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**ACCOMMODATION OF UNPROTECTED ACCIDENTS BY
INHERENT SAFETY DESIGN FEATURES IN
METALLIC AND OXIDE-FUELED LMFBRs***

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ABSTRACT

This paper presents the results of a study of the effectiveness of intrinsic design features to mitigate the consequences of unprotected accidents in metallic and oxide-fueled LMFBRs. The accidents analyzed belong to the class generally considered to lead to core disruption; unprotected loss-of-flow (LOF) and transient over-power (TOP). The results of the study demonstrate the potential for design features to meliorate accident consequences, and in some cases to render them benign. Emphasis is placed on the relative performance of metallic and oxide-fueled core designs.

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INTRODUCTION

The objective of inherent safety is a widely-accepted principle that has received emphasis in the design, construction, and operation of EBR-II (1), Super Phenix (2), and PFR (3), as well as other liquid-metal cooled fast breeder reactors (LMFBRs). Inherent safety is also a primary tenet in the development of the Integral Fast Reactor (IFR) concept (4). In the IFR concept, a pool-type primary system arrangement is combined with an advanced metallic fuel design and an on-site fuel cycle facility. The pool-type primary system, together with the low-pressure, liquid-metal coolant, provide intrinsic protection against fuel over-heating in both normal and off-normal events. All of the primary system sodium is contained within the reactor vessel, along with the core, the primary pumps, and the intermediate heat exchangers. Natural circulation cooling of fuel is assured for both normal shut-down decay heat removal and for abnormal events. Intrinsic protection against pipe rupture-caused accident is therefore provided by the pool-type primary system. In addition, the high heat capability of the pool design provides long time margins for corrective action in the event of heat sink loss.

The IFR metallic fuel design is an advanced concept developed as a result of experience with metallic fuels in EBR-II and other reactors (5). In the IFR fuel design, the fuel is cast as a uranium-plutonium-zirconium alloy. Some of the properties of the IFR metallic fuel are compared with a typical oxide fuel in Table I. So the data in Table I show, metallic fuel is denser than oxide, with a thermal conductivity higher by an order of magnitude, and lower specific heat. The thermal expansion coefficient of metallic fuel is higher than oxide, and the melting point is much lower. To allow for fuel swelling upon irradiation, the IFR metallic fuel design features an as-fabricated smear density of 75%. Since the U-Pu-Zr alloy is chemically compatible with sodium, the fuel rod is submerged in liquid sodium, together with the high thermal conductivity, give the metallic fuel pin an order-of-magnitude faster thermal response time compared to the lower conductivity, gas-bonded oxide fuel.

The high thermal conductance provided by the band-gap sodium lowers the fuel surface temperature of metallic fuel compared to oxide fuel, and due to its higher thermal conductivity, metallic fuel exhibits relatively small radial temperature gradients. Metallic fuel therefore operates, at much lower temperatures than oxide fuel, and the amount of stored heat at normal operating conditions is reduced correspondingly.

Table I. Oxide and Metallic Fuel Thermal Performance Characteristics

	<u>Oxide</u>	<u>Metal</u>
Nominal Composition	UO ₂ -PuO ₂	U-15% Pu-10% Zr
Density, g/cc	10.6	15.8
Thermal Conductivity, w/cm-°C	0.023	0.22
Specific Heat, J/g-°C	0.38	0.20
Thermal Expansion Coefficient, °C ⁻¹	1.2x10 ⁻⁵	2.0x10 ⁻⁵
Melting Point, °C	2750	1160
Fuel Pin Thermal Time Constant, sec.	~3	~0.3

REACTIVITY FEEDBACK MECHANISMS

The key to successful prevention of core disruption in unprotected (i.e., without scram) over-power and under-cooling accidents is the provision in the design for inherent, passive mechanisms which respond to the upset condition and act to restore the balance between reactor power production and system cooling. In this context, core disruption is taken to be any failure or event which leads to an irreversible re-arrangement of the reactor. Near-term, short-time core disruption would be indicated by gross fuel melting leading to numerous pin failure, or by coolant boiling. In the longer term, core disruption could occur due to plastic yielding of an over-heated core support structure.

