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Changing the World's Energy Future

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Abstract –

Nuclear fuels using alloys of uranium, or metallic fuels, have many beneficial properties. The classical metallic fuel design uses a loose fitting cylindrical "slug" of fuel placed inside stainless-steel cladding tubes where the gap is filled with sodium. This sodium bond is liquid at operating temperature and conducts heat from the slug to the cladding, especially in early life before fuel swells into contact with the cladding. Despite the benefits of sodium bonding, there is a desire to develop metallic fuel technologies without it chiefly to reduce chemical reaction hazards in spent fuel storage from sodium fast reactors operating on once-through fuel cycles. Elimination of the sodium bond may also help unlock potential benefits for fuel fabrication, reactor neutronics, and compatibility with other types of reactors. Creating a sodium-free metallic fuel revolves around the problem of manufacturing fuel slug geometries which are in close contact with the cladding at beginning of life to facilitate heat transport while alleviating fuel-cladding chemical interactions (FCCI) at this interface and providing enough free volume to accommodate fuel swelling. Accelerating development and qualification of this fuel system will require careful selection of design and manufacturing options. To this end, a design trade-off study was performed to evaluate candidate options. Several design and manufacturing options were assessed, weighted, scored, and ranked with respect to fabrication, normal reactor operation, off-normal scenarios, and back-end considerations. This effort was performed both for "baseline" needs, which represented a once-through fuel cycle at temperatures and burnups known to be viable for sodium-bonded metallic fuel, and for "enhanced" needs to represent opportunities for closed fuel cycles and/or more aggressive temperatures/burnups. The outcomes of this study prioritized a baseline technology using U-Zr alloy with additives to mitigate FCCI, produced in annular slug geometry by continuous casting, clad in austenitic stainless-steel alloy, and followed by a final step to swage the cladding down to close the gap. This study prioritized an enhanced fuel technology using U-Mo alloy, also produced by continuous casting into an annular geometry, followed by coating/plating with an FCCI barrier on the slug, again with a final step to swage the cladding diameter down using oxide dispersion strengthened steel. It was noted that development of the enhanced fuel technology would entail more risk, thus U-Zr alloy was put forth as a backup to U-Mo if challenges are encountered with FCCI barriers, and advanced ferritic/martensitic steels are put forth as a backup to oxide dispersion strengthened steels if swaging and welding are found unworkable.

Keywords – Metallic Fuel, Fuel Design, Fuel Fabrication, Sodium Fast Reactors

I. Introduction

Metallic fuel systems offer numerous beneficial features for sodium-cooled fast reactors (SFR). The classical metallic fuel design uses an internal liquid sodium bond (between fuel slug and cladding inner diameter) which offers significant thermal fuel performance benefits. However, this design feature has certain undesirable impacts, such as requiring reactive metal handling in fuel fabrication, creating modest detriments to reactor neutronics, and increasing chemical reactivity hazards in shipping, storage, and geologic disposal scenarios. The latter issue is particularly important for SFRs designed to utilize a once-through fuel cycle with direct disposal of spent fuel rather than continuous fuel recycle that would only dispose of waste forms generated during the recycling process. An engineering trade-off study was undertaken to evaluate fuel design and fabrication process options for developing a so-called sodium-free fuel (SFF) not subject to these undesirable features while still retaining many of the traditional benefits of metallic fuels. The primary purpose of this trade study was to identify and prioritize future research tasks in order to accelerate the overall development cycle leading to the future deployment of SFRs utilizing metallic fuel technology.

The use of sodium-bonded metallic fuels in SFRs, and especially their use in a full-core application in the Experimental Breeder Reactor – II (EBR-II) over thirty years of operation, demonstrated a number of beneficial features. (1) Metallic fuels are capable of consistent and reliable performance to high burnup. (2) The high thermal conductivity of metallic fuels allows them to operate at high power densities while maintaining relatively low fuel temperatures, which is even further enhanced using a liquid sodium bond in the fuel-cladding gap. (3) Relatively low fuel temperatures translate into low stored energy within the reactor core that must be dissipated during accident scenarios. (4) With liquid sodium present in the fuel-cladding gap, the extremely tight tolerances on fuel diameter typical for oxide fuels are unnecessary, which makes metallic fuel fabrication easier, more efficient, and cheaper than oxide fuels. (5) The high thermal expansion coefficient of metallic fuels can contribute significantly to the negative reactivity feedback characteristics of SFR cores during overpower transients. However, elemental and reactive sodium present in spent metallic fuel classifies it as mixed hazardous waste and makes it unacceptable for direct geologic disposal (at least relative to the regulatory constraints associated with the Yucca Mountain Nuclear Waste Repository). In past decades, metallic fuels used in SFR applications were most often considered as part of closed fuel cycle scenarios with recycling processes that could produce high level waste forms acceptable for geologic disposal so that elemental sodium present in spent metallic fuel was not an issue. Today, however, open fuel cycles that make use of direct geologic disposal of spent fuel without processing are preferred, which makes the use of a sodium bond in metallic fuels problematic. Thus, new metallic fuel designs which retain as many of their historic, beneficial features as possible, while eliminating the use of a sodium bond, are of great interest, which is the context for the present trade study.

I.A. Motivation for Accelerated Fuel Development

Several thought leaders in the nuclear fuel community have recently focused their strategic thinking on methods that accelerate the nuclear fuel development life cycle. These discussions often lament the schedule such efforts take and propose accelerated experimentation to support maturation of mechanistic fuel performance models in a way not achievable historically due to computational limitations. While this strategic approach is becoming better published [1][2][3][4], plans for applying it to specific fuel technologies are less available. The prospect of accelerating fuel development and qualification will not only require more rapid task execution and better modeling but will also require thoughtful planning and foresight to mitigate false starts and unnecessary iterations. In other words, often the most time-consuming part of the fuel qualification process is deciding what fuel design and fabrication options to pursue in the first place. For these reasons, a design and fabrication options engineering trade-off study, or simply “trade study”, was undertaken to assess candidates for sodium free metallic fuel.

The length of the “fuel qualification” cycle is often described as greater than 20 years, but phrases such as “development” and “qualification” are often confused or mixed in these discussions. It is important to be precise with these terms in outlining an accelerated development strategy. It is not the present purpose to perfectly equate terms between published flowsheets, but it is insightful to observe some commonalities as shown below in Figure 1.

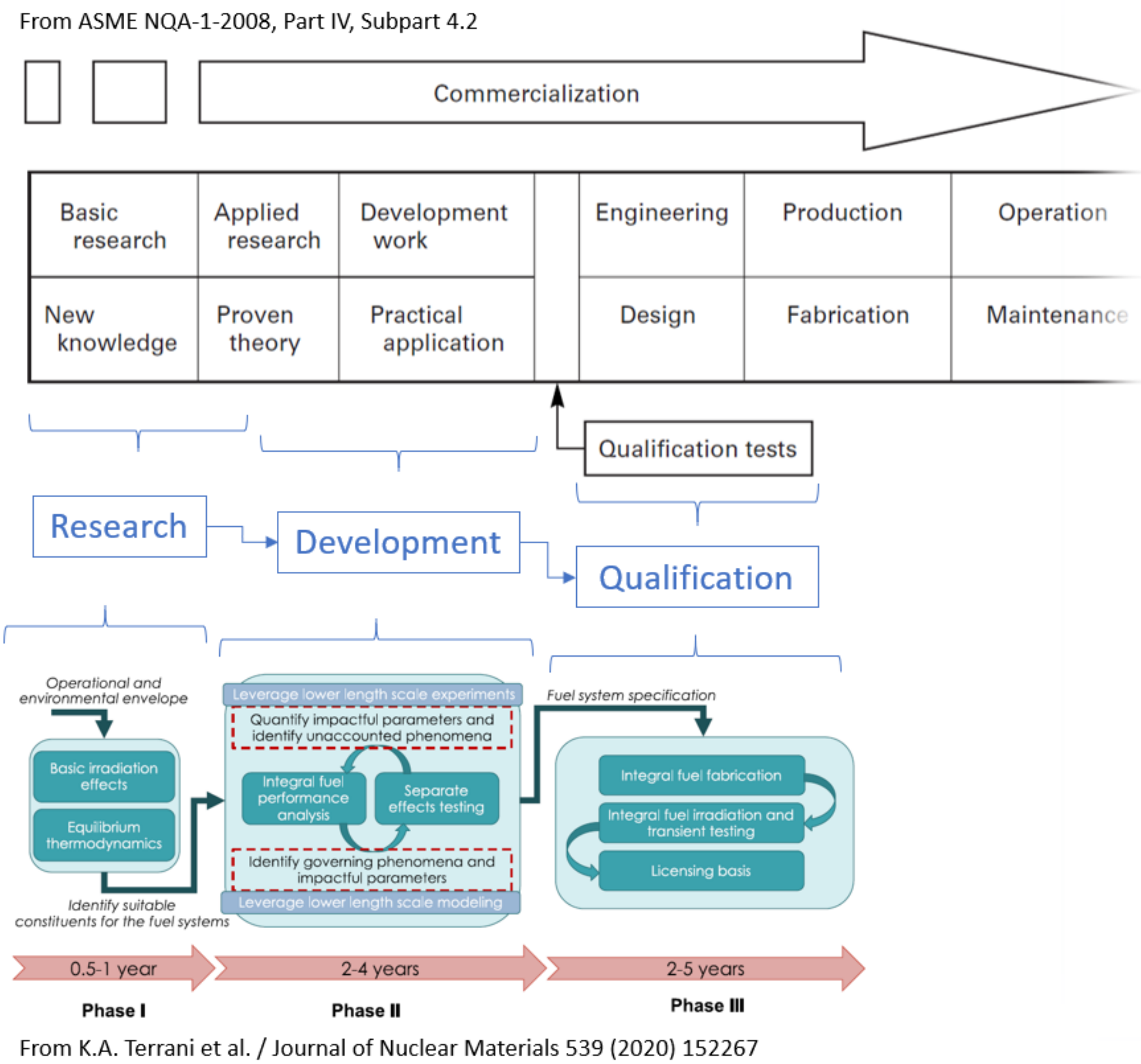

Figure 1: Cross-Comparison of Development Flow Charts

Here one can see that first half of the technology life cycle (the half associated with discovery, innovation, and technology maturation) as outlined in American Society of Mechanical Engineers, Nuclear Quality Assurance (ASME-NQA-1) [5], and the process flow proposed by Terrani et al. [1], can be roughly equated to each other in three phases hereafter referred to as 1) Research, 2) Development, and 3) Qualification. No attempt is made here to reconcile the oft-cited technology readiness level gradation scheme as these levels are too finely divided for present purposes, except to point out that the above three phases are roughly synonymous with Fuel Development Phases 1, 2, and 3 proposed in the crosswalk published by Crawford et al. [6]. A brief overview of the purpose of these three phases is offered below.

