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Abstract – *The choice of fuel type for a sodium-cooled fast reactor can have a significant impact on the severity of consequences arising from accidents, especially for severe accidents of low probability. The successful prevention, mitigation, or accommodation of all consequences of potential events, including accidents, is typically accomplished by using multiple barriers to the release of radiation, including the cladding on the fuel, the intact primary cooling system, and most visibly the reactor containment building. More recently, this has also included the use of 'inherent safety' concepts to reduce or eliminate the potential for serious damage in some cases. Past experience with oxide and metal fuel has demonstrated that both fuel types are suitable for use as fuel in a sodium-cooled fast reactor. However, safety analyses for these two fuel types have also shown that there can be substantial differences in accident consequences due to the neutronic and thermophysical properties of the fuel and their compatibility with the reactor coolant. Accident phenomena are discussed for the sodium-cooled fast reactor based on the mechanistic progression of conditions from accident initiation to accident termination, whether a benign state is achieved or more severe consequences are expected. General principles connecting accident phenomena and fuel properties are developed from the oxide and metal fuel safety analyses, providing guidelines that can be used as part of the evaluation for selection of fuel type for the sodium-cooled fast reactor.*

I. INTRODUCTION

There have been several types of fuel proposed for use in fast reactors, including oxide, metal, nitride, and carbide. Early development in the United States in the 1950's and 1960's focused on metal fuel, as was used in EBR-I and EBR-II. Testing in EBR-II in the late 1960's identified difficulties with achieving significant burnup with metal fuel, so the oxide fuel type that had been successfully used in commercial LWRs and naval propulsion was selected for further development in the FFTF and CRBR projects. Internationally, oxide fuel was preferred as well due to the similarity with the fuels used in existing thermal reactors. Subsequent metal fuel testing, both in parallel with oxide fuel development during the 1970s and as part of the IFR program in the 1980s demonstrated that the burnup limitation could be overcome by changing the fuel pin design specifications. Today, both oxide and metal fuel types have had significant development, testing, and operational experience, with either fuel type being available for use in a future fast reactor.

The decision on which fuel to use in a fast reactor can be based on many criteria, including those related to fuel performance, fuel fabrication, safety implications, and processing, since fast reactors are usually used as part of a closed fuel cycle. The safety performance of the reactor system is briefly discussed for both oxide and metal fuel types, identifying both similarities and differences that may be of safety significance.

II. FAST REACTOR SAFETY

Any nuclear facility must be designed and operated with the protection of the public and the environment as a priority. Other than small test or research reactors, a fast reactor would be licensed by the NRC after a detailed and comprehensive safety evaluation. While CRBR was the first fast reactor being planned for construction after the formation of the NRC, the CRBR was in licensing proceedings when the project was terminated, so that CRBR was not licensed by the NRC. In the 1990's, as part of the ALMR program, General Electric was involved in discussions with the NRC on the PRISM design, which progressed to the point of a Preliminary Safety Evaluation Report being issued in 1994. With the termination of the ALMR program at that time, no further licensing activities were pursued. As a result, the NRC does not have a set of regulations and requirements in place that have been used to license a fast reactor, but since the fast reactor would be an advanced reactor, there are general guidelines that would be used as a starting point for a safety evaluation.

According to the NRC, there are several categories of accidents that will need to be evaluated for a prospective design. There would be two general categories based on the probability of occurrence, Anticipated Operational Occurrences (AOOs), and Accidents, with the distinction being that AOOs are expected to occur at least once during the plant lifetime, while accidents are not expected to occur but are theoretically possible. A special subcategory of accidents is the Anticipated Transient Without Scram (ATWS), where it is assumed that the scram system fails to operate. This group is of particular interest in the fast reactor, as inherent safety principles can be used to prevent or mitigate serious consequences. The guidance maintains the NRC position on both prevention and mitigation for the protection of workers, the public, and the environment. With this background, it is possible to discuss the relative impact of the choice of fuel type, oxide or metal, or any other fast reactor fuel type.

