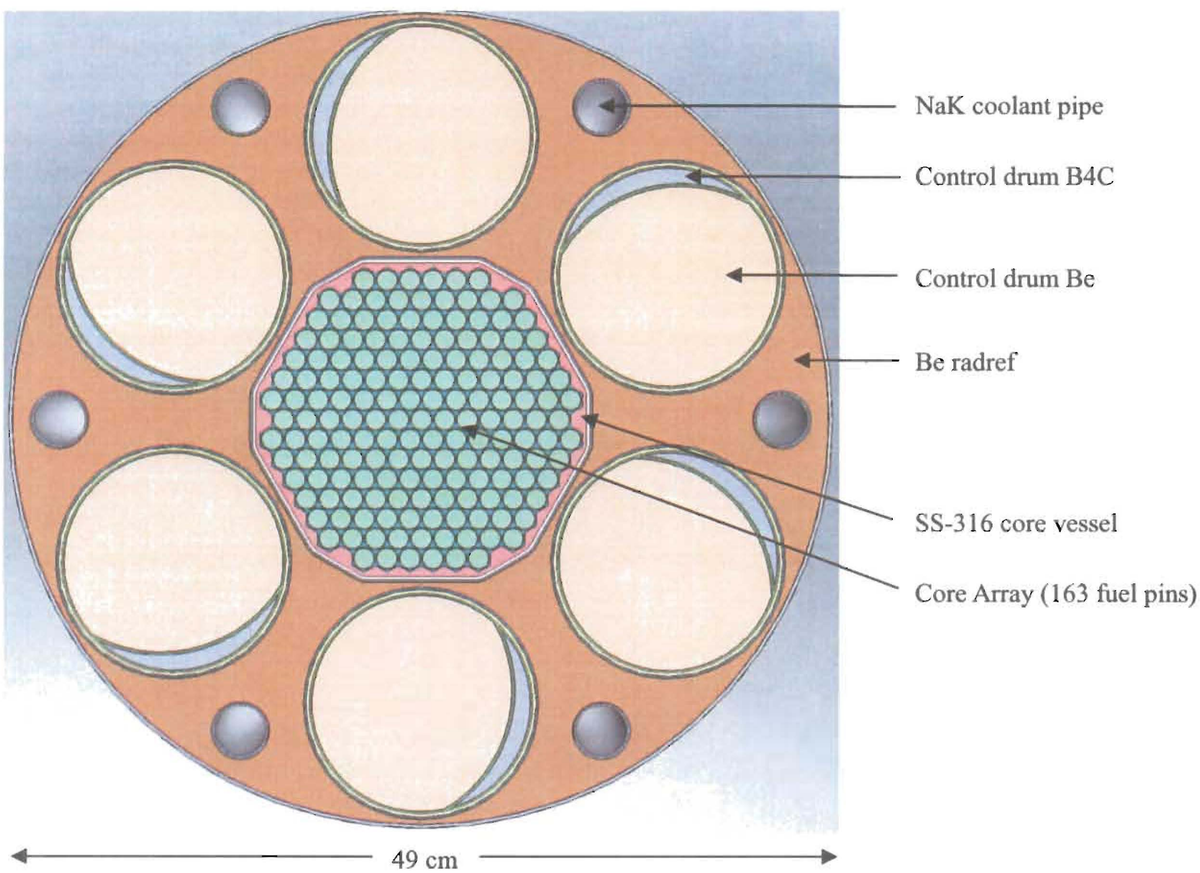

Fig. 1. Plan view of core and radial reflector assembly.

many potential reactor issues, e.g. there are no reactivity effects caused by buildup/decay of fission products (most notably "Xe poisoning"), local heterogeneous reactivity effects, moderator temperature, etc. Cross sections are well understood in the fast spectrum (most importantly U-235), and the effect of changes in cross section with temperature are small. The compact geometry, in combination with the very hard spectrum, creates tight neutronic coupling within the core. Power and flux peaking factors are relatively low; the overall fuel peak-to-average power density is 1.50, the peak-pin-to-average-pin power is 1.23, and the average axial peaking factor is 1.22. The tight coupling also makes it unlikely there could be isolated local reactivity effects and/or spatial neutronic instabilities. As mentioned previously, one of the most significant benefits of the fast spectrum is that it allows the system to be designed without the need for in-core shutdown rods. An additional benefit of a reactor with these characteristics is that the use of point kinetics (which predicts transient reactor flux/power response in a lumped parameter model) has little uncertainty. This greatly simplifies transient modeling and predictions, making it easier to qualify calculations and benchmark to warm-critical experiments. This also makes power input to a resistance-heated core simulator much easier, making non-nuclear testing more realistic.