1) **Research:** This phase implies discovery. Discoveries can pertain to fundamental phenomena, material systems, or technology concepts that address salient problems. Given that most nuclear technologies have been investigated to varying degrees historically, modern fuel researchers are likely to find that a significant amount of this phase has been accomplished already. Still, in such cases researchers would do well to organize this information as it applies to modern problem statements to formulate latter phase execution plans, especially if they plan to do so with an accelerated schedule.
2) **Development:** The purpose of this phase is to mature understanding and develop fuel specifications. Efficiently executing this phase is particularly important to address accelerated paradigms as the development phase is most likely to see "back-to-the-drawing-board" iterations, especially if the plans, metrics, and decisions made in the preceding research phase were poorly formed. Recent advances in accelerated testing methods [2] [3] should be seen for their value in this phase to reveal end-of-life phenomena and compare candidate systems more rapidly. The role of advanced fuel performance modeling should be seen for its value potential in this phase and is thus needed to guide experiment design and account for distortions created by accelerated test environments. This phase will see selection of key fuel design options including development of fabrication specifications. Studies performed during this phase focus on elucidating physical phenomena to mature models, and thus so-called "analytic tests" should be performed in this phase to help isolate and understand phenomena of interest.
3) **Qualification:** This phase has a culminating function to produce evidence showing that the specified product meets its performance requirements. Qualification work is not expressly purposed to create discoveries or refine options, but rather to demonstrate that the selected specifications yield a product which meets acceptance criteria. The definition offered by the United States Nuclear Regulatory Commission is helpful here: "Qualified fuel means fuel for

which reasonable assurance exists that the fuel, fabricated in accordance with its specification, will perform as described in the safety analysis." [8] While studies performed in the preceding development phase often focus on isolating features and phenomena to refine understanding, qualification work typically focuses on combining relevant aspects of the fuel system and design environment.

Since qualification is the culminating step in the above progression, the entire process is sometimes referred to as "fuel qualification", but this can terminology be misleading. Qualification work does require the most exacting requirements on material fabrication, test control, and data analysis, but is less likely to produce unexpected discoveries than preceding phases and can typically be planned with greater certainty. Thus, concluding that "fuel qualification" requires onerous schedules can be confusing since much time can be used during the research and development phases. A long-term grand challenge for the advanced fuels enterprise is to develop understanding and models sufficiently in the development phase so that little-to-no qualification testing in needed. Perhaps this goal is achievable and is at least helpful in a philosophic sense, but it is generally acknowledged that a track record of predictions corroborated by qualification tests will be needed to establish confidence in this pathway. In the near-term pragmatic sense, it is thus most prudent to focus current efforts on setting the foundation for development work in a way that appropriately sequences tasks and reduces risk for restarts.

II. Methods

In product development few junctures are as pivotal as design concept selection. An engineering trade study is a structured way of assessing design options and deciding on preferred candidates. Sometimes referred to as "optioneering," a trade study endeavors to reduce subjectivity and avoid classical problems in design decisions such as favoring concepts that just seem better or that are simply preferred by an influential member of the team. Textbook descriptions of design selection methods advocate the use of decision matrices where criteria are listed, concepts are generated, and candidates are assessed by an expert team who ranks them [9]. Ideally predictive models can assess each candidate and be compared to quantitative criteria, but often in research applications these models are immature, and prioritizations must be made based on the best information and expertise available. In these situations, criteria are weighted based on their importance and the ranking exercise is determined on a numeric scale. This process is semi-quantitative and requires expert judgment, so it is still somewhat subjective, but the various viewpoints which are expressed and reconciled during the ranking process add confidence to the decision reached. This is the process followed in the present work to prioritize SFF design and fabrication options. Finally, in keeping with the axiom that you don't understand what you're thinking until you read what you've written, this paper was written not only to publish information, but also to facilitate the refining effect of team review/cross-checking and independent peer review.

It was important to set some limitations for the design environment and scope of the trade study in order to achieve a focused effort. It was assumed that the SFF candidates would be used in classical SFR designs where fuel material is clad in cylindrical tubes to create fuel pins, that these pins would be helically wrapped with a wire to maintain their spacing in a hexagonal array, and that bundles of pins would be shrouded in hexagonal metallic ducts. The study did not consider design options beyond the fuel system (i.e., beyond the fuel and cladding). The study assumed that the fuel material would be an alloy of primarily uranium and that a commercial supply of enriched uranium would be available. Thus, options for establishing enriched uranium supply were not evaluated.

The SFF trade study was performed over the course of a few months using several team sessions, rather than a single long session, in order to give time for team members to generate new concepts. This approached was productive in avoiding meeting fatigue and in spurring new ideas. The main outcome of the study was organized in a spreadsheet where fuel design and fabrication options were ranked relative to impact on fuel fabrication, normal reactor operation, off-normal reactor scenarios, and storage/disposal situations. Within these four categories, each option received two rankings, one each for a "baseline" and an "enhanced" set of performance metrics. The baseline category assumed a once-through uranium-based fuel cycle with state-of-the-art reactor performance needs (10% burnup HM, 100 dpa cladding, 600°C peak inner cladding temperature). The enhanced category encompassed plutonium and minor actinide bearing fuel designs and strived for more challenging irradiation conditions (20% burnup HM, 200 dpa cladding, 700°C peak inner cladding temperature).

Concepts, options, and candidates were organized into two main categories including 1) Design options (the composition, geometry, and configuration of the fuel system) and 2) Manufacturing options (methods to produce, process, and assemble the fuel system). Naturally, these two categories were not totally independent. Some fuel geometries, for example, could only be produced by some of the manufacturing options. Still, the team endeavored to rank each option as independently as possible with respect to the ranking criteria. This method of decomposing the complete system into discrete sub-options was helpful in viewing each candidate for its merits and weaknesses. This approach set the foundation for a final activity to bring it all together by synthesizing recommendations as complete fuel systems.

II.A Fuel Life Cycle Considerations for SFF

This design study assessed fuel design and manufacturing candidates for the merits relating four categories. A score was determined for each option (1 through 5, with 5 being most favorable), for each category, and for both the baseline and enhanced functional needs, so each option received eight scores. The four criteria categories included 1) Fabrication, 2) Performance in Normal Reactor Operations, 3) Performance in Off-Normal Scenarios, and 4) Back-end Concerns. Each criterion was weighted differently, also by discussion and expert judgment of importance using the same 1 through 5 scale. The baseline functional need categories were weighted more heavily to help prioritize near term technology options in the average score, but the baseline and enhanced scores were also tracked discretely to identify candidates which diverged into near-term and long-term development potentials. Importantly, the baseline category was assumed to represent technologies which could be credibly developed in less than 10 years given appropriate resources. The ultimate scores for each option were simply determined by summing the products of criteria weighting and candidate scores.

A list of influential considerations was tabulated for each of the four criteria areas. The options were not scored for each consideration in these lists as this approach would have been too granular for such a study. Instead, these considerations were important questions to think about and discuss when determining the score. As such, the team referred to these lists often during the ranking discussions. The influential considerations, functional needs, and important weighting used in this trade study are shown below in Table 1 along with some explanation in the sections that follow.

Table 1: Summary Trade Study Scoring Criteria, Influential Considerations, and Functional Needs

	Influential Considerations	Category	Functional Need	Weight
Fabrication	Labor, duration, & quantity of processing steps	Baseline	Economic to fabricate in a fresh uranium HALEU licensed fabrication facility	4
	Capital investment (facility and equipment)			
	Utility demand (electricity, natural gas, etc.)			
	Tolerances, repeatability, yield rate			
	Magnitude and hazard level of waste disposal			
	Raw material cost (fuel, cladding, consumables)	Enhanced	Fabrication processes viable for adaptation to include Pu and/or minor actinides	2
	Process continuity, batch size (criticality limits)			
	Ability to recycle/recover scrap			
	Acceptable range for special process controls			
	Ability to inspect product characteristics			
Normal Operation	Isotropy of fuel swelling	Baseline	Perform reliably to 10% burnup, 100 cladding dpa, and 600 C inner cladding temp.	5
	Fuel density and swelling free space			
	Cladding mechanical properties evolution			
	Strength and defect propensity in end cap weld		Enable long reactor operation cycles with predictable reactivity evolution using once-through fuel cycles	
	Neutron absorption of materials in active core			
	Cladding void swelling/bowing			
	Constituent redistribution, fuel cladding chemical interaction, cladding wastage	Enhanced	Perform reliably up to 20% burnup, 200 cladding dpa, and 650-700 C inner cladding temp.	3
	Thermal hydraulic performance, heat flux, heat transfer rate			
	Fuel cladding mechanical interaction		Perform reliably under routine power adjustments (e.g., daily load following cycle)	
	Fission gas release, plenum pressure accumulation			
	Solid fission product driven fuel swelling		Perform reliably with the addition of Pu and/or minor actinides	
	Fission gas driven fuel swelling and pore interconnection			
Off-Normal Scenarios	Reactivity change from axial expansion, melt relocation, & sodium expulsion	Baseline	Enable passively safe plant designs (no damage in DBA, no cladding failure in BDBA) for baseline category normal operation needs	4
	Fuel thermal conductivity (stored energy) & melting temperature			
	Cladding fuel eutectic penetration			
	Cladding mechanical properties (resistance to high temperature deformation, fuel thermal expansion, & pressure driven rupture)	Enhanced	Enable passively safe plant designs (no damage in DBA, no cladding failure in BDBA) for enhanced category normal operation needs	2
	Coolant/fuel chemical compatibility, benign behavior in run beyond cladding breach, non-violent behavior in cladding burst			
	Propensity for fuel particle ejection & channel blockage			
Back-end	Chemical compatibility of fuel system constituents with air/water	Baseline	Viable for direct disposal in a once-through fuel cycle, does not create severe chemical interaction hazards in storage, transportation. Not considered "mixed waste"	3
	Ability to separate constituents and recycle into new fuel pins	Enhanced	Facilitate reprocessing in closed-fuel cycles by electrorefining or aqueous methods	1