III. FUNDAMENTAL THERMOPHYSICAL PROPERTIES AND REACTOR SYSTEM CHARACTERISTICS

The thermophysical properties of oxide and metal fuel are substantially different, and these differences play a role in the safety performance of the reactor system. Typical fuel properties are summarized in Table I. The difference in the thermal conductivity results in a much higher steady-state operating temperature for oxide fuel, which along with the higher heat capacity, causes there to be more stored thermal energy in the reactor core for oxide fuel than for metal fuel. It is also important to note that both oxide and metal fuel operate at about the same fraction of the melting temperature, roughly 80%, implying that both fuel types have approximately the same relative margin to melting during transient events. For reference, the sodium coolant outlet temperature from the core is usually in the range of 500-550 °C (773-823 K), which is important in understanding the potential interaction between the fuel and the cladding for each fuel type. For metal fuel, there is a chemical interaction between the fuel constituents and the cladding that lowers the solidus temperature for fuel/cladding alloys to 1000 K from the nominal 1675 K. For oxide fuel, the interaction is mainly a mechanical interaction between the fuel as it swells and stresses the cladding. A more extensive discussion of fuel properties and performance is given in Ref. 1.

TABLE I

Fast Reactor Fuel Thermophysical Properties

Fast Reactor Fuel Type Fresh Fuel Properties	**Oxide UO_2-20PuO_2**	**Metal U-20Pu-10Zr**
Theoretical Density, g/cm^3	10.9 (673 K) 10.1 (2373 K)	15.5 (673 K) 15.1 (1073 K)
Melting Temperature, K	3000	1350
Thermal Conductivity, W/cm-K	0.043 (673 K) 0.021 (2373 K)	0.18 (673 K) 0.28 (1073 K)
Peak Centerline Temperature at 40 kW/m, K, and (T/T_{melt})	2360 (0.8)	1060 (0.8)
Fuel Cladding (HT9) Solidus, K	1675	1000*
Thermal Expansion, 1/K	0.9 – 1.8 x 10^{-5} (673-2373 K)	1.7 -2.0 x 10^{-5} (673-1073 K)
Heat Capacity, J/gm-K	0.29 – 0.46 (673-2373 K)	0.17 – 0.21 (673-1073 K)

The fuel pin designs for oxide and metal fuels are similar, but there can be many significant differences depending on design choices. Examples of oxide and metal fuel pin and assembly designs are shown in Table II for ABR-1000, which in this report is used as a representative example of a modern fast reactor.[2,3] In these examples, the fission gas plenum is located above the fuel, with a length of 1.5 times the core height, a typical value for high burnup fast reactor fuel pins, and the lower shield region below the fuel is part of the individual fuel pins. Note that the oxide fuel core is about 30% longer than the metal fuel core. The smear density in the fuel pin is 85% for the oxide fuel (to accommodate fuel swelling and to reduce the temperature drop between the fuel surface and the cladding) as compared with 75% for the metal fuel (to accommodate fuel swelling). The oxide core height is larger to achieve the same burnup reactivity loss as the metal fuel, compensating for the lower heavy metal density of the oxide fuel as listed in Table I. The oxide fuel pins are filled with an inert gas to provide thermal conduction between the fuel and the cladding since oxide fuel can be chemically reactive at normal operating temperatures. With the use of an inert gas, it is also possible to place the fission gas plenum below the core, which is in a region of much lower temperature and would result in lower fission gas temperature, and thus pressure, inside the pin which may offer operational or other advantages.