VI.A. Core/Reflector Assembly

Figure 1 shows a radial cross section through the center of the FSP core/reflector assembly. Figure 2 shows a 3D axial cross section. The majority of the neutronic, thermal, and mechanical design and analysis of this assembly is well beyond the scope of this paper. The following paragraphs provide a brief description and some of the key parameters.

Fuel Pins: The core contains 163 SS/UO_2 fuel pins with a 1.28 cm pin OD and a SS-316 clad thickness of 0.051 cm. The fuel meat is assumed to be 94% theoretical dense, 93% enriched UO_2, with a nominal 0.0065 cm assembly gap between the fuel and clad (cold/BOL). The cold/BOL height of the fuel column is 48 cm. Within the fuel pin there is 9 cm of BeO pellets on each side of the fuel pellets to serve as an axial reflector. There is a small expansion region at the top of the pin, which also serves as a fission gas plenum; however, the fission gas production/release at this burnup and temperature does not cause stress/creep concerns in the cladding. The operating conditions of the fuel are very benign relative to past reactor experience. The peak fuel burnup is 1.2 % (FIMA – Fissions per Initial Metal Atom), the peak power density is 32 W/cc, and the peak linear heat rate is 3.4 kW/m. There is no anticipated pellet clad mechanical interaction (PCMI) throughout the life of the reactor because the gap grows with temperature (SS-316 expands at a greater rate than UO_2) and fuel swelling is small (~0.8% in the peak pellet). The peak cladding temperature during nominal operation is 860 K (average clad temperature = 828 K). The peak cladding fast fluence is 5.0e21 n/cm^2, which is below the threshold of significant ductility loss. The peak center-line (C/L) fuel temperature during nominal operation is 950 K (average fuel C/L temperature = 917 K, overall average fuel temperature = 865 K). More information on the fuel, including fabrication and lifetime issues, can be found in Porter[9].

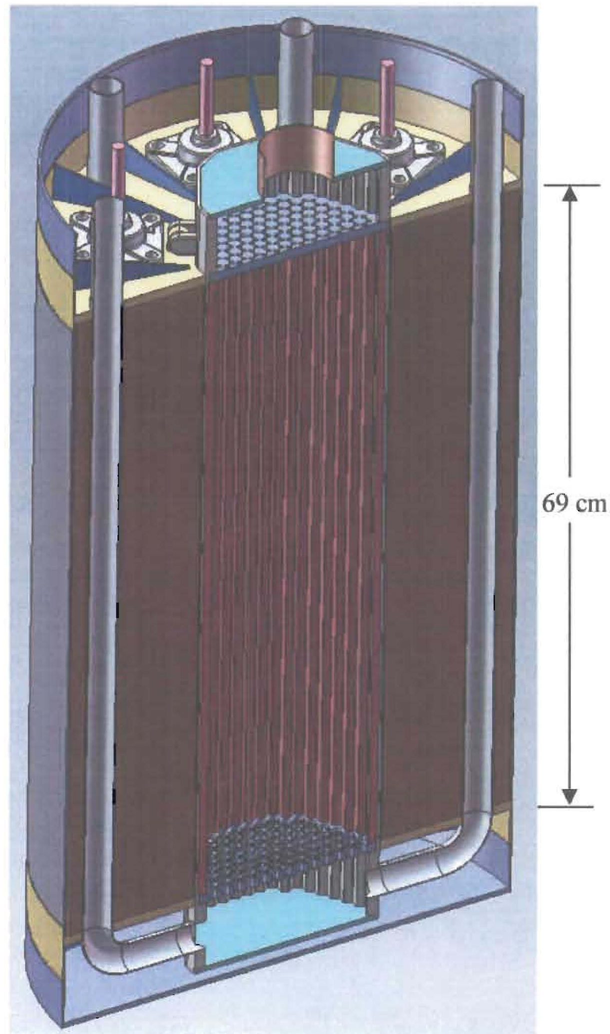

Fig. 2. 3D view of core/radial reflector assembly.

