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NOVEL ACCIDENT-TOLERANT FUEL MEAT AND CLADDING

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A novel accident-tolerant fuel meat and cladding are here proposed. The fuel meat design incorporates annular fuel with inserts and discs that are fabricated from a material having high thermal conductivity, for example niobium. The inserts are rods or tubes. Discs separate the fuel pellets. Using the BISON fuel performance code it was found that the peak fuel temperature can be lowered by more than 600 °C for one set of conditions with niobium metal as the thermal conductor. In addition to improved safety margin, several advantages are expected from the lower temperature such as decreased fission gas release and fuel cracking. Advantages and disadvantages are discussed. An enrichment of only 7.5% fully compensates the lost reactivity of the displaced UO_2 . Slightly higher enrichments, such as 9%, allow uprates and increased burnups to offset the initial costs for retooling. The design has applications for fast reactors and transuranic burning, which may accelerate its development. A zirconium silicide coating is also described for accident tolerant applications. A self-limiting degradation behavior for this coating is expected to produce a glassy, self-healing layer that becomes more protective at elevated temperature, with some similarities to MoSi_2 and other silicides. Both the fuel and coating may benefit from the existing technology infrastructure and the associated wide expertise for a more rapid development in comparison to other, more novel fuels and cladding.

I. INTRODUCTION

In relation to the events following the tsunami at Fukushima and the loss of coolant accident, interest to develop more accident-tolerant fuels has increased. A particular focus of accident tolerant fuel has been cladding, almost to the exclusion of any fuel meat modifications, because of the rapid high-temperature oxidation of the zirconium-based cladding with the evolution of H_2 when water is a reactant. Nonetheless a fuel meat with high thermal conductivity can be envisaged that introduces lower temperature operation and slower thermal excursions during accidents, which increases response time. In this regard, a novel annular

fuel form is here proposed that yields a major reduction in operating temperature, as determined with the BISON fuel performance code and corroborated with known fuel thermal characteristics of solid oxide fuels.

The novel annular fuel design recognizes the variety of experience with solid oxide fuels, annular fast reactor fuels, and dual-clad annular fuels with interior coolant flow. The design involves placing thermally conducting central inserts (rods or tubes) in the fuel pellet annulus (perhaps one long tube or rod) and placing thermally conducting discs (or washers) between these pellets (Fig. 1). For the case where the discs and inserts are made from niobium, the peak fuel temperature is lowered more than 600 C. These fuel modeling results are described followed by a discussion of many advantages and the disadvantages for the fuel design. One particular advantage for this fuel meat design is its applicability of the design for both LWR accident tolerant fuel and for fast reactor transuranic burning; and this advantage, along with others to be discussed, may stimulate its more rapid development than a fuel meat with only LWR applications.

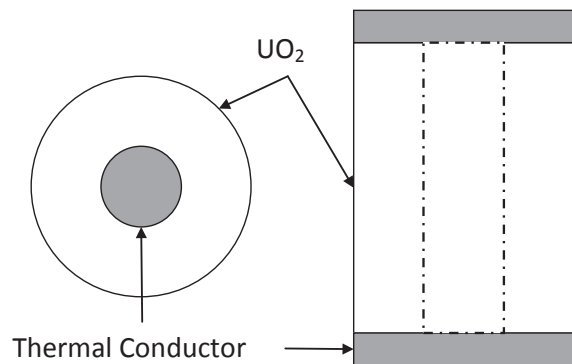


Fig. 1. Annular fuel schematic with annular inserts and discs capping the fuel pellet.

While the annular fuel meat design may be compatible with a variety of claddings, especially zirconium-based cladding, a novel accident-tolerant coated cladding is also described here. Some key features of the coated cladding include high-temperature resistance

to oxidation, lower adiabatic temperature for oxidation (for burning in air), and high melting point of the coating. Zirconium alloys exhibit a reasonably high melting temperature so that a coating for the cladding is appealing if the coating increases the high-temperature resistance to oxidation. In this case, the cladding mass is protected from complete oxidation, abating the thermal excursions arising from cladding oxidation. For these reasons, a novel coating is proposed that is expected to exhibit glassy, self-healing properties above approximately 1000 °C and improving at higher temperatures.

