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INTEGRAL FAST REACTOR CONCEPT INHERENT SAFETY FEATURES*

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ABSTRACT

The Integral Fast Reactor (IFR) is an innovative liquid-metal-cooled reactor concept being developed at Argonne National Laboratory. The two major goals of the IFR development effort are improved economics and enhanced safety. The design features that together fulfill these goals are: 1) a liquid metal (sodium) coolant, 2) a pool-type reactor primary system configuration, 3) an advanced ternary alloy metallic fuel, and 4) an integral fuel cycle.

This paper reviews the design features that contribute to the safety margins inherent to the IFR concept. Special emphasis is placed on the ability of the IFR design to accommodate anticipated transients without scram (ATWS).

INTRODUCTION

The goals of the fast reactor program sponsored by the U.S. Department of Energy are focused on development of a Liquid Metal Reactor (LMR) system in which investment costs are minimized and safety margins are maximized (1). The emphasis on economics and safety is in response to the realization that commercial acceptance of the LMR reactor concept depends on its adaptability to near-term marketing and licensing requirements. The twin goals of improved economics and enhanced safety are being accomplished in large part by the adoption of a safety philosophy which emphasizes utilization of natural, or inherent thermal, mechanical, hydraulic, and neutronic responses to normal and off-normal operating conditions. This philosophy, and the design choices which implement it, provides enhanced safety margins and permits reduction of the number and complexity of engineered, safety-grade systems and structures, leading to a corresponding reduction in plant investment costs.

The generic LMR design is particularly amenable to the inherent safety philosophy, due to its superior performance characteristics. The LMR's coolant, molten sodium, operates at near-atmospheric pressures, with a margin to boiling greater than 400 K (700°F), eliminating the need for thick-walled pressure vessels. Liquid sodium exhibits high thermal conductivity and specific heat capacity, and enables an LMR to operate at decay heat levels under natural circulation, without the need for forced flow. The high breeding gain possible in an LMR reduces the burnup cycle reactivity swing, and the required external control reactivity. Thus, the reactivity available for accidental addition is limited. In over-power conditions, the prompt negative Doppler reactivity feedback limits the power rise. All of these inherent mechanisms contribute to the superior safety performance of an LMR.

While the concept of inherent safety is not new, recent developments in the LMR program have highlighted the inherent safety performance potential of advanced LMRs. In particular, the Integral Fast Reactor (IFR) program at Argonne National Laboratory (2) has pointed out the superior inherent safety and economic potential of pool-type LMRs with advanced metallic fuel designs. In the pool-type LMR design, all primary system components (including the core, pumps, and intermediate heat exchangers) are submerged in liquid sodium in a single reactor vessel, with no pipes connecting components other than the pump outlet to the core inlet. This assures that, in the unlikely event of a severe accident, the core will remain submerged in liquid sodium, and natural circulation flow paths will be maintained. Furthermore, the large heat capacity of the pool provides long times for corrective operator action in the event of decay heat removal system failure. In an LMR, metallic fuel provides enhanced safety performance due to its high thermal conductivity. At normal operating conditions, the high conductivity of metallic fuel results in a relatively shallow radial temperature gradient in the fuel pin. In any accident situation, this minimal temperature gradient yields a reduced positive Doppler reactivity feedback to be compensated during the power reduction to decay heat levels. In protected transients, external control requirements are reduced, and in unprotected transients, system temperature rises are reduced.

INHERENT SAFETY PERFORMANCE CHARACTERISTICS

The consequences of unprotected (i.e. without scram) accidents have traditionally played a very significant role in the evaluation of safety performance and the determination of containment requirements for licensability of LMRs. This comes about due to the potential in an LMR for reactivity transients following core disruption, resulting in energy releases which could challenge containment integrity and present some measure of risk to the public health. Concern over the potential consequences of unprotected accidents has led LMR designers to develop comprehensive, redundant, engineered safety systems, with the reliability of these systems assured by design to reduce the likelihood of any unprotected accident to an acceptably low level. However, because every engineered system has some residual failure probability, there has been a continuing, open-ended dialog between LMR safety analysts and regulators concerning unprotected accidents.