Core Geometry: The reference core uses a triangular pitch pin-lattice arrangement. A tie-structure holds the pins axially and radially on one end, but allow the pins to float axially on the other end. The low power allows pin spacing to be very tight (P/D = 1.04), which is beneficial for two reasons: (1) it allows the void fraction to be low enough so that internal safety rods, or other measures, are not needed to maintain flooded subcriticality, and (2) it keeps the potential reactivity effects of pin movements small, even if the spacing mechanisms should fail. Wire wrap is used to help maintain spacing and promote interchannel mixing (although preliminary analysis shows that mixing between channels is not needed in this system). The assembly clearance between the wire and adjacent pin is 0.0076 cm so that ample flow can be provided even if pins are clumped together, and again, to keep reactivity effects small (on the order of cents). Flow is highly turbulent (Re=15,000), and the film temperature drop in the coolant is only a few degrees K, so the design is very tolerant to any thermal-hydraulic changes caused by pin movements.

Vessel and Plenum Geometry: The reactor vessel is 0.25 cm thick SS-316. A dodecahedron vessel is used to allow the radial reflector and control drums to be closer to the fuel, which provides significantly more reactivity swing for postulated accidents (and also reduces mass). The vessel thickness was sized to meet 1/3 ultimate and 2/3 yield stress criteria during the postulated worst-case transient (unmitigated loss-of-flow). If structural or fabrication issues arise with the dodecahedron vessel, a cylindrical vessel could be used at the cost of reactivity margin and mass. The peak vessel fluence is well below significant SS-316 damage thresholds. There is no coolant downcomer within the reactor vessel. The flow is fed to the bottom plenum of the reactor via piping that travels through the radial reflector (as seen in Fig. 2). This allows the ex-lattice flow area and hydraulic diameter to be large (minimizing pressure drop), and more importantly brings the radref and control drums closer to the core and removes a potential flooded region in the reactor (making criticality requirements easier to meet). The primary drawback of this approach is a more complicated core/radref integration (depending on where the shield, reflector, and feed-pipes would integrate in a downcomer design). At the current level of mechanical design, the assembly appears relatively simple for either the pipe-downflow or downcomer configuration, but this feature will depend on more detailed design and analysis.

Radial Reflector and Control Drums: The radial reflector is Be metal in a SS-316 can. Be is generally a heavier option than BeO, but Be is less susceptible to radiation/temperature induced swelling and cracking. The Be temperature and fluence in the baseline design is low enough that there should be no significant degradation, and data suggests that swelling will be <1%. The radref is 49 cm in diameter, which results in maximum thickness of 15.1-cm (from the smallest vessel flat). The SS-316 can ranges from 0.1 cm to 0.2 cm in thickness depending on the location. Control drums are baselined because of simpler integration into a 4-pi shielded system and previous heritage with external rotational control mechanisms. The drums are 13.5 cm in diameter, and are also composed of Be in a SS can, with a 112 degree banana-shaped arc of B_4C absorber to provide control. The maximum thickness of the B_4C within this arc is 1 cm. Each drum is baselined to be powered by a dedicated motor and drive mechanism. A nominal 2-mm gap is baselined between drums and reflector to prevent contact that might hinder drum movement. A thermal-structural analysis has been performed for the entire radref/drum assembly and it indicates that there should not be significant bowing or deformation. This analysis shows radref temperatures are <800 K; however the peak temperatures in the drums approach ~900 K, which may or may not be a problem with the current reference configuration depending on more detailed analysis (temperatures can be reduced by various changes if needed).

VI.B. Reactor Heat Transport

The function of the pumped-NaK heat transport system is to deliver reactor power to the Stirling engines. The NaK loops operate at relatively low pressure (~140 kPa) and at temperatures (<850 K) for which corrosion should not be a problem. The major components of a reactor heat transport system are pumps, accumulators, piping, and possibly intermediate heat exchangers (IHXs). Note that NaK-to-He heat exchanger at the Stirling hot head is considered part of the PCS system; the heat transport system (and reactor module) end at the NaK pipes that feed the Stirling engines. A schematic that shows the portion of the reactor heat transport system above the shield is shown in Fig. 3.

Number of Loops: One of the major design trades for the FSP is whether to flow NaK directly from the core to the PCS, or to utilize intermediate heat exchangers (IHX) and flow loops. The benefits of the intermediate loop system are that it 1) potentially mitigates the system consequences of the breach of the He-to-NaK interface at the Stirling heater head, 2) provides a good method to reduce activated NaK dose to above shield components, 3) provides more flexibility in the flight unit Assembly, Launch and Test Operations (ATLO), and 4) allows the delta-T across the Stirling head to be adjusted separate from the delta-T across the core. Some of the detriments of the intermediate loop system are that it 1) adds system complexity, in the number of components, sensors, power feeds, etc., 2) adds several potential failure modes because an entirely new subsystem is added (these introduced failures have to be weighed against the positive reliability affect of possibly protecting the primary loop from a He-to-NaK breach, and thus allowing 50% power), 3) complicates system startup and operation (including the need for more time and electricity for startup), 4) increases the chance of NaK freeze causing system failure, because the intermediate loops might be significantly harder to prevent from freeze, 5) complicates system integration and the number of tasks that need to be completed during ATLO, and 6) adds significant mass to the system (~500 kg) due mostly to the additional hardware (pumps, accumulators, IHXs), but also because the intermediate-loop system requires a higher power reactor, PCS, and radiator (the additional temperature drop through the IHX decreases efficiency and the total pumping power is higher).