The novel cladding coating involves the application of zirconium silicide onto Zr-based cladding. Intermetallic silicides compounds, such as MoSi_2 , are stable in air at very high temperatures, and for this reason, silicide coatings on cladding offer the potential for improved reliability at normal operating temperatures and at the higher transient temperatures encountered during accidents. In contrast to the behavior of MoSi_2 at high temperatures, the oxidation of zirconium silicides can produce the glassy silica layer (SiO_2) along with, or after producing ZrO_2 and ZrSiO_4 (zircon) because of the more negative free energy of the Zr-oxides; consequently, a rapid, in-service degradation (described below) is important for the coating to give superior performance. Key features include: the degradation should be self-limiting and the degraded film should be self-healing.

Since this novel coated cladding proposal describes some anticipated but unproven behaviors, it bears mentioning that all novel coated claddings and novel claddings are still in the early stages of development for nuclear fuel applications. As will be seen, the zirconium silicide coating described here is not far behind other options, because a great deal of information is available for silicides generally. In addition, the apparent level of complexity for the desired degradation behaviors is not more complex than other options or even the current ZrO_2 corrosion layer in an LWR environment.

These new designs, for fuel meat and for cladding,¹ rely on a wide variety of research experience and existing technology infrastructure. As a result, a more rapid development and deployment can be expected in comparison to brand new concepts and proposals. Likewise, the acceptance of the new design with regulatory bodies should be more streamlined. Finally, familiarity with these established materials and existing technology platforms will aid the identification of the key results that warrant either continued research or its abandonment.

II. THE ANNULAR FUEL MEAT

Other researchers have examined annular fuels, have examined discs between pellets with solid and hollow annular fuel, have examined partitioned fuel regions, and have examined dual-cooled annular fuel rods with coolant

flowing in the annulus as well as on the exterior.^{2,3,4,5,6,7,8} This fuel design incorporates and combines the benefits of those features while eliminating some of their attending problems. As mentioned, the annular fuel design is composed of oxide pellets with thermally conductive inserts in the annulus in addition to thermally conductive discs between the pellets (Fig. 1). The inserts can be solid rod or tubes. The inserts and discs can be made from the same or different materials.

Several significant advantages can be expected to result from this fuel design, not just lower peak temperature for accident tolerant applications. These include less fission gas release, less fuel cracking and distortion, less concern for wet and dry storage among others. Disadvantages also exist, the chief one being the reduced reactivity resulting from displaced UO_2 . However, the reduced reactivity is not substantial, especially in comparison to dispersion-type fuels,⁹ because only a small volume of thermal conductor is required. In fact, an enrichment of only 7.5% U-235 is needed for the present geometry to give the same reactivity as 5% enriched solid UO_2 pellets. Advantages and disadvantages are described in more detail after a summary of the thermal modeling results.

II.A. Thermal Modeling of the Fuel Meat

The thermal response of this design has been evaluated using the BISON¹⁰ fuel performance code.¹¹ The peak temperatures in relation to linear power are illustrated in Fig. 2 for a thermal conductivity of 60 W/m-K (which is appropriate for niobium discs and inserts). The calculations assume a pellet height of 1.08 cm and pellet diameter of 0.82 cm. The annular geometry with discs uses a disk height of 0.12 cm and insert diameter of 0.35 cm. Overall, a major reduction in peak fuel temperature is obtained for this design in comparison to solid pellets. For irradiated fuel where the gap has closed significantly, the peak temperature is reduced by more than 600 °C at a linear heat generation rate of 426 W/cm when using a material with a thermal conductivity of 60 W/m-K. For fresh fuel (*not illustrated in Fig. 2*, with a 82 μm as-fabricated gap), the peak fuel temperature is reduced by 1000 °C. The benefit is attributed primarily to the annular form of the UO_2 fuel and the large number of high conductivity discs in contact with the hot central regions that serve as heat fins. These calculations were corroborated with analogous calculations using BISON for *solid* UO_2 (no annulus, no discs) that agree with known temperature characteristics for oxide fuels in LWRs (included in Fig. 2).

