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An Assessment of Nuclear Fuel Options for Microreactors

May 2023

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Reviewed by: S. Widgeon Paisner, A. Yacout

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Idaho National Laboratory

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EXECUTIVE SUMMARY

An engineering trade-off study was conducted for various nuclear fuel systems based on the desired characteristics and weighted ranking criteria developed specifically for microreactors. A semiquantitative method of consensus ranking on a numeric scale was used with input from several nuclear fuel experts. The purpose of this study was to assess options and provide recommendations for further nuclear fuel technology development to better support small reactor cores. The ideal fuel attributes were developed to capture crucial features including neutronic efficiency, fuel performance in diverse scenarios, fabrication/fuel-cycle considerations, and technology maturation potential.

Modern microreactor concepts have only recently begun emerging and some vary greatly in their design. The purpose of this study was not to determine which type is best (e.g., coolant type or neutron energy spectrum), but rather to assess fuel system options within five microreactor categories inspired by: 1) Very High Temperature Reactors (VHTR), 2) Sodium Fast Reactors (SFR), 3) System for Nuclear Auxiliary Power (SNAP) reactors, 4) Gas Fast Reactor (GFR), and 5) Molten Salt Reactors (MSR). The order in which these reactor types were just listed generally represents the amount of current interest and technological maturity in the microreactor community. As such, the conclusions drawn for each reactor type category have varying levels of certainty. There is confidence in the broad conclusion that known fuel technologies can support small reactors, but that microreactors will be able to maximize their performance potential if these fuel systems are further optimized. Most of these optimization opportunities revolve around increasing uranium loading and improving behaviors/understanding for long time-at-temperature conditions.

The outline below describes a summary of the outcomes of this study. Acronyms are not defined in the outline below for conciseness but are defined later in the detailed body of this report.

Type 1 (VHTR inspired designs)

- UCO TRISO in graphite scored highest because its performance is well known and extremely robust. Future work is recommended to address the following:
  - Fuel development and testing with increased fissile density (e.g., larger diameter kernels and smaller porous carbon layers) at lower power/burnup microreactor conditions.
  - Assess the viability of integrating burnable absorbers into graphitic materials.
  - Research long time-at-temperature fission product migration and diffusion through SiC coatings.

Type 2 (SFR inspired designs)

- U-10Zr metallic fuel in F/M steel scored highest owing to its superb fissile density, graceful behavior in postulated accidents, and relatively low cost to manufacture. Future work is recommended to address the following:
  - Fuel development and testing with increased fissile density (e.g., larger diameter pins) at lower power/burnup microreactor conditions.
  - Implement FCCI mitigation features such as lanthanide arresting alloy additives or cladding liners to enable longer time-at-temperature performance.

Type 3 (SNAP inspired designs)

- UZrH in Austenitic SST scored highest on account of its combination of respectable uranium density and intrinsic moderation. Future work is recommended to address the following:
  - Collate existing performance data using higher uranium density (45 wt%) and provide for NRC review to help expedite licensing for use at maximum uranium density.

- Assess potential design modification using smaller diameter fuel rods and optimized burnable absorber strategies to support higher thermal outputs and longer core life.

Type 4 (GFR inspired designs)

- Two fuel options scored similarly high including UN pellets in refractory alloy cladding and UC pellets in SiC/SiC composite cladding. Future work is recommended to address the following:
  - UN in refractory option: Alloy development to identify neutronically acceptable options with adequate tolerance to temperature and manageable behavior in the event of air ingress.
  - UC in SiC/SiC option: Irradiation of SiC/SiC composite under high fast fluence to ensure that it remains viable for fast reactor use.

Type 5 (MSR inspired designs)

- Chloride-based salts scored slightly higher than fluoride options, but a different determination could have been made depending on valuation of thermal vs. fast spectrum designs. No further recommendations are made except that MSR developers, and partner DOE programs, should continue in their technology maturation plans to determine the viability of MSR plants and fuel designs.

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1. INTRODUCTION

The US Department of Energy (DOE) Microreactor Program is dedicated to enabling deployment of advanced nuclear reactors which are much smaller than historical commercial power plants, and even more compact than small modular reactor designs. These so-called "microreactors" offer advantages in enabling factory-based manufacturing, transportability to deployment sites, and in some cases mobility between multiple sites. Microreactors can potentially meet the needs of less traditional deployment sites such as isolated military bases, remote communities, disaster relief, and space exploration applications [1]. Microreactors could also offer benefits for integration with local electrical grids and intermittent generation from renewables [2]. Historic examples of small reactor designs can be inspirational for modern day microreactors but cannot be duplicated directly to meet modern needs primarily due to current nonproliferation policy and/or the desire for passively safe design strategies. Numerous participants from the national laboratory complex, industrial partners, and academic collaborators are currently engaged in the development of modern microreactor technologies.

1.1 Motivation

Interestingly, most of the pioneering 1950's nuclear designs were closer to the microreactor class power output than today's gigawatt-class commercial plants. For example, the Shippingport Atomic Power Station was the first full-scale nuclear power plant devoted to civilian needs. In its lifetime, the Shippingport fuel design was modified and the core largely reconfigured as these technologies progressed [3]. This pioneering plant set the foundation for most of the Light Water Reactor (LWR) technology that followed, yet later plants would eventually be scaled up to more than 10 times its energy output. Evolution and optimization of nuclear fuel technologies and core designs were essential developments in this progression toward more economic nuclear power. The physical size of a microreactor design may be capped by certain constraints which enable access to some markets (e.g., standard shipping container size). Still, it's logical to assume that later generations of modern microreactors will benefit from increased energy generation capability within these constraints. The ability to generate more energy with uprated maximum power and/or longer-lived cores are inseparably related to the fuel technology used. Thus, the study of nuclear fuel systems will be a fundamental area in maximizing the performance potential of small reactors.

This report documents an assessment of the current state of nuclear fuel technologies, with special consideration toward microreactor needs, by a semiquantitative expert consensus method known as a "trade study". The purpose for this work is to emphasize the advantages and disadvantages of candidate fuel options. The conclusions drawn will help identify and prioritize opportunities for DOE's fuel development programs to augment data, enhance understanding, and optimize fuel designs that would enable the current "Shippingport era" generation of microreactor designs to quickly progress toward their full capability.

1.2 Scope of Assessment

Terms such as "optioneering" or "decision matrices" have been used to describe engineering trade-off studies. While these types of processes are somewhat subjective, they are an efficient means of prioritizing future work and can help avoid classical pitfalls such as selecting inferior options because they are familiar or preferred by an influential team member [4]. Accordingly, these types of processes can be pivotal in reducing risk of "false starts" and in accelerating technology development and deployment. Trade studies have various formats and protocols, but at the simplest level are essentially the same process where criteria are listed/weighted, candidate options are generated, and a group of knowledgeable experts discuss candidates relative to each criterion to assign numerical scores on a relative scale. In the present study a scale of whole numbers 1-5 was used both for criteria weight (5 being the most important) and candidate scoring (5 being the most advantageous). Thus, candidates with the highest sum of the products (criterion weight × candidate score) represent the most ideal options. Some options, however, were found to have nuanced pros and cons in specific scenarios. Notes made during the deliberation process and the discussion contained in this report help to capture some of these considerations.

Some of the most important yet challenging aspects of a complex trade study are defining the "ground rules" about what is to be directly addressed in the study and then creating a taxonomy for grouping considerations/candidates. The key points used to scope this study are summarized below:

- This study does not assess and prioritize which reactor type is most ideal (coolant type, neutron spectra, etc.)
    - This study, however, is grouped into general reactor categories to avoid logical errors (e.g., fuel systems with intrinsic moderation need not be assessed for fast reactor application).
    - From a fuel system standpoint, microreactors and "nuclear batteries" are not significantly different, thus no distinction is made.
- This study is limited to nuclear fuel systems for self-critical fission-based reactors and does not include fuel for fusion (e.g., lithium, deuterium) and radioisotope power sources (e.g., Pu-238).
- This study does not include fuel systems which are extremely specialized toward or only viable at low temperature and/or near-zero burnup (e.g., aluminum-clad fuel systems or nuclear thermal propulsion fuel systems).
- This study does not include other core materials (e.g., moderators, coolants, burnable absorbers, control rods, channel boxes, ducts, or vessels). Such a study is warranted but excluded from the present scope.
- This study does not explicitly address fuel assembly design parameters (e.g., pebble vs. prismatic, duct vs. open bundle, square vs. hex pitch, etc.)
- This study does not include fuel systems which are conceptual (options for which there is little-to-no data or experience) and thus performed on "known" fuel systems only.
    - Some flexibility is afforded to moderate modifications which could be used to adapt and optimize known fuel systems toward improved microreactor applications.
- This assessment concerns nuclear fuel as a system and includes combination of both fissile materials (e.g., kernels, pellets, slugs, etc.) and their primary fission product barriers (e.g., coatings, claddings, etc.)