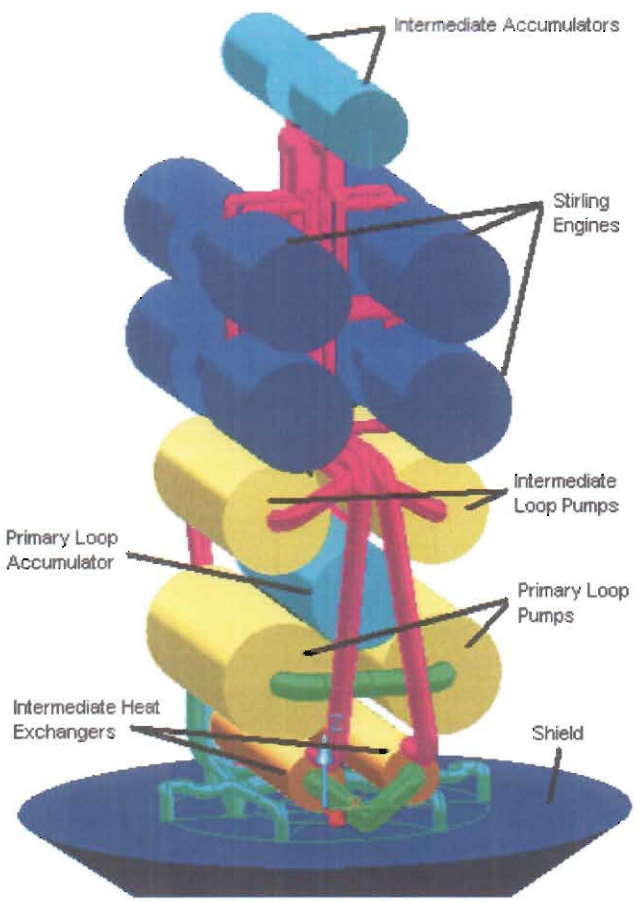

Fig. 3. Layout of FSP components above shield.

For the reference system, it was decided to include two 50% power intermediate loops, mostly because of the uncertainty of the heater head He-to-NaK failure probability and how it might propagate. The preferred approach to this issue is to design the Stirling heater head so that a He-to-NaK breach is an incredible failure (or at least a small fraction of Stirling engine failures). If this is not practical, then the focus will have to be on whether or not this failure will induce a failure in the primary loop as well (including the option of designing pressure relief into the system).

System Flow Configuration: The reactor primary loop delivers 185 kWt via heated NaK to a pair of intermediate NaK-to-NaK HXs. The primary loop has a NaK flow rate of 4.3 kg/s, a hot temperature of 850 K, a cold temperature of 800 K, and an estimated loop pressure drop of 20 to 25 kPa (the pressure drop will depend significantly on final loop configuration). The primary NaK coolant flows up the core through the interstitials between the fuel pins. Flow enters then exits the upper plenum into a single pipe that flows straight through the upper shield. A straight pipe simplifies fabrication and integration, and radiation streaming is not a problem given the current configuration and shield requirements (because the solid angle of a 1-mm gap is very small over a 1-m run of piping). The primary flow then splits into 2 50% pipes and passes in parallel through the IHXs (through the tube side of a tube-and-shell heat exchanger). The flow then recombines into a 100% flow pipe and passes through the 2 primary pumps in series. After a pass by the accumulator (which is offset from the flow by a tee), the flow then splits into 6 smaller pipes that travel back down through the shield. These pipes then neck down and continue straight through the radref and then bend inward to feed the reactor lower plenum. While straight pipes simplify fabrication and integration, they can also exacerbate thermal expansion/stress issues in the flow loop. If expansion stresses make mechanical design problematic for the flight system, more "give" will have to be incorporated into the loop.

