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Integral Fast Reactor Safety Features*

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J. E. Cahalan, J. M. Kramer, J. F. Marchaterre, C. J. Mueller,
D. R. Pedersen, R. H. Sevy, D. C. Wade and T. Y. C. Wei

Argonne National Laboratory
Reactor Analysis & Safety Division
9700 S. Cass Avenue
Argonne, IL 60439

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Abstract

The Integral Fast Reactor (IFR) is an advanced 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. In addition to liquid metal cooling, the principal design features that distinguish the IFR are: 1) a pool-type primary system, 2) an advanced ternary alloy metallic fuel, and 3) an integral fuel cycle with on-site fuel reprocessing and fabrication.

This paper focuses on the technical aspects of the improved safety margins available in the IFR concept. This increased level of safety is made possible by 1) the liquid metal (sodium) coolant and pool-type primary system layout, which together facilitate passive decay heat removal, and 2) a sodium-bonded metallic fuel pin design with thermal and neutronic properties that provide passive core responses which control and mitigate the consequences of reactor accidents.

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Introduction

The Integral Fast Reactor (IFR) is an advanced liquid-metal-cooled reactor (LMR) concept being developed at Argonne National Laboratory in a program sponsored by the U.S. Department of Energy. The two major goals of the IFR development effort are improved economics and enhanced safety. The enhanced safety goal has focused on designing for reliance on inherent processes to provide neutronic shutdown and reactor cooling in response to accident initiators. While they are not considered to be part of the reactor design basis, the consequences of unprotected (i.e. without scram) accidents have traditionally played a significant role in the evaluation of safety performance and the determination of containment requirements for licensability of liquid metal-cooled reactors.

Concern over the potential consequences of unprotected accidents has traditionally 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, a continuing dialog between LMR safety analysts and regulators concerning unprotected accidents and their accommodation in design has accompanied every LMR commissioning.

The IFR development has focused on self-regulating designs that prevent core disruption as a means to reduce reliance on engineered safety features. The essence of the passive safety idea is to provide for intrinsic LMR performance characteristics that maintain the balance between reactor cooling capability and power production and prevent core disruption in instances when engineered safety systems have failed. These response characteristics are achieved by use of inherent mechanical, hydraulic, and neutronic reactor system properties, which are determined by the choice and arrangement of reactor materials.

The principal safety-related features of the IFR design are 1) liquid metal cooling, 2) a pool-type primary system, and 3) an advanced ternary alloy metallic fuel design.

In the IFR concept, the liquid sodium coolant operates at atmospheric pressure, and maintains a design point margin to boiling greater than 400 K (700°F). This eliminates the need for a pressurized primary system and thick-walled pressure vessels. With its high thermal conductivity and specific heat capacity, liquid metal cooling enables the IFR to operate at decay heat levels in natural circulation, without the need for forced flow. At nominal operating conditions, liquid metal cooling permits a compact core configuration that complements the neutronic advantages provided by a fast neutron energy spectrum.

The primary system in the IFR concept is arranged with the core, the intermediate heat exchangers, and the primary pumps all submerged in a large pool of liquid sodium. Thus, all radioactive materials, and the coolant that travels through the core, are confined within the large, steel-walled reactor vessel. A back-up guard vessel guarantees that all major components will remain submerged even in the event of a reactor vessel leak. This pool-type arrangement, in which the only major high pressure pipes are submerged within the pool and run between the pump outlet and the core inlet, reduces the likelihood and consequences of a pipe rupture accident. In the event of such an accident, no coolant spills are possible, and core cooling is maintained. With the whole primary system submerged, natural circulation paths are assured for all normal as well as abnormal operating conditions. In addition, the large heat capacity of the sodium pool provides long grace periods for response to cooling system faults.

However, the most significant safety aspects of the Integral Fast Reactor result from its unique fuel design, a ternary alloy of uranium, plutonium, and zirconium. This fuel design was developed at Argonne based on experience gained through more than 20 years operation of the EBR-II reactor with a uranium alloy metallic fuel. In the IFR concept, the ternary fuel is injection cast as cylindrical slugs and placed inside the cladding. Liquid sodium bond in the fuel-cladding gap provides an efficient heat transfer medium that, along with the high fuel thermal conductivity, maintains low fuel operating temperatures. The fuel-cladding gap is sized for a low smear density (typically 75%) to accommodate irradiation-induced fuel swelling so as to permit high burn-up.