2. REACTOR TYPES AND FUEL OPTIONS

2.1 Reactor Categories

Although unlikely to be conclusive, a different study regarding preferred reactor coolant/spectrum type should probably be performed with the unique needs of very small reactors in mind to give insight and guidance for technology developers. In any case, the scope of the present study was not designed to make prioritizations about this age-old nuclear debate, but fuel system candidates had to be imagined in a particular design environment to make reasonable assessments of their benefits and detriments. Similarly, the criterion applied to fuel candidates had to be weighted based on their relative importance to microreactors of different coolant/spectrum types. Five very generalized reactor category types were put forth for this purpose with key design environments relevant to fuel performance and basic assumptions about intrinsic physics related to their fuel. These assumptions were not viewed as firm engineering requirements but were used as context to imagine the environment fuel systems would need to endure. These assumptions are outlined below:

Type 1 (VHTR inspired designs)

- Design environment:
  - Helium at ≥700°C
  - ~10 at% burnup
  - Thermal spectrum, ~5 dpa (graphite equivalent) in structural materials
- Assumptions about fuel architecture:
  - Composite fuel systems where particle coatings retain fission products and matrix provides fuel structure and neutron moderation.
  - Low fissile density fuel necessitates materials with very low neutron absorption and moderation characteristics to achieve minimal core size.
  - Very high temperatures deter use of traditional metallic cladding tubes.

Type 2 (SFR inspired designs)

- Design environment:
  - Liquid sodium at ≥500°C
  - ~10 at% BU
  - Fast spectrum, ~100 dpa (SST equivalent) in cladding materials
- Assumptions about fuel architecture:
  - Fast spectrum reactors with high density fuel systems to achieve compact cores.
  - Moderate-high temperature, fast neutron atom displacement damage, liquid sodium compatibility, and high fission gas pressures require workhorse iron-based alloy cladding
  - Positive sodium void coefficient in severe accidents → fuel systems with low stored energy and graceful failure behaviors simplify plant safety strategy

Type 3 (SNAP inspired designs)

- Design environment:
  - Liquid sodium potassium (NaK) at ≥400°C
  - ~5 at% BU
  - Thermal spectrum, ~5 dpa (SST equivalent) in cladding materials and thermal neutron transmutation in relevant materials
- Assumptions about fuel architecture
  - Fuel systems with moderate fissile density and built-in moderation required to achieve very small cores with prompt negative temperature feedback.

Type 4 (GFR inspired designs)

- Design environment:
  - Helium at ≥700°C
  - ~10 at% BU
  - ~100 dpa (SST equivalent) in cladding materials
- Assumptions about fuel architecture:
  - Fast spectrum requires high fissile density to achieve a small core size (deters use of low density VHTR-type composite designs).
  - Helium coolant eliminates corrosion, but high temperatures and modest heat transfer conditions require very high temperature materials to survive postulated accidents.
  - Fast spectrum requires high dpa tolerance in materials.

Type 5 (MSR inspired designs)

- Design environment:
  - Molten salt at ≥600°C in contact with nickel-based alloy reactor vessel and piping
- Assumptions about fuel architecture:
  - Actinides dissolved into liquid molten salts with continuous processing to manage fission product inventory and to replenish fissile/fertile isotopes for reactivity management.
  - Thermal expansion of salt drives negative temperature coefficient.
  - Molten salt contained by reactor vessel/piping system requires corrosion behaviors to be considered and addressed.

2.2 Assessment Teams

The following experts participated in the expert team discussions and scoring deliberations:

- **Type 1 (VHTR inspired designs)**
  - Paul Demkowicz
  - John Stempien
  - Jeff Phillips
- **Type 2 (SFR inspired designs)**
  - Colby Jensen
  - Doug Porter
  - Steve Hayes
- **Type 3 (SNAP inspired designs)**
  - Adrian Wagner
  - Eric Woolstenhulme
  - Dennis Keiser
- **Type 4 (GFR inspired designs)**
  - Kevan Weaver
  - Boone Beausoleil
  - Jennifer Watkins
- **Type 5 (MSR inspired designs)**
  - John Carter
  - Guy Frederickson
  - Guoping Cao

2.3 Fuel Options

For simplicity in terminology all candidate fissile phases are expressed as uranium compounds (e.g., UO_2 rather than uranium-plutonium mixed oxide, MOX) but this terminology is not meant to exclude the possibility of other actinides (e.g., Pu, Th, Am, etc.) when ranking attributes pertinent to such fuel cycles. The following list shows the fuel option candidates generated by the trade study teams. The rationale for assessing these options is described in great detail in later sections:

- **Type 1 (VHTR inspired designs)**
  - UO_2 TRISO in Graphite Matrix
  - UCO TRISO in Graphite Matrix
  - UCO TRISO in SiC FCM
  - UN TRISO in SiC FSM
- **Type 2 (SFR inspired designs)**
  - U-10Zr in F/M Steel
  - UO_2 in Austenitic SST
  - UN in ODS Steel
- **Type 3 (SNAP inspired designs)**
  - UZrH in Zr Alloy
  - UZrH in Austenitic SST
  - UO_2/BeO in Austenitic SST
  - UC in Austenitic SST
- **Type 4 (GFR inspired designs)**
  - UN in Refractory
  - UO_2 in SiC/SiC Composite
  - UC in SiC/SiC Composite
  - UC Bi-Coated SiC in SiC FCM
- **Type 5 (MSR inspired designs)**
  - Fluoride-based salts
  - Chloride-based salts

A brief description of the commonly used acronyms and abbreviations for constituents in candidate fuel systems is listed below in the order in which they first appear in this report:

- **Fissile Compounds**
  - UO_2: Ceramic material composed of uranium dioxide, often referred to as "oxide fuel".
  - UCO: Composite ceramic mixture of uranium dioxide and uranium monocarbide.
  - UN: Ceramic material composed of uranium mononitride, often referred to as "nitride fuel". UN denotes a composition which is predominately nitride, although it can exist as a solid solution of uranium nitride with uranium carbide.
  - U-10Zr: An alloy of uranium with 10 wt% zirconium, often referred to as "metallic fuel", although there are other high uranium alloys which sometimes receive this designation.
  - UZrH: An alloy of uranium and zirconium treated to absorb significant quantities of hydrogen, often referred to as "hydride fuel" or by its trade name TRIGA ® (Training, Research, Isotopes, General Atomics).
  - UO_2/BeO: Composite ceramic mixture of uranium dioxide and beryllium oxide.
  - UC: Ceramic material composed of uranium monocarbide, often referred to as "carbide". UC denotes a composition which is predominately carbide, although it can exist as a solid solution of uranium carbide with uranium nitride.

- Fluoride-based salts: A mixture of various elements (such as lithium, sodium, beryllium, and fissile/fertile actinides) combined with fluorine in a liquid salt.
- Chloride-based salts: Similar to fluoride-based salts, except that elements are combined instead with chlorine.

- **Fission Product Barriers and Matrixes**
  - TRISO: Tristructural Isotropic, a multi-layer coating architecture applied to ceramic fuel kernels including first a porous carbon buffer, inner pyrolytic carbon, silicon carbide, and finally outer pyrolytic carbon.
  - Graphite Matrix: A fuel particle matrix composed of carbon primarily in the graphitic crystal structure.
  - SiC FCM: A fuel particle matrix composed of silicon carbide often referred to as Fully Ceramic Microencapsulated (FCM).
  - F/M Steel: Steel alloy cladding tubes composed of Ferritic/Martensitic metallurgic phases.
  - Austenitic SST: Stainless steel alloy cladding tubes composed of Austenitic metallurgic phases, sometimes referred to as "300 series stainless steel".
  - ODS Steel: Oxide Dispersion Strengthened steel alloy cladding tubes.
  - Zr Alloy (Zry): Zirconium alloy cladding tubes where trace Hafnium is mostly removed from the zirconium for neutronic reasons, often referred to as "zircaloy".
  - Refractory: Alloys cladding tubes composed of heat resistant metallic elements such as Niobium alloys. In this study, the term "refractory alloys" also refers to a general class of alloys with a few such elements in equal mixture referred to as multi-principal element alloys (MPEA) or high entropy alloys (HEA).
  - SiC/SiC Composite: Ceramic composite cladding tubes where silicon carbide fibers reside in a matrix of silicon carbide.
  - Bi-Coated SiC: A two-layer coating architecture applied to ceramic fuel kernels including first a porous silicon carbide layer, and then a fully dense silicon carbide layer.
  - Nickel-based alloy piping: "Superalloys" typically proposed for reactor vessel/piping materials in molten salt reactors (e.g., Inconel, Hastelloy).

3. FUEL SCORING CRITERIA

3.1 Desired Fuel Attributes

The following characteristics were developed based on the functional role of nuclear fuel, and unique attributes about its use in microreactors, as described below. These attributes are thought of in a philosophic sense as the characteristics of the perfect or "ideal" microreactor fuel system recognizing that there is unlikely to be a single system which completely satisfies all these attributes.