Each intermediate loop delivers ~93 kWt via heated NaK at 820 K to two Stirling converters. The intermediate loops have a NaK flow rate of 3.5 kg/s, a hot temperature of 820 K, a cold temperature of 790 K, and an estimated loop pressure drop of 9 to 12 kPa. The intermediate NaK flow proceeds from the shell side of the IHX, splits into two 50% flow pipes and flows to 2 Stirling engines in parallel (technically each Stirling engine is a pair of opposed Stirling engines, but functionally they serve as one unit). The flow passes through the Stirling heater heads, recombines into a full flow pipe and then passes by the intermediate volume accumulator. Next, the flow passes through the intermediate loop pump, and then back to the shell inlet of the IHX.

ALIP Pumps: There are 4 total pumps in the reference system: 2 pumps in the primary loop (each capable of 100% flow for redundancy), and 1 pump in each intermediate loop. The characteristics of the primary ALIP pump is listed in Table III.

TABLE III

FSP ALIP Primary Pump Parameters

Pump Characteristics	Value
Weight	82 kg
Length	69 cm
Diameter	24 cm
Operating Temp	800-825 K
Nominal exit Pressure	194 kPa
Developed Head Pressure	58-68 kPa
Fluid Flow	4.3 kg/sec
Inlet / Exit pipe diameter	5.1 cm

The key design trade considered in the design of the FSP pump included maximizing pump efficiency while keeping the overall size of the pump to a manageable level. Other considerations included successful operation at high temperature, ability of pump components to tolerate high radiation fields, and optimization of voltage, current, and frequency values to create a fairly robust design. Performance predictions for the flight pumps indicate an operating efficiency of ~15%. Given the flow rate and pressure drops of the NaK loops, the primary pump will require ~850 We and the intermediate pumps will each require ~300 We.

Considerable detail about the FSP ALIP pumps and their design can be found in 2 companion papers at this conference: Werner[13] and Maidana[20].

Volume Accumulators: There are 3 total accumulators in the FSP reference system, one for the primary loop and one for each of the 2 intermediate loops. The FSP reference is to use fixed-volume accumulators for the flight system (as opposed to a bellows-type system). An initial charge of inert gas sets the pressure of the system, and thereafter determines the pressure as a function of coolant and gas temperature (and geometry changes with temperature). In a simple free-surface system, positioning at the top of the system is desirable to help ensure that gas remains in the volume, given the uncertainties in orientation and g-forces that could occur from the time the system is sealed until it is operated. Mesh screens can be used to help keep/trap gas within the accumulator volume(s) and there is the possibility to utilize multiple accumulator volumes at various points in the system to reduce sensitivity to orientation and g-forces. Mesh screens are very beneficial in microgravity type conditions, but it needs to be determined if the combination of the high NaK surface tension and 1/6-g on the moon will provide adequate free-surface behavior (even if gases have shifted during transport). Future analysis and testing will have to confirm that gas will indeed end up in the accumulator volume(s) under all credible scenarios, and whether a simple free surface system is sufficient or a mesh-screen is desired to help contain gas. The component layout in Fig. 3 shows the accumulators in a horizontal configuration, which considerably shortens the axial profile of the component stack and allows the activated NaK in the primary accumulator to be effectively shielded by the intermediate pumps and accumulators. This configuration will be more sensitive to potential tilting of the system on the surface, but if the piping enters at the center of the accumulators, and the bottom of the cans are tapered towards the center, then this should not be a significant issue.

Four variables can be used to size the accumulator; for the reference case these were: room temperature loop volume = 50 liters, accumulator cold coolant volume = 8 liters, accumulator peak gas volume = 25 liters, and gas pressure at cold conditions = 34.5 kPa (5 psi). These conditions result in an accumulator with a total room temperature volume of 56 liters and 0.76 moles of fill gas. The change in loop volumes and pressures at various state points is shown in Table IV.

TABLE IV

Primary Loop Volumes and Pressures at Various State Points

Loop Parameter	Min. Temp.	Room Temp.	Oper. Temp.	Max. Temp.
Ave. coolant temp.(K)	264	295	810	1000
Nak density (g/cc)	0.88	0.87	0.75	0.70
Vapor pressure (kPa)	0.0	0.0	5.4	56.6
Loop physical volume(L)	49.9	50.0	51.4	52.0
Total NaK volume(L)	57.6	58.1	68.2	85.1
Total physical volume(L)	105.6	105.8	108.8	110.1
Gas volume(L)	48.0	47.7	40.6	25.0
Gas pressure(kPa)	34.5	38.8	125.1	250.9
Total pressure (kPa)	**34.5**	**38.8**	**130.4**	**307.5**

The maximum design-basis loop temperature has not been specified, but a value of 1000 K may be a reasonable limit. In an over-temperature transient the loop pressure will depend greatly on the distinction between the average coolant temperature and the accumulator gas temperature (in the above table, it is assumed that the coolant and gas temperature are the same, which is a poor assumption in some cases). The values in Table IV are a beginning-of-life, and pressures will increase slightly throughout lifetime as gases are produced due to neutron capture in the NaK. The total gas production over the 8-year life at full power has been calculated as ~0.05 moles – .01 moles of He and .04 moles of Ar (there is also 0.5 moles of H produced, but it is presumed to leak out). The gas production would increase pressure by 7% over the system lifetime.