The essence of the inherent safety idea is to provide for intrinsic LMR performance characteristics which maintain the balance between reactor cooling capability and power production and prevent core disruption, especially in instances when engineered safety systems have failed. These response characteristics must therefore be based on the inherent thermal, mechanical, hydraulic, and neutronic reactor system properties, which can be determined by the choice and arrangement of reactor materials. In the full spectrum of unprotected accidents, three specific initiators have emerged to serve as quantifiers of safety margins. They are: 1) the loss-of-flow (LOF) accident, in which power to the coolant pumps is lost, 2) the transient overpower (TOP) accident, in which a single, inserted control rod is withdrawn, and 3) the loss-of-heat-sink (LOHS) accident, in which feedwater supply to the steam generators is lost. For all three initiators, it is also assumed that the plant safety system fails to insert the shutdown control rods. These events are generally classed as anticipated transients without scram (ATWS). The key to successful prevention of core disruption under these conditions is the provision in the design for reactor performance characteristics which 1) limit mechanisms leading to reactor damage, and 2) promote mechanisms responding to the upset condition and acting to restore the reactor power production/cooling balance. An example of the first is the minimization of individual control rod worths, to limit the inserted reactivity in the TOP accident. For economy, it is desirable to limit the number of control rods, so the objective is to reduce the total burnup reactivity swing, without introducing burnable poisons which degrade fuel cycle economics. This is achieved in an LMR by maximizing the breeding potential and conversion of fertile uranium into fissile plutonium.

An example of the second, a mitigating mechanism in ATWS accidents, is core radial expansion. As the outlet coolant temperature rises during an ATWS transient, heat is transferred to the above-core load pads, which expand and increase the mean core diameter. The negative reactivity effect associated with load pad heating (or with core support grid expansion for cases with inlet coolant heating) acts to reduce the reactor power level and restore equilibrium between the power and the heat rejection rate, at an elevated system temperature. Another mechanism which can act to restore equilibrium is differential thermal expansion of control rod drives and the core support structure to yield a net insertion of the control rods.

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. In the final, equilibrium state, the positive and negative reactivity feedbacks combine for a net zero reactivity, with the final steady state at reduced power with the coolant flowing under natural circulation at an elevated temperature.

In a transient overpower event, rod withdrawal introduces positive reactivity, which leads to fuel heating and prompt negative Doppler feedback. As the fuel expands, the density decrease also yields negative reactivity. Coolant heating leads to load pad and control rod driveline expansion (negative feedback) and coolant density reduction (positive feedback). In the transient, the power rises and then falls, and finally the system equilibrates to the available heat sink at an elevated temperature.

In the loss of heat sink accident, the temperature of the core inlet coolant rises, heating the core support structure and spreading the core radially, reducing the reactivity and the core power level. With the coolant pumps continuing to run, the system equilibrates at a reduced power level to any available residual heat sink.

In all three of these ATWS accidents, the key to avoidance of short-term core disruption is to maintain the coolant outlet temperature below its boiling point. At normal operating conditions, the core inlet temperature is around 600 K (620°F), and the average coolant temperature rise through the core is around 150 K (270°F). To avoid coolant boiling, the transient, normalized power-to-flow ratio must be kept below about 4 in order to keep core-average coolant temperatures below the boiling point of sodium at around 1200 K (1700°F). In the long term, the overall negative feedback will tend to bring the reactor power into equilibrium with the available heat rejection rate, and the system will approach an asymptotic temperature distribution. To avoid core disruption in the long term, it is necessary that the peak asymptotic temperatures in strategic components (reactor vessel, core support structure, fuel cladding) be maintained below levels at which creep could cause failures. Avoidance of both short- and long-term core disruption in ATWS events depends on 1) providing sufficient negative reactivity feedback to overcome the power-to-cooling mismatch and return the system to equilibrium at slightly elevated system temperatures, or alternately 2), reducing the positive reactivity feedback components acting to resist the transition to system equilibrium. In this second respect, metallic fuel provides superior inherent safety performance in ATWS events, due to its thermal and neutronic properties.

METALLIC FUEL PROPERTIES

Early LMR designs employed metallic fuel designs because a) metallic fuel is chemically compatible with sodium, b) metallic fuel offers superior thermal and neutronic performance, and c) metallic fuels were well known and understood at the time (3). When requirements for higher burnups and coolant outlet temperatures were applied, emphasis on metallic fuel decreased, and ceramic fuels, particularly (U, Pu) O_2, became favored. In more recent times, LMR system designs have featured reduced coolant temperatures, and metallic fuel designs have been developed which are capable of reliable performance at high burnups. Combined with the inherent safety advantages of metallic fuel, these factors have prompted a renewed interest in metallic-fueled reactor designs, and have served as the technical basis for the development of the Integral Fast Reactor concept at ANL (2).

