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Impact of Reducing Sodium Void Worth on the Severe Accident Response of Metallic-Fueled Sodium-Cooled Reactors*

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IMPACT OF REDUCING SODIUM VOID WORTH ON THE SEVERE ACCIDENT RESPONSE OF METALLIC-FUELED SODIUM-COOLED REACTORS

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ABSTRACT

Analyses have been performed on the severe accident response of four 900 MWth reactor cores, all designed using the metallic fuel of the Integral Fast Reactor (IFR) concept. The four core designs have different sodium void worth, in the range of -3$ to 5$. The purpose of the investigation is to determine the improvement in safety, as measured by the severe accident consequences, that can be achieved from a reduction in the sodium void worth for reactor cores designed using the IFR concept.

I. INTRODUCTION

The sodium coolant void worth has historically been of concern due to a combination of two major factors, with several other contributing factors. The first point is that for core designs which are sodium-cooled and neutronically-efficient, i.e. having small reactivity changes as irradiation proceeds, there is typically a positive sodium void worth of several dollars. The value of the sodium void worth is dependent on the fuel type, the core geometry, the presence of internal blankets, and other design parameters. Previous studies have shown that lower sodium void worths can only be obtained at the expense of neutron economy, which means that lower sodium void worth will increase the reactivity loss (or decrease any reactivity gain) with burnup. Briefly, this is due to the balance between the spectral, leakage, and capture components of the sodium loss on core reactivity. The positive sodium void reactivity effect is caused by the same physical phenomena that enables the efficient internal breeding in the core required for minimal reactivity loss with burnup, which means that a low sodium void worth and a low burnup reactivity swing are fundamentally opposing design goals.[1]

The second point relates to early experimental results which indicated that it was possible to achieve very high superheat in liquid sodium before boiling commenced. This led to the concern that it might have been possible in accident situations to have a high superheat in much of the liquid sodium in the core, which then had the potential to void rapidly at the onset of boiling. This in turn would have had the capability of introducing most of the reactivity associated with voiding the sodium coolant in a very short period of time, less than needed for response by engineered safety systems, leading to a super-prompt-critical excursion.[2] As research progressed, it was determined that it was not possible to obtain high superheat in liquid sodium in fuel-pin bundles, but that superheat would be expected to be in the range of 5-10°C. However, while this result has removed the possibility of rapid large-scale voiding in the core by this mechanism, the presence of a positive sodium void coefficient can still be a cause for concern.

Depending on the details of the core design, there may be the possibility of coolant boiling in the reactor core as a result of one or more accident initiators. The severity of the accident conditions required for the occurrence of coolant boiling can be a function of the core fuel type, the steady-state operating conditions, the degree to which favorable passive reactivity feedback mechanisms have been included, and many other design considerations. If coolant boiling should occur, the introduction of positive reactivity during an accident transient could have severe consequences, depending on the magnitude and timing of the events. For this reason, the impact of reducing the sodium void worth needs to be investigated to establish the gains that can be made in safety performance.

II. PASSIVE SAFETY RESPONSE

As part of the effort to develop an advanced reactor concept, a key feature of the IFR program has been to develop fuel designs, reactor core designs, and the related systems to minimize or eliminate core damage in response to a variety of accident initiators. Examples of this approach are the use of metallic fuel in the core, the design of low-burnup-swing cores to minimize the reactivity vested in the control rods, and designing the reactor to take full advantage of the available passive reactivity feedback mechanisms. As a result of this effort, it is possible to design a reactor which avoids coolant boiling and core damage for a wide variety of accidents, including unprotected, i.e. unscrammed, accidents.[3,4,5] For example, the response to a "double-fault" accident where there is a failure of one major engineered system and a failure to scram, such as an unprotected loss-of-flow (LOF), is controlled by the favorable reactivity feedback generated from the temperature increase in the core, combined with the small positive Doppler feedback generated as the power decreases due to the use of metallic fuel. Minimum margins to coolant boiling of 200°C or greater can be obtained, with no core damage resulting from this accident. This safety performance has been calculated for a variety of metallic-fueled cores, including large reactors as well as reactors with a zero sodium void worth.