1. The ideal microreactor fuel system should accommodate high fissile density without significant non-burnable neutron absorbers.
    - Basis: Microreactors should be able to operate for several years (up to ~10 years) at effective full power without refueling nor requiring high enriched uranium or ^{239}Pu in the as-fabricated fuel. This is a key attribute to reduce fuel fabrication cost and enable small cores with room for other reactivity management features (e.g., burnable absorbers, control rods). Smaller cores offer reduced size, weight, and cost of reflector/shielding materials (volume increases roughly by core radius cubed for a given thickness) and thus are crucial in bolstering microreactor economic efficiency.
2. The ideal microreactor fuel system should perform reliably under normal full power conditions. Reliable fuel is defined as a fuel system with very low probability of leaking fission products from its primary barrier, nor causing rapid devolving conditions if it does.
    - Basis: Higher outlet temperatures (compared to LWRs) are a key feature in enabling efficient electrical generation cycles and process heat applications to sustain microreactor economic efficiency. Many microreactor sites will lack the infrastructure needed for on-site refueling or replacement of defective fuel assemblies, thus long-lived and reliable fuel systems are crucial. Based on their size, however, the plumbing arrangement in microreactors may be mostly shielded and enable continued operation with modest amount of fission product leakage from the fuel, so long as such leakage does not propagate to further damage or complications.
3. The ideal microreactor fuel system should be able to support continued reactor operation after Anticipated Operational Occurrences (AOO), should retain its fission products in the primary barrier in Design Basis Accidents (DBA), and should aid the passive safety features of plant design to preclude offsite dose in Beyond Design Basis Accidents (BDBA).
    - Basis: Fuel systems which support this licensing posture are important to microreactor economics by reducing costly active/redundant safety systems as well as the required reactor operation and maintenance staff. In postulated off-normal events the fuel system's properties can be significant in reducing stored energy, aiding negative temperature reactivity feedback, and in minimizing system damage consequences.
4. The ideal microreactor fuel system should tolerate loading cycles such as tens of power cycles from arctic cold to full power, thousands of power cycles from ~half to full power, and a handful of zero power transport evolutions in some cases over primitive roads with a range of atmospheric temperature conditions (arctic to equatorial) throughout the fuel service life (fresh to full burnup).
    - Basis: Microreactors should be able to tolerate shutdown, transport, and restart in arctic climates and adjust power on microgrids which will have frequent power variations. Microreactor designs will be transportable to/from deployment sites at the beginning and end of life. Some microreactor designs are further envisioned to be mobile with the ability to be transported to several deployment sites during service. It is not foreseen that

microreactors will operate during transport so the core could approach atmospheric temperatures (depending on decay heat load).

5. The ideal microreactor fuel system should tolerate high accelerations and exposure to cryogenic space-cold temperatures.
   - Basis: A few specialized microreactors may be used in space applications.
6. The ideal microreactor fuel system should perform similarly if the as-fabricated fuel contained actinides other than uranium and be compatible with both direct disposal and recycling processes based on known cost-effective technologies (e.g., electrorefining, aqueous) and waste forms.
   - Basis: HALEU-based once-through fuel cycles are the primary near term microreactor fuel cycle for reasons relating to policy and fuel fabrication cost. The ideal fuel system, however, would perform similarly when including other actinides (Th, Pu, Am) to support alternate fuel cycles when they become desired. The final disposition strategy for microreactor fuels is not currently known, but recycling compatibility may be beneficial in public acceptance and preventing onerous disposition dilemmas in the future. Expended cores of lifetime designs typically contain a large amount of valuable fissile material which increases the desirability of fuel recycling in a future with significant microreactor deployment penetration.
7. The ideal microreactor fuel system should be economic to fabricate, inspect, and certify with the ability to recover and reuse scrap HALEU without enormous investments in capital equipment and factories.
   - Basis: A key feature in microreactor economics is the low cost of unit production in factories. Fuel will be a significant cost fraction in each unit. Scarcity of HALEU, especially in the near-term supply chain, requires that microreactor fuels utilize this material efficiently.
8. The ideal microreactor fuel system would be based on materials, features, and combinations thereof that have undergone past fabrication development and performance testing (especially relevant irradiation testing) for which the data are recoverable, available to the United States, and generally useful in reducing the risk of unexpected performance and setting the foundation for accelerated development and qualification in microreactor applications (<10-year qualification project). The ideal fuel system would be under active research by current programs with existing or nascent capabilities for fabrication and testing.
   - Basis: Given the novelty of modern microreactors, it should be expected that fuel systems truly optimized for these reactors will require some amount of development and qualification testing to reduce unnecessary conservatisms and unlock their full performance potential. Still, preference is given to fuel systems which have a fair level of technological maturity based on testing and use in other reactor types so that qualification could credibly be achieved within ten years from the start of an earnest project.

3.2 Importance Weighting of Fuel Attributes

Each of the above fuel characteristics was weighted for its importance level relative to the different reactor categories as summarized in Table 1 below. The importance rating for each of the attributes was mostly consistent across each reactor category with a few exceptions that warrant some explanation.

Attribute 1 essentially captures features that enable compact core design which is naturally weighted rather high for microreactors. Relative to the others, this weighting was reduced slightly for Type 1 reactors since low power density is a key part of the design strategy (i.e., type 1 reactors are likely to be the largest of the microreactor types). This weight was also reduced for Type 5 reactors as it was presumed that some online refueling would be implemented for micro-MSRs to maintain reactivity.

Attributes 2 and 3 pertain to fuel performance in normal operations and postulated off-normal scenarios, respectively, and were thus weighted high. Relative to the others, these weights were reduced slightly for Type 3 designs to represent the reduction in consequence to operation or public dose when used in space exploration (which is a prominent application for this very small category of microreactor). Likewise, Type 3 reactors received a high weighting for Attribute 5 for pertinence to conditions in space exploration.

All reactor types were weighted at the moderate level for their ability to endure dynamic power cycling and transportation evolutions since all microreactor types are envisioned to need to retain this ability to offer advantages not currently exhibited in gigawatt-class reactor designs.

The fast spectrum reactor categories (Type 2 and 4) and MSR category (Type 5) were weighted moderately for fuel cycle considerations (Attribute 6) owing to innate features that help burn actinides and/or facilitate recycling processes. Type 1 reactors were weighted slightly lower since this reactor type is primarily envisioned in once-through HALEU-based fuel cycles using fuel systems that are more challenging to recycle. Type 3 reactors were weighted lower still since their size, deployment volume, and total fuel consumption is envisioned to be small and thus not warrant investment in fuel cycle infrastructure for these reactor types.

Since fuel cost and HALEU utilization are projected to be significant considerations in the overall manufacture of a microreactor plant, each reactor type category was weighted moderate to high for Attribute 7. Relative to the others, Type 3 reactors were weighted slightly lower for this attribute owing to their foreseen use in boutique applications where manufacturing cost is less concerning.

Attribute 8 envelops several considerations involving technological maturity and the potential for near term development and deployment. Accordingly, reactor types based on more established reactor technologies (Type 1, 2, and 3) were weighted high for this attribute. Reactor types which require more development time (Type 4 and 5) were weighted lower for this attribute since there is likely more time to also develop fuel technologies for them.

Table 1: Summary of Importance Weighting for Fuel System Attributes

Attr. No.	Attributes of the ideal microreactor fuel system	Type 1 (VHTR inspired designs)	Type 2 (SFR inspired designs)	Type 3 (SNAP inspired designs)	Type 4 (GFR inspired designs)	Type 5 (MSR inspired designs)
		Weight	Weight	Weight	Weight	Weight
1	High fissile density, low parasitic neutron capture, supports compact core physics	4	5	5	5	3
2	Reliable performance under full power operations, supports efficient electrical conversion	4	4	3	4	4
3	Reusable after AOO, retain fission products in DBA, aid passive safety to reduce consequences in BDBA	4	4	3	4	4
4	Endures tens of power cycles from arctic cold to full power, thousands of power cycles ~half to full power, and a handful of transport evolutions.	3	3	3	3	3
5	Tolerates high-G and cryogenic conditions	1	1	4	1	3
6	Similar fuel performance with other actinides, compatible with direct disposal and recycle by known methods	3	5	1	4	4
7	Economic to fabricate & recover process scrap HALEU with modest capital investment	4	4	3	4	4
8	Low technology risk, behaviors known, under active development, viable to qualify for microreactors in <10 yrs	4	4	4	2	2

It should be noted that these candidate fuel options were discussed and assigned scores relative to each other only within a given reactor type, rather than against candidates for other reactor types. In this way, to use colloquial terms, apples were compared to apples, and oranges to oranges. Moreover, the apple experts and orange experts were separate teams each with their own average character and biases. As a result, this study should not be used to suggest that red apples are better than mandarin oranges, or in other words that high scoring fuel systems in one reactor type category are better than moderately scoring fuel systems in another reactor category. This clarification is apparent, as will be seen later, when considering Attribute 1 where the highest fissile density fuel option for Type 1 reactors naturally scored a 5, but this fuel option in fact has much less uranium that the even the lowest fissile density option for Type 2 reactors.

4. FUEL OPTION RANKINGS

4.1 Type 1 (VHTR Inspired Designs)

Many current industrial microreactor designs fit into the VHTR inspired category as they use helium gas environments and TRISO based fuels. Not all of these designs, however, use the same TRISO architecture. The fuel options assessed here only include candidate fuel kernel and matrix materials and did not include detailed parameters such as kernel diameter, coating thicknesses, and particle packing fraction. It was recognized, however, that tuning such parameters is also important for achieving microreactor design optimized based on size, power density, and burnup needs. Unlike the others, the UO_2 in graphite option is not targeted for any particular microreactor design but was included as a baseline option representing historic TRISO designs. The UCO in graphite option essentially represents current generation TRISO under development by the DOE Advanced Gas Reactor (AGR) program [5][6]. Presently FCM matrix options are starting to be developed in earnest and represent potential next generation designs where different fabrication methods can help achieve higher fuel packing fractions [7].

Attribute 1, Neutronic Performance: UO_2 and UCO have approximately the same uranium density with UCO being slightly higher while UN offers a more notable increase in uranium density. It was assumed that UN would be manufactured using nitrogen that had been enriched in ^{15}N content to minimize parasitic neutron absorption. There is not a big difference between the neutron absorption cross sections of graphite vs. SiC (they are both extremely low), but graphite is a better neutron moderator than SiC. Importantly the FCM fabrication does not involve compaction and thus allows higher fuel particle packing fractions than graphite-based designs. With all these things considered, UN in SiC FCM matrix option was ranked highest for its superior fuel loading density, followed by UCO TRISO in SiC FCM, then UCO TRISO in graphite, and finally UO_2 TRISO in graphite.