II.A.1 Fuel Fabrication Considerations

Fabrication assessments focused on the ability to produce fuel pins that meets all design parameters, such as compositional, dimensional, and microstructural requirements. Fuel production evaluations also considered options in terms of manufacturing cost/time efficiency, material resource utilization, and waste minimization. Prior to fuel manufacturing, specifications will be developed to describe requirements for the alloy, slugs, cladding, and hardware for features such as composition, geometry, and physical properties. During fabrication these parameters must be either inspectable to show compliance or must have a robust qualification program which assures characteristics based on process control. Fuel manufacturing must be economically viable if the system is to be adopted for commercial use. Economic viability includes time and cost of production, including raw material costs, and the fabrication line and equipment cost. Process yield is an important factor in economic viability, including the ability to efficiently recycle out-of-spec products and scrap material. Most waste from fuel fabrication lines is considered radiological waste, and in some case mixed radioactive-hazardous waste, thus waste production and disposal are also important considerations driving fabrication choices. An example that is commonly discussed in this regard is the amount of waste produced by consumable quartz molds traditionally used in counter-gravity injection casting.

II.A.2 Normal Reactor Operations, Fuel Performance Considerations

Design options must be assessed for the impact on normal operation steady-state fuel performance. A brief discussion is included here to help define and clarify what is meant by successful fuel performance. To perform acceptably, the fuel system must:

1. Position fissile material in the reactor core in a stable manner to allow a controlled and predictable fission reaction.
2. Allow effective transfer of nuclear reaction heat from the fuel to the coolant (or heat transfer medium).

3. Provide containment of radionuclides (fuel and fission products) for operational convenience and as a first barrier for safety.
4. Provide/allow a convenient means of loading fresh fuel into the core and removing and managing spent fuel.

To satisfy requirement (**1**) the axial fuel swelling must be predictable and relatively small. The fuel swelling isotropy should be predictable. Fuel column slumping is not allowed for steady-state operation. Creep and void swelling of the cladding should be predictable, and small enough so as not to create dimensional changes of the fuel pins which could interfere with coolant flow or create distortions in the assembly to hinder fuel handling or control rod operation. The thermal creep of the cladding material is also important to preventing cladding rupture and thus also applies to requirement (**3**). Cladding performance requires design equations for the accurate prediction of void swelling and of mechanical property changes created by temperature or neutron irradiation.

In considering requirement (**2**) it should be noted heat transfer between fuel and cladding is greatly enhanced by liquid sodium. Fabrication of sodium bonded fuel involves a thermal treatment to ensure that fuel and cladding are wetted by the sodium and help remove any voids or bubbles. Achieving a suitable heat transfer configuration without sodium in the gap is the key challenge with SFF technology. The design options evaluated in this study were all thought to offer some potential for a fuel system with adequate heat transfer configuration. Cladding deformation can also play a role in requirement (**2**) because cooling must be maintained on the exterior of the pins. Distortion of cladding tubes in the fuel bundle may decrease flow channels and apply stresses to the fuel assembly structure.

Requirement (**3**) helps ensure very low rate of fuel pin breaches during steady-state operation, typically less than one breach per core loading [12] [13]. These requirements are typically assured by predicting cladding thermal creep behavior or cumulative damage fraction calculated using design equations for cladding stress rupture. The confidence in the cladding material deformation and stress rupture design equations are crucial in assessing burnup limits for the fuel design. FCCI is another important phenomenon related to this requirement. For metallic SFR fuel, FCCI is chiefly caused by interdiffusion of fuel and fission products with the cladding [15]. The effect is that a brittle layer forms in the cladding that must be considered wastage and reduces the usable lifetime of fuel pins. For some cladding alloys, (e.g., ferritic/martensitic steels, FMS) carbon can be 'leached' from the cladding, transforming it into soft ferrite and weakening the cladding. The amount and release fraction of fission gas from the fuel determine gas pressure accumulation in the fuel pin gas plenum. Fuel swelling and gas release drive the Fuel/Cladding Mechanical Interaction (FCMI) which provides an additional driver for cladding deformation and has traditionally been one of the most difficult performance properties to predict. Candidate SFF designs must employ much smaller gaps between fuel and cladding at beginning-of-life for the heat transfer reasons discussed earlier. Thus, FCCI and FCMI will both likely become even more crucial behavior in understanding sodium free designs. Cladding temperature limits are also important to ensure adequate strength and thermal creep performance and to avoid eutectic formation at elevated temperature (> 715 °C for U-based fuel and stainless-steel cladding). Formation of eutectic phases can potentially liquifying fuel/cladding mixtures at their interface, effectively thin the cladding adding, and add to the likelihood of breach. While the formation of 'eutectics' for steady-state operation can be avoided by setting maximum allowable peak inner cladding temperature, it also reduces margins for transient operation.

Requirement [**4**] is self-explanatory and relates to having a safe and repeatable method of fabrication, with a minimum of waste, and providing for an environmentally acceptable and safe method for final fuel disposal.

II.A.3 Off-Normal Scenarios, Fuel Performance Considerations

In addition to steady-state performance, anticipated operational occurrences (AOC), design basis events/accidents (DBA), and beyond design basis events/accidents (BDBA) are to be considered. AOC's are those conditions of normal operation which are expected to occur one or more times during the life of the nuclear power unit. For light water reactors this includes (but is not limited to) loss of power to all recirculation pumps, tripping of the turbine generator set, isolation of the main condenser, and loss of all offsite power. The reactor, and thus the fuel, are expected to survive AOC's. DBA's are postulated accidents that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety. The fuel, as a system, will need to be robust enough to retain fission products during DBA's, or the facility can be designed to capture/contain fission products if released from the fuel. However, the requirement to ensure public health and safety can be better achieved by ensuring the fuel is robust enough to withstand a DBA. Metal fuel could be capable of withstanding a DBA without having major impact on the plant. BDBA's are accident sequences that are possible but are not fully considered in the design process because they are judged to be too unlikely. However, BDBA's are analyzed to fully understand the capability of a design.

Historically there has been much focus on overpower transients on fuel at appreciable burnups where cladding mechanical strain from thermal expansion of the swollen fuel slugs and fission gas pressures are important in describing the forces which can cause cladding rupture. The underlying driver behind cladding rupture is formation of uranium-iron eutectic phases which can rapidly consume the cladding. Another safety performance area which receives particular attention for SFF designs is the concern for fuel melt and slumping in early life behavior (before appreciable fuel swelling) given the absence of a liquid sodium to conduct heat through open volume. The key concern here revolves around core rearrangement into a neutronic state with more reactivity.

II.A.4 Back-End Considerations

The back-end considerations used in this study are important because they are the principal motivation behind SFF development. These considerations are also perhaps the simplest. The combination of a chemical reaction hazard (sodium) and radioactive hazard (spent nuclear fuel) categorizes sodium bearing spent fuel to be considered "mixed waste" and thus undergo onerous processing before it can be disposed. Decades later these efforts are still underway for spent fuel from EBR-II, but the technologies have been successfully demonstrated [14]. The concern for combined radiologic and chemical hazards also applies to storage and transportation scenarios. Removal of the sodium bond significantly reduces the chemical reaction hazards in irradiated metallic fuel and is especially important in considering once-through fuel cycles.

When considering continuous recycle “closed fuel cycles”, it is important to note that fuel and sodium final waste forms end up separated in these processes. Afterall, sodium bonded metallic fuel and continuous fuel recycle were both created as key parts of the same grand invention, the Integral Fast Reactor. Naturally this creates the question: Why would one even consider SFF for continuous recycle use at all? As will be shown, the findings of this study did not arrive at a wholehearted endorsement of SFF for a close fuel cycle. Still, some of the less prominent SFF advantages such as removal of sodium from fresh fuel fabrication process, reactor neutronic benefits, and common technologies/synergies in a potential future fleet where many SFRs operate with once-through fuel cycles could perhaps create a persuasive case for using SFF designs in closed fuel cycles.

III. Results

III.A Design Options

Design options were categorized into four groups including 1) Fuel Alloy, 2) Cladding Alloy, 3) Fuel Geometry, and 4) FCCI Mitigation. Manufacturing options were categorized into three categories including 1) Fuel Slug Production, 2) Liner Application, and 3) Slug Installation, Gap Treatment. In all option categories the first option to be scored represented the baseline sodium-bonded fuel technology used in EBR-II Mk-IV fuel assemblies. The sodium bonded baseline technology was not included as a concept that could be ultimately selected, but primarily as a reference case to help “calibrate” scores against a familiar system.