TABLE II

Assembly Design Parameters of ABR-1000 Fuel Assemblies

	Fuel assembly	
	Oxide	Metal
Assembly data		
- Number of pins	271	271
- Assembly pitch, cm	16.142	16.142
- Inter-assembly gap, cm	0.432	0.432
- Duct outside flat-to-flat distance, cm	15.710	15.710
- Duct thickness, cm	0.394	0.394
- Gap between duct and interior duct, cm	-	-
- Interior duct thickness, cm	-	-
- Interior duct inside flat-to-flat distance, cm	-	-
- Overall duct height, cm	477.52	477.52
Pin data		
- Pin material and type	MOX	U-TRU-Zr
- Bond material	He	Na
- Overall pin length, cm	381.0	332.7
- Active core height, cm	106.7	81.3
- Pellet smeared density, % TD	85.0	75.0
- Pellet diameter, cm	0.627	0.557
- Cladding material	HT9	HT9
- Clad outer diameter, cm	0.755	0.755
- Pin pitch-to-diameter ratio	1.180	1.180
- Cladding thickness, cm	0.056	0.056
- Wire wrap diameter, cm	0.131	0.131
Volume fraction at fabrication, %		
- Fuel or Absorber	37.0	29.2
- Bond	2.0	9.8
- Structure	25.7	25.7
- Coolant	35.3	35.3

Metal fuel pins are filled with sodium to provide the thermal bond between the fuel and the cladding, and this sodium is a liquid at normal reactor core operating temperatures. Metal fuel is chemically compatible with liquid sodium, and since liquid sodium has a much higher thermal conductivity than inert gas, this helps to lower the operating temperature for metal fuel as compared to oxide fuel when the fuel pins are operating at the same linear power and have comparable diameter (as in Table II). For both types of fuel pins, the fuel swells with irradiation, closing the gap between the fuel and the cladding, greatly reducing the temperature difference between the inside surface of the cladding and the outer surface of the fuel.

The fuel assemblies are hexagonal ducts containing the fuel pins. The lower shielding is contained within the fuel pins, although it can also be placed separately in the lower part of the assembly, and not part of the fuel pins. The reactor core is assembled from these fuel assemblies, along with control, reflector, and shield assemblies. The sodium coolant flowing through the core provides the heat removal capability from the fuel. The relative placement of the main components of the reactor system, including the reactor core, steam generators, and turbines usually has the core at the lowest point in the system to encourage natural circulation flow in the event that forced flow is lost. This is intended to be an example of a typical fast reactor system, and is used in this report to provide the basis for outlining the response of the system to various events and accidents.

IV. ANTICIPATED OPERATIONAL OCCURRENCES

As described above, AOOs are events that are expected to occur at least once in the lifetime of the reactor, i.e., events with a probability of about 10^{-2} per reactor year or greater. These would include plant upsets, turbine trips, station blackout and other such conditions including those where the plant protection system would respond to protect the reactor. As a result, differences in reactivity feedback between oxide and metal fuel are not relevant for these accidents. Experience has shown that proper design of the reactor system with either fuel type can result in a satisfactory response, sufficient to ensure that the NRC goals are met for this class of events.

For this category of events, the main difference between oxide and metal fuel is the higher operating temperature and higher stored heat with oxide fuel. On the one hand, the higher steady-state temperature and stored heat could be detrimental if the changes in plant conditions are such that the resulting temperature transient for the core and reactor structures presents challenges, e.g., peak temperatures are outside the allowable range for the system component. On the other hand, lower stored heat with metal fuel could also be detrimental depending on the transient response, e.g., if coolant temperatures drop rapidly, there could be a thermal shock to system components. Proper system design will account for these considerations in either case, such that an acceptable system is possible with either fuel type, but design details would likely be different.

Another class of events in this category is a breach in the fuel pin cladding, also called ‘local faults.’ This occurs when there is a local failure of the fuel pin cladding, breaching the boundary between the fuel and the coolant. Such an event allows fission gas from inside the fuel pin to escape into the sodium coolant, and is detectable by monitoring the activity of the sodium coolant and the cover gas region within the reactor vessel. Experience has shown that such breaches are usually very small, and can result from excessive local stress on the cladding during operation, or cracking caused by cladding thinning or embrittlement. Both oxide and metal fuel will release fission gas to the sodium coolant in this event.