More detail on FSP accumulator issues and technology can be found in a companion paper at this conference: Qualls[21].

Heat Exchangers: The FSP reference design includes 2 IHXs. The reference is to use a standard 1-pass tube-and-shell configuration. For shielding and reliability reasons, the preferred configuration has the primary flow through the tubes and the intermediate flow through the shell. There is considerable experience with small liquid-metal-to-liquid-metal tube-and-shell heat exchangers; therefore this component is not viewed as a significant technical risk to the program. However, this IHX will have to be more robust internally than other traditional HX applications. In many tube-and-shell HX designs, it is accepted that there might be internal leaks between the tube and shell side, and the only penalty is a small drop in efficiency. For FSP, as was discussed above, the primary reason for selecting the intermediate loop option was to mitigate a He-to-NaK breach at the Stirling heater head. This failure is only mitigated if the IHX remains completely hermetic internally, because an internal leak will cause the primary loop to fail as well. The reason for this is that the moles of gas (He) in the Stirling engines completely overwhelms the amount of gas (Ar) in the volume accumulators. It has been determined that it would be impractical to try and oversize the volume accumulators to handle this influx of gas, thus it is has been accepted that if there is a He-to-NaK breach then the associated flow loop will fail. Therefore, if there is an internal leak in the IHX (either one that develops during operation or one that is created during the strong pressure wave that will occur when the He gas is purged) then the primary loop will fail as well. If an intermediate loop system is indeed chosen for the flight system because the He-to-NaK breach is found to be a major contributor to system reliability, then the IHX will have to be designed to be very robust. The current FSP technology program includes fabrication and testing of the flight-like IHX.

Other Components: The FSP flow loops may or may not have chemistry control (e.g. cold traps). Previous experience and data with NaK/SS loops has indicated that corrosion should not be a problem as long as the initial fill of NaK is very low in oxygen content (<20 ppm). Multi-foil insulation will definitely be part of the heat transport system (and probably every FSP system). The loop will likely be insulated as much as possible; however, there is an incentive to have a small fractional heat loss in the flow loop to better tolerate overheat transients. The possible inclusion of other components, such as sensors and trace heaters, are discussed in later paragraphs. Of course all subsystems require structural design and components, but there has been no design of structure for the heat transport system (but a mass estimate has been included in the system mass total).

VI.C. Reactor Instrumentation and Control

The affordable design strategy is to simplify the instrumentation and control (I&C) system as much as practical. The reactor has a very limited number of control parameters. The voltage and frequency of the electrical power supplied to the pumps are control variables that are anticipated to require adjustment during the startup phase of operation. Once system equilibrium has been achieved, the power to the pumps is expected to remain unchanged, which will maintain a constant flow rate in the three coolant loops. Ideally, the reactor system will perform only one function after startup and initial operations – to control reactivity via drum movement based on reactor temperature. Enough reactivity margin is provided so that the mission can be completed if 1 of the 6 drums cannot be initially moved from its launched/stowed position. Once the reactor has reached criticality, only 1 drum has to remain working through end-of-life to provide the reactivity needed (even if all drums were to fail, there would be a modest drop in temperature, and thus power throughout lifetime). A maximum drum rotation rate will be specified to prevent significant overpowering and temperature during startup or spurious drum movement, while still allowing reactor startup in <1 day. The low thermal power of the system results in low decay-power and a low adiabatic heat up rate. Therefore, the reactor requires little, if any, control response to possible transients (loss of PCS load, loss of flow, spurious reactivity insertion). Preliminary calculations show that the system could survive transients of this nature without a response from the control system, which could greatly simplify control system design, development, and qualification.

An important part of the I&C system is the control drum drives and bearings. Candidate components have been identified that should be able to handle the temperature and radiation environments that they might be exposed to. The identification of these components, and the data that assures adequate performance, is part of the FSP technology project. More details concerning the reference FSP I&C system and approach can be found in Qualls[22].