Fuel alloy options included uranium with Zr (U-Zr), uranium alloyed with molybdenum (U-Mo), and micro-alloy uranium where minimal constituent content is added to solution-harden pure uranium. Cladding options included austenitic stainless-steel alloys, ferritic/martensitic steel (FMS) alloys, and Oxide Dispersion Strengthened (ODS) steel alloys. Fuel geometry options included “sodium-bonded” loose-fitting solid cylindrical slugs, “annular” tight-fitting fuel slugs with a central hole, “grooved” tight-fitting fuel slug with external slots, “Split C” slugs which are essentially the annular geometry except split into two halves, “particle” fuel where spherical fuel particles are packed inside the pin, and “lotus” or porous metal slugs with entrapped porosity. The fuel geometry options are illustrated in Figure 2. All fuel geometry options, except the sodium-bonded design, were assumed to have helium gas initially filling the free space within the fuel pin. Finally, the FCCI mitigation options considered include the reference option without FCCI mitigation, alloy additives which help immobilize lanthanides from interacting with the cladding, and physical diffusion barriers between fuel slugs and the cladding.

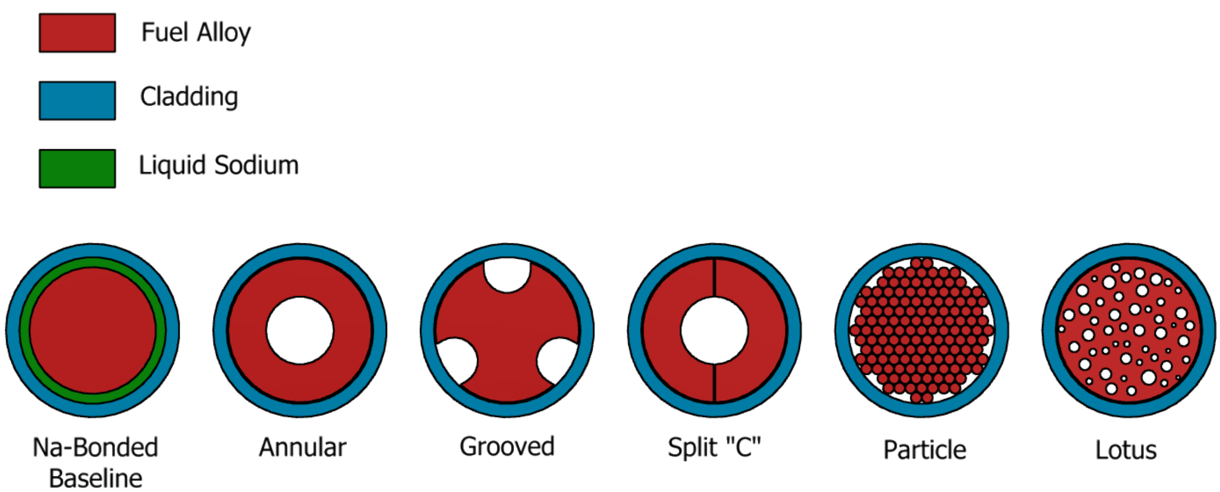

Figure 2: Cross Section Schematic of Fuel Geometry Options

All fuel design options were assessed to prioritize categories of sub-options rather than to determine detailed engineering parameters and tolerances. For example, fuel alloys were thought of as “U-Zr” or “U-Mo” with Zr or Mo content on the order of ~10 wt%, but no specific decision was reached on the exact alloy composition. Cladding alloys were assessed as “austenitic alloys” rather than D9 vs. 316, and “FMS alloys” rather HT-9 vs. Gr-92. The fuel geometry options were envisioned to occupy 75% of the cross-sectional area inside the cladding (so-called 75% smear density, SD). The FCCI-mitigating additive option was assessed based on the capabilities of known additives such as antimony [25] and tin [26]. The FCCI barrier option was assessed based on use of a zirconium layer. All these parameters represent fuel design and optimization parameters that should be assessed and specified further through future studies.

Simply put, the trade study options were assessed at a categorical level only in order to help prioritize future efforts precisely because future work would be needed to develop detailed design specifications.

Manufacturing options for slug production included injection casting into sacrificial quartz molds, slug extrusion followed by heat treatment to develop more equiaxed grains, continuous casting, injection/gravity casting into reusable molds, and additive manufacturing by a direct energy deposition method. Options for FCCI barrier application included a baseline no-barrier option, integral production slug/barrier in a single process (e.g., casting into a liner, or coextrusion), deposition of barriers onto slugs (e.g., electroplating, plasma spray), and deposition of barriers inside cladding tubes (e.g., chemical vapor deposition). Manufacturing options were essentially considered in three categories of clearance between the slug outer diameter and the cladding tubes termed: loose, medium, and tight. The corresponding options to install slugs into cladding and treat the gap included loading loose-fitting slugs followed by sodium bonding, loading medium-fitting slugs followed by mechanical swaging of cladding, loading medium-fitting slugs followed by external pressure treatment of cladding (e.g., hot isostatic press), loading medium-fitting slugs followed by a process to fill the gap with barrier material (e.g., chemical vapor infiltration), and loading tight-fitting slugs with no further processing of the gap. Like the design options, these manufacturing options were considered in a categorical sense while imagining established or known examples to aid in the assessment, but detailed selections of method, equipment, or specifications were not made during the present study.

III.B – Assessment of Design Options

III.B.1 Assessment of Design Options for Fabrication Considerations

Fuel Alloy: The alloys under consideration have all been used previously in various reactors. As shown by previous reactor use the alloys have feasible fabrication paths. These fuels have all shown to have adequate mechanical properties to allow forming into the required fuel forms. Higher temperature alloys, such as U-Zr, may be more difficult to produce (alloy and casting) but there is ample evidence through the Integral Fast Reactor program that U-Zr can be successfully alloyed and cast with proper equipment. The alloy composition will have little effects on the other considerations. When the enhanced fuel requirements were considered, specifically the addition of plutonium or other minor actinides, no differences were identified for the U-Mo or U-Zr options, although only U-Pu-Zr has seen significant reactor use. The major difficulty expected in the low/micro alloy case would be an excessive lowering of the melting point may impact some slug fabrication routes which were assessed separately.

Cladding Alloy: The consideration of cladding alloys on fabrication basically follows commercial availability and experience, in other words, economic feasibility and ability to predict irradiated properties. The austenitic steels scored highest as they currently have commercial availability in typical cladding dimensions. FMS alloys received an intermediate score as cladding tubes have been produced in commercial quantities in the past, but currently are unavailable in typical cladding dimensions. ODS were scored the lowest due to lack of historic experience at scale and due to the inherent fabrication difficulties associated with alloy fabrication, anisotropic behavior, difficulties in forming tubing, and joining difficulties. The cladding alloy options scored the same for baseline and enhanced fuel needs.

Fuel Geometry: Fuel geometry naturally saw the largest impacts on the fabrication. Based on the long history of loose-fitting sodium bonded fuel slug irradiation in EBR-II this method was scored the highest. This is because the dimensional tolerances can be set at a fairly large range as there is no tight-fitting components, therefore forming, inspections, and loading processes can be less precise. Annular and split "C" both need to be formed to precise dimensions which generally will include a muti-step fabrication path and possibly subtractive manufacturing processes (e.g., machining). The annular fuel concept will require tight tolerance control on both the inner and outer diameters. Further, due to the high aspect ratio and the interval void area of annular fuel slugs possible fabrication routes are limited, in other words, annular fuel slugs cannot be produced using traditional injection casting or similar processes. The split "C" concept may be more feasibly manufactured using traditional casting methods because all the open volume is external to all surfaces. However, because two separate fuel components must be mated together in an exact manner, the amount of precise forming and machining is likely to increase. Grooved fuel still requires a tight fit against the cladding leading to tighter tolerances on the major diameter surfaces. However, it does have the advantage that all free volume, the grooves in this case, are external and therefore can be more easily fabricated and inspected. Particle fuel has the presumed advantages of easier loading and established inspection techniques for particle size. However, uranium alloys are reactive and can oxidize very quickly, possibly pyrophorically depending on particle size, therefore particle fabrication is not straight forward for these fuels. The lotus concept has not been performed for uranium alloys and verifying total porosity and morphology of the porosity will be difficult whether through inspection or special process control. Enhanced fuel options were ranked generally lower because of the difficulties of working with transuranic fuels which may include remote operations. Remote casting of fuel has been shown to be feasible, particularly in the case of counter gravity injection casting. However, all the non-sodium bearing fuel geometries require more precise tolerance control than has typically been required for the loose-fitting sodium bonded fuel slug.

FCCI Mitigation: Omission of deliberate FCCI mitigation features has been the standard method of fuel fabrication for some time and, of course, scored the highest as it is easiest from the fabrication standpoint. Alloy additives may make casting slightly different, however the additive content is generally small and effects of casting or alloying behavior can be overcome through parameter selection. Additives received a slightly lower score than the no FCCI mitigation option as additive could affect mechanical properties important to some manufacturing methods. Barrier application increases the fabrication process complexity and may also complicate the loading process of the tight-fitting slugs. If the FCCI barrier is not robust enough, it could sustain damage when the fuel slug is slid down during fuel slug loading. The, inclusion of a physical FCCI barrier was viewed as the most difficult option from a fabrication viewpoint.

III.B.2 Assessment of Design Options for Normal Operations

Fuel Alloy: The options of U-Zr, U-Mo and micro-alloy uranium were chosen because of the volume of experience of the metallic alloys with nuclear fuel. U-Zr alloys were tested in the 1950s and 1960s for potential use in SFR's. U-10Zr was used later in EBR-II as part of the Integral Fast Reactor (IFR) program [16]. U-Mo alloys were used in some of the early fast reactors (Dounreay, Fermi) and, also used in the 'Fs' alloy in early U-5Fs EBR-II fuel, where the majority of the Fs alloy composition consisted of

Mo and Ru. So, there is experience with these fuels, and their main advantage is the potential of having a higher uranium density. The low-alloy fuels were developed in the 1960s for use in the Savannah River Reactors, heavy-water cooled, based upon using a low level of alloying to solution-harden pure uranium, lessening fuel swelling [17]. There is little or no experience with using them in an SFR for driver fuel.

If selected for 'Baseline Operation', U-10Zr, was originally chosen for the initial IFR fuel because of potential FCCI mitigation. It has been demonstrated as a successful alloy for driver fuel in EBR-II and there is a Fuels Irradiation & Physics Database (FIPD) [18].

