SAFETY CHARACTERISTICS OF THE INTEGRAL FAST REACTOR CONCEPT

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ABSTRACT

The Integral Fast Reactor (IFR) concept is an innovative approach to liquid metal reactor design which is being studied by Argonne National Laboratory. Two of the key features of the IFR design are a metal fuel core design, based on the fuel technology developed at EBR-II, and an integral fuel cycle with a colocated fuel cycle facility based on the compact and simplified process steps made possible by the use of metal fuel.

The paper presents the safety characteristics of the IFR concept which derive from the use of metal fuel. Liquid metal reactors, because of the low pressure coolant operating far below its boiling point, the natural circulation capability, and high system heat capacities possess a high degree of inherent safety. The use of metallic fuel allows the reactor designer to further enhance the system capability for passive accommodation of postulated accidents.

INTRODUCTION

The Integral Fast Reactor (IFR) is an innovative approach to develop an advanced Liquid Metal Reactor (LMR) concept that could promise improved inherent safety characteristics, low capital cost, and economic fuel cycle closure. The IFR is a generic reactor concept, not a specific design. A few technical features give it a set of characteristics that form this generic concept. These features are: (1) liquid sodium cooling, (2) pool-type reactor configuration, (3) metallic-fuel core design, and (4) an integral fuel cycle with a colocated fuel cycle facility, based on pyrometallurgical reprocessing and injection-cast fuel fabrication.

The safety characteristics of the IFR derive from these technical features. The use of a liquid metal coolant and a pool configuration provide inherent protection and long times for corrective action for many off-normal events. The use of liquid metal coolant provides a low pressure system that
is insensitive to postulated coolant boundary failures because coolant "flashing" cannot occur. All of the primary system sodium is contained within the reactor vessel, along with the core, the primary pumps, and the intermediate heat exchangers. If a heat sink is available the fuel can be cooled by natural circulation. In addition, the large heat capacity of the pool provides long time margins for corrective action in the event of loss-of-heat sink. The use of metallic fuel allows the designer to further improve the already excellent safety characteristics of LMR's.

Metallic fuel provides this enhanced safety because of two characteristics. First, the high thermal conductivity of metal fuel allows avoidance of sodium boiling and thus core disruption for extremely unlikely events such as loss-of-flow without scram. In accidents of this type, avoidance of sodium boiling requires reactivity feedbacks which cause power to decline on a time scale similar to decaying flow. This declining power causes the fuel rod radial temperature gradient to collapse and generates a positive fuel feedback component from Doppler and axial expansion. The high thermal conductivity of metal fuel minimizes this positive component and allows large margins to boiling. These margins are so large that the reactor can tolerate combined effects such as a seismically-induced reactivity insertion and loss-of-flow coupled with failure to scram. Secondly, the sodium bond or fission gas entrapped within the alloy matrix enhances the already large margins of metal fuel to core disruption in overpower accidents. The sodium bond or fission gas is expected to provide a self-dispersive mechanism within the cladding which would terminate transient overpower events. Preliminary tests have been conducted in the TREAT reactor to substantiate this mechanism.

**Inherent Safety**

Designing LMRs with an objective of providing inherent safety is receiving increasing emphasis in the US program. The objective is to provide intrinsic, passive features in the design that will limit the consequences of accident initiators and/or provide long time margins for corrective action. One of the goals of inherent safety in reactor designs is to provide a design which can tolerate any component failure or Anticipated Transient Without Scram (ATWS) event without the action of any active system.
In studies of IFR inherent safety, two specific initiators, the loss-of-flow without scram and the transient overpower without scram coupled with station blackout have been used as developing transients to investigate the fault tolerance of the IFR concept. The response of the system under these conditions is discussed below.

Response to Transient Undercooling Accidents

Prevention of core damage in undercooling accidents in LMRs can be provided by passive means if specific features are included in the design. The goal in the IFR is to provide a reactor response that will adjust the reactor power to the available heat rejection capability and to limit the coolant temperature increase if reactor flow is reduced.