The IFR metallic fuel design is an advanced concept developed as a result of experience with metallic fuels in EBR-II and other reactors (3). 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. As the data in Table I show, metallic fuel is denser than oxide, with a thermal conductivity higher by an order of magnitude, and a lower specific heat. The thermal expansion coefficient of metallic fuel is higher than that of 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 inside the cladding. The bond-gap sodium, together with the high thermal conductivity, give the metallic fuel pin an order-of-magnitude faster thermal response compared to the lower conductivity, gas-bonded oxide fuel.

Table I. LMR Fuel Properties

	Oxide	Metal
Nominal Composition	UO_2 - 20% PuO_2	U - 15% PU - 10% Zr
Density, kg/m^3	11000	15800
Thermal Conductivity, W/m-K	2.3	22
Specific Heat, J/kg-K	340	190
Thermal Expansion Coefficient, K^{-1}	1.1×10^{-5}	2.0×10^{-5}
Melting Point, K	3020	1380
Fuel Pin Thermal Time Constant, sec.	~3	~0.3

The high 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 energy at normal operating conditions is reduced correspondingly.

The high thermal conductivity is the key characteristic of metallic 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 minimizes this positive component and provides large margins to core damage limits.

In addition to its favorable thermal properties, metallic fuel exhibits superior neutronic properties that give enhanced safety margins. Because the average energy of the neutron distribution in a metallic-fueled reactor is higher than in oxide-fueled reactors, higher internal breeding of fissile material is achieved with metallic fuel. This reduces the excess reactivity and control rod worth requirements to compensate for burnup effects, which in turn limits the amount of reactivity available for insertion in control rod runout (TOP) accidents. Reduction of the amount of reactivity insertion in the TOP accident yields a corresponding reduction in the degree of thermal upset in the reactor and accident consequences.

ATWS ANALYSIS RESULTS

Detailed analysis of unprotected loss-of-flow (LOF), transient overpower (TOP), and loss-of-heat sink (LOHS) accidents in reactor designs that incorporates the IFR concept features have been carried out with the SASSYS systems analysis computer code (4). The results presented here are a summarized version of typical results obtained from the detailed SASSYS analyses.

Results from an unprotected LOF accident are presented in Fig. 1, which shows the core inlet and outlet temperature histories, and the core average fuel, cladding, and coolant temperatures. As the pump coastdown proceeds and the flow decays to natural circulation, system temperatures slowly rise. This lowers the net reactivity by negative reactivity feedback and reduces reactor power. Eventually, the reactor power is at decay heat levels, and the temperature drop from the fuel through the cladding to the coolant collapses. For the next few hours, the decay heat continues to drop, until it falls below the capacity of the decay heat removal system. Following this, the system temperatures decrease as the reactor self-adjusts to the decay heat removal capability. The final state of this accident is one in which the reactor is at hot shutdown conditions, with system temperatures slightly elevated above normal operating temperatures.

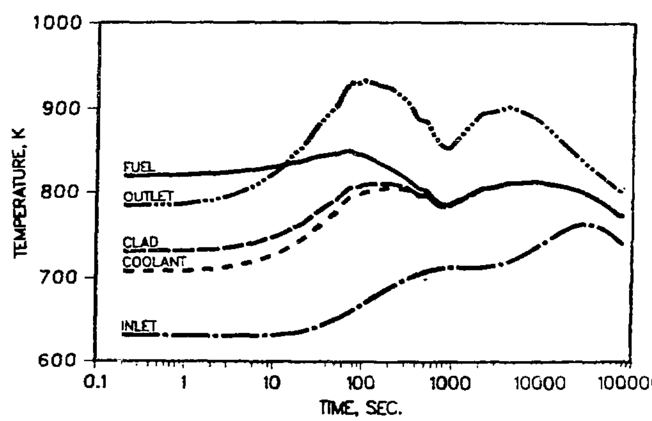

FIG. 1 IFR RESPONSE IN UNPROTECTED LOSS-OF-FLOW ACCIDENT

Figure 2 depicts core average temperatures during an unprotected control rod runout in an IFR design. The reactor power initially rises in response to the rod withdrawal, increasing core and outlet coolant temperatures. The system temperature increase brings about negative reactivity feedback, reducing the reactor power. Eventually, the energy production rate equilibrates with the available heat rejection rate, and the system temperatures stabilize at levels slightly above normal operating temperatures.