Use of 316 stainless steel for the assembly hardware limited the fuel burnup to 10 at.% HM, because of void swelling of the wrapper, but qualification assemblies demonstrated the fuel could be operated to much higher exposures, nearing 20 at.%. For 'Enhanced Operation' there may be FCCI issues not yet completely studied.

U-10Mo has the next largest database for SFR operation, this will likely be exacerbated for the 'Enhanced Operation' if protection for the cladding (coating, liner) is not selected as an additional design option.

There just isn't enough testing information, or experience as to the operation of the low-alloy uranium for fast reactors, especially related to the high operating temperature. But, both U-10Mo and low-alloy options could provide the opportunity for higher uranium densities than U-10Zr. Table 2 provides those uranium densities at room temperature and 800°C. The density difference is not large for U-10Mo and U-10Zr but may be helpful for reactor design for the "Enhanced Operation" option, where extended lifetimes would be expected for the fuel.

Table 2: Uranium densities for the various fuel alloy options

Alloy	Uranium Density (20°C), gU/cm^3	Uranium Density (800°C), gU/cm^3
U-10Zr	14.4	13.7
U-10Mo	15.5	15.0
Uranium	19.0	17.9

Cladding Alloy: The cladding alloy choices were purposely limited to those which have been studied for this application in the U.S. So, the well-studied, Ti modified-316-type austenitic stainless steel. The nickel content was increased, and some Ti was added, to increase the incubation period (in fast neutron exposure) for void swelling to begin. These alloys include D9 (U.S., and used in India with modifications), AIM 1 and AIM-2 in France, and PNC-FMS in Japan. An advantage of these alloys is that there is a well-developed fabrication infrastructure for the alloys and components. The void swelling for the European (France) alloys, from the earlier '15-15 Ti' (15wt% Ni – 15 Cr wt% plus Ti) to AIM1, is shown in Figure 3 [19].

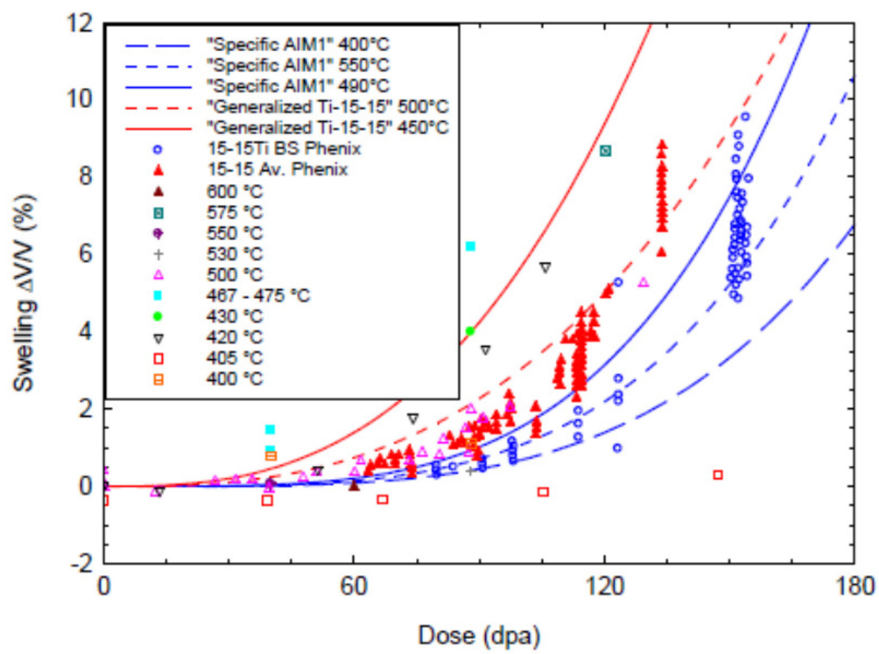

Figure 3: Comparison between measured swelling data and swelling correlations for heats of AIM1 and 15/15Ti as a function of neutron damage dose (dpa). ΔD/D of the cladding will be roughly 1/3 of ΔV/V.

Note that 15/15Ti *may* work for 100 dpa exposure of the 'Base Operation' but will not be acceptable at 'Enhanced Operation'. AIM1 will be acceptable for Base Operation but also will not work for 'Enhanced Operation.'.

Ferritic/martensitic steels were represented by HT-9 due to extent of previous study, but noting that others (e.g. T91) were also potential choices. These materials are known for superior resistance to void swelling when used as SFR cladding [20], They will meet both base and enhanced operations in terms of void swelling.

A deficiency seems to be in high-temperature strength and perhaps limits its use, especially for the Enhanced Option. A comparison between typical yield strength values for HT-9, cold-worked D9 (CWD9) and CW type 316 stainless steels is shown in Figure 4 [21]. Heat-to-heat variation are possible with the alloys, as are variations with heat treatment for HT-9.

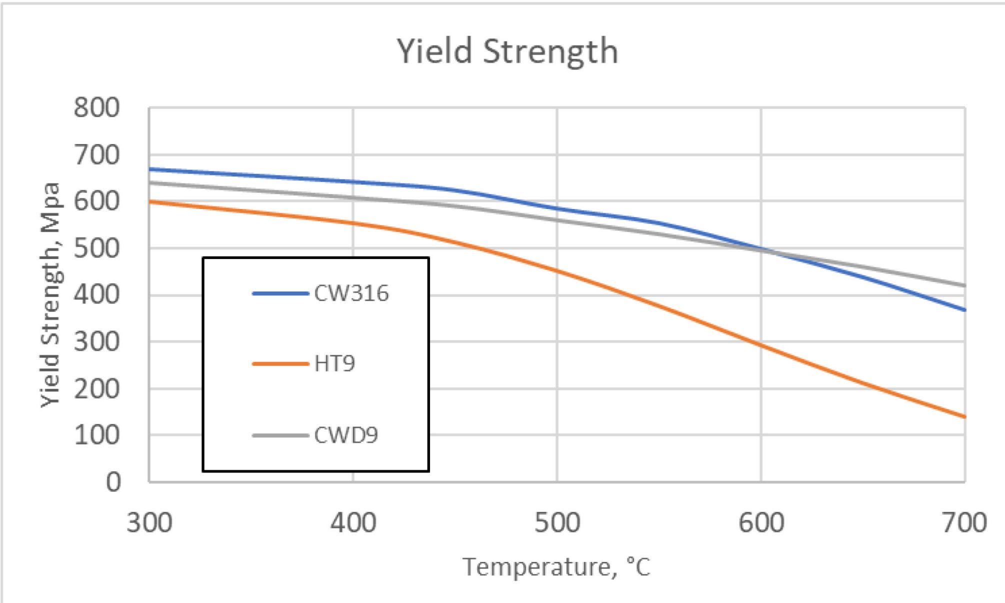

Figure 4: Yield strength as a function of temperature for unirradiated ferritic/martensitic (HT-9) and two unirradiated austenitic stainless steels. "CW" = cold-worked. With irradiation hardening, the HT-9 yield strength will be higher, but drops off sharply at temperatures above 650 °C.

KAERI and others have been looking at the potential use of versions of F/M alloy T92 (9Cr-1Mo). The advantage improved mechanical properties at higher temperatures than either T91 or HT-9 [22], The basic T92 alloy is modified with reduced Ni, Si and Mn, and thermal/mechanical treatments are optimized produced an improved microstructure, including precipitate types, to improving high temperature mechanical properties. It is worth following testing of fueled experiments with this alloy to see if it can be a replacement for HT-9.

Oxide-Dispersion Strengthened, ODS, F/M options have received some development and irradiation testing, for irradiation performance and fabrication [23]. Fabrication has been difficult in maintaining the uniform dispersion of fine oxide particles, particularly difficult when operations involving melting are applied. The dispersion of oxide particles is designed to enhance high-temperature strength, and uniform particle dispersal is required. Recent investigations on modified fabrication techniques have indicated potential for solving these fabrication issues [Kevan mentioned such a reference, Kobe Steel]. While some alloys like these may be necessary for optimization of fuels for 'Enhanced Operation', it is currently not ready to choose as the cladding option.

Fuel Geometry: The baseline metallic fuel geometry for an SFR has basically been a solid circular cylinder of the fuel Na-bonded to a larger (ID) stainless steel cladding tube. The fuel slug, or slugs if they are stacked, is smaller in diameter than the inner diameter (ID) of the cladding to allow fuel swelling until steady-steady fission gas release can be achieved. The design characteristic known as smeared density is given by the cross-sectional area of the fuel divided by the cross-sectional area inscribed by the ID of the cladding. In this case, usually the smeared density is 75 %, (slug OD)/cladding ID), also known as the smeared density (SD). An SD of 75% uses a fuel slug small enough in diameter to allow rapid gas release.

Older designs, like co-extruded fuel and cladding for EBR-I and Dounreay were used for fuel with a very low burnup expectation and had higher smeared density. Even EBR-II started with an 85% SD in their MK-IA design.

For the sodium-free concept, the options for fuel geometry included 1) annular, 2) grooved (sold cylinder, near 100% smeared density, with a slotted outer surface) [24], 3) split 'C', 4) particle fuel, and 5) 'Lotus'. The standard, 75% smeared dense, solid cylinder, sodium bonded, was included for comparison. The others were sodium free, helium bonded. The smeared density in those cases is calculated the same way, cross-sectional area of the fuel divided by the cross-sectional area inscribed by the ID of the cladding.

Discussions of the option included, "Loose slug easiest option, annular requires multiple steps and tight tolerances, grooved fuel and split-C also require tight OD tolerance but open volume features are external and give other fab options, split C has multiple-part tolerance stack up, particle option naturally achieves packing fraction via pour it in method, porous lotus metal difficulty expected in process control and inspection." Please see discussions of fabrication methods to see details on the difficulties that options may impose. Of the four options, annular fuel was selected, largely for fabrication reasons, but also for some fuel performance reasons discussed here.