However, there is a significant difference in the subsequent behavior of the fuel if reactor operation is continued. With oxide fuel, the fuel chemically reacts with the sodium coolant forming reaction products around the failure site. The progression of this event may cause local overheating of the fuel pin due to reduction in size of the coolant channel and in heat transfer between the pin and the coolant, and enlargement of the breach due to the chemical reaction is also possible, potentially with the release of fuel to the coolant.[4] Given these considerations, fast reactors using oxide fuel will usually have systems in place to detect fuel pin failure, sufficient to allow identification of the failed fuel pin or assembly, and procedures for shutdown and removal of the assembly before the effects of the breach increase. In this way, ‘local faults’ are managed with oxide fuel so that there are no further safety implications beyond fission gas release to the coolant.

In contrast, metal fuel is not chemically reactive with liquid sodium (which is also used inside the fuel pin for thermal conduction between the fuel and cladding), such that in the event of a fuel pin breach, there is no chemical reaction at the failure site, and there is no tendency towards breach enlargement. Experience has shown that failed metal fuel can be operated for extended periods of time without incident, aside from the release of fission gas to the coolant. This allows more flexibility in planning for shutdown, as well as reducing concern that the failed fuel will cause further damage within the assembly.

Since there are no differences of safety significance between oxide and metal fuel for AOOs, and given that both fuel types have been successfully used in fast reactors and that reactor performance is acceptable in both cases, it is reasonable to conclude that there is no significant fundamental difference in safety performance between oxide and metal fuel for this category of events.

V. ACCIDENTS

As described above, accidents are those events that are not expected to occur during the lifetime of the plant, approximately less than 1×10^{-2} per reactor year, but are theoretically possible based on the design of the reactor. For simplicity, the accidents can be classed in terms of multiple failures of major systems, possibly in combination with failure of the reactor or plant protection systems. For the purposes of this discussion, it is useful to use the NRC goals of core damage frequency $< 1 \times 10^{-4}$ per reactor year and large release frequency $< 1 \times 10^{-6}$ per reactor year to categorize the types of accidents. The first group could then be between 1×10^{-2} per reactor year and 1×10^{-4} per reactor year, where one would design the reactor to avoid core damage for accidents in this probability range, Accidents in this range can be considered to be the “design basis accidents (DBAs),” although one can include other accidents in this group. These accidents could be ones where there is the failure of one major system as the accident initiator, also known as a single-fault accident, or multiple failures of other systems. The accidents that tend to present the greatest challenges to the design limits tend to be the ‘single-fault’ accidents. An example of such an accident is the loss of power to the coolant pumps, followed by reactor scram to shut down the reactor and prevent any serious consequences.

The next group of accidents can be selected to have a probability of occurrence between 1×10^{-4} and 1×10^{-6} per reactor year, so that core damage may occur, but large releases are avoided. Given this range of probability of occurrence, these accidents can involve the failure of two major systems, where they are known as ‘double-fault’ accidents, or even more numerous failures of other systems. The greatest challenges to plant limits for this category of accidents tend to occur with the special cases of accidents where one of the failures is a failure to scram (anticipated transient without scram, or ATWS), such as loss of power to the coolant pumps followed by a failure to scram the reactor. These accidents may be referred to as “beyond-design-basis accidents (BDBA),” if accidents of this probability have not been part of the design basis for the plant.

The last category of accidents is for probabilities of occurrence of $< 1 \times 10^{-6}$ per reactor year, where there is the potential for large releases to the containment and the environment could occur. Accidents of such low probability have more severe accident initiators such as the failure of three or more major systems. Examples would be the uncontrolled withdrawal of all control rods with failure to scram the reactor, or a very large seismic event that fails all of the pumps instantaneously along with failure to scram the reactor. In the past, such accidents have been referred to as ‘residual risk’ or ‘emergency planning events,’ although it is not clear that such categories would be retained as the NRC licensing approach continues to evolve. However, such categories are useful in the present discussion for relative performance of oxide and metal fuel to identify any differences in safety performance.