The use of molybdenum with a higher thermal conductivity (on the order of 110 W/m-K) will further reduce the peak temperature, but at the expense of poorer neutronics performance. It would seem reasonable to examine the use of molybdenum discs along with niobium

tube inserts in the annular region for optimizing performance. A parametric study of various thermal conductors and various dimensions of thermal conductors is planned for a separate report.

II.B. Advantages to the Fuel Meat Design

The lower temperatures not only improve accident tolerance, but also allow uprates because of the significant widening of the safety margin for operating temperature. The uprates can help pay for the added fuel fabrication costs. Lower peak temperatures will also reduce stresses in the UO_2 . As a result, less cracking will occur in the ceramic giving further improvement to the thermal conductivity in comparison to the partially fragmented pellet. In addition, fission gas release will be less for the lower temperatures, and fission gas pressure should be reduced correspondingly. The improved thermal conductivity may allow the possibility that the reactor can be restarted without refueling for some milder accident scenarios. The improved thermal conductivity may also mitigate some of the issues with wet and dry storage.

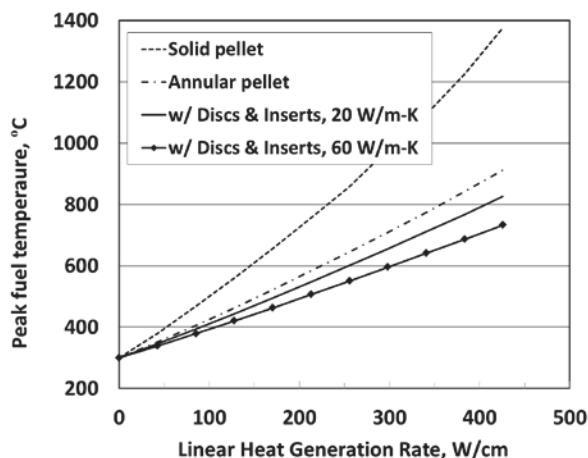


Fig. 2. Temperature Profiles in Relation to Linear Heat Generation Rate (LHGR). Helium-filled gap sizes of 3.0 microns are assumed with constant thermal conductivity of 0.3 W/m-K. The two upper curves represent the reference cases, solid and annular UO_2 without discs and inserts. These two curves agree with expected temperatures for solid and annular LWR fuels. The bottom two curves demonstrate the thermal advantage for the discs and inserts. The thermal conductivity for niobium is $\sim 60 \text{ W/M-K}$ at 1000°C .

This fuel design has the added advantage of its applicability to both LWRs and fast reactors. In fast reactor applications, with or without transuranic burning, the peak temperatures are very high so that annular fuel designs provide significant benefit against centerline melting. Both the inserts and discs will provide the

mechanical integrity that will keep the annular fuel intact, preventing fuel fragments from falling into the annulus and causing variations in reactivity, especially at the bottom of the fuel column. With the higher peak temperatures of fast reactor fuel, the use of either niobium or molybdenum should be satisfactory because of their high melting points and similar reductions in peak temperature for the fuel (although that analysis is not reported here).

Lastly, the components of the fuel design are familiar within the industry. The design retains UO_2 as the fuel and uses a simple annular design with inserts and discs made from accessible materials (such as niobium and molybdenum). The fuel can be readily prepared and readily tested, in ATR, for example. Thus the technology platform exists and does not need to be built from the ground up.