The impact of reducing the core sodium void worth on accident response where the consequences are limited below coolant boiling has already been completed, using the same four core designs that are used in this study.[6] The results indicated that for an unprotected LOF accident, the peak coolant temperature attained during the transient decreases with decreasing void worth due to a more favorable reactivity feedback balance. All cores exhibited margins to coolant boiling of at least 200°C. For the unprotected single control rod withdrawal (transient overpower, or TOP), the small amount of reactivity vested in the control rods for the low-burnup-swing, highest void worth core dominated to provide the best transient response, while the cores with intermediate values of sodium void worth show poorer performance. As with the unprotected LOF, all core designs provided margins to coolant boiling of several hundred degrees, although there was the potential for prolonged operation at elevated temperature and power in the low void worth cores which could lead to long-term effects such as delayed fuel-pin failures, or loss of the main heat sink. Overall, there was not a definitive conclusion as to which core design would provide the best safety performance, but it appeared that either the lowest void worth core or the low burnup swing design would be better than the cores with intermediate values of void worth for providing improved accident response.

In order to further investigate the effect of reducing the coolant void worth, it was necessary to increase the severity of the accident initiators substantially to eventually cause coolant boiling and fuel-pin failures in the core. This study is the continuation of the previous study, considering the effect of the sodium void worth on severe accident consequences .

III. REACTOR CORE DESIGNS

Four different core designs, all 900 MWth, were used in this study. All designs utilize the metallic fuel of the IFR concept, and are of a "tightly coupled" radially heterogeneous configuration. The core shape is varied such that the sodium void worth spans a range from -3$ to 5$. Reducing the core height-to-diameter (H/D) ratio was selected as the method for reducing the sodium void worth based on the conclusion that this method minimizes burnup reactivity loss and fissile enrichment penalties.[1] Conventional assembly and fuel pin designs were utilized, with changes required only in the active fuel height. The characteristics of the four core designs are listed in Table I. The design limit for the peak linear power is 50 kW/m (15 kW/ft); all cores had peak linear power in the range of 42 kW/m (13 kW/ft). The core inlet temperature is 357°C, with an average core temperature rise of 150°C. In each core design, the fission gas plenum length is set to 1.5 times the length of the active fuel. The metallic fuel uses a sodium bond within the pin, since the initial fuel diameter is less than the clad diamter to accomodate fuel swelling on irradiation until there is sufficient porosity in the fuel to allow fission gas to escape to the plenum. As is typical with reactor cores designed using the IFR concept, there are no axial blankets on the fuel. Fuel pin spacing is determined by using wire-wrapped pins. The plant design for each core is basically identical. As the

Table I. Reactor Core Characteristics

H/D	0.484	0.299	0.192	0.060
Core Height, m	0.965	0.676	0.508	0.235
Pin Diameter, mm				
Driver	7.239	7.239	7.239	7.239
Blanket	9.957	9.957	9.957	9.957
Pins/Assembly				
Driver	271	271	271	271
Blanket	169	169	169	169
Sodium Void Worth, $[a]	5.407	3.926	1.552	-1.935
Burnup Reactivity Swing, $	0.45	6.20	10.40	12.36

[a] The sodium void worth listed is as modelled with the SAS4A code, which is higher than the actual void worth due to limiting the axial extent of the reactivity worth curves, and represents the core region and part of the region above the core.

data listed in Table I demonstrate, there is a substantial increase in the reactivity swing with burnup as the core sodium void worth decreases, even for the core with a void worth of 3.926$.