V.A. Accidents with Probability 10^{-2} to 10^{-4} per Reactor Year

This class of accidents, where there is a failure of one major system, is typically accommodated by scram of the reactor to prevent damage to the core or any other parts of the plant. The reactor scram stops the fission process, quickly reducing power to decay heat levels, and making the accident consequences more of an issue of heat removal capability in light of the initial system failure.

Due to the reactor scram, the difference between oxide and metal fuel becomes one of the different stored heat in the reactor during steady-state, being much higher for oxide fuel when linear power and fuel pin diameter are comparable for both the oxide and metal cores, as listed in Table I. These events are similar to the AOOs, but with more serious consequences in the sense that the temperature transients will be larger, including exceeding temperature limits that apply to the AOOs. In this sense, experience has shown that the differences between oxide and metal fuel are likely to be small, in that both fuel types have been used in a reactor with acceptable performance for DBAs, if appropriate accommodation is made in the design so that large consequences are avoided, i.e., there is still no core damage such as fuel melting, etc.

V.B. Accidents with Probability 10^{-4} to 10^{-6} per Reactor Year

Many of the more challenging accidents in this category are associated with the failure of two major systems. If the reactor is scrammed in response, then the issue becomes one of decay heat removal, as for the AOOs and DBAs. In that case, it is likely that either oxide or metal fuel can be used as long as the design accommodations are made to prevent excessive temperatures or temperature variations (in this case, these events may be categorized as DBAs, but they don't have to be). If design accommodations are not made, so that the accidents are BDBA, especially if the accidents are ATWS events where there is a failure to scram, the difference between the two fuel types is more significant.

In the case of an ATWS event, regardless of the fuel type, the fast reactor will respond depending on the net reactivity of the reactor core, with negative net reactivity reducing power while positive net reactivity increases power. For an ATWS event, the net reactivity is determined by a balance of all of the inherent reactivity feedbacks, including fuel Doppler, control rod driveline expansion, sodium density change, etc. The reactivity feedback is dependent on both fuel type and design details, especially for reactivity feedback from radial expansion of the core. Analysis and testing has shown that it is possible to use the inherent reactivity feedback to limit the severity of the transient in ATWS events for both oxide and metal fuels, as long as appropriate design accommodation is made to limit reactivity feedback from phenomena that tend to increase core reactivity.[5] In practice, this has meant more design accommodation when oxide fuel is used due to the high steady-state operating temperature for the fuel. It would be beneficial if the average fuel temperature in the oxide core is reduced, either by reducing the linear power or by reducing the pin diameter and using more pins per assembly, or other design options can be considered that will introduce favorable reactivity feedback in some cases. These approaches will lower the detrimental effect of fuel contraction of oxide fuel for accidents where reduction to decay heat power level is essential for avoiding severe consequences, such as loss-of-flow and loss-of-heat-sink events. This is also relevant for transient overpower events as well, since any significant transient overpower accident will result in a loss of heat sink as the power level rises. The lower operating temperature of metal fuel makes it unnecessary to further lower fuel temperature or power to achieve an acceptable response.

With the proper use of inherent reactivity feedback, it has been shown that it is possible to avoid large releases for this category of accidents for both fuel types, although some fuel melting (core damage) may occur, both of which are within the NRC goals for accident consequences.[5] There is no failure of the fuel pin cladding, preventing release of fuel and fission products into the sodium coolant.

V.C. Accidents with Probability of less than 10^{-6} per Reactor Year

This class of accidents is associated with multiple failures of major systems, with consequences that may be severe, up to and including large releases to the environment. Evaluation of the differences between oxide and metal fuel for this category of accidents requires examination of experimental results on intentional overheating and failure of fuel pins and subassemblies, and the understanding developed about the behavior of fast reactor fuel under these conditions.