II.C. Disadvantages to the Fuel Meat Design

One of the disadvantages to the annular fuel meat is the reduced reactivity arising from the displaced mass of UO_2 . To restore the reactivity the enrichment must be raised in the active volume of UO_2 . Analysis has shown that the enrichment only needs to be raised to approximately 7.5% for the cited annular and disc dimensions to give the reduced temperatures cited above. This change in enrichment is not significant technically, but it is significant economically. However, it should be mentioned that the cost will be great even if the fuel meat is changed to U_3Si_2 or UN while keeping the enrichment at 5%. These costs are great because all of the safety documentation, licensing, procedures, container and batch sizes, equipment staging, etc. will need to be reviewed and potentially revised in both cases. However, a comparative incremental cost in the case of 7.5% enriched UO_2 may occur in relation to the cost of producing and delivering UF_6 at the higher enrichment. These costs would need to be evaluated for a potential return on investment.

Another disadvantage is the incremental cost for retooling the fuel manufacturing and possibly materials. Fabrication costs may possibly be reduced by using the annular pellet design only in the hotter regions of the fuel column while using solid fuel pellets in the remainder of fuel column. More importantly, manufacturing costs could be offset through another increment in enrichment. The enrichment could be raised higher than 7.5%, to perhaps 9-10%, and this higher enrichment can support uprates and higher burnups which will at least partially offset the investment on manufacturing modifications. It seems reasonable that one of the higher priority economic analyses that may be done should be directed at identifying the costs for any needed retooling and resizing of the enrichment plants to produce commercial fuel grade UF_6 at 9-10% U-235.

A final disadvantage is common to all fuel development efforts; this is the cost for initial developmental testing and irradiation testing from rodlet scale through lead test assembly (LTA). These tests include optimizing the engineering design to accommodate the differential expansion of any new materials adopted. However, technology platforms, technical experts, and materials exist for each of the components in the fuel design. For example, since molybdenum has a higher thermal conductivity than niobium,¹² but molybdenum has a higher thermal neutron cross-section than niobium,¹³ it would be advisable to minimize the use of molybdenum. Since molybdenum has no solubility in α -Zr,¹⁴ but niobium has slight solubility in α -Zr,¹⁵ it would therefore be advisable to use molybdenum for the discs which might contact the zirconium alloy, while using niobium for the annular inserts. Likewise, the expansion characteristics for the annular pellet with inserts and discs will have to be understood to optimize the initial and developing gap between the fuel periphery and interior cladding wall. These are the kinds of specialized technological puzzle pieces that can be addressed, using prior knowledge, to expedite development of this fuel meat design.

III. THE NOVEL CLADDING COATING

Review of existing literature and analysis of thermodynamic data indicate that a ZrSi_2 or ZrSi coating offers excellent prospects to provide a more protective barrier than the native ZrO_2 films that form on alloy cladding during routine plant operations, and excellent prospects to provide an exceptional protective barrier during high-temperature accident scenarios. The enhanced protective barrier is derived intentionally by controlling phase and property transformations that occur in the coating during temperature excursions.

A coating may be prepared similar to the schematic given in Fig. 3. The desired performance is comparable or superior to ZrO_2 on zirconium cladding alloys during normal service, and greatly superior to ZrO_2 on cladding alloys during accident and loss-of-cooling scenarios. It is believed that zirconium silicide coatings have the potential to degrade during irradiation in a way that enhances the protective nature of the barrier layer through self-healing and transport-limiting processes. The literature for zirconium silicide coatings¹⁶ supports the contention for its superior performance over ZrO_2 on zirconium,¹⁷ and the literature for the degradation of MoSi_2 ¹⁸—a commercial material that is comparable in some ways—suggests that the performance of zirconium silicides will be superior to cladding alloys under high-temperature accident conditions. Zirconium silicides are preferred over MoSi_2 because the zirconium is strongly oxophilic, so that the zirconium silicide layer is expected to bond more strongly to the inner, native ZrO_2 layer than

a MoSi_2 layer would bond to it. Some limitations do exist, which are discussed in the next section.¹⁹