To assure a self-limiting response to accident conditions, specific features must be included in the system design. In the unprotected loss-of-flow and overpower accidents, the upset leads to an increase in the coolant temperature rise through the core. Negative reactivity feedbacks keyed to the coolant temperature increase can be effective in limiting accident consequences. Two such mechanisms can be provided by radial core expansion driven by subassembly duct and above-core load pad thermal expansion, and by differential thermal expansion of control rod drives and the core support structure to yield a net insertion of the control rods.

For load pad thermal expansion to be effective, it is necessary that the radial core restraint system be configured to provide contact at the load pad plane during normal operation. In addition, provision must be made to allow for thermal expansion during the transient. A low-tension core restraint system allows for duct expansion and load pad growth as the coolant temperature rises, providing a negative reactivity feedback. To enhance

differential control rod expansions, core outlet coolant flow may be ducted around rod drive-lines, and core-support members can be located in area that heat relatively slowly during an accident. This assures that the differential movement of control rods early in the transient acts to insert control material into the reactor.

Because of the time required for core outlet sodium to travel to the control rod drive elevation and for heat to be transferred from the heat sodium into the subassembly load pads, it may be necessary to provide for elongation of the natural primary pump flow coastdown to avoid power-to-flow mismatches resulting in near-term coolant boiling. Specific designs might employ flywheels geared to the pump shaft or battery-fed power supplies on the pump pony motor.

Radial core expansion and control rod drive elongation provide the overall negative reactivity feedback to lower the reactor power during an unprotected loss-of-flow event. As the accident proceeds other reactivity effects that must be considered are fuel Doppler feedback, coolant density feedback, and fuel thermal expansion. As the power decreases, the fuel temperatures will drop, yielding a prompt positive reactivity effect. The heat-up of the coolant causes a corresponding coolant density decrease, adding a positive reactivity mechanism. Finally, the chilling fuel will contract, and the fuel density increase will add positive reactivity.

In a transient over-power event, fuel over-heating will lead to a prompt negative Doppler feedback reactivity. As the fuel expands, the density decrease will also yield a negative reactivity feedback. With continued heating, the temperature fields in the fuel and cladding may develop so that some of the fuel in the interior of the pin reaches temperatures at which the strength of the fuel matrix is reduced in comparison to the surrounding fuel and the cold cladding. This is especially true for metallic fuel which loses strength and melts at temperatures lower than those for the stainless steel cladding. For oxide fuel, which becomes brittle with irradiations, the melting and strength-loss temperatures are much higher than those for the cladding, but the temperature gradient in the oxide pin is also much higher due to the low thermal conductivity. If unreleased fission gas bubbles trapped in the fuel matrix can pressurize during the overpower transient, low strength or molten fuel may be extruded (upwards, due to the axial temperature profile) within the cladding, producing a strongly negative reactivity feedback. Smith and co-workers (6) have concluded that the oxide fuel, significant prefailure internal pin fuel motion would occur in high ramp rate (3 \$/second and higher) overpower transients. For lower ramp rates, internal pin fuel motion was found to be inhibited by freezing and plugging of relocated fuel in the cold, above-core region. This would not be the case for metallic fuel, since the axial temperature profile peaks at the top of the core, and relocating fuel would encounter heat conditions. Therefore, prefailure internal pin fuel motion would be expected in metallic fuel pins even at lower overpower ramp rates.

ANALYSIS OF UNPROTECTED ACCIDENTS

In order to quantify the inherent safety margins available in metallic and oxide-fueled reactors, unprotected loss-of-flow and transient overpower accidents in two representative US reactor designs have been analyzed, with

consideration of the inherent reactivity mechanisms discussed above. One design was a 2740 MWt (1000 MWe) plant, and the second was a 900 MWt (365 MWe) plant. Both plants have pool-type primary system layout, and an oxide and a metallic-fueled core was designed for each plant size. A heterogeneous (i.e., with "internal blanket" breeder subassemblies arranged within the core proper) core layout and an average fuel linear power rating of 8 kW/ft for the oxide pins and 10 kW/ft for the metallic pins was assumed as a design constraint. Doppler coefficients and coolant void reactivity worths for the four cores are summarized in Table II. As the table shows, Doppler coefficient for the metallic cores are less than half those for the oxides cores, due to the harder neutron spectrum with metallic fuel. The spectral shift also increases the coolant void reactivity worth for the metallic cores.