IV. SEVERE ACCIDENT RESPONSE

Severe accidents have traditionally been those where the accident consequences included coolant boiling, fuel melting, and fuel pin failure, with fuel relocating outside of the original pin boundary. Depending on the accident, such events could lead to an "energetic" response, which implies that sufficient energy has been deposited in the fuel to cause rapid fuel vaporization, or upon contact with the liquid sodium coolant, rapid coolant vaporization, such that the expanding vapor is capable of doing work. Usually the work is in the form of accelerating materials, such as liquid coolant, and having the material impact on the reactor vessel structure to threaten the integrity of the reactor vessel. As discussed in Section II, the developments in the IFR program concerning fuel type, core design, and the use of passive reactivity feedback mechanisms, have resulted in a reactor concept where the accident consequences are not severe, even for "double-fault" unprotected accidents such as unscrammed LOF, TOP, and loss-of-heat-sink initiators.

Given the level of passive safety achieved with the IFR concept, it is difficult to increase the magnitude of the disturbance caused by the accident initator in a plausible manner so that the accident consequences lead to coolant boiling and fuel melting. For the purposes of this study, it was determined that two accident initiators, which might be characterized as triple-fault or greater based on their probability of occurrence, have been identified to serve as "test" accidents to evaluate the effect of varying the sodium void worth. The first "test" accident is termed the unprotected "rapid" loss-of-flow, where all coolant flow through the core is stopped essentially instantaneously (flow down to 50% of nominal within 250 msec, and down to 10-15% by one second) while the reactor is operating at nominal full power conditions, along with failure to scram the reactor. Such an accident might occur if all coolant pumps seized simultaneously, or if all piping between the pumps and the inlet plenum broke simultaneously, which could be postulated to happen in response to an extremely large seismic event, which would provide at least several g's of acceleration. The second "test" accident is a multiple control rod withdrawal, where all of the control rods are removed from the reactor while the reactor is operating at nominal full power conditions, along with failure to scram the reactor. Such an accident would require several major control and safety system failures. The probability of occurrence of each of these accidents has not been estimated, but is certainly well below the 10^{-6} or 10^{-7} value which is associated with "double-fault" accidents.

In the following sections, the response of each reactor to each of these accidents is discussed and compared. Following the discussion, the overall conclusions are given, along with the implications for core design.

A. Unprotected "Rapid" Loss-of-Flow

The results for the transient response of each reactor core is presented separately in this section, as different physical phenomena and timing of the events are encountered, depending on the sodium void worth of the core. All results have been calculated with the SAS4A Accident Analysis Code.[7]

1. Results for Core H/D = 0.484

The core with H/D = 0.484 was modelled with SAS4A in detail, using 19 SAS4A channels to represent the 32 driver assemblies in one-third of the core, with the core having one-third symmetry. The internal and radial blankets are grouped into 3 channels, as they are not expected to reach coolant boiling or fuel melting during the transient. The contribution of the blanket assemblies is important, though, since 2.447$ of the 5.407$ sodium void worth for this core is in the blanket assemblies.

The transient begins with the rapid drop in coolant flow through the core, with flow down to 50% by 250 msec and to 10% by 1.4 seconds. The reactor is not scrammed, so that the power remains near nominal until the onset of coolant boiling, with sufficient negative reactivity feedback from axial fuel expansion, fuel Doppler, and radial core expansion, to counter the positive reactivity feedback from the decrease in coolant density as the core temperatures rise. Initial boiling occurs at 2.4 seconds after the start of the transient. Boiling introduces positive reactivity feedback so that the power begins to increase slowly. As boiling spreads to other assemblies, more positive reactivity is added and the power rises more rapidly. The rise in power causes fuel melting within the fuel pin, until the molten fuel region reaches the top of the fuel column. At that time, the molten fuel within the pin expands axially into the fission gas plenum. The fuel motion is driven by the higher pressure in the fission gas retained in the fuel as compared to the fission gas plenum pressure, which is due to the much higher temperature of the fuel. The expansion of the fuel introduces substantial negative reactivity, which is sufficient to stop the power rise at 3.44 times nominal at 2.97 seconds. At that time, boiling was occuring in 28% of the core driver assemblies, and the net reactivity peaks at 0.68\$. The negative reactivity associated with the upward axial motion of fuel within the pin in one SAS4A channel, representing 3 assemblies out of the 96 drivers, counteracts the positive reactivity from continued boiling in the core, keeping the power and net reactivity limited until in-pin fuel motion occurs in other fuel assemblies.