In transient undercooling accidents, the flow reduction leads to an increase in the coolant temperature rise through the core. Negative reactivity feedbacks caused by this temperature increase can be effective in limiting core temperature rises under these conditions. The two main negative feedbacks under these conditions are provided by thermal expansion of the control rod drives and the core support structure to yield a net insertion of the control rods, and by radial core expansion. For these negative feedbacks to be effective the reactor core must be configured to allow them to act. Radial core expansion may be brought about through 1) heating and expansion of the above-core load pads, or 2) differential heating of the hex-can flats and subassembly bowing. Each of these effects can be brought about by the appropriate design choice of the configuration of the core restraint system. Because of close thermal communication between the coolant and the hex-can walls and load pads, radial core expansion feedback is characterized with a relatively short time constant, on the same order as the coolant heat-up.

On a longer time scale, control rod drive heating by core outlet coolant flow can lead to control rod insertion and negative reactivity feedback. This mechanism has a relatively long time constant, due to the time required to transport core outlet coolant to the drive lines, and the time required to transfer heat from the coolant to the drive lines. To enhance differential control rod expansion, core outlet flow may be ducted around rod drive lines. In order for this mechanism to be effective, it may be necessary to provide for a pump coast-down, or coolant flow decay time, that maintains a
relatively high flow for a period of time sufficient to transfer heat generated in the core to the control rod drive lines.

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 heatup 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.

The use of metallic fuel in the IFR concept gives superior performance in the ability to design a reactor system to tolerate unprotected transient undercooling accidents. The IFR metallic fuel is a fuel developed as a result of experience with metallic fuels in EBR-II (1). The reference IFR fuel is a uranium-plutonium-zirconium alloy. This U-Pu-Zr alloy is chemically compatible with sodium and is submerged in liquid sodium inside the cladding to thermally bond it to the cladding.

The bond-gap sodium, together with the fuel's 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 higher thermal conductance provided by the bond-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.

The high thermal conductivity is the key characteristic of metal fuel which gives inherent protection in loss-of-flow accidents. As the reactivity feedbacks discussed above cause the power to decline, the radial temperature gradient in the fuel collapses and causes a positive feedback component from Doppler and fuel axial expansion. The high thermal conductivity of metal fuels minimize this positive component and allows large margins to core damage. Typical results showing the expected temperature transients for oxide
and metal fuel are shown in Fig. 1. As can be seen, after about 1000 sec following loss of power to the primary pumps, the power in the metallic core is approaching decay heat removal levels and the coolant temperature has risen less than 100°C. Because of these large margins, the metallic core can tolerate combined effects such as a seismically-induced reactivity insertion and loss-of-flow with failure to scram.

Response to Transient Overpower Accidents

Core designs based on the IFR concept have a high tolerance for inadvertent reactivity insertions for the following reasons:

(1) Large margins to fuel pin failure exist under normal operating conditions. The relative power to failure is about 4 to 1 compared to about 2.5 to 1 for an oxide fuel pin.

(2) Because of the higher internal breeding gain with metallic fuels, control rod worths can be reduced, thus limiting the effects of reactivity insertions due to uncontrolled rod withdrawals.

(3) If large reactivity insertions occur in a metal fuel core, in-pin fuel motion driven by sodium vapor and/or fission gas will act to shut the reactor down.

The larger margins to fuel pin failure in metal fuel exist because of the following mechanisms leading to pin failure in metal fuel, which are distinctly different from those of oxide:

(1) Expansion upon melting is negligible.

(2) Metal fuel is sufficiently compliant compared to the steel cladding that fission-gas-induced transient pressures are accommodated by deformation of the fuel matrix itself and do not lead to significant localized clad loading as happens in the case of oxide.

(3) The principal transient clad loading therefore comes from increasing fission gas plenum pressure as that gas is heated by overheating coolant passing over the plenum. This, together with the declining strength of the cladding as it heats, plus some eutectic thinning, eventually leads to a simple tube burst type of failure.
Fig. 1. Representative results showing coolant temperature histories for the unprotected loss-of-flow accident.
Calculations based on these concepts show that for typical reactor design conditions the relative power to failure in an end-of-life fuel pin is about 4 to 1. These calculations are in good agreement with TREAT test results discussed below.

Because of the high thermal conductivity of metallic fuel, fuel melting in overpower transients will have a central molten fuel column which rapidly develops all the way to the outlet end of the fuel. At that point entrapped sodium and/or fission gas can act to disperse the fuel within the cladding. The subsequent negative feedback will act to shut the reactor down. Tests to confirm this behavior have been conducted in TREAT and verify this behavior under overpower conditions.