For oxide fuel, the experimental results show that the important considerations are the melting point and the compatibility with the sodium coolant and core structures.[6,7] Accident progression for such conditions typically begin with loss of adequate cooling for the core fuel, a failure to scram, and the inability of the inherent reactivity feedback to keep the power in balance with the heat removal capability of the coolant. As a result, the core fuel overheats, possibly boiling the coolant, but leading to temperatures sufficient to melt both the fuel and the cladding. Analyses have shown that there are several possibilities for the conditions in the assembly at the time of fuel melting, including cases where the liquid sodium coolant is still present, coolant is boiling, or the coolant has voided the assembly and only coolant vapor remains. The coolant vapor may have substantial velocity as well. If the assembly is voided of coolant, the stainless steel cladding can melt and be carried upwards by the sodium vapor into the cooler regions of the assembly above the core. It is also possible that the fuel will melt at the same time, also moving upwards along with the steel and coolant vapor, or that the fuel will fragment and the solid fuel pieces would move along with the steel and coolant vapor. For many accidents, the end result of such material motion is that both the steel and/or fuel will solidify rapidly since the above core region is well below the melting point for both materials. Experiments have shown that this will block flow (liquid or vapor) in the assembly, blocking any materials from moving upwards out of the core region.

Once this occurs, the remaining molten materials in the subassembly will drain downwards, again into regions of the core that are well below the melting point of either the cladding or the fuel. Similar solidification of the steel and/or fuel will occur, eventually preventing fuel from leaving the subassembly either upwards or downwards. Since there is still significant power generation, the molten fuel will melt through the assembly wall and the wall of the neighboring assembly, propagating the effects to the neighboring assemblies.[8] Although uncertainty about the details of this process are high, the result is a growing molten region of fuel and steel, approximately contained within the original core boundary, but capable of arranging the molten fuel into configurations that will lead to significant positive reactivity, recriticalities, and excessive power generation. Calculation of subsequent accident progression at this point is highly uncertain, and has been the subject of simulation development for several decades, but the end result is always an energetic event sufficient to permanently disperse the fuel so that further criticalities are no longer possible. As part of the CRBR licensing process, such an event was assessed to possibly have the potential to threaten the containment, resulting in a large release to the environment. Recent efforts have been exploring design options when oxide fuel is used for facilitating the downward movement of molten fuel so that recriticalities may be mitigated or eliminated by providing specific large channels within the core that would not readily be blocked by solidifying steel or cladding. At this time, there appears to be a large uncertainty as to the effectiveness of such approaches. The conclusion is that for these very unlikely severe accident conditions, using oxide fuel with its high melting point (which makes it impossible to cool molten oxide fuel with liquid sodium) will likely lead to energetic events that have the potential to threaten the integrity of the reactor vessel and the containment.

For metal fuel, the experimental results show that the phenomena are completely different, and other issues become important.[9,10] Metal fuel has a relatively low melting point and has the ability to form lower-melting-point alloys by chemical interaction with the cladding, which can be a cause of cladding failure, but it also provides the ability to cool the molten fuel/cladding alloys with liquid sodium. As discussed for oxide fuel, accident progression for the severe accident conditions being considered in this section begin with loss of adequate cooling for the core fuel, with a failure to scram, and the inability of the inherent reactivity feedback to keep the power in balance with the heat removal capability of the coolant. As a result, the core fuel overheats, possibly boiling the coolant, but leading to temperatures sufficient to melt both the fuel and the cladding. Simultaneously, the molten fuel interacts with the cladding to form alloys with relatively low melting points, below the boiling point of the sodium coolant. Experimental results and analyses have shown that there are several possibilities for the conditions in the assembly at the time of fuel melting, including cases where the liquid sodium coolant is still present or the coolant is boiling. For temperatures high enough to boil sodium coolant, metal fuel readily melts and interacts rapidly with cladding, failing the cladding and releasing fuel and/or fuel-cladding mixtures into the assembly coolant channels. Either the liquid sodium or the coolant vapor can have velocity sufficient to carry molten materials upwards into the cooler regions of the assembly above the core. In this case, unlike that for oxide fuel, the result of the material motion is that the fuel/steel mixtures do not solidify in the region above the core since the temperature of the above core region is at or above the melting point for the relocating fuel and steel. Experiments have shown that upward flow is not blocked, and that the fuel and steel will move well into the above core structure, perhaps out of the subassembly entirely. The removal of fuel from the core region prevents recriticalities as the accident progresses, and reduces or eliminates the potential for energetic events in the reactor. Unlike the case for oxide fuel, it appears that no special modifications are needed to facilitate removal of fuel from the core under these conditions. This behavior is completely different from that for oxide fuel and is the result of the different thermophysical properties, alloying between metal fuel and cladding, and the ability to cool the relocating fuel materials with liquid sodium, resulting in a significant difference in safety performance between oxide and metal fuel.