Table II. Reactor Safety Performance Characteristics

	<u>Small Reactor</u>		<u>Large Reactor</u>	
	<u>Oxide</u>	<u>Metal</u>	<u>Oxide</u>	<u>Metal</u>
Doppler Coefficient, $T \frac{dk}{dt}$				
Driver Fuel	-0.0032	-0.0013	-0.0061	-0.0025
Breeder Fuel	-0.0037	0.0014	-0.0055	-0.0022
Coolant Void Reactivity, β				
Driver Fuel	2.4	3.9	2.6	3.9
Breeder Fuel	1.6	2.4	1.3	2.0

Results from a transient overpower ramp sensitivity study for the small reactor design are given in Table IV. In this study, the reactivity feedback mechanisms considered were Doppler, axial fuel expansion, coolant density reduction, control rod drive expansion, and radial core thermal expansion. For the oxide fuel, only axial fuel thermal expansion was included, but for the metallic fuel, internal pin fuel extrusion driven by trapped fission gas in closed porosity was also estimated. Calculations were terminated at the first indication of an irreversible upset condition. For the metallic cores, with a high fuel thermal conductivity, the indicated failure was coolant boiling initiation. For the axial cores, the terminal upset condition was pin failure in the highest power subassembly. The results in Table IV show that the oxide cores, Doppler feedback is the dominate negative reactivity mechanism. For the metallic core, axial thermal expansion and internal pin fuel thermal expansion and internal pin fuel extrusion combine to provide a tolerance for externally imposed reactivity which is generally greater than that offered by the oxide cores.

Table IV. Results for Ramp Sensivity Study

	<u>1 ¢/sec</u>		<u>10 ¢/sec</u>		<u>100 ¢/sec</u>	
	<u>Oxide</u>	<u>Metal</u>	<u>Oxide</u>	<u>Metal</u>	<u>Oxide</u>	<u>Metal</u>
Time @						
Termination, sec	233.2	361.6	22.6	38.0	2.7	4.6
Reactivities @						
Termination						
Programmed	2.33	3.62	2.26	3.80	2.75	4.60
Doppler	-1.20	-0.39	-1.20	-0.40	-1.37	-0.50
Axial Expansion ¹	-0.68	-2.36	-0.68	-2.72	-0.81	-3.49
Coolant	0.09	0.17	0.10	0.18	0.15	0.26
Control Rod	-0.24	-0.49	-0.06	-0.19	-0.01	-0.01
Radial Expansion	0.27	-0.53	-0.24	-0.51	-0.11	-0.39
Net	0.03	0.03	0.18	0.16	0.60	0.47
Power @						
Termination	2.2	3.3	2.6	3.4	7.6	5.1

Results from a study of an unprotected loss-of-flow accident in the large reactor design are shown in Fig. 1. The reactivity feedbacks considered in this analysis were the same as for the transient overpower study, except that no in-pin fuel extrusion was observed due to the fuel chilling in all cases. As the accident develops, the coolant temperature rises, causing radial core expansion and control rod drive elongation. The major positive reactivity feedback is provided by the Doppler effect in the cooling fuel. Because the temperature drop is much more severe in the low thermal conductivity oxide fuel, the metallic core experiences a much milder reactivity and temperature transient, as the power and coolant temperature histories in Fig 1. After 1000 seconds following loss of power to the primary pumps, the power level in the metallic core is approaching decay heat removal levels and the coolant temperature has risen less than 100°C. On the other hand, in the oxide core, the power remains significantly above decay heat removal capabilities, and the peak coolant temperature is approaching the boiling point.

¹Metal fuel results include in-pin fuel extrusion.

CONCLUSIONS

The results of this analysis demonstrate that inclusion of specific features in LMFBR designs can lead to successful attainment of inherent safety goals. The design features considered here depend only on basic passive mechanisms, such as thermal expansion. Metallic fuel designs have been shown to provide greater inherent safety margins than oxide fuel designs, due solely to their intrinsic thermal and neutron properties. The adoption of design features such as a pool-type primary system and metallic fuel offer the possibility of a more fault-tolerant overall design that provides large time margins for response to upset conditions, extending even to severe unprotected accidents normally considered to lead to core disruption.