TREAT Tests

A series of tests is being conducted in TREAT to obtain information on metal alloy fast reactor fuel behavior. Two general characteristics of metal fuel of importance being studied in these tests are (a) pre-failure in-pin axial extrusion (elongation of fuel due to the forces of fission gas and liquid sodium entrapped within the solid fuel matrix), and (b) the characteristics of cladding penetration by fuel-steel eutectic formation assisted by internal pin pressure under unprotected transient overpower conditions. The tests have been designed to observe and quantify the extrusion behavior due to fission gas retained in the fuel and the eutectic penetration behavior in order to confirm the existence of these mechanisms and to provide guidance for modeling these mechanisms in fuel behavior models and accident codes that have been developed for other fuel types.

A series of tests is underway in loops with flowing sodium. Two tests have been performed, each with three uranium -5 w/o fission EBR-II Mark-II fuel elements. That fuel is a suitable and available stand-in for the ternary U-Pu-Zr fuel. Each pin was in an orificed flow tube. Three different burnup levels have been tested: near-fresh (sodium fuel-cladding bond remaining, low plenum pressure), medium (fuel swelled to cladding, fuel interconnected porosity fully developed), and high (like medium burnup but high plenum pressure). The ternary U-Pu-Zr alloy will be used in subsequent tests, each of which will test only two fuel pins since the prototypic pins are of larger diameter than the EBR-II Mark-II driver pins.
Fuel thermal-hydraulic conditions representative of a transient-overpower event are generated in these tests. The power transient first preheats the fuel to nominal operating conditions and then increases the fuel power on as slow a period as practicable within limits set by TREAT capability and the requirement to cause cladding breach. Test-fuel temperature is increased to above the point at which the fuel strength is very low and axial self-extrusion of solid fuel might occur. Further temperature increase and duration-at-temperature is programmed to provide additional opportunity for potential in-pin dispersion and substantial eutectic penetration into the cladding wall.

It is the intent to obtain information on axial fuel expansion and cladding eutectic penetration both in pins carried to incipient cladding breach and in pins carried slightly beyond breach. Test termination at incipient breach provides in-pin fuel-motion evidence to a point somewhat short of breach and also provides samples for posttest examination of in-pin fuel extrusion and partial cladding penetration from this accident simulation. Test termination just after breach allows the entire extent of pre-failure fuel extrusion to be observed, indicates the margin to cladding breach under these heating conditions, and shows the nature of the initial post-failure fuel motion resulting from this type of accident.

Preliminary evaluations of the two tests which have been conducted have been carried out. The test results support the postulated behavior of metallic fuel during transient overpower conditions. The following are some of the key observations from the tests:

a) Pin failures occurred at about four times nominal power (nominal power ≈ 12 kW/ft peak) and are consistent with pretest predictions based upon a simple tube burst failure model with failure caused by increasing plenum pressure and decreasing clad strength due to increased temperature and some eutectic-induced clad wall thinning. By comparison, calculations based upon the commonly accepted 50% fuel melt fraction failure criterion for UO₂ indicate pin failures at about 2.5 times nominal power for that fuel.

b) Prefailure, in-pin fuel extrusion exceeding 10% occurred in the low- and medium-burnup pins. (the high burnup pin failed before extru-
sion). Similar behavior in the IFR would imply several dollars of reactivity insertion within a few tenths of a second. Whereas the time "window" to failure was only ~1 second, the neutronic (prompt jump) response would be an immediate reduction to or below normal power, and the thermal response of the metal fuel would be very rapid - coolant transit time 0.1 s; fuel pin time constant 0.3 s. Prefailure extrusion therefore may preclude or substantially reduce fuel pin failures.

c) Subsequent to pin failure, the cladding tubes appear to have become largely disgorged of fuel which, upon entering the flow channel, was transported several inches downstream. This fuel relocation was monotonically dispersive.

d) The 15-mil-thick flow tubes, located immediately adjacent to the pins, were not penetrated. This would imply a minimal attack upon pins adjacent to any failed pin in a reactor.

CONCLUSIONS

Studies of the response of reactors based on the IFR concept have shown this system can attain the inherent safety goals desirable for advanced LMR designs. The combination of a pool-type primary system and metallic fuel offer the possibility of a 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.

REFERENCES

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