There are several unique reactor dynamics issues with compact, fast reactors such as the FSP reactor. Some of the well established characteristics of compact, fast-spectrum reactors are that point kinetics is generally very accurate for these systems and that temperature and burnup reactivity feedback mechanisms are relatively small and simple. Beyond this, there are two unique aspects of highly reflected fast reactors that do not occur in more traditional reactors. (1) The neutron reflector has a very important impact on dynamic performance, and in some cases the temperature coefficient of the radref is higher than that of the fuel. The thermal time constant of the reflector is much longer than that of any component in the core, which requires all reflector temperature and expansion effects to be modeled individually. (2) Reflected neutrons have a much longer fission lifespan than in-core neutrons. In effect, this creates additional delayed neutron groups, referred to as geometric delayed neutron groups. These groups can have lifespans orders of magnitude longer than neutrons that do not leave the core, and have much higher worth due to moderation. For compact beryllium reflected reactors there is also a measurable delayed group of photo-induced neutrons that result from delayed gammas. An in-depth discussion of these issues, and several example calculations on reactors similar to FSP are provided in Poston[23].

A good deal of system transient analysis has been performed as part of the FSP reference design process. In addition to the modeling reactor startup, several transients have been or are soon to be evaluated; a listing of these transients is in Table V.

TABLE V

List of FSP Transients Considered

Component	Transient to evaluate
Stirling Engine	-One set of Stirling engines fail
Primary Pump	-Mass flow drops by 50% -Overspeed or underspeed incidents -Pump failure in primary loop, possibly followed by backup pump startup
Secondary Pump	-One pump fails
Radiator	-¼ of radiator effectiveness lost
Lunar Environ	-Lunar day/night thermal cycle
Stirling Displace.	-Displacement drops by 20%
Control Drums	-Stuck drums at startup -Drum freezes in place during operation
Pressure Boundary	-LOCA in primary loop -LOCA in one secondary loop

The analyses and discussion of many of these transients can be found in a companion paper at this conference by Radel[24].

VI.D. Radiation Shielding

There are 2 primary aspects to shielding the radiation from the fission reactor: 1) the shielding of FSP components and 2) the shielding of the outpost or other locations where the astronauts might spend a significant length of time. There are also other shielding issues like shielding the gammas from activated NaK, and even shielding reactor radiation from the regolith to prevent overheating (discussed in next section). As discussed earlier, the shielding of the astronauts is highly architecture dependent, and requires its own paper for a sufficient explanation[4]. Even the local component shielding approach is architecture dependent; for example a buried configuration substantially reduces the dose from neutrons that leak out of the system radially (technically, this dose is from regolith capture gammas that result from neutrons that leak from the core), whereas a bare above-surface system might have the majority of FSP component dose result from radial neutron and gamma leakage.

VI.E. System Thermal Protection

A significant aspect of FSP reactor design is to ensure that all component temperatures are acceptable during nominal, and possibly overheating and overcooling scenarios. Approximately 3% to 4% of fission power is deposited in the radref and shield (~2% radref, and ~1% to 2% in the shield depending on the architecture); this power, plus a small fraction of thermal radiation from the vessel to the radref, must be rejected from the external system boundary during nominal operation. A summary of ex-core power deposition is listed in Table VI.

TABLE VI

FSP Ex-Core Power Deposition (buried system)

Region	Power (Watts)
Radref Be	924
Radref SS	121
Drum Be	1376
Drum SS	256
Drum B_4C	1190
Total in Radref	**3867**
Upper Shield	210
Radial shield	2265
Lower shield	356
Total within Cavity	**6698**
Regolith	194
Total Outside of Core	**6892**

As was discussed earlier, it is important to keep beryllium temperatures ~800 K during nominal operation – this proves to be difficult if simple thermal radiation gaps are assumed between components and materials within the components. Potentially more difficult than steady-state thermal balance is the removal of decay heat during certain transients. During loss-of-PCS load or loss-of-flow transients, more power is radiated from the vessel to the radref, but there is a substantial drop in fission power deposition, thus the total power rejected from the system decreases. The strong dependence of reflector temperature on fission power, combined with a large negative temperature feedback coefficient, provides a unique "power" coefficient for this type of reactor.