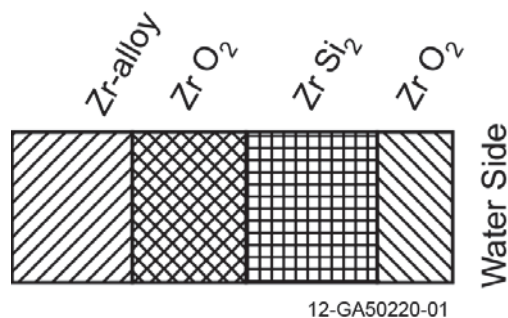


Fig. 3. As-fabricated coating schematic, not to scale. The outer layer composition (water-side) depends on the silicide used and possible pretreatment conditions.

III.A. Thermodynamic Basis for Cladding Coating

Films of ZrO_2 on zirconium cladding alloys (hereafter, referred to as cladding) render the alloys kinetically stable for satisfactory commercial application in LWR reactors. The alloys, however, are not thermodynamically stable toward H_2O at coolant temperatures (Fig. 4). The “passivated” ZrO_2 films that form, whether native or anodized, serve as a protective barrier to slow or prevent further oxidation of the alloy and generation of hydrogen.

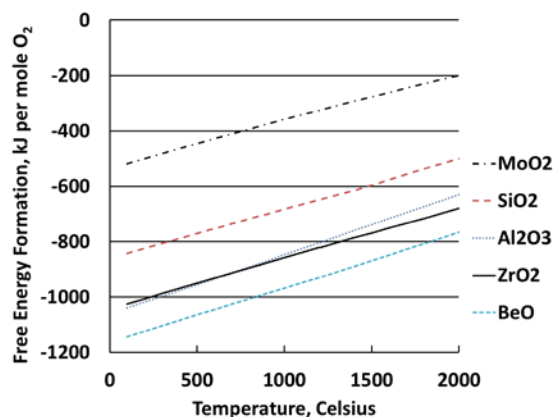


Fig. 4. Free energy of formation for selected oxides.

Despite the inability of thermodynamics to predict the success of Zr-based fuel claddings, the thermodynamics of the Zr- ZrO_2 system indicates the protective layer will fail with increasing temperatures. ZrO_2 changes from monoclinic to tetragonal at 1205°C, and the tetragonal phase to the cubic at 2377 °C, and as low as 1525°C when off-stoichiometry (36 atom% Zr).²⁰ In the cladding film, the tetragonal phase can be stabilized

adjacent to the alloy, while on the water-side the monoclinic can predominate for thicker films, creating stresses in the oxide.²¹ These structural changes in the film induce microcracks that enhance oxide ion transport through the film for further reaction with the cladding.²² Subsequently, the ZrO_2 film can spall off leading to undesirable consequences at very high temperatures. Of course, if H_2O reaches the metal through microcracks, then oxidation is very rapid.

Intermetallic silicide compounds, such as MoSi_2 , are stable in air at very high temperatures,²³ and for this reason, silicide coatings on cladding offer the potential for improved reliability at normal operating temperatures and at the higher transient temperatures encountered during accidents. At high temperatures, silicides form a mobile silica layer on the surface that impedes further oxidation of the silicide. Cracks and fissures in the silicide coating can develop upon thermal cycling, as these arise from differential expansion between the coating and the substrate. However, experience shows that these potential problem areas self-heal upon reheating. As a result, silicides have widespread commercial use in high-temperature applications.

As with ZrO_2 films on cladding, silicides have limitations. MoSi_2 , for example, is unstable at low temperatures (940–1040°C). The silica layer is not dense enough to prevent oxidation of molybdenum, and the volume expansion resulting from MoO_3 formation fractures the film and fails the part. At intermediate temperatures, film ductility improves and fracture does not occur. Above 1540°C, a dense silica film forms that substantively halts the formation of MoO_3 . MoSi_2 is therefore preheated to very high temperatures in order to gain some stability for its use at low and intermediate temperatures.