The superior thermal and neutronic performance of the IFR fuel design complements the safety advantages available with liquid metal cooling and the pool-type primary system. Together, these features combine to enhance safety margins in both normal operating modes and accident situations. In particular, the IFR is designed to maximize the measures of safety associated with inherent reactor response to unprotected, double fault accidents, and to minimize risk to the public and plant investment.

IFR Fuel Thermal Performance

Many of the superior safety performance characteristics of the IFR ternary alloy fuel design can be traced to its thermal and mechanical properties, with the most important of these being its high thermal conductivity. At operating temperatures, typical fresh IFR fuel has a thermal conductivity of around 20 W/m-K. This yields a very low radial temperature rise across the fuel at operating conditions (less than 200 K), and a comparatively low stored heat. (As the fuel is irradiated, it swells into contact with the cladding, displacing the initial gap bond sodium and establishing even better fuel-cladding thermal contact).

The low temperature gradient across the fuel gives a correspondingly small zero power-to-full power Doppler reactivity swing, resulting in reduced control reactivity requirements and less external reactivity available for accidental insertion. The low operating temperature also yields a smaller positive Doppler reactivity feedback in transients input where power is recuced. For unprotected transients such as loss-of-heat-sink (LOHS) and loss-of-flow (LOF), this permits other naturally occurring negative reactivity feedbacks, such as axial and radial core thermal expansion, to overcome the positive Doppler component, resulting in self-adjustment of the reactor core power to equal available decay heat removal capacity.

The low stored heat in the metallic fuel leads to reduced system heating in multiple-fault accidents, allowing increased time for operator action to correct flow or cooling deficiencies.

The melting point of the IFR fuel is relatively low (around 1400 K) compared to ceramic fuels. Additionally, uranium forms a eutectic with iron in the cladding, with the formation speed reaching a maximum near the fuel melting point.

IFR Fuel Neutronic Performance

The metallic fuel form also offers favorable neutronics properties. Specifically, the absence of low mass moderating atoms in the fuel leads to a hard neutron spectrum, increasing the neutron production per neutron absorbed in the pin. This occurs both because of the higher η value for Pu^{239} with the harder neutron spectrum and because of the enhanced fast fission in U^{238}. The combined effect increases the number of neutrons available for breeding and parasitic losses ($\eta_{eff}-1$) from about 1.65 for oxide systems to about 1.95. Moreover, the effective heavy metal density is increased by use of the metallic fuel relative to the traditional oxide fuel form. For example, in an internal blanket assembly with 50% fuel volume fraction, U/10% Zr metallic pins at 85% smear density provide 35% more U^{238} atoms than do UO_2 97.7% TD pellets at 93% smear density. Both of these characteristics can be used to increase core internal conversion ratio -- to a point where zero burnup control swing is achievable in a four or five batch core with 12 to 20 month refueling.

The harder neutron spectrum attendant the metallic fuel form has two important effects on reactivity feedback coefficients. The negative Doppler reactivity coefficient, $T \frac{dk}{dT}$, is reduced by about a third relative to oxide systems. The positive sodium density coefficient becomes more positive by about 1/3. The net effect of the lower temperature rise across the pin radius and the shifts in reactivity coefficient is to make the component of the power coefficient which is vested in the coolant temperature rise larger than that which is vested in the fuel temperature rise. This partioning of the power coefficient components (which is opposite to that of oxide fuel) is the key to the favorable passive reactivity shutdown response attainable in the IFR.

Design Basis Transients

In the context of the USNRC Standard Review Plan (SRP) [1] the anticipated operational occurrence class of events corresponds to the ANSI

18.2 standard condition II (incidents of moderate frequency) and condition III (infrequent incidents) transients. These design basis accidents, including some condition IV limiting faults transients, have been evaluated for the IFR concept from the perspective of the generalized design criteria and 10CFR100. Those SRP events relevant to the LMR appear to lead to consequences well within conservatively interpreted acceptance guidelines when "traditional" values for the plant protection system (PPS) setpoints are used. The improved passive safety capability of the pool configuration and the improved reactivity feedback response