Experiments show that this behavior would be expected for severe transient overpower and loss-of-heat-sink events, especially for irradiated fuel. Experiments have not yet been performed for loss-of-flow conditions, although simulations using phenomenological models based on the available results indicate that the same phenomena would occur and prevent recriticality.

VI. SUMMARY AND OBSERVATIONS

The preceding discussion has provided a brief review of the current understanding of the safety performance of fast reactors using oxide and metal fuel. While there are differences for the two fuel types for all classes of events, the only significant differences appear to occur only for events of extremely low probability, as follows:

- Probability > 10^{-2} per reactor year (AOOs) - no substantial difference, with proper design to accommodate the characteristics of each fuel type
- 10^{-2} > probability > 10^{-4} per reactor year - no substantial difference, with proper design to accommodate the characteristics of each fuel type
- 10^{-4} > probability > 10^{-6} per reactor year (core damage allowed) – no substantial difference if inherent safety principles are used and special design accommodation is made done to lower the steady state fuel temperature for oxide fuel to avoid significant positive reactivity introduction when power must be lowered to successfully survive a transient event
- Probability < 10^{-6} per reactor year (large releases allowable – there is a substantial fundamental difference between oxide fuel and metal fuel due to the high melting point of oxide fuel and the low melting point of metal fuel, along with the ability of metal fuel to alloy with cladding to form materials with lower melting points, facilitating fuel removal from the core early in the accident progression.

The question becomes one of assessing the level of concern that one assigns to the extremely low probability events, since this is the only class of events for which there appears to be a significant fundamental difference in safety performance between oxide and metal fuel. It is important to emphasize that the NRC has a goal of restricting accidents with potentially large releases to probabilities of less than 10^{-6} per reactor year. With proper design and use of inherent safety principles, it is possible to achieve this goal for both oxide and metal fuel. The concern is one of assessing the risk to the public and the environment (and to the project) at such low levels of probability.

While in principle it appears that both oxide and metal fuel can be used, there are some additional cautions that should be considered. First, metal fuel has significantly less capability (or perhaps none at all) to threaten the reactor vessel and containment boundaries with energetic events resulting from accident conditions. Second, even though large releases may be allowable for accidents with very low probability, one of the NRC principles beyond prevention and mitigation is delay time, i.e., time for evacuation of people in the event of a serious accident. The NRC requires that the containment doesn't breach for at least 24 hours in these cases. The difficulty with the fast reactor accidents considered in this discussion is that there would be very little time from the initiation of such an accident to the failure of the containment, if that were to occur, and is likely to be insufficient to allow any evacuation in a timely manner. Third, for both fuel types, depending on the accident conditions (such as complete loss of any heat removal capability), it is possible to eventually fail the reactor vessel by melting through the vessel, resulting in core materials being released to the containment area. Sufficient accommodation of this eventuality would be required.

Overall, it is seen that both oxide and metal fuel can be successfully used in a fast reactor, and that the NRC goals can be met where core damage only occurs for probabilities < 10^{-4} per reactor year and large releases only occur for accidents with probabilities < 10^{-6} per reactor year. The decision to choose one fuel type over the other based on safety performance depends on the judgment of the importance of accident consequences for extremely low probability events, and the potential risk given oxide fuel behavior for such extremely unlikely events.

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