In other applications, additives have been used to promote formation of the dense glassy silica layer. Fused slurry silicide coatings were prepared for protection of tantalum alloys.²⁴ Their cyclic oxidation tests showed that a slurry composition of 25Zr-30Mn-45Si provided coating lifetimes exceeding 100 thermal cycles for tests to 1427°C and 10 Torr (air). This system and a range of others were investigated in an effort to tune the mobility of the dense glassy silica layer (*cf.* glass transition temperature).

Zirconium silicides have received some recent interest in nuclear applications. The superior corrosion resistance of $\text{ZrSi}/\text{Zr}_2\text{Si}/\text{Zr}$, compared to zirconium metal, was reported by Caillet, et al.²⁵ This result is somewhat surprising from arguments in the literature, because the greater stability of ZrO_2 favors its formation compared to SiO_2 (Fig. 2); consequently, the protective silica barrier layer is not expected to form. We propose to develop a silicide coating system that addresses the above limitations by producing a coating with a performance comparable or better than native or anodized ZrO_2 on cladding, and superior performance at elevated

temperatures of accident scenarios. The reasons we expect to realize this improvement are based on the high-temperature performance of MoSi_2 .

III.B. Desired Coating Behavior and Preparative Routes

The as-fabricated coating (in Fig. 3, above) will involve the zirconium alloy substrate, an inner ZrO_2 layer, the silicide layer, and an outermost layer of $\text{SiO}_2/\text{ZrO}_2$ (or zircon, ZrSiO_4), which will be exposed to the reactor coolant. The inner layer of ZrO_2 will be present either as the native film or as an anodized layer. It is believed that the existence of the ZrO_2 inner layer will improve the performance of the coating that follows from the expected self-limiting degradation that develops through thermal excursions, either prior to or after reactor insertion (Fig. 5).

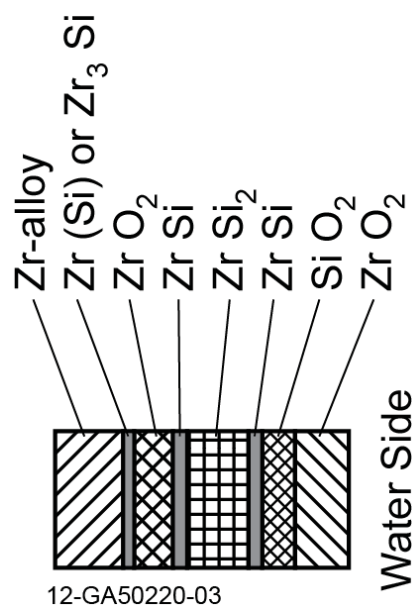


Fig. 5. Expected degradation behavior for the coating.

Initial choices for the silicide layer material include ZrSi_2 and ZrSi . Even though ZrSi_2 melts at 1620°C, this temperature is only 230°C below the melting point of zirconium metal. Based on thermodynamic arguments, ZrSi_2 should give better performance than ZrSi . The lower zirconium activity in the ZrSi_2 is expected to compensate in some measure for the greater stability of ZrO_2 compared to SiO_2 , allowing the formation of the SiO_2 barrier layer under the water-side ZrO_2 layer. On the other hand, the monosilicide, ZrSi , is not expected to readily produce an effective silica barrier layer, producing instead the thermodynamically favored ZrO_2 outer layer, lacking the mobility and barrier properties of the silica layer. However, the higher melting point of ZrSi , its

greater thermodynamic stability, and its superior performance in limited testing warrants its investigation along with ZrSi_2 , and both silicides may turn out to be effective if the degradation phenomena described next accounts for the noted superior performance of ZrSi .²⁶

At high temperatures during operation, and possibly during a pretreatment, an outer layer of ZrO_2 (and possibly zircon, ZrSiO_4) will form outermost on the coating (water-side, Fig. 5). As this layer forms, the zirconium activity in the silicide layer will be reduced, favoring oxidation of silicon to SiO_2 . This inner layer of silica can now provide the barrier layer to oxygen and moisture transport, and its glassy properties at elevated temperatures will also accommodate the structural transformation of the outer ZrO_2 from the monoclinic to tetragonal phase under accident scenarios.