One such issue was maintaining adequate thermal conductivity from fuel to coolant. There must be a fuel/cladding gap to load the fuel into the cladding and that gap is expected to be filled with He as a conductive medium. But only small gaps could result in overheating and poor performance. One 'fix' discussed was to give the pin a final swaging treatment to ensure adequate fuel/cladding contact. Grooved fuel would have the same problem, but the swaging operation may damage the cladding in the areas where fuel and cladding were in close contact.

The suggested sodium-free particle fuel concept here is different than known composite or dispersion fuels where fuel particles, typically less than 50 vol%, reside in a conductive matrix. The key concern with this concept is that numerous contact gap thermal resistances with very little total contact surface area between particles would drive high centerline temperature until later life when particles swell into each other and fill these gaps fill voids. Indeed, similar vibropac design have been used in some nuclear fuels, but these applications have typically used ceramic fuel types which have increased margin to melting temperatures.

FCCI Mitigation: Of all the issues with metallic fuel performance, the fuel/cladding chemical interaction, where there is a solid-state interdiffusion of fuel and fission products with the cladding, effectively thinning the cladding. All Fe-based cladding options are prone to this issue with metallic fuels at SFR operating conditions, although less so for Base Operation [15]. Zirconium in the fuel was thought to mitigate the problem, but that was found to be only a general effect and not consistent over the entire fuel/cladding interface. Reasons for this are suggested in a study of T91/U-10Zr diffusion couples [25] where it shown that certain phases form as the fuel/cladding interdiffusion begins, but this happened heterogeneously on the interdiffusion surface.

Other options proposed were fuel additives that form stable compounds with the lanthanide fission products, such as Sb, and thereby prevent these fission products from interacting with the cladding [26].

Further work is needed to prescribe compositions that would prevent lanthanide fission product FCCI. FCCI effects of uranium and cladding interdiffusion, are not mitigated.

It was therefore concluded that a barrier is required to prevent FCCI. The barrier could be either in the form of a coating or liner to the cladding, or because, in the sodium-free designs, the fuel is already in close contact with the cladding, the fuel could also be coated. Again, fabrication issues must be studied to arrive at a final suggested design. Mitigation of FCCI does not lead to a specific fuel alloy choice.

III.B.3 Assessment of Design Options for Off-Normal Scenarios

One of the major advantages of metal fuel over oxide fuel is fuel-coolant compatibility. This is especially important during off-normal events that may result in a breach of the cladding. There are little to no interactions between the metal fuel and sodium coolant, whereas there is a vigorous reaction between the oxide fuel and sodium coolant. This was confirmed during the run-beyond-clad-breach tests with metal fuel in EBR-II. For the metal fuels under consideration in this study, we presumed that no damage would occur during a DBA, and no cladding failure would occur during a BDBA.

Fuel Alloy: In many off-normal events, a rise in temperature is experienced. For the U-Zr and U-Mo based metal fuels, the alloying constituent is a significant factor in the melting temperature of the fuel, i.e., the solidus temperature typically increases with an increasing amount of the alloying constituent (Zr or Mo). For the micro-alloyed fuel, the fuel melting temperature can be low enough to cause concern during certain off-normal events, e.g., loss-of-flow. In addition to the higher melting temperatures, the alloying constituents can inhibit FCCI (e.g., Zr); this is discussed further in the sections below. For high burnup fuel (>20%), an additional concern is FCMI as the solid fission products begin to fill in the voids created by fission gases during normal operations. This will start to increase the stress and strain on the clad via direct contact between the fuel and cladding as the fuel swells.

Cladding Alloy: The austenitic steels behave fairly well under off-normal events (assuming an increase in temperature), while it was discussed earlier that the ferritic-martensitic (F/M) steels have lower yield strength (compare to austenitics) as temperatures increase. This may not be as important when considering the more advanced F/M steels as they have higher yield strength than previous generations. However, the newer F/M steels have little to no irradiation data, which could impact the performance during off-normal events. ODS steels have the potential for higher resistivity to temperature increases due to their high yield strength, and they have shown to be highly resistant to radiation damage. Finally, the major concern with cladding during off-normal events is FCCI, which is discussed in a section below.

Fuel Geometry: The fuel geometry could have an impact if an off-normal event occurred at the beginning of life, particularly for an annular fuel. One might envision a scenario where the increase in temperature during an off-normal event could result in the collapse of the annulus, and an attendant increase in reactivity as the fuel is relocated at the bottom of the fuel pin. Other geometries may not be as reactive in the scenario described above, but could still pose challenges when considering off-normal events at the beginning of life. More work needs to be performed via transient testing to verify the scenarios described above.

FCCI Mitigation: As was discussed in the previous section (Normal Operations), FCCI is of the highest concern, and even more so during off-normal events. All the cladding being considered is Fe-based, which poses challenges regarding eutectics formed between the fuel and the cladding. The mitigation options that were discussed for this study included barriers between the fuel and cladding (in various forms, e.g., liners, coatings, etc.), and would also be effective during off-normal events.

III.B.4 Assessment of Design Options for Back-End Considerations

Fuel Alloy: Fuel pins are essentially just placed into long term storage or repository without further processing in the baseline once-through fuel cycle. The team did not see a strong difference between any of the fuel alloy options in this scenario. The enhanced fuel cycle, however, does include further processing to recycle fuel alloys. All of the fuel alloy options were foreseen to be compatible with electrorefining, but the U-Mo and low-alloy options scored slightly higher than U-Zr because the zirconium constituent can create hazardous compounds after acid dissolution if used in aqueous recycle processes.

Cladding Alloy: Similarly, the team did not identify any strong difference in back-end performance for cladding alloys. It was acknowledged that austenitic and ODS might offer enhanced creep resistance in storage scenarios, and that ODS alloys might be more difficult to cut into smaller pieces for recycle processing, but these considerations were not significant enough to warrant different scoring for cladding alloy needs relative to back-end considerations.

Fuel Geometry: All of fuel geometry options essentially scored the same for both the baseline and enhanced fuel cycle back-end scenarios, except the sodium-bonded option which naturally scored lower due to the chemical reaction hazard and mixed-waste designation associated with this fuel type. The sodium bonded option was noted to create a slight nuisance in maintaining chemical purity of molten salt used in electrorefining continuous recycle processes, but this aspect was not considered significant enough to warrant different scoring.

FCCI Mitigation: Finally, the FCCI mitigation design options all scored the same for back-end considerations. It was noted that if zirconium was used as an FCCI barrier, then it could create the same concern as U-Zr in aqueous recycle processes. This aspect was not viewed as significant enough to warrant a different score, especially noting that other viable materials could be likely be selected if the FCCI barrier option was to be used for continuous recycle via aqueous processing.

A summary of the design options ranking matrix is shown in Table 3.

Table 3: Summary of Design Options Scoring Matrix

	Category	Weight	Fuel Alloy			Cladding Alloy			Fuel Geometry						FCCI Mitigation		
			U-Zr	U-Mo	Micro alloy U	FMS	Austenitic	ODS	Na-Bonded Slug	Annular	Grooved	Split "C"	Particle	Lotus	None	Alloy Additives	Barrier
Fabrication	Baseline	4	3	3	3	3	5	1	4	2	3	2	2	1	5	4	3
	Enhanced	2	3	3	2	3	5	1	3	1	2	2	1	1	5	4	3
Normal Operation	Baseline	5	3	2	2	3	3	3	5	4	2	3	1	2	3	3	3
	Enhanced	3	3	2	1	3	2	5	4	3	1	2	1	1	1	2	4
Off-Normal Scenarios	Baseline	4	3	2	2	3	3	3	5	3	4	3	1	2	3	3	3
	Enhanced	2	4	2	1	3	4	5	5	2	3	2	1	2	1	2	4
Back-end	Baseline	3	3	3	3	3	3	3	1	3	3	3	3	3	3	3	3
	Enhanced	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3
		Baseline Score	48	39	39	48	56	40	64	49	47	44	26	31	56	52	48
		Enhanced Score	25	19	12	24	27	30	31	18	16	17	10	12	18	21	29
		Overall Score	73	58	51	72	83	70	95	67	63	61	36	43	74	73	77

III.C Manufacturing Options Assessment

III.C.1 Assessment of Manufacturing Options for Fabrication Considerations

Similar to the design portion of the study a trade study was undertaken more specifically for manufacturability. Slug production examined the method that fuel slugs would be fabricated. In general, metals are first formed to at least a rough shape, if not net shape, by a variation of a casting process or in some cases by an additive manufacturing process. Many advanced concepts call for and application of a diffusion barrier to either the fuel or the cladding tube itself. The application and location, i.e. cladding inside diameter or slug outside surface, as well as application through the slug manufacturing process or deposition on either the slug or cladding tube was ranked. After slugs are produced, they must be assembled into the cladding tubes. Without the sodium heat transfer through the helium and to the cladding become very important to fuel behavior in the SFF. The slug fit in relation to the cladding inside diameter, loose fitting having a radial gap on the order of 0.25-0.50 mm or greater, tight fitting having a radial gap on the order of less than 0.025 mm, and medium fitting in between those two extremes, and how to close that gap in the case of a loose or medium fitting slug, was evaluated as well.

Fuel Slug Production: Injection casting into quartz molds is the baseline process and has been shown to be a robust process having been used to successfully produce over 100,000 fuel pins that were irradiated in the EBR-II. However, despite this history, process weaknesses are evident. The single use glass molds produce a very large radiological waste stream for disposal, adding significant cost to the manufacturing process. During EBR-II operations the precision formed quartz molds were custom manufactured for EBR-II. However, because EBR-II has not operated since 1994 the supply chain has not been maintained for the specialty sized glass. Also, because of the nature of injection casting, a significant amount of material, the heel, must be left in the crucible during casting to not allow air ingress to the molds during filling. Although this material is recycled back into the process, it brings with it impurities and lowers the overall charge to fuel slug yield. Also, injection casting is not feasible for annular fuels, without further processing such as drilling, increasing the amount of waste to be disposed of or recycled and lowering yields.