Attribute 2, Normal Operation Performance: UO_2 and UCO TRISO in graphite designs have extensive databases demonstrating high tolerance to burnup and temperature. There is less data for FCM fuels, but with higher fuel loadings and lower matrix thermal conductivity, it is believed that FCM designs will be more susceptible to thermomechanical fracture (at least at high power density). Regarding the FCM options, the team had no reason to discriminate between UCO and UN based kernels based on the present state of knowledge. TRISO architectures are known to be some of most robust fuel systems ever developed and all scored high with UCO in graphite highest, UO_2 in graphite next, followed by the two FCM matrix options.

Attribute 3, Accident Performance: Again, UO_2 and UCO TRISO in graphite designs have extensive databases demonstrating high tolerance to burnup and temperature via furnace testing. It was noted, however, that there is little fast transient performance data for TRISO systems [8] which could be important for safety performance in some microreactor designs having lifetime cores with high initial excess reactivity or significantly different nuclear kinetics based on use of non-graphitic moderators [9]. Here UCO is known to perform better than UO_2, especially at even higher burnups and in more extreme accident temperature conditions. Given the similarities in high temperature driven performance phenomena each of the fuel systems scored the same as they did for Attribute 2.

Attribute 4, Power/Transport Cycles: All candidates scored similarly and on the higher side of the scale based on experience with the robustness of composite fuel systems under power cycling. The graphite matrix options scored slightly higher than the SiC options here due to graphite's better thermal conductivity and the role it would play in minimizing cyclic thermomechanical stress in power cycling. Anecdotally, it was noted that graphite based TRISO test specimens irradiated in the Advanced Test Reactor have been shipped across dirt roads on the INL desert to hot cells and have never shown damage from shipping, giving confidence in using them for mobile microreactors.

Attribute 5, Space Exploration Considerations: The team could not identify any known reason to discriminate between these candidates with respect to unique high-G or cryogenic temperature conditions they might encounter in space exploration applications, and thus were all ranked the same. It was also noted that type 1 reactors are likely the largest of the microreactors and may be challenging to use in space exploration.

Attribute 6, Fuel Cycle Versatility: None of the fuel systems considered for type 1 reactors are particularly optimized for compatibility with other actinides or recycle processes. But experience with these uranium ceramic compounds, including with other types of reactors, suggests that other actinides could likely be included without significant detriment in fuel behavior. The key distinction which caused FCM matrix concepts to score lower with regard to Attribute 6 is the relative difficulty in recycling SiC materials vs. graphite.

Attribute 7, Fabrication Economics: Owing to their coatings, composite architecture, and multiple processing steps, none of the type 1 fuel candidates are especially simple to manufacture. There is no strong distinction here between UO_2 and UCO kernel types, but UN synthesis would likely require additional processing steps and ^{15}N enrichment of the nitrogen supply. Established processes for graphite overcoating, pressing, and thermal treatment would exhibit simpler and more scalable manufacturing than the relatively slow chemical vapor infiltration processing needed for FCM concepts. Thus, the graphite-based options were ranked highest, followed by UCO in FCM, and then UN in FCM.

Attribute 8, Maturity & Development Potential: Finally, highest marks were given to UCO in graphite with respect to technology maturity and continuity of R&D programs based on the ongoing work of the AGR program. UO_2 in graphite also scored quite high based on significant historic data and some ongoing international interests. Naturally, the FCM concepts are relatively new, and less data currently exists for their performance. Among the FCM concepts the UCO option scored slightly higher than UN owing to the maturity of UCO as a fuel kernel in TRISO designs. Programs and industrial interests in all these fuel types are currently ongoing and these maturity rankings should be expected to evolve in the future.

Summary: When summing the totals UCO TRISO in Graphite emerged with the highest score (see Table 2), but this does not imply that the current specifications for this fuel system are optimized for microreactor applications. The expert team identified a few key recommendations for further developing and expanding the known parameter envelope for this fuel system to better support microreactor designs as discussed in the concluding section of this report.

Table 2: Summary of Type 1 Trade Study Rankings

Attr. No.	Attributes of the ideal microreactor fuel system	Type 1 (VHTR inspired designs)				
		Attr. Weight	UO_2 TRISO in Graphite	UCO TRISO in Graphite	UCO TRISO in SiC FCM	UN TRISO in SiC FCM
1	High fissile density, low parasitic neutron capture, supports compact core physics	4	2	3	4	5
2	Reliable performance under full power operations, supports efficient electrical conversion	4	4	5	3	3
3	Reusable after AOO, retain fission products in DBA, aid passive safety to reduce consequences in BDBA	4	4	5	4	4
4	Endures tens of power cycles from arctic cold to full power, thousands of power cycles ~half to full power, and a handful of transport evolutions.	3	5	5	4	4
5	Tolerates high-G and cryogenic conditions	1	3	3	3	3
6	Similar fuel performance with other actinides, compatible with direct disposal and recycle by known methods	3	3	3	1	1
7	Economic to fabricate & recover process scrap HALEU with modest capital investment	4	4	4	2	1
8	Low technology risk, behaviors known, under active development, viable to qualify for microreactors in <10 yrs	4	4	5	3	2
		Score:	99	115	82	78

4.2 Type 2 (SFR Inspired Designs)

The fuel systems considered were all developed and irradiated in historic SFR plants which made the Type 2 microreactor fuel assessment relatively straightforward. It should be noted that all three fissile phases (U-10Zr, UO_2, and UN) could be used any of the three cladding alloys (F/M steel, Austenitic SST, and ODS Steel). Rather than assessing all nine possible combinations, the team combined them by pairing each fissile phase with the cladding alloy most well matched with each other's value proposition. The U-10Zr option in F/M Steel was envisioned as the design with greatest fissile density able to drive small lifetime cores to the highest burnup and thus required the cladding alloy most tolerant of fast fluence damage. The UO_2 in Austenitic SST design was envisioned as the "baseline option" able to make most use of well-known fabrication methods. The UN in ODS Steel design was envisioned as the option where the properties of both fissile phase and cladding combined to enable higher temperature operation.

<u>Attribute 1, Neutronic Performance:</u> None of the cladding alloys considered here are meaningfully different in their neutron absorption, especially if used in a fast spectrum design, but the fissile phases considered offer significant differences in uranium density. In order to afford room for fuel swelling U-10Zr, UN, and UO_2 are typically designed to occupy 75%, 85%, and 80% of the area inside the cladding, respectively. Thus, the effective uranium "smeared density" inside the cladding inner diameter for U-10Zr, UN, and UO_2 is approximately 10.5, 8.6, and 7.6 gU/cm^3, respectively, making it straightforward to rank U-10Zr highest, UN next, and then UO_2 with respect to Attribute 1.

<u>Attribute 2, Normal Operation Performance:</u> The U-10Zr in F/M steel option would require fuel/cladding temperature to be maintained at ~575 C to endure long time at temperature operations in microreactor cores, but it was noted that this temperature could be increased if fuel cladding chemical interaction (FCCI) mitigation features (e.g., liners, alloy additives) were employed. The UO_2 in Austenitic SST option could likely support slightly higher fuel/cladding temperature (~600 C) to manage similar fuel/cladding interaction considerations. The UN in ODS option would be foreseen to enable a significant increase in fuel/cladding temperature (~675C) due to the thermophysical properties of these materials. With respect to burnup/fluence tolerance U-10Zr in F/M Steel expected to perform well to the highest burnup, then UO_2 in Austenitic SST, and lastly UN in ODS Steel. It was noted that all of these fuel systems have been shown to endure rather high burnups probably higher than can be achieved in lifetime-core microreactor designs. Strictly speaking these fuel designs do not perform equivalently, but they all scored equivalently for normal operation performance because each offers unique benefits depending on whether a given microreactor emphasizes the value of higher burnup, higher temperature, or something in between. More information on the irradiation performance of these fuel systems can be found in references [10], [11], [12], and [13].

<u>Attribute 3, Accident Performance:</u> There was a greater distinction between fuel options when considering performance in accident scenarios. The safety behavior of U-10Zr and UO_2 options is relatively well characterized from past in-reactor experiments. This work supported U-10Zr receiving a high score because of its low stored energy (as result of its high thermal conductivity), negative temperature feedback from fuel column axial expansion, and predictable/graceful failure modes if high temperature eutectic penetration causes cladding breach and sweep out of fuel material. UO_2 scored rather low based the high stored energy at initiation of a transient (a result of its low thermal conductivity) and its increased propensity to create positive reactivity insertion through sodium voiding and propagating pin failure through coolant channel blockages. The UN option has not undergone safety testing like the others, but based on its properties is projected to behave more like U-10Zr owing to high thermal conductivity and chemical compatibility with sodium. There was some modest concern for UN behavior in extreme conditions where, rather than breaching "early" from eutectic penetration, high temperature ceramic fuel chunks would melt through the cladding and create more significant sodium voiding and perhaps coolant channel blockages. Still, UN was thought to perform well overall and scored only slightly lower than U-10Zr.