As the transient progresses, coolant boiling spreads throughout the driver assemblies in the core. The positive reactivity effects of boiling are countered by the negative reactivity associated with additional in-pin fuel motion in other assemblies, resulting in two more smaller peaks in power. The first pin failures occurred at 3.50 seconds at a power of 150% of nominal. At this time in the transient, there is boiling in 84% of the driver asssemblies, and the positive reactivity introduced from voiding and from coolant density decrease in the non-voided part of the core is 3.05\$, with a net reactivity of 0.12\$.

The initial pin failure occurs at 75% of the core height, so that there is only a slight positive fuel motion reactivity feedback before dispersal in the coolant channel causes a large reactivity loss from the core. The reactor becomes subcritical at 3.62 seconds after the start of the transient, with reactivity decreasing from additional fuel pin failures at a rate of approximately 7\$/sec. The calculation terminates with the reactor at a net reactivity of -3.10\$. The peak fuel temperature of 1585°C occurred at 3.55 seconds, just before fuel pin failure. At the end of the calculation, the peak fuel temperature was just over 1400°C. The result is that the energy generated during the transient is not large, the fuel temperatures are well below the fuel vaporization point, and there is not expected to be any chance of a coherent fuel/coolant interaction which would lead to an energetic event.

Overall, the response is determined initially by the balance between the reactivity feedback components until coolant boiling occurs, then boiling drives an increase in power until in-pin fuel motion takes over. Fuel pin failures follow shortly afterward, taking the reactor well subcritical and terminating the initating phase of the transient. Of major importance is the abililty of metallic fuel to partially melt and expand axially within the pin to counteract the effects of boiling and limiting the consequences of the accident. There have been numerous assemblies with fuel pin failures, approximately 44% of the drivers by the end of the calculation, with the core power at 34% of nominal, although more pin failures may occur as the reactor power drops to decay heat levels and natural circulation cooling is established.

2. Results for Core H/D = 0.299

The core with H/D = 0.299 was modelled with SAS4A in detail, with 21 SAS4A channels to represent the 21 driver assemblies in one-sixth of the core, with the core having one-sixth symmetry. The internal and radial blankets are grouped into 5 channels. The contribution of the blanket assemblies to the total sodium void worth of the core is 1.742\$ out of 3.926\$.

The transient begins with the rapid drop in coolant flow through the core, with flow down to 50% in 250 msec and down to 15% at 0.8 seconds. There is a slight drop in power prior to coolant boiling, due to a more favorable reactivity balance as compared to the core with H/D = 0.484, with a net negative reactivity of -0.15\$ at the onset of coolant boiling. Once boiling commences at 2.50 seconds, the positive reactivity feedback associated with coolant boiling drives the power up until in-pin fuel motion stops the power rise at 2.31 times nominal at 3.14 seconds. The peak net reactivity is 0.56\$. The transient response for this core is quite similar to that observed for the core with H/D = 0.484, except that the power peak is lower and there is only one peak due to the lower positive reactivity introduced by coolant boiling.

The first fuel pin failure occurs at 3.64 seconds, with power at 0.987 of nominal and a net reactivity of -0.098\$. Boiling and the decrease in the coolant density in the non-voided part of the core has contributed a positive reactivity of 2.26\$ at this time in the transient, with boiling occurring in 81% of the driver assemblies. There are a large number of assemblies with fuel pin failures as the accident progresses, with pin failures in 71% of the driver assemblies at the time the calculation terminates. At the end of the calculation, the reactor was subcritical with the net reactivity at -4.29\$ and reactivity decreasing at a rate of over 3.5\$/sec. The peak fuel temperature is 1300°C, occurring just prior to fuel pin failure. At the end of the calculation, the peak fuel tempearture has decreased to less than 1200°C. The results indicate that no energetic response to this accident would be expected, the same as with the results for the core with H/D = 0.484.