As silicon is depleted in the silicide layer adjacent to the water-side ZrO_2 , the silicide composition should be driven toward the higher melting zirconium silicide phases (Fig. 6). For example, ZrSi_2 depleted of silicon is driven toward ZrSi ; likewise, ZrSi depleted of silicon is driven toward Zr_5Si_4 . Both of these silicides are more stable and have higher melting temperatures than their precursors, indicating the protective nature of the barrier layer will be enhanced.²⁷ Another possibility, however, is that the silicon (in the silicide) oxidized to SiO_2 is just the balance of silicon remaining from oxidation of zirconium in the silicide to ZrO_2 or ZrSiO_4 .

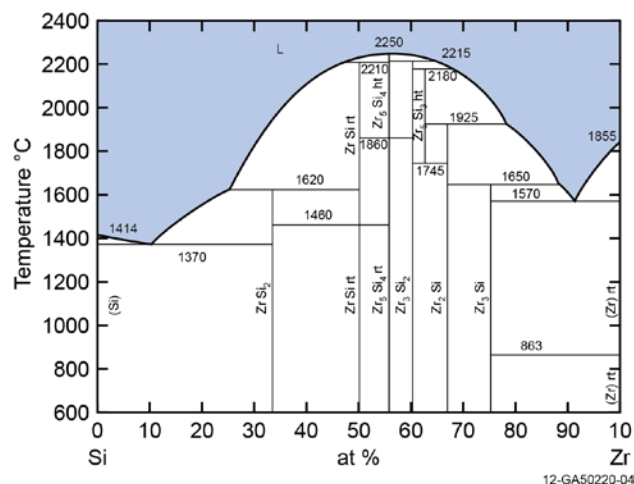


Fig. 6. Binary Si-Zr Phase Diagram. As silicon is depleted from ZrSi_2 , the silicide is enriched and driven toward the high melting silicide phases. (Redrawn.²⁸)

In the silicide layer adjacent to the inner, cladding-side ZrO_2 (Fig. 3), the film is initially chemically stable, but not thermomechanically stable, due to mismatch in thermal expansion. Likewise the initial ZrO_2/Zr interface (in Fig. 3) is chemically stable, but not thermomechanically stable. As a consequence of normal

thermal cycling for reactor maintenance, these interfaces are expected to develop cracks and fissures. Under ordinary conditions, in the absence of a silicide coating, further oxidation of the zirconium cladding would result. However, for these two initial interfaces (Zr/ZrO_2 and $\text{ZrO}_2/\text{ZrSi}_2$ shown in Fig. 3) it is expected that self-healing will occur driven by a higher mobility of silicon in the ZrO_2 as compared to oxygen in the silicide.²⁹ These mobility differences are expected because of the greater stability of ZrO_2 compared to SiO_2 and the differences in the melting points. The resulting silicon migration toward the cladding will result in its reaction and uptake into the cladding (Fig. 5). As silicon is removed from the silicide coating near the inner layer, the zirconium silicide composition is driven toward the higher zirconium compounds with higher melting points and greater thermodynamic stability (Fig. 6).