Attribute 4, Power/Transport Cycles: Unlike safety performance, there is not such an empirical database for behavior under several power cycles for any of the candidate fuel systems. Still, U-10Zr scored highest because of its properties, namely its ductile fuel/cladding behaviors which should comply well when increasing power and fuel temperature. The UO_2 and UN options scored lower based on the expectation that ceramic materials will not behave this way and cladding strain would be more significant. In this regard, UO_2 scored lower than UN because its lower thermal conductivity will cause radial thermomechanical fractures (creating stress concentrations at the cladding/crack interfaces) and yield higher temperature driven thermal expansion. There was no known reason to discriminate between these fuel options with regard to reactor transportation. It was generally thought that their strong iron-based claddings would make them robust in such scenarios.

Attribute 5, Space Exploration Considerations: Similarly, there was no known reason to discriminate between these fuel options with regard use in space exploration. Setting aside the complications of startup sequencing for a reactor with frozen coolant in a space environment, and just considering the fuel system, it was again noted that strong iron-based cladding alloys should tolerate space exploration conditions well.

Attribute 6, Fuel Cycle Versatility: Owing to the beneficial physics of fast spectrum reactors in this area, all the fuel systems considered have been investigated and tested for fuel cycle considerations. U-10Zr scored well based on its similar fuel performance when alloyed with plutonium and relative ease in recycling by electrorefining and injection casting methods in hot cells (this is essentially why metallic fuel was originally invented). UO_2 also scored well because it is known to behave acceptably with plutonium (in fact most oxide fuel applications in SFRs to date have been as MOX) and for its compatibility with aqueous methods for recycling. UO_2 scored slightly less than U-10Zr in this regard because the aqueous recycling process is more complicated and existing infrastructure primarily exists in other countries. UN is compatible with electrorefining methods, but scored moderately for fuel cycle considerations because its performance is known to degrade somewhat, specifically that its fragmentation behavior increases, when plutonium is included. It was also noted that ODS steel cladding could be more difficult to mechanically remove in order to support reprocessing, but this was thought to be surmountable and not a significant point for discrimination.

Attribute 7, Fabrication Economics: Metallic fuel was originally developed in the context of fuel recycle operations performed within the constraints of shielded hot cells. As a result, the magnitude and simplicity of fresh fuel casting/assembly equipment, along with the fuel system's natural tolerance to impurities and other fabrication deviations, were cited as reasons for it to score well for fabrication economics. U-10Zr did not receive the highest marks possible, however, because some of the historic supply chain for F/M Steel tubes and casting molds is presently atrophied. As the most ubiquitous fuel system in the world presently, UO_2 also scored well, but slightly lower than U-10Zr because an oxide fuel system for fast spectrum use would require a greater fissile isotope concentration than current light water reactor fuel factories can support. Thus, the UO_2 option would likely require a new factory to support production for microreactors and the amount of equipment would represent a larger capital investment than needed for U-10Zr. The UN in ODS option scored lowest because UN requires processing steps beyond those required for UO_2 and it has never been performed on commercial or pilot scale. It was also noted that enrichment of nitrogen would be needed to optimize neutronic performance and that fabrication of ODS tubes currently requires mechanical alloying, difficult tube elongation processes, and challenging end cap welding procedures.

Attribute 8, Maturity & Development Potential: Both U-10Zr in F/M steel and UO_2 in Austenitic SST fuel systems scored well as they are mature products with much historic experience and current development projects both domestically and internationally. The international operational experience base for UO_2 is larger than for U-10Zr, but data and legacy materials for U-10Zr is easier to access for purposes in the United States. At present neither U-10Zr or UO_2 should be considered fully qualified for the fabrication specifications and performance needs unique to microreactors, but the prospect of doing so could be accomplished in a reasonable schedule owing to current expertise and fuel development infrastructure. UN in ODS naturally scored lower since these materials have smaller historic performance databases, but ongoing interest in UN for application in other kinds of reactors does pose some synergy potential for its future development. Irradiation tests in the ATR with thermal neutron filtering have been shown to be useful in progressing technological maturity for fast reactor fissile materials [14] but cannot currently create enough fast neutron displacement damage to support substantial advancements in cladding technologies. Fast flux boosting irradiation testing concepts have been proposed for ATR to help this situation [15] but have not yet been deployed in ATR. Thus, one point of concern noted for further development of ODS cladding is that its historic fast spectrum irradiation database is relatively small and there are no fast spectrum reactors currently available to the United States.

Summary: The total scores for these three fuel candidates revealed U-10Zr in F/M steel to be the preferred option for SFR inspired microreactor designs as shown in Table 3. This conclusion was not surprising owing to its exceptional fissile density, beneficial safety performance, and potential for economic manufacture. The total scores for UO_2 in Austenitic SST and UN in ODS were similar with the former only slightly leading. Advancements in fabrication technology and performance understanding for UN in ODS Steels could easily tip this balance in the future and make it the preferred fuel system when higher temperature operation is heavily weighted. A final point of clarification is that UN would probably be selected as the fuel system of choice for its improved chemical compatibility with lead-based coolants in fast reactors of this design [16]. Lead fast reactors have some overlap in fuel selection considerations as SFRs, but presently lead coolants are not being pursued in the United States for microreactor application and hence these considerations were not emphasized in the present study.

Table 3: Summary of Type 2 Trade Study Rankings

Attr. No.	Attributes of the ideal microreactor fuel system	Type 2 (SFR inspired designs)			
		Attr. Weight	U-10Zr in F/M Steel	UO_2 in Austenitic SST	UN in ODS Steel
1	High fissile density, low parasitic neutron capture, supports compact core physics	5	5	3	4
2	Reliable performance under full power operations, supports efficient electrical conversion	4	4	4	4
3	Reusable after AOO, retain fission products in DBA, aid passive safety to reduce consequences in BDBA	4	5	2	4
4	Endures tens of power cycles from arctic cold to full power, thousands of power cycles ~half to full power, and a handful of transport evolutions.	3	5	2	3
5	Tolerates high-G and cryogenic conditions	1	3	3	3
6	Similar fuel performance with other actinides, compatible with direct disposal and recycle by known methods	5	5	4	3
7	Economic to fabricate & recover process scrap HALEU with modest capital investment	4	4	3	1
8	Low technology risk, behaviors known, under active development, viable to qualify for microreactors in <10 yrs	4	4	4	2
		Score:	136	96	91

4.3 Type 3 (SNAP Inspired Designs)

The SNAP program used nuclear technologies to provide compact electrical power for space exploration and other special remote applications. Some of these designs generated heat through radioisotope decay, but several were fission reactor designs that stand out as some of smallest reactors ever created and operated. These types of designs were very small, even by microreactor standards, based on the need to integrate them into early earth-orbiting spacecraft. The SNAP-10A reactor was successfully placed into orbit and weighed less than 1000 lbs [17]. Naturally, these designs have been inspirational in some modern microreactor designs. The right blend of respectable fissile density, modest neutron absorption in materials, and intrinsic moderation are necessary features in the fuel system, especially since the liquid metal NaK coolant provides little moderation. There are only a few known fissile phases which could meet these needs. These designs used a blend of uranium and zirconium which is then treated to absorb hydrogen (thus UZrH). This fuel system is also used today in numerous low power water pool research reactors at universities and elsewhere. The SNAP-8 design used high enriched uranium and was able to support a small core design with a UZrH blend of only 10 wt% uranium [18]. More commonly this fuel system is used at 20-30 wt% uranium for low enriched uranium applications [19] and data exists for UZrH performance up to 45 wt% uranium [20]. Two UZrH concepts were assessed here to capture the neutronic/thermal trade-offs of using zirconium alloy and austenitic SST cladding, both of which have been used in the past. A different composite fuel system using UO_2 in a matrix of BeO was included. This fuel system was viewed as relevant since it was developed for and continues to be used in the Annular Core Research Reactor (ACRR) [21] which was essentially an upgraded capability from a preceding UZrH core design. Finally, UC ceramic in Austenitic SST was assessed because it has been developed to some degree for other types of reactors and the inclusion of carbon was thought to have some potential in neutron moderation.

Core designs with similar nuclear attributes could possibly be achieved with other fuel systems (i.e., those without intrinsic moderation) and other moderators elsewhere in the core (e.g., metal hydrides, beryllium compounds), but these options were not discussed as the present study excluded unfueled moderators and other core materials. It was also noted that this type of core design would exhibit less thermal coupling between fuel and moderator to the detriment of prompt negative temperature feedback coefficients.

<u>Attribute 1, Neutronic Performance:</u> UZrH in Zry scored highest for Attribute 1 based on its adequate uranium density, inclusion of significant hydrogen moderator, and lack of neutron absorbers in the cladding. UZrH in SST scored second highest for the same reasons, except demerited slightly based on neutron absorption in cladding. The UO_2/BeO in SST system was ranked moderately noting that its composite architecture limits uranium density but use of beryllium, which is both moderator and neutron multiplier, helps to achieve compact core physics. Similarly, the UC in SST option scored moderately noting that its uranium density is rather high, but that carbon is a less effective moderator per volume.