Average temperature behavior during an unprotected loss-of-heat sink accident are shown in Fig. 3. As heat removal through the steam generator is lost, the core inlet temperatures rises. This increases core temperatures, introducing negative reactivity feedback

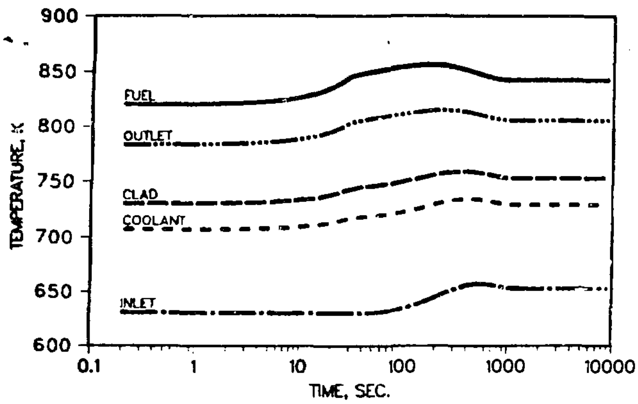

FIG. 2 IFR RESPONSE IN UNPROTECTED TRANSIENT OVERPOWER ACCIDENT

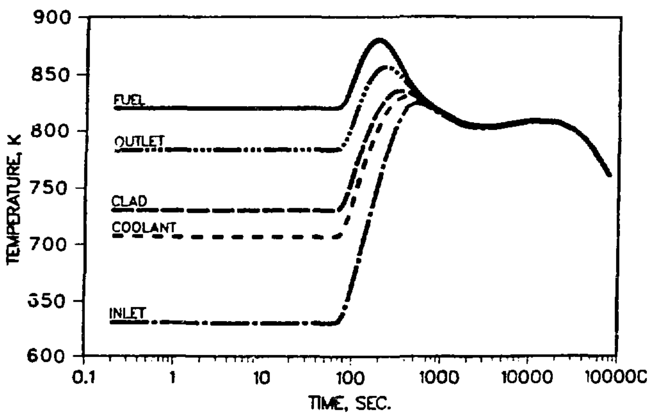

FIG. 3 IFR RESPONSE IN UNPROTECTED LOSS-OF-HEAT SINK ACCIDENT

which reduces the reactor power to decay heat levels. Core temperature differences collapse as the reactor power declines. Eventually, the decay heat production falls below the decay heat removal system capacity, chilling the system. The final state of this accident leaves the reactor at hot shutdown conditions, with the system at a slightly elevated temperature in equilibrium with the capacity of the decay heat removal system.

In all three of the unprotected transients analyzed here, the inherent thermal, neutronic, and hydraulic properties of the IFR concept provide negative reactivity feedback to limit accident consequences. Detailed analyses from which these summary results were taken indicate that the IFR design features offer superior passive safety performance, and the potential for improved safety margins and system economy through reduction of the complexity and number of engineered safety systems.

IFR SAFETY EXPERIMENTS

The IFR safety program at ANL includes in-pile and out-of-pile experimental tests to confirm the inherent safety performance characteristics of the IFR and in particular its metallic fuel.

The system performance characteristics of IFR during anticipated transients without scram have been verified in a series of full-scale tests in the EBR-II plant (5). Both loss-of-flow and loss-of-heat sink accidents in IFR were simulated. The results of the tests clearly demonstrated the inherent safety margins available in IFR.

The first five tests in a series of metallic fuel behavior experiments in the ANL TREAT reactor (6) have demonstrated the high failure threshold of metallic fuel in general and the IFR candidate alloy in particular. In addition, the TREAT tests have also demonstrated the potential for fission-gas-driven in-pin fuel expansion prior to cladding failure. This mechanism provides a self-limiting, negative reactivity feedback mechanism in accidents with more severe initiators than those considered here, and promises to be an effective means for eliminating concerns over energetics and public protection in core disruption accidents.

CONCLUSION

Analyses of reactor designs based on the IFR concept have demonstrated the feasibility of attaining inherent safety goals in advanced LMR designs. The combination of a liquid metal coolant with a pool-type primary system and metallic fuel yields a fault-tolerant design that responds passively to upset conditions, providing large margins to coolant boiling, fuel melting, and system failures. In many unprotected accidents normally considered to lead to immediate core disruption, the need for operator action may be eliminated, or delayed for long time periods before system limits are approached.

The analyses demonstrating the IFR system performance potential are being verified by full-scale experimental tests in EBR-II. The behavior of metallic fuel in accident conditions is being demonstrated in TREAT.

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