Extrusion has been used for manufacturing of fuel slug, particularly in Pu production reactors. It has the advantages of being flexible for fuel geometries and produces long length of fuel with little loss, in other words, high yields. In order to mitigate the crystallographic texture produced through the extrusion process a heat treatment is generally specified for the fuel. Also, it should be noted, that because uranium is generally hot extruded dimensional tolerances may not be as tightly controlled as is required for direct use in some fuel systems, so secondary process may be required to dimensional requirements.

Continuous casting has been proposed for fuel slug fabrication but has not been implemented. The potential advantages include a high yield as there will be little to no heel left in the crucible. Molds or dies are incorporated into the crucible/casting system so there will be essentially no mold waste, in comparison to quartz molds. Also, because during continuous casting the solidification rate and location of the solidification front are tightly controlled the grain structure will be a non-textured equiaxed structure. Additionally, annular fuels could be directly cast using continuous casting technology. Surface finish and dimensional consistency will require further analysis and experimentation as fuel pins are substantially smaller than what is often continuously cast in the metals industry.

Casting into reusable molds hold some of the same advantages as continuous casting and had been examined, although with limited success with injection casting. The high aspect ratio of fuel pins will require a more complex mold design, likely a split mold design, and although some success has been seen on the laboratory scale, the high aspect ratio is not generally a geometry conducive to standard casting technology. As with injection casting, annular geometries will not be feasible without substantial post casting subtractive manufacturing processing.

Additive manufacturing processes, such as the direct energy deposition method, hold promise for very complex geometries and non-standard fuel designs, so called “one-off” designs. However, the high aspect ratio of the standard fuel slug and the required production rate are not suitable for additive manufacturing.

Also, the particulate feedstock needed for direct energy deposition methods is not readily available and will require substantial resources to produce a suitable supply.

For the enhanced fuel category, it was assumed that the manufacturing processes would at a minimum be operated in a glovebox type containment and possibly a hot cell environment. Injection casting into quartz molds, despite its limitations is attractive in this scenario as it has been shown to be compact enough and operate in either environment. Because of the footprint, high pressures, and complexity extrusion and to a greater extent additive manufacturing was seen much less attractive for installation in a full containment.

FCCI Barrier Application: The baseline process is to apply no barrier, because the options were scored based on ease and efficiency of manufacturing and fulfilling the design requirement this option was scored the highest. There is ample evidence from previous irradiations that fuel systems without a barrier can perform adequately to 10% heavy metal burnup.

If a barrier is applied at the same time as slug production, an additional processing step is not added which is attractive because a fuel performance benefit may be added with little cost or additional processing. Application on the external surface of the fuel is preferred because the barrier material can be more easily inspected to ensure a complete flaw free coating is applied. Barrier application to the slug is only beneficial for annular geometries where the external surfaces see little or no swelling unless the barrier can expand with the swelling fuel slug. If the barriers are applied by casting into a sheath made from a barrier material, such as zirconium, this may also have the added benefit of enabling or reducing wear on reusable molds. Casting into a zirconium liner or sheath has been shown to a limited extent in previous fuel development work. Another, more mature, application method is co-extrusion with the fuel slug. Co-extrusion has been shown to be feasible for fuel alloys and has been used routinely in cladding applications. Another attractive option is to deposit a barrier material onto the fuel slug. The High Performance Research Reactor (HPRR) program has successfully developed electroplating technology for zirconium onto U-Mo fuel foils. Although this would be an additional processing step the benefits such as improved FCCI mitigation, inspect-ability, minimal impact on the overall fabrication process are still applicable.

The final option, deposition of barrier material onto the inside surface of the cladding tubes was scored the lowest. Although, application to the cladding tube would be advantageous by not adding any processing steps to the radiological operations, it has several disadvantages which must be considered. Barrier application has been examined previously, although some deposition methods have shown promise at the laboratory scale, less than 12” of cladding tube, no deposition process has shown feasibility on full length tubes. Perhaps the most successful concept is co-drawing liner material with the cladding tube. This has been shown to be feasible, although because of the barrier material must first be fabricated for assembly into the cladding tube the number of tubes to be fabricated essentially doubles. Also, from a fuel performance standpoint the barrier tube wall thickness is on the order of 25μm all thickness, which will require specialized tubing manufacturing processes. It should be noted that barrier tubes used for co-drawing would generally be the entire length of the reactor core, while similar tubes used for incorporation onto the fuel slug or re-usable molds would only need to be as long as the fuel slug itself, making fabrication easier. The largest issue of barrier application to the cladding tubes is the inspect-ability of the barrier. If the FCCI barrier is to mitigate FCCI it must protect all of fuel-cladding interface as any flaw would be a potential site failure due to FCCI, in other words the barrier must be completely free of flaws. Because of this necessity, the ability to inspect and ensure integrity of the barrier is very important and would be more complex on an internal tube surface versus the external fuel slug surface.

Slug Installation, Gap Treatment: The baseline process that was used for EBR-II fuel slugs is a high temperature “bonding” process. After the slug is surrounded by sodium in the fuel pin, the pin is heat to approximately 500°C and held for 1 hour while being agitated. The temperature and time allow the fuel and cladding to be wet by the sodium which reduces residual porosity in the sodium annulus between the fuel and cladding. The agitation was also used to reduce this porosity. Following the bonding step, an inspection was performed to ensure the bond integrity. This process adds several steps and possible reworks and rejections to the pin manufacturing process, increasing manufacturing time, and decreasing overall efficiency.

The second process evaluated was a medium fitting slug following by swaging of the cladding to reduce or eliminate the fuel cladding gap. This process is particularly attractive because the medium fit slug allows for some diameter and straightness variability while still loading the slug with minimal effort. Swaging is an industrial process used through the manufacturing industry, it can be automated, and is a simple process. This process does necessitate some level of ductility in the cladding and will impart a small amount of cold work into the material. This is not seen as a problem because cladding alloys must have some level of ductility to be formed into the precision cladding tubes, although may be an issue for some ODS alloy tubes. The additional cold work added is assumed to not negatively affect cladding performance in the reactor. This assumption is based on the improved swelling resistance seen in austenitic alloys. It should also be noted that that the amount of cold will be small limiting the irradiation performance effects and necessary ductility.

The third process is similar to the second, although a source of isostatic pressure, presumably a hot or cold isostatic press, is used to close the gap. This option was scored substantially lower because the pressure would also close the plenum area as well without appropriately designed plenum spacers. Also, these isostatic pressure processes are batch processes, and in the case of hot isostatic pressures, must have a long enough time at temperature that the cladding has time enough to creep down. Adding in this type of step would add substantial amount of time to the manufacturing process.

As an alternative to using pressure to fill the gap of a medium fitting slug, the gap could be filled with a FCCI liner material. This process is seen as attractive because it combined FCCI mitigation, with the ease of loading a medium fitting slug. However, the experts are not aware of any process that has been developed that could be used to reliably fill the cladding fuel gap with a FCCI barrier material. However, it should be noted that this process should be of interest for manufacturing development.

The final process examined was insertion of a tight-fitting slug into the cladding. To allow insertion of a tight fitting slug very tight diametral and straightness tolerances must be required to avoid “stuck slugs" during loading. This process would be quite similar to the current processes used to load light water reactor (LWR) fuel pellets into the cladding. Although this is possible, in the case of the LWR fuel industry this is made possible by precision grinding and forming each pellet ensuring tight diametral tolerances can be met, and the pellets are a much shorter length than typical metallic fuel have been, so straightness tolerances can also be relaxed substantially as compared to a 30-45 cm long metallic fuel slug. Although not impossible, to shorten the fuel slug length on the order of ceramic pellets negates some of the fabrication advantages of the metallic fuel. If precision grinding is needed this would reduce overall production yield based on increased scrap levels, and the grinding waste would require substantial processing before it could be recycled back into the process. Other precision forming processes are possible and could likely meet the dimensional tolerances needed, however, all of the processes will increase complexity and time, thereby reducing overall efficiency, of the fuel manufacturing process.

III.C.2 Assessment of Manufacturing Options for Normal Operations

Fuel Slug Production: The methods of slug production were evaluated for their influence on normal operation steady state fuel performance. There is considerable data showing that a cast microstructure yields microstructure with equiaxed grains and ultimately produces isotropic fuel swelling. For this reason, both the injection casting into consumable molds and continuous casting options were scored favorably. The option to cast into reusable molds scored slightly lower because casting into reusable molds (e.g., book molds) could create melt cooling and resulting microstructures in ways that are not radially symmetric or create local features such as parting lines. These features could influence swelling isotropy or create stress concentrations with the cladding, but it was judged that these concerns could likely be minimized with adequate process refinement. Extrusion processes were also scored similarly because the process would elongate alloy grains, which cannot likely be fully recovered in heat treatment, thus causing some amount of non-isotropic fuel swelling. Finally, the option to use additive manufacturing received moderate scores primarily due to the anisotropic stress state that layer-by-layer sintering creates and concerns for its effect on early life swelling isotropy.

FCCI Barrier Application: The methods for applying FCCI barriers all received the same favorable score for steady operation for their potential to mitigate FCCI and cladding wastage in steady state operations. The team did not identify a significant difference between the barrier application process, except that this category of manufacturing options also included a baseline option for no barrier which naturally scored lower. The disparity between the barrier options and the no barrier options was greater for the enhanced fuel needs category where the presence of an FCCI barrier was judged to be practically essential to enabling higher temperature/burnup operation.