<u>Attribute 2, Normal Operation Performance:</u> There is some data for UZrH fuel at appreciable burnup, but its typical application has been in water-cooled low power research reactors which operate intermittently. In these environments UZrH fuels have proven reliable up to respectable burnups [22], but there is little data for their long-term performance in liquid metal coolants such as sodium potassium (NaK). Owing to the wealth of data showing reliable performance of SST cladding in high temperature SFRs, and the meager high temperature mechanical properties and relative dearth of data for Zry cladding in liquid metal environments, the UZrH in SST option scored very high while UZrH in Zr alloy scored somewhat low. While the UO_2/BeO in SST system is composed of high temperature materials, it scored modestly because this system has only been used in ACRR, primarily for pulsing operations, and there is little post irradiation data showing its high fluence composite behavior with fission gas and helium gas generation in the UO_2 and BeO, respectively. UC in SST scored rather high because there is some amount of data showing good behavior in higher temperature SFR irradiations, but it was demerited slightly because there is little information about UC performance with the pronounced radial burnup gradients it would experience in the thermalized spectrum typical of Type 3 reactors.

Attribute 3, Accident Performance: UZrH and UO_2/BeO designs are both routinely used in pulsed operations with success. Their especially strong negative temperature feedback coefficients effectively prevent fuel damage by overpower transients. There is virtually no information about their behavior under longer decay heat-driven undercooling accidents, but SST cladding should behave well up to appreciable temperatures and better than the Zr alloy UZrH option which scored lowest in this category. Recent work has shown that hydrogen dissociation temperatures remain the thermal limit for UZrH overtemperature performance rather than U-Fe eutectic formation as seen in metallic SFR fuels [23]. The noble gas release behavior of UO_2/BeO in longer overtemperature events has not been studied but is not postulated to be particularly severe owing to the refractory nature of these materials. For these reasons, the SST clad options for UZrH and UO_2/BeO both scored fairly high. Finally, UC in SST is also expected to perform fairly well under accident conditions owing to its high temperature properties, but it was rated moderately based on the expectation that its moderator density would not exhibit negative temperature feedback as strong as the other options, which is a key feature in the passive safety design strategy for this reactor category.

Attribute 4, Power/Transport Cycles: UZrH and UO_2/BeO fuel systems have routinely undergone numerous power pulses in operating reactors. It should be noted that ACRR's fuel design places UO_2/BeO pellets inside of niobium "cups" which are stacked inside of its SST cladding. These cups primarily serve to delay heat transfer and prevent water boiling under extreme power pulses but could also mask any power cycle reliability issues that would occur if used without these cups. These past experiences do not perfectly simulate the fuel cladding interaction behaviors that would occur in frequent adjustment of sustained reactor power levels, but reliable pulsing operations still gives some confidence in their ability to tolerate power cycles. The UZrH in Zr alloy option scored lower than its SST counterpart because iodine assisted stress corrosion cracking is a known issue for power cycling with Zr alloy cladding in LWRs [24], but it was noted these phenomena may not occur without the cladding creep down effects caused by pressurized coolant. The UC in SST option also scored somewhat lower owing to lack of data for any kind of deliberate power cycling and the expectation that monolithic ceramic pellets will be more prone to cause deleterious fuel/cladding mechanical interactions.

Attribute 5, Space Exploration Considerations: As the only nuclear fuel system option that has actually been used in space exploration via the SNAP program, it was straightforward to give high marks to UZrH in SST option. The UZrH in Zr alloy option should also perform well, but it scored slightly lower based on the expectation that weaker Zr alloy cladding would exhibit less resistance to high-G launch conditions. The UO_2/BeO and UC options both have more brittle properties and could potentially struggle with large accelerations and extreme thermal shock from cryogenic temperatures, but fracture of ceramic fuel pellets can usually be tolerated so long as fissile material does not significantly rearrange within cladding tubes that remain structurally intact. Hence these two options were scored moderately for use in space exploration.

Attribute 6, Fuel Cycle Versatility: Of the fuel options considered here only UC has been studied in any detail for alternate fuel cycles where it has known difficulties with common recycling processes. Hence UC scored somewhat low. The UO_2/BeO option also scored somewhat low based mostly on the expectation that separation and disposition of irradiated beryllium will be troublesome. Both UZrH options scored the same, only slightly higher than the others, based on the assumption that hot cell-based processes could heat the fuel material to drive off hydrogen and leave a U-Zr product that can be recycled in fashions similar to those used for metallic SFR fuel.

Attribute 7, Fabrication Economics: Fabrication of UZrH requires special controls to perform the hydriding treatment, and this fuel is not currently manufactured in mass quantities because low power research reactors do not often need to be refueled. However, some limited-throughput capabilities and expertise exist upon which larger UZrH factories could be based, which is why this system scored fairly high. The UO_2/BeO option has only ever been manufactured once for ACRR's current core decades ago. Modern medical knowledge for beryllium hazards would now require extra precautions to reinvent this fuel fabrication technology. Hence this system was rated low for manufacturing. UC in SST has been manufactured at the bench scale for SFR pins but is not currently manufactured in the United States. Still, it is known to be more easily fabricated than its nitrogen-rich sibling UN, and thus the UC in SST option was rated moderately.

Attribute 8, Maturity & Development Potential: UZrH options scored high for technical maturity and continuity of research programs, with the SST cladding option slightly higher, due in no small part to ongoing efforts to use this fuel system in the MARVEL microreactor [25]. There are also current efforts to design a replacement reactor for the aging ACRR facility potentially including new UO_2/BeO fuel fabrication efforts, but these efforts presently assume that the historic fuel will remain serviceable [26]. Still, there is very little data about the high burnup performance of this fuel system and inclusion of uranium with beryllium will assuredly impede rapid progress for fabrication and testing of samples, hence this option scored rather low. Similarly, the UC option scored low because its modest historic database revolves around SFRs; an application for which it is unlikely to be revived in modern SFR programs who prefer metallic or nitride fuel systems.

Summary: Not surprisingly, the fuel system which scored the highest overall is the UZrH in SST system used historically for SNAP reactors and also planned for the MARVEL reactor. It was also shown that the UZrH in Zr alloy option could provide a viable combination with greater neutronic benefit but likely only achievable at lower temperature conditions. The UO_2/BeO and UC options also offered some benefits, but were not enough to offset their drawbacks, as reflected in their similar scores that were lower than the UZrH options as shown in Table 4.

Table 4: Summary of Type 3 Trade Study Rankings

Attr. No.	Attributes of the ideal microreactor fuel system	Type 3 (SNAP inspired designs)				
		Attr. Weight	UZrH in Zr Alloy	UZrH in Austenitic SST	UO_2/BeO in Austenitic SST	UC in Austenitic SST
1	High fissile density, low parasitic neutron capture, supports compact core physics	5	5	4	3	3
2	Reliable performance under full power operations, supports efficient electrical conversion	3	2	5	3	4
3	Reusable after AOO, retain fission products in DBA, aid passive safety to reduce consequences in BDBA	3	2	4	4	3
4	Endures tens of power cycles from arctic cold to full power, thousands of power cycles ~half to full power, and a handful of transport evolutions.	3	3	4	4	3
5	Tolerates high-G and cryogenic conditions	4	4	5	3	3
6	Similar fuel performance with other actinides, compatible with direct disposal and recycle by known methods	1	3	3	2	2
7	Economic to fabricate & recover process scrap HALEU with modest capital investment	3	4	4	1	3
8	Low technology risk, behaviors known, under active development, viable to qualify for microreactors in <10 yrs	4	4	5	2	2
		Score:	93	114	73	76

4.4 Type 4 (GFR Inspired Designs)

This category of reactor design proved more challenging to assess than the previous three because GFR type designs, despite their numerous value propositions, have been held back from deployment in large part because no fuel system technology has yet to achieve their unique needs. The key challenge is that fast reactor designs need high power and fissile densities to achieve their full neutronic potential, but postulated accidents with loss of pressurized/flowing gas coolant require fuels to endure extremely high temperatures [27]. As a result, there is no strong fuel design precedence or a canonical GFR fuel design. Still, microreactors may offer new opportunities for GFR type designs and the team generated and assessed options to the best of their ability. The first option was inspired by the historic SP-100 space reactor program and would use UN pellets in refractory alloy tubes [28]. The next two concepts would both use SiC/SiC composite ceramic tubes cladding but differ in using either UO_2 or UC pellets. The final concept would employ a bi-coated particle composite architecture where UC kernels are coated with porous SiC, then dense SiC, and finally placed in an FCM SiC matrix. This final concept was suggested by Meyer *et al*. as a candidate GFR fuel system [29].

Attribute 1, Neutronic Performance: The options with UN and UC solid pellets naturally scored highest, followed by the option with UO_2 pellets, and finally the bi-coated UC particle concept, all based on fissile density. It was assumed that nitrogen used in the UN concept would be enriched in ^{15}N isotope and that the refractory alloy selected would avoid significant quantities of some of the stronger neutron absorbing elements (e.g., hafnium).

Attribute 2, Normal Operation Performance: The fuel performance assessment for these concepts was largely supposition based on lack of data, but the UN in refractory cladding option scored highest because UN is known to behave well at relevant temperatures with low fission gas release, and refractory alloys have been investigated for fast reactor application with some success. The UC in SiC/SiC option also scored fairly well based on past experience with UC in SFRs and chemical compatibility with SiC-based cladding, followed by UO_2 whose behavior is well known at high temperatures, but its low thermal conductivity gave some concern for thermal expansion driven strain on SiC/SiC cladding. It was noted that thermal spectrum irradiations of SiC/SiC have shown thermal conductivity degradation and swelling in early life which seem to eventually saturate and cease [30]. However, there is no data showing SiC/SiC behavior at the levels of atom displacement damage consistent with fast reactor application. The coated UC particle option scored moderately as well noting that the outer SiC coating (the fission product barrier) would become damaged by fast fluence while retaining fission gas pressure in designs where core physics push to minimize inner porous SiC layer thickness.