The uptake of some silicon into the cladding (Fig. 5) is perceived to be a benefit for these coatings. As an impurity, silicon may be expected to promote plasticity and further enable the self-healing for thermal cycling. In excess of its low solubility in zirconium, the silicon in cladding can form Zr_3Si and may induce creep from the associated stresses. On the other hand, dispersions of small precipitates of Zr_3Si can possibly stabilize the morphology and slow down creep, and the radiation-induced displacement processes may support such dispersions. Routine thermal cycling for reactor maintenance, then, may induce their aggregation and crystallization, which would be a negative effect. As can be seen from this discussion on prospective long-term evolution of the cladding, the cladding itself will be altered and in-pile testing is therefore required. However, these investigations can only be done after irradiation, and the expense of irradiation testing warrants that the coatings first be developed and evaluated for their microscopic, thermal, mechanical, corrosion, and fretting behaviors.

Based on the above arguments, the degradation of the silicide coating is expected to be self-limiting as with ZrO_2 , except the silicide is expected to be more stable with temperature and time. Furthermore, its resulting properties are expected to be self-healing with regard to thermal cycling. Lastly, the high-temperature barrier to rapid oxidation and hydrogen evolution is expected to be enhanced.

Coatings may be applied following one or more methods described in the literature. Two particularly interesting coating methods described in the literature are fused-slurry³⁰ and silane³¹ (SiH_4) decomposition on heated substrates. In the fused slurry method, a slurry of powdered precursors is air-brushed onto the substrates. The precursors are zirconium and silicon powders that were milled together in appropriate proportions. After application, the coated substrate is vacuum-heated to 1400–1500°C to melt or react the powders. Silane

decomposition, the second method, is simple and direct but requires care in handling. In this case, SiH_4 reacts with hot substrates to produce silicides and by-product hydrogen. This latter method appears to preclude anodizing pretreatments to enhance the ZrO_2 layer on the substrate, as thicker layers of ZrO_2 would complicate the reaction. Short thermal exposures may be performed to develop the coatings to help avoid altering the substrate microstructure as much as possible. However, the primary interest is to establish the performance of the coatings (such as corrosion and thermal conductivity in relation to coating thickness), as it is believed that microstructure retention or recovery would be possible using lower temperature fabrication routes, forced-cooling fabrication routes, or additional stress / heat treatments.

III. CONCLUSION

An annular fuel meat design with inserts and discs between pellets is appealing for rendering the fuel assembly more accident tolerant when the inserts and discs have high thermal conductivity, regardless of the cladding used if the materials are compatible. The major advantage for this fuel design is the significant reduction in peak temperature, from 1325 C to less than 700 C for one set of achievable conditions. The lower peak temperature increases the operating safety margin, increases the response time under accident conditions, and should improve other behaviors such as fission gas release and fuel cracking. The main disadvantage is the need for increasing the enrichment to approximately 7.5% to regain a reactivity equivalent to 5%, because of the UO_2 displaced by the annular inserts and discs. Since this fuel form is appealing also for fast reactors and burning transuranics TRUs, it can be developed alongside the economic analyses for LWR applications. The annular fuel meat design can be readily fabricated and tested in the Advanced Test Reactor to examine fuel performance, it can be instrumented as fuel pin for testing in Halden to verify thermal performance, and it can be readily modeled.

Zirconium silicide coatings are applicable to existing Zr-based cladding alloys, so that they can be more rapidly developed using existing cladding technology with some modifications. Straightforward preparative methods for silicide coatings have been demonstrated, and the preparative methods would need to be parametrically tested and evaluated for Zr-based cladding alloys. If the preparation of the coatings is satisfactory, out-of-pile corrosion behavior would be evaluated next. In-pile tests can follow for coupons, sealed tubes, or hollow tubes. Instrumented tests can be performed at Halden with heaters in sealed, coated, cylindrical capsules. These silicide coatings are conceivably an attractive alternative to the use of zirconium-free coatings on zirconium

claddings or to the lengthy development of SiC claddings and coatings.

As indicated in the above text, economic incentives do not exist for modifying the cladding or fuel meat to render it more accident tolerant. However, uprates resulting from increased enrichments can offset the initial developmental and incremental fuel fabrication costs, and a lower peak fuel temperature widens the normal operating safety margin to permit those uprates.

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