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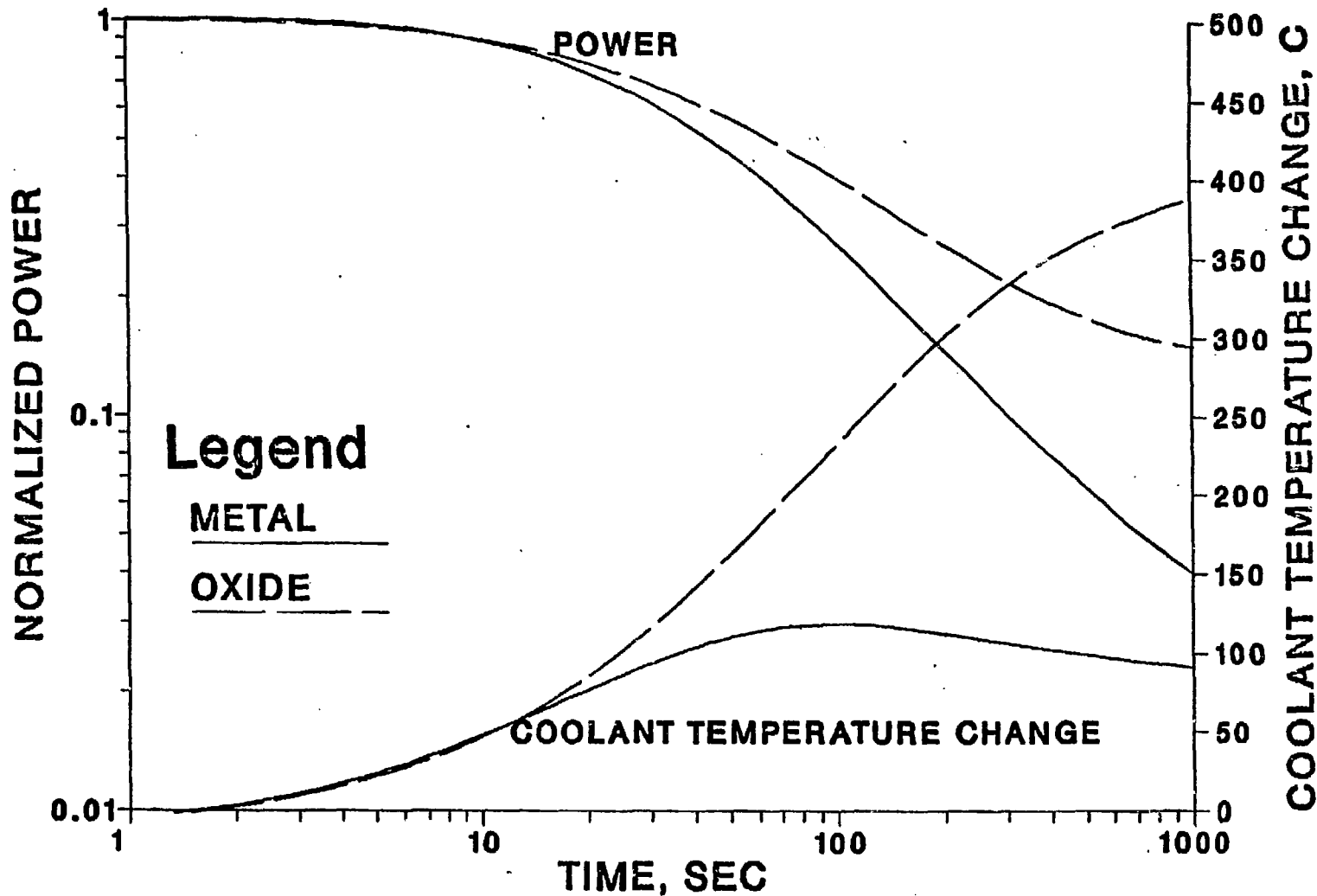


Fig. 1. Reactor Power and Coolant Temperature Histories for Unprotected Loss-of-Flow Accident