Attribute 3, Accident Performance: The accident performance area is typically where GFR fuel systems are thought to encounter their greatest challenges. Not surprisingly, none of the candidates scored high in this regard. Still the UC in SiC/SiC and coated UC particle concepts scored moderately based on their inertness and fully ceramic high temperature properties. The UO_2 in SiC/SiC option scored lower because its inferior thermal conductivity will yield an extra measure of stored energy at transient initiation. The UN in refractory option was thought to perform well in some types of upset conditions, especially those where rapid overpower driven thermomechanical stress gradients are of chief concern, but it was ultimately scored somewhat low based on concern for oxygen reaction with refractory metals in air ingress accidents.

Attribute 4, Power/Transport Cycles: Owing to the low ductility nature of all materials considered in these fuel candidates, none could be foreseen as particularly amenable to power cycling and rugged transport evolutions. All of the ceramic pellet options will tend to drive thermal expansion strain on cladding. Perhaps the refractory alloy cladding, being the least brittle of the candidates, would tolerate power cycling best, but would also be most likely to creep down onto pellets at lower power due to external coolant pressure and thus experience more strain upon power increase. It was also noted that the refractory alloys may exhibit poor ductility during shipping at very cold shutdown temperatures. SiC is a brittle ceramic, but in the fiber composite form it can tolerate some small amount strain without fracture. However, moderate strains can cause fracture of the SiC matrix, likely followed by leakage of noble gas and volatile fission products. This behavior would be expected to be more severe using UO_2 pellets due to lower thermal conductivity and greater thermal expansion. The coated UC particle option was thought to be perhaps most forgiving to frequent power and mechanical loading cycles, but some concern was noted for thermomechanical stress/fatigue causing SiC matrix fracture which could result in cleaved particle coatings, especially if high fast fluence continue to degrade its thermal conductivity. These considerations were reflected in the scores, and it was noted that power cycling in these types of reactors would likely require careful management of power-to-cooling ratios and ramp rates.

Attribute 5, Space Exploration Considerations: For all of the same reasons described above for Attribute 4, none of the fuel candidates considered scored particularly well for tolerance to high-G accelerations and rapid cold-to-hot full power temperature shifts. These fuels could probably still be viable for use in space exploration, but it would be on account of other engineering and operational controls (shock isolation, controlled power ramp rates) and not because of the virtues of the fuel system.

Attribute 6, Fuel Cycle Versatility: All of the fissile phases considered here have been studied for potential in fuel recycling. UN scored the highest for its compatibility with electrorefining methods followed by UO_2 which can be reprocessed by slightly more complicated but well-known aqueous methods. It was noted that high burnup UN can exhibit additional fragmentation when plutonium is included, but its behavior should generally be manageable with proper stoichiometric control at fabrication considering the burnups expected in a GFR-type micro-size lifetime cores. The two options using UC as the fissile phase scored fairly low since UC cannot be recycled by established methods, and the coated UC particle option would be worse yet due to difficulties in separating fuel kernels from the SiC matrix.

Attribute 7, Fabrication Economics: Creation of quality UN, as discussed previously, is a rather onerous process whose expense is only increased by the need for high sintering temperatures and enriched ^{15}N supply. Fabrication of refractory alloy tubes can also be challenging due to their resistance to deformation at easily achievable temperatures. Thus, the UN in refractory option was scored somewhat low. Fabrication of UO_2 and UC pellets is not quite so challenging, but creation of SiC/SiC cladding tubes requires costly nuclear grade SiC fiber, specialized weaving equipment, unique chemical infiltration processes, and specialized end plug sealing methods. SiC/SiC tube production has been demonstrated at bench scale for LWR application but will likely remain somewhat costly even at n^{th} of kind production. These reasons caused both the SiC/SiC candidates to be scored moderately. Finally, the coated UC particle option manufactured process would be similar to the FCM TRISO concepts discussed previously where multiple steps must be employed to create spherical kernels, multiple coatings, and matrix infiltration which are likely to be both feasible and somewhat costly. Hence this option was scored moderately as well.

Attribute 8, Maturity & Development Potential: In a broad sense GFRs are not as widely pursued in the United States as most other reactor types, but ongoing efforts in development of SiC/SiC cladding for LWR accident tolerant fuels, general interest in studying UN and refractory alloys, and coated particle FCM pursuits for TRISO-based systems all suggest that the fuel candidates assessed here could begin earnest development for microreactor applications without starting from "ground zero". The UO_2 in SiC/SiC option scored highest because of ongoing ATF work for this exact combination of materials (albeit in water-cooled thermal spectrum conditions). The other candidates all have synergistic work ongoing and some level of existing and relevant data and were scored slightly lower than UO_2 in SiC/SiC. Like SFR fuel systems, progress is hampered by lack of a fast spectrum test reactor available to the United States, but unlike the SFR situation there are no existing GFR fission product barrier options demonstrated at high fast fluence, nor are there near term plans to build commercial GFR plants. For this reason, none of the fuel systems considered for Type 4 could be scored high for their rapid development potential.

Summary: In total, the two leading options which scored virtually the same for Type 4 microreactors were UN pellets in refractory alloy tubes and UC pellets in SiC/SiC tubes. The UO_2 pellets in SiC/SiC tubes scored somewhat lower, followed by the concept of bi-coated UC particle fuels in FCM SiC matrix. The development challenge to achieve a qualified fuel form for GFR-inspired microreactors was found to be greater than the other reactor types assessed thus far, but some recommendations for next steps were captured in the conclusions section of this report. See Table 5 for the summary of fuel design candidate scores.

Table 5: Summary of Type 4 Trade Study Rankings

Attr. No.	Attributes of the ideal microreactor fuel system	Type 4 (GFR inspired designs) Attr. Weight	UN in Refractory	UO_2 in SiC/SiC Composite	UC in SiC/SiC Composite	UC Bi-Coated SiC in SiC FCM
1	High fissile density, low parasitic neutron capture, supports compact core physics	5	4	2	4	1
2	Reliable performance under full power operations, supports efficient electrical conversion	4	5	3	4	3
3	Reusable after AOO, retain fission products in DBA, aid passive safety to reduce consequences in BDBA	4	2	2	3	3
4	Endures tens of power cycles from arctic cold to full power, thousands of power cycles ~half to full power, and a handful of transport evolutions.	3	2	2	3	3
5	Tolerates high-G and cryogenic conditions	1	1	1	1	1
6	Similar fuel performance with other actinides, compatible with direct disposal and recycle by known methods	4	4	3	2	1
7	Economic to fabricate & recover process scrap HALEU with modest capital investment	4	2	3	3	3
8	Low technology risk, behaviors known, under active development, viable to qualify for microreactors in <10 yrs	2	2	3	2	2
		Score:	83	67	82	59

4.4.1 A Supplementary Option for GFRs

One option was considered for Type 4 microreactors in addition to those described above, but ultimately not included in the final candidate score matrix because there was too little information or analogous experience to put forth any reasonable experience or intuition-based rankings. This option's fissile phase is an equimolar solid solution of uranium and zirconium monocarbide and mononitride $U_{0.9}Zr_{0.1}(C_{0.5}N_{0.5})$. This fissile phase could offer some of the key features needed for Type 4 microreactors including respectable fissile density and high temperature tolerance. Presumably this uranium compound would need to be housed in a suitable refractory metal or ceramic composite cladding such as those described above to form a complete solution for Type 4 microreactors. This fissile phase has primarily been pursued under Russian programs [31] [32] and includes crucial irradiation testing data, but little information is available to the United States.

4.5 Type 5 (MSR Inspired Designs)

Molten salt fuel designs stand out with some unique considerations for this study. There is only a modest amount of experience with in-reactor MSR fuel performance, the essence of which shows chemical behaviors are of chief concern rather than fuel-cladding thermomechanical behaviors [33] [34] [35] [36]. Only two molten salt reactors have been constructed and operated to date, both for limited run time and using fluoride-based salt chemistry [37] so much of the assessment was based on supposition and extrapolation of known physics and phenomena. A tremendous number of fuel systems can be imagined as various salt chemical combinations which, for practical purposes, could not all be considered in this study. The team determined that the two most basic fuel chemistry categories, namely fluoride-based and chloride-based salts, should be compared for their application in microreactors. The rest of this microreactor fuel system trade study did not address materials outside of the fuel system such as reactor pressure vessel alloys. Fissile material is dissolved in the recirculating salt coolant for Type 5 reactors making them unique since reactor vessel and piping materials also serve the function of fission production retention. The fuel options considered were assessed in the context of contact with nickel-based alloys, but no further assessment was made to determine which specific alloys would be ideal.

Attribute 1, Neutronic Performance: Chloride salts scored slightly higher than fluoride because the uranium solubility limits permit a higher fissile loading. It was noted that fluoride-based options often include lithium which would need to be enriched in ^{7}Li to maximize neutronic efficiency, but also noted that there are uncertainties in the nuclear data cross sections for chlorine isotopes which could affect neutronic performance.

Attribute 2, Normal Operation Performance: Irradiation performance of liquid fuels, unlike solid fuels, has little to do with fission gas retention since the expected retention for liquid fuels is approximately zero. Instead, the key parameter to consider is chemical interaction with the piping. Fluoride based salts scored slightly lower because fluorine has a greater reaction potential than chlorine, but it was noted that nuances in fission product concentrations, specific salt chemistry, and the alloy in contact with the salt could all affect this behavior more significantly than the difference between fluorine and chlorine.