Slug Installation, Gap Treatment: The method of installing fuel slugs and treating the fuel-to-cladding gap received a range of scores for steady state fuel performance. The sodium-bonded option scored well owing to its unique ability to facilitate heat transfer from fuel to cladding in early life, and to help recover fuel thermal conductivity in late life, but among sodium free candidates the option to install a medium-fitting slug and swage down the cladding for a tighter fit scored highest. This option was viewed for numerous benefits in providing a loose enough fit to protect FCCI barriers (if present) during slug installation, closing the thermal resistance gap for better heat transfer in early life, and in providing additional cold work which is known to improve void swelling behavior in austenitic stainless steels. It was noted, however, that the swaging operation could impart additional strain which could be problematic in less ductile cladding alloys such as ODS. This interaction is an example of one area where it was difficult to assess a manufacturing option totally independent of the design options. In any case, the swaging option was scored slightly lower for the enhanced needs category to reflect this consideration. The external pressure "creep down" option did not score favorably since it was anticipated that such a process (e.g., Hot Isostatic Press) would occur at temperatures that negatively affect cladding mechanical properties. The option to fill the fuel-to-cladding gap with liner material was also not scored favorably due to concerns that any process with this ability (e.g., chemical vapor infiltration) would likely struggle to achieve 100% infiltration into a long thin annular gap; thus creating local gaps areas without barrier. The option to install a tight-fitting slug with no further processing was scored unfavorably based on the expectation that the final gap clearance would be larger than the other options in order to support practical slug/cladding dimensional tolerancing which, along with the increased risk for FCCI barrier damage during slug installation, could negatively affect fuel performance.

III.C.3 Assessment of Manufacturing Options for Off-Normal Scenarios

Fuel Slug Production: The methods of slug production alone (not considering slug composition or geometry design options that had previously been assessed) were not viewed as creating any significant effect in off-normal performance. Certainly, the method of slug production could influence microstructural features that are important for normal steady state fuel performance, but the chief phenomena of concern in safety scenarios largely occur at temperatures where these microstructural features are erased or irrelevant (e.g., melting, eutectic formation).

FCCI Barrier Application: No strong differentiating factors were identified when comparing off normal performance of various methods of FCCI barrier application, except that one of the options was to apply no barrier at all. All options with barriers scored higher than this option owing to their potential to impede fuel-cladding eutectic formation. The scorings reflected a greater demerit to the no barrier option in the more aggressive enhanced needs category due to reduced temperature margin.

Slug Installation, Gap Treatment: The method of installing fuel slugs, and particularly for treating the fuel-to-cladding gap, received significantly different scores for off-normal fuel performance. The principal reason for these differences related to relationships between manufacturing options and the thermal resistance gap should an accidental condition occur in early irradiation life before fuel has swollen into intimate contact with the cladding. The baseline sodium-bonded option, although not a contender for SFF manufacturing, naturally scored high due to its beneficial heat transfer properties with resulting margin to fuel melting. The option to load medium-fitting slugs and swage cladding down for a tighter fit also scored well as it represented an option that could minimize the early life heat transfer gap and avoid damaging FCCI barriers (if present) during slug installation. As identified in the design option assessment, FCCI barriers were seen for their value in impeding eutectic formation in off-normal conditions. The similar option where external pressure would be used to close the gap did not score as well since such processes (e.g., hot isostatic press) would likely employ temperatures which degrade cladding mechanical properties and increase risk for creep rupture. The option to fill or infiltrate gap with liner material did not score well since difficulties were expected in achieving full penetration/coverage in the gap, potentially leaving unfilled areas with increased thermal resistance gaps and no protective barrier. The option for tight-fitting slugs without further gap treatment, like the assessment for normal operation, scored low based on the projection that it would a larger nominal heat transfer gap compared to other options, thus elevating fuel temperature in early off-normal situations, while creating additional risk for FCCI barrier damage during installation.

III.C.4 Assessment of Manufacturing Options for Back-End Considerations

All Manufacturing Options: The scoring of manufacturing options for the back-end considerations were similar to those for the design options. The team did not identify any relationships between how the SFF would be manufactured that would significantly affect how it would be disposed or recycled, except the natural conclusion that using a sodium bond was a significant detriment in the baseline once-through fuel cycle.

A summary of the manufacturing options ranking matrix is shown in Table 4.

Table 4: Summary of Manufacturing Options Scoring Matrix

			Fuel slug production					FCCI Barrier Application				Slug Installation, Gap Treatment				
	Category	**Weight**	Injection cast into quartz mold	Extrude w/ heat treat	Continuous casting	Cast into reusable mold	Additive Process	No barrier	Combined slug & barrier production	Deposit barrier onto slug	Deposit barrier in cladding tube	Loose slug fit, sodium bond	Med slug fit then swage cladding down	Med slug fit, creep down w/ ext. pressure	Med slug fit, fill gap w/ liner material	Tight slug fit, no further process
Fabrication	Baseline	4	2	4	5	3	2	5	4	4	2	3	5	2	2	2
	Enhanced	2	4	2	3	3	1	5	4	4	2	3	5	1	2	2
Normal Operation	Baseline	5	5	4	5	4	3	2	3	3	3	5	4	2	2	2
	Enhanced	3	5	4	5	4	3	1	4	4	4	5	3	2	2	1
Off-Normal Scenarios	Baseline	4	3	3	3	3	3	2	3	3	3	5	4	2	2	2
	Enhanced	2	3	3	3	3	3	1	4	4	4	5	4	2	1	1
Back-end	Baseline	3	3	3	3	3	3	3	3	3	3	1	3	3	3	3
	Enhanced	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3
		Baseline Score	54	57	66	53	44	47	52	52	44	60	65	35	35	35
		Enhanced Score	32	25	30	27	20	18	31	31	27	34	30	15	15	12
		Overall Score	86	82	96	80	64	65	83	83	71	94	95	50	50	47

IV. Discussion

The U-Zr alloy emerged as the highest-ranking alloy option because of its known behaviors and large experience base. As the lowest risk alloy from a technology development standpoint, it was not surprising to find it prioritized for the baseline needs category. U-Zr, however, does not exhibit the uranium density advantage offered by the other options. When considering enhanced burnup targets, for which reactor core designs benefit greatly from higher uranium density, U-Mo was viewed as the priority candidate in offering the right balance between uranium density and melting temperature. U-Zr still received a slightly higher enhanced score primarily because U-Mo is known to exacerbate FCCI behavior. This is one area where the trade study method did not capture the relevant outcomes entirely since each design option category was ranked independent from other categories. The U-Mo fuel performance scores did not take credit for the possibility of an FCCI barrier, but the FCCI barrier scored well in its own category. Thus, U-Mo is conditionally recommended for an enhanced fuel design assuming FCCI barrier success, otherwise U-Zr should be considered the recommended backup option. Development of FCCI barrier manufacturing technology, followed by irradiation testing, are key future research tasks needed to support a final determination in this regard.

Austenitic stainless steels naturally scored highest for the baseline needs due to fabrication experience and known behavior in modest dpa and temperature conditions. The value of improved mechanical properties combined with void swelling resistance gave ODS alloys the clear advantage in the enhanced needs category, but here the recommendation is also put forth conditionally. Concerns for ODS alloy high yield tube fabrication and welding must be addressed through fabrication studies and irradiation testing before ODS can be unequivocally recommended. If these concerns are not retired, then advanced FMS cladding alloys should be considered the recommended backup option for an enhanced fuel design.

Several fuel geometry options were evaluated. Among sodium-free options, and despite the fabrication challenges associated with creating an internal hole, the annular geometry emerged as the winner for both baseline and enhanced requirements primarily due to heat transfer configuration and lack of discontinuous features at the cladding interface. Use of FCCI mitigation features was recommended, which seemed appropriate for SFF designs given that fuel-cladding contact begins almost immediately rather than after accumulating 2-3% burnup as it does in loose-slug designs. The less challenging irradiation conditions, combined with relative ease of including them during alloying, caused the alloy additives option to be score highest for the baseline fuel design. The application of physical FCCI barriers, although a complication for fabrication processes, scored highest for the enhanced fuel design where increased time and temperature effects would very likely require such a feature.

In terms of sequence, this overall trade study scored and prioritized design options first and manufacturing options second. It was known that this sequence could create the risk of selecting an ideal-performing fuel design that cannot realistically be manufactured. This concern is why design options were assessed against fabrication considerations, as well as fuel performance needs, in the first exercise. This effect could be seen as most of the manufacturing options which were generated and assessed revolved around design features that had already been identified (e.g., annular fuel, FCCI barrier).

Perhaps the most important outcome from this study is that continuous casting emerged as the preferred method to produce annular fuel geometries with a microstructure known to perform well. The preferred method of applying an FCCI barrier was to deposit the layer onto fuel slugs after they had been cast, presumably by methods such as physical vapor deposition or plasma spray. It should be noted that the FCCI barrier was particularly recommended for the enhanced fuel design service conditions, but if the application process is found to be simple and affordable, then consideration should be given towards using it for lower temperature baseline fuel designs as well. Finally, this study suggested that a process step should be added to swage-down the cladding outer diameter after slug loading. Normally the cost-conscious designer of a fuel fabrication line would not suggest adding another step, but this step was not projected to be particularly difficult or time consuming and should favor slug yield by affording more liberal tolerances on the slug outer diameter. Thus, the combined recommendation of slug production continuous casting, and swaging cladding down after slug loading, created a valuable proposition. It is worth mentioning that extrusion methods were also viewed as a promising option, especially if more exact fuel outer diameter dimensions were needed, which could be a key enabler for sodium-free fuels using less-ductile cladding alloys such as ODS.

V. Conclusions

The highest ranked options identified for the baseline technology would use U-Zr alloy with additives to mitigate FCCI, produced in annular slug geometry by continuous casting, clad in austenitic stainless-steel alloy, and followed by a final step to swage the cladding diameter down slightly to close the slug/cladding gap. The highest ranked options for the enhanced fuel technology would use U-Mo alloy slugs (with U-Zr as a backup option if FCCI barrier application is found unworkable), also produced by continuous casting into an annular geometry, followed by coating/plating with an FCCI barrier on the slug outer diameter, again with a final step to swage the cladding diameter down using ODS steel (or advanced FMS if swaging and welding are found unworkable for ODS).

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