3. Results for Core H/D = 0.192

The core with H/D = 0.192 was modelled using 28 SAS4A channels to represent the 28 driver assemblies in one-sixth of the core, with the core having one-sixth symmetry. The internal and radial blankets are represented by 5 channels. The contribution of the blanket assemblies to the total sodium void worth of the core is 0.879\$ out of the 1.552\$ total.

The transient is initiated by the rapid drop in core flow to 50% of nominal by 270 msec, and down to 15% of nominal by 1.15 seconds. There is a significant drop in power prior to coolant boiling at 3.05 seconds, down to 60% of nominal caused by the overall favorable reactivity feedback balance. The net reactivity is -0.46$ at the onset of boiling. Due to the low sodium void worth for this core, the process of boiling adds reactivity slowly, such that the net reactivity rises to near zero by the time of the first fuel pin failures, which occur at 4.5 seconds and a power of 0.81 times nominal. At the time of the initial pin failure, boiling was occurring in 57% of the driver assemblies. The low power throughout the transient prevented sufficent fuel melting within the pin prior to fuel pin failure to connect the molten fuel cavity with the fission gas plenum, with a peak fuel temperature of 1180°C, and there was no in-pin fuel relocation upwards within the pin. The fuel pin failure causes a slight rise in power to 0.86 times nominal before ex-pin fuel motion causes the reactor to go subcritical. At the end of the calculation, the power is just under 60% of nominal, with a positive reactivity contribution from coolant boiling and coolant density decrease of 1.02$, a net reactivity of -0.42$, and reactivity decreasing at a rate of just under 3$/sec. Fuel temperatures had not started to decrease at the end of the calculation, and boiling had spread to 86% of the driver assemblies.

4. Results for Core H/D = 0.060

The core with H/D = 0.060 was modelled using 27 SAS4A channels to represent the 34 drivers in one-twelfth of the core, where the core has essentially one-twelfth symmetry. The internal and radial blankets are represented by 5 channels. The sodium void worth of the core and above-core region is -1.935$, of which the contribution from the blanket assemblies is -0.191$.

The transient initiator causes the flow to drop to 50% of nominal by 150 msec, and to 15% of nominal by 0.75 seconds. Prior to coolant boiling, there is a drop in power to 0.88 times nominal. Boiling begins at 2.14 seconds after the start of the transient. Coolant boiling introduces a small, rapidly varying amount of positive reactivity, with a maximum of 0.46$. The net reactivity of the core continues to drop on average throughout the transient, up to the point where the calculation terminates at 10.98 seconds. The net reactivity at that time is -1.45$, with the power at 0.234 times nominal. Boiling is occurring in all of the core driver assemblies. The calculation terminated before fuel pin failures had occurred, but based on the cladding damage at 10.98 seconds, it is estimated that one-third of the driver assemblies will have pin failures within another 20-30 seconds. It appears that the fuel motion after the pin failures should provide enough negative reactivity feedback to reduce the power to decay heat levels fast enough to prevent further pin failures. It is not expected that the pin failures will present the possibility of a rapid increase in power, as the net reactivity is estimated to be around -1.50$ to -2.00$ at the time of initial pin failure. The peak fuel temperature of 1450°C occurs at 5.2 seconds, and has dropped to just under 1200°C at 10.5 seconds.

5. Summary of Results for the Rapid LOF

Several trends are noted in the transient performance in response to the unprotected rapid LOF as the sodium void worth of the core is reduced. First, the peak power during the transient becomes lower, with the cores with H/D of 0.484 and 0.299 having peaks above nominal power, while the two cores with H/D of 0.192 and 0.060 do not. Second, in-pin fuel relocation occurs only for the cores with H/D of 0.484 and 0.299, although there is fuel melting within the pin in all cases. There is also a trend of decreasing peak fuel temperature with decreasing sodium void worth, except for the core with the lowest sodium void worth. However, at the time the calculations terminate, the rate at which reactivity is being lost from the core by ex-pin fuel motion is decreasing with decreasing sodium void worth. In all cases, there would appear to be no possibility of an energetic event, as the peak material temperatures are too low, and the dispersal characteristics of the metallic fuel outside of the pin in the coolant channel increase the likelihood of being able to cool the relocated fuel.