One of the challenges of an emplaced system is heat removal from ex-core components and core decay power during certain transients (regolith in a vacuum is a very poor thermal conductor), and protection of certain system elements from regolith interactions and/or infiltration. The reference design includes a shroud surrounding the system which is cooled by H_2O heat pipes that are attached to a small radiator above the surface. This shroud is integrated with the outside of the shield and extends above the shield to enclose the PCS, control, etc. components. Thermal balance and transient calculations have estimated that a nominal HP/radiator temperature of 370 K would be appropriate. The peak power rejection of this system would be between 5 to 7 kWt, depending mostly on the amount of core radial shielding. One additional advantage of an H_2O HP rejection system is that it will shut off when system temperatures get low (very low vapor pressure below 300K, freeze at 273 K). This will essentially halt heat removal from the system once temperature has decreased below ~300 K (because of the insulating effect of the regolith and/or the insulation provided to prevent freeze before emplacement), thus it would take a very long time until any of the NaK coolant could freeze (even before any significant decay heat has been generated).

Preventing system freeze is just as important as preventing overheating. The reference design approach is to keep the reactor NaK molten at all times, and not try to accommodate a freeze/thaw cycle (although this could be done if it was deemed necessary). If the reactor has operated for any significant period of time, there should be enough decay heat to keep the system liquid for a long time (assuming that the system is amenable to natural circulation). Prior to operation, initial calculations have shown that it should be possible to design the system to preclude bulk freezing over a lunar night (note: there is virtually no possibility of NaK freeze during the lunar day). This would require a very well-insulated system, with assurance that there would be no cold spots (e.g. a location where insulation got stripped off for some reason). A well-insulated system should be possible due to the existence of highly-effective, space-qualified multi-foil insulation. If the loop components are all placed within a shroud (which is the reference condition), then the shroud will provide an extra thermal radiation barrier and help redistribute heat. In addition, it should not be too difficult to add trace heaters to the system and/or run the pumps at low power to prevent freezing (running the pumps at low power helps via circulation and thermal power input (pump efficiency will presumably be low at low powers).

One of the biggest surprises encountered during the design process is that there are cases when even the regolith has to be "thermally protected". In a buried case without a radial shield, >2 kWt is deposited into the regolith by fission neutron and gammas. A heat conduction model, which used the conductivity of loose regolith, calculated temperatures higher than the melting temperature of the rock. It is possible that the regolith will sinter, and thus increase the conductivity to a level where overheating would no longer occur, but this would be hard to verify, plus the sintered material might crack and leave radiation streaming paths to the surface. Also, very hot regolith might off-gas materials that could attack the FSP system. To avoid this issue, the reference buried case utilizes a radial shield that cuts the regolith power deposition by an order of magnitude (shown as 194 W in Table VI). This adds considerable mass (>1000 kg) to the system, but keeps the peak regolith temperature <1000 K. The determination of a peak allowable regolith temperature (if any) will be needed to dictate how much radial shielding is needed around the core.

VII. SYSTEM MASS

The calculated mass of the reference reactor module (minus shielding and cavity cooling) is ~1300 kg: ~400 kg core/reflector assembly, ~800 kg heat transport, ~100 kg I&C. Shield mass for most options is generally between 2000 kg to 3000 kg depending on architecture assumptions (e.g. buried system, landed with berm, landed with regolith fill, etc.), although there are some options with shield masses <1000 kg. The cavity cooling subsystem, which is needed for a buried system, should weigh ~100 kg. The balance of the FSP system (PCS, PCAD and heat rejection) is estimated to have a mass of 1900 kg. This puts the total FSP system mass best-estimate between 5000 and 6000 kg, depending on numerous requirements (most importantly shielding), assumptions (e.g. regolith properties), and design decisions (e.g. direct vs intermediate flow). Part of the affordable approach is to not emphasize mass, provided that the system can be launched and landed on projected NASA vehicles. Certainly, mass is important and the system is designed with low-mass in mind, but for the FSP project more emphasis has been given to reducing technical risk and cost.

VIII. CONCLUSIONS

The FSPS is a modest performance, low-technical risk surface power system that is designed to provide a net power of 40 kWe for 8 years on the lunar surface. This paper describes the reference design of the FSP reactor module, and provides several references to the more detailed work behind the concept. In accordance with NASA's long term exploration goals, the FSP concept has used only technologies that would be compatible with a Martian surface mission. The reactor concept uses stainless-steel based, UO_2-fueled, NaK-cooled fission reactor coupled to free-piston Stirling converters. The concept has been designed to minimize both the technical and programmatic safety risk, and to simplify operations and the I&C system. The ultimate goal of this work is to provide a "workhorse" power system that NASA can utilize in near-term and future Lunar and Martian mission architectures, with the eventual capability to evolve to very high power, low mass systems.

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