Attribute 3, Accident Performance: Safety performance for MSR type plants, so far as the fuel selection is concerned, primarily hinges on the properties of the salt which cause it to heat up, expand, and provide negative reactivity feedback in overpower events. Based on present understanding of thermophysical properties, there was no known reason to discriminate between fluoride and chloride-based salts. A key design basis accident postulated for MSRs is vessel rupture where release of fission products and potential recriticality in various flow/pool configurations are among the dominant concerns. Again, based on current understanding of fission product retention and flowing/freezing behaviors there was no reason to discriminate between fluoride and chloride-based options.

Attribute 4, Power/Transport Cycle: Liquid fuels will not cause thermal expansion stress on cladding tubes, which is one of the classical fuel performance concerns for power cycling, and thus one might conclude that MSR type microreactors would be amendable to frequent load following regardless of specific salt chemistry. However, the prospect of allowing salt to freeze, transporting the reactor, and then remelting it could be viewed as a relevant constraint with respect to Attribute 4. Past experience has shown that storing fluoride-based salts in the solid state can allow production of UF_6 through radiolysis, and there is no experience yet to prove whether such considerations are relevant for chloride designs. It was noted that chloride-based designs typically employ a faster neutron energy spectrum and based on salt proximity to vessel/piping, could cause additional atom displacement damage and embrittlement in the metal which reduces resiliency to cyclic loading in chloride-based designs. Hence the chloride option scored slightly lower for Attribute 4.

Attribute 5, Space Exploration Considerations: There was no readily identifiable reason to discriminate between these two fuel options with regard to space exploration and thus both scored moderately.

Attribute 6, Fuel Cycle Versatility: There is experience with chloride-based salts in electrorefining. Since the chloride option, as it is formulated for use in reactor, would already be in a form well understood for recycle processing. Thus the chloride-option was viewed as more beneficial and scored higher for fuel cycle versatility.

Attribute 7, Fabrication Economics: Both salt options would likely support improved neutronic efficiency in small cores if some of the constitutive elements were enriched in lower neutron absorbing isotopes. In the case of fluoride salts, lithium is often used and would very likely require ^{7}Li enrichment to support microreactor core physics. In the case of chloride salts, the need to enrich chlorine may not be as impactful and could perhaps be avoided depending on the physics of a particular core design. It is also noted that fluoride-based salts typically include beryllium which requires special mitigations for health hazards during salt synthesis. Thus, chloride-based salts were scored somewhat higher for fabrication considerations.

Attribute 8, Maturity & Development Potential: In a general sense very few MSR technologies, including candidate fuel systems, are especially mature. Fluoride-based MSR reactors are the only type to have been constructed and operated historically, and thus fluoride salts scored slightly higher, but it was noted there are active programs working on both salt types and chloride-based systems are more prominent in the related field of fuel recycle technology.

Summary: The total scores in the Type 5 reactor category show that chloride-based salts are superior to fluoride for microreactor application, but the difference in total score was not large (see Table 6). It was recognized that the decision between these two might be more related to the value proposition and overall plant design strategy for thermal vs. fast spectrum considerations in micro-MSR's.

Table 6: Summary of Type 5 Trade Study Rankings

Attr. No.	Attributes of the ideal microreactor fuel system	Type 5 (MSR inspired designs) Attr. Weight	Flouride based	Chloride based
1	High fissile density, low parasitic neutron capture, supports compact core physics	3	2	3
2	Reliable performance under full power operations, supports efficient electrical conversion	4	3	4
3	Reusable after AOO, retain fission products in DBA, aid passive safety to reduce consequences in BDBA	4	3	3
4	Endures tens of power cycles from arctic cold to full power, thousands of power cycles ~half to full power, and a handful of transport evolutions.	3	3	2
5	Tolerates high-G and cryogenic conditions	3	3	3
6	Similar fuel performance with other actinides, compatible with direct disposal and recycle by known methods	4	3	5
7	Economic to fabricate & recover process scrap HALEU with modest capital investment	4	2	4
8	Low technology risk, behaviors known, under active development, viable to qualify for microreactors in <10 yrs	2	3	2
		Score:	74	92

5. RECOMENDATIONS

Trade studies are semiquantitative only and should not be viewed as the definitive prioritization of design options. Furthermore, different experts assessing the same options would probably come to a few different conclusions, especially if the assessments were performed at different times when new data, understanding, and priorities could affect the outcome. With those disclaimers noted, one of the key reasons to perform such as study goes beyond the mere generation of a ranking table but uses the tension of attempting to mindfully quantify something that is not easily expressed numerically to extract new insights about technology development opportunities. Some of these key points emerged through the process and were noted so that they could be expressed in this final section as shown below:

Type 1 (VHTR inspired designs)

Current generation UCO TRISO in graphite ranked the highest in this category primarily because its performance is well known and extremely robust. That said, the present fuel architecture and performance database comes from efforts to optimize this fuel system for the enormous cores of VHTRs, not the diminutive footprint of transportable microreactors. With active expertise and industrial interest in miniaturizing VHTRs into microreactor systems, a recommendation is made that DOE fuels research programs should move forward with fuel development and testing to expand the current TRISO qualification basis and address modifications that increase fissile density specific to microreactor conditions. One example might include testing of TRISO compacts with larger diameter kernels and smaller porous carbon buffer layers to better support microreactor designs which can harvest value from compact cores that do not require the same power density or burnup achieved in AGR series irradiations. Such a campaign could also benefit reactor designers by assessing the viability of integrating burnable absorbers into graphitic materials and performing research on long time-at-temperature fission product migration and diffusion through SiC coatings. As DOE is presently organized, the AGR program represents the right skillset to address such a recommendation, but presently has no budget directive to specifically address fuel development for microreactors.

Type 2 (SFR inspired designs)

U-10Zr metallic fuel ranked highest in this category owing to its superb fissile density, graceful behavior in postulated accidents, and relatively low cost to manufacture. Since micro-SFR designs are foreseen to operate at lower power densities, but longer time-at-temperature conditions, metallic fuels could very likely be further optimized for microreactors by employing slightly larger diameter pins (to increase core uranium loading) and implementing FCCI mitigation features such as lanthanide arresting alloy additives [38] [39] to increase resilience at elevated fuel/cladding temperatures. The key cladding technologies needed to enable such a fuel design already have significant data from past SFR irradiations and these new fuel-centric advancements could be achieved using data from spectral modification in tests conducted in the ATR. Construction of commercial SFRs is on the near-term horizon in the US, which should help generally support SFR fuel and related technology supply chains and expertise and supports the conclusion that DOE fuels research programs should act on this technology push opportunity to enable more efficient microreactors. As DOE is presently organized, the AFC program represents the right skillset to address such a recommendation, but like AGR has no current budget directive to specifically address fuel development for microreactors.

Type 3 (SNAP inspired designs)

The existing UZrH in SST fuel design was identified as the preferred candidate for these very small microreactor designs owing to its combination of respectable uranium density and intrinsic moderation. This fuel system was used in NaK-cooled SNAP reactor designs and is well-known for use in low power water pool research reactors often licensed by the NRC. There is existing data for the performance of this fuel system at higher uranium densities than currently expressed in NRC-reviewed reports. A recommendation is made to collate this data and provide it for NRC review to help expedite licensing for microreactor designs wishing to use this fuel at maximum uranium density. It is noted that application in water pool research reactors, historic SNAP reactors, and the future MARVEL reactor have not driven toward an "uprated" power density version of this fuel as evidenced by its rather larger fuel diameter. One could imagine a modified design using smaller diameter fuel rods and optimized burnable absorber strategies to support higher thermal outputs and longer core life. The capabilities to perform this type of fuel development and testing currently exist, but with DOE's only research reactor development program entirely focused on aluminum-clad plate fuel it is unclear who would receive such a recommendation. Given the high relevance of this reactor type to space exploration perhaps programs with interest in space nuclear technologies would benefit greatly from such work.

Type 4 (GFR inspired designs)

Two fuel options emerged at the top for this design category including UN pellets in refractory alloy cladding and UC pellets in SiC/SiC composite cladding. The key uncertainties that would need to be resolved for the UN in refractory option would likely include alloy development to identify neutronically acceptable options with adequate tolerance to temperature and manageable behavior in the event of air ingress. The key data gap for the UC in SiC/SiC option would involve irradiation of SiC/SiC composite under high fast fluence to ensure that it remains viable for fast reactor use. Both of these recommendations could be challenging to act on immediately given the lack of fast neutron irradiation facilities available to the United States, but material development work and irradiation in spectrally modified positions in the ATR could be pursued to help assess viability of fuel technologies for micro-GFRs. The AFC program researches some materials systems similar to these for application in other types of reactors and thus has relevant expertise and capabilities. However, there is presently no meaningful direct support within AFC or other DOE programs for GFR fuels so it is unclear who would support this work in the near future.

Type 5 (MSR inspired designs)

Chloride-based salts were ranked slightly higher than fluoride options for microreactor application, but it was acknowledged that a different determination could have been made depending on the valuation of thermal vs. fast spectrum MSR type designs. Presently a handful of MSR designs, only a few of which are small enough to be considered "micro", are progressing with various salt chemistries and plant design strategies. Presently no further recommendation is made except that these developers, and partner DOE programs, should continue to move forward with their technology maturation plans to determine the viability of MSR plants and fuel designs.

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