B. Unprotected Multiple Control Rod Withdrawal

The results for the transient response of the core with an H/D = 0.484 were calculated with the SAS4A code. Based on the results, the behavior of the other three cores is estimated.

1. Results for Core H/D = 0.484

The calculations used the same SAS4A model as for the unprotected rapid LOF. The transient was initiated by the withdrawal of the 12 control rods at a rate of 0.05$/second. The total worth is set at 0.45$, equivalent to the reactivity swing during an irradiation cycle. During the transient, the power increases in response to the added reactivity. This in turn causes the core temperatures to rise, generating reactivity feedback. Early in the transient, the dominating negative feedback components are radial expansion of the core and axial expansion of the fuel. The peak net reactivity is 0.24$ at

9.0 seconds, at the end of the reactivity addition, with power at 1.98 times nominal. The core power then drops slowly, down to 1.77 times nominal at 110 seconds, at which time the net reactivity of the core has returned to zero. The reactor remains slightly subcritical up to at least 200 seconds, when the calculation was terminated. The minimum margin to coolant boiling was almost 400°C, no fuel melting occurred, and there was essentially no cladding damage. The calculation assumed that the steam generator outlet sodium temperature remained constant throughout the transient, which is dependent on the plant design. At sustained high power, the period of time that the steam generator can accept the heat load is limited, and will eventually result in a loss of the main heat sink. As previous analyses have shown, there are no consequences to this event for cores designed using the IFR concept.

In an attempt to cause coolant boiling and fuel pin failures, it was assumed that due to uncertainties in the neutronics as well as in manufacturing, as much as 1.50$ of additional reactivity would be added to the core to ensure criticality throughout an irradiation cycle. This increases the total amount of reactivity that could be added to the core when all control rods are withdrawn to 1.95$. The reactivity is again added at a rate of 0.05$/second. In this case, there is sufficient positive reactivity from the control rods withdrawal to cause fuel melting within the pin leading to in-pin fuel motion, beginning at 13.8 seconds, with power at 2.67 times nominal. In-pin fuel motion in a number of assemblies reduces the rate of power rise such that the power is only 3.33 times nominal at the time of the initial pin failure at 28.8 seconds.

The initial fuel pin failure occurs in one SAS4A channel, representing 3 driver assemblies. The pin failure is located at the top of the fuel column, and the subsequent fuel motion causes a rapid loss of reactivity from the core, taking the reactor subcritical within 200 msec after the failure.[8] Due to the core power at failure, there was a substantial amount of molten fuel within the fuel pins, which exits the pin upon pin failure. This causes a rapid drop in power to below nominal power 1.5 seconds after the initial pin failure. Continued fuel motion outside of the fuel pin in these 3 driver assemblies takes the net core reactivity further subcritical before the calculation stops. At the end of the calculation, the fuel which had been molten in the other assemblies is refreezing. The core power is 86.5% of nominal, and the net reactivity is -1.25$. At that time, the continuing withdrawal of the control rods has 0.45$ of reactivity remaining to add to the core, implying that it will not be possible for the core to go critical again. The peak fuel temperatures during the transient were observed just prior to the fuel pin failure, at just over 1600°C.

2. Results for the Lower Void Worth Cores

The other three cores were also analyzed for their response to an unprotected withdrawal of all of the control rods. In all cases, the transients followed a similar pattern, where power would rise leading to fuel melting within the fuel pin. The subsequent in-pin movement of the fuel upwards would reduce the rate of power increase until there was a fuel pin failure in one SAS4A channel. The pin would fail at the top of the fuel column, so that the subsequent ex-pin fuel motion would cause a negative reactivity feedback, reducing the power.[8] The power at which pin failure occurs is around three times nominal in all cores. The only difference in the final result for each core is a consequence of the amount of reactivity that can be added to each core by withdrawing all of the control rods.

As listed in Table I, the reactivity swing with burnup increases rapidly as the sodium void worth of the core is reduced. Therefore, the amount of reactivity that needs to be balanced by ex-pin fuel motion after fuel pin failure also increases rapidly. One would expect that it would require a greater number of assemblies to fail and disperse fuel to terminate this accident as the void worth is lowered. Further compounding the problem is the reduction in fuel worth, on a per kilogram basis, as the sodium void worth is lowered. This implies that more fuel would need to be displaced from the core for a given amount of reactivity for the lower void worth cores. In the extreme case where the core H/D = 0.060, the total worth of the fuel in the core is 60.7$, as compared to a total of 117.3$ for the core with H/D = 0.484.

In consideration of these facts, the transient behavior of each core is a series of power increases, with each power rise terminated by fuel pin failures in one or more groups of assemblies. The fuel dispersal and reactivity loss associated with the fuel pin failures would drop the power to near nominal. As more reactivity is added by the continuing withdrawal of the control rods, another power rise sequence would occur, again terminated by further fuel pin failures. Eventually, the control rods would all be fully withdrawn from the core, and the reactor would stabilize with no further power increases or fuel pin failures. The trend of the results would indicate that as the void worth is lowered, more fuel pin failures would be required and more repetitions of a power rise terminated by fuel pin failure would be encountered. In all cases, though, the peak fuel temperatures should be comparable, and dispersal of the metallic fuel would ensure coolability of the relocated fuel outside of the fuel pin.[8]

V. CONCLUSIONS

There are several significant conclusions from this study regarding the performance of the metallic fuel used in the IFR concept in response to severe accident conditions., and the influence of the sodium void worth on the consequences:

1. It is extremely difficult to postulate a credible accident initiator which would result in coolant boiling and fuel pin failure. Traditional "double-fault" events, such as an unprotected loss-of-flow, are withstood with large margins to coolant boiling and fuel pin failure, regardless of the value of the sodium void worth.[3]
2. Considering the unprotected "rapid" loss-of-flow accident, all four core designs survived the transient without energetic consequences by a substantial margin. There appears to be a trend of lower peak transient power and lower peak fuel temperatures with decreases in the sodium void worth. In addition, the fuel pin failures occur at lower power and lower net reactivity as the sodium void worth of the core is decreased.
3. The results for the unprotected withdrawal of all control rods in the core also indicate that all four cores would survive this accident without an energetic event, and by a large margin. There is a trend towards more fuel pin failures and more fuel relocating outside of the fuel pins as the sodium void worth of the core is decreased.

The overall result is that all core designs successfully survived the accident initiators postulated with a large margin to energetic events. The details of the results indicate no significant difference in behavior for the unprotected "rapid" loss-of-flow, other than variations in the peak transient fuel temperature. There is an increase in the amount of core damage and the mass of relocating fuel that occurs in response to the unprotected multiple control rod withdrawal as the sodium void worth is lowered.

Therefore, there appears to be no safety advantage to be gained in reducing the sodium void worth of the core, due to the use of the concepts developed in the IFR program, especially the fuel pin design with a metallic fuel form. This conclusion has now been demonstrated for accidents where the consequences of the accident are limited to below coolant boiling and fuel pin failure, as well as for accidents where significant core damage occurs. There is some operational disadvantage associated with the large reactivity swing during burnup that results from reducing the sodium void worth, which causes a greater number of fuel pin failures and the requirement to relocate a larger mass of fuel in response to the unprotected withdrawal of the control rods. The results imply that the attempts to lower the sodium void worth to reduce the introduction of positive reactivity during an accident sequence is traded for positive reactivity which can be added by inadvertent withdrawal of the control rods. As indicated in Table I, the trade is not necessarily beneficial for moderate reductions in the void worth, since the reactivity swing with burnup increases much more rapidly than the sodium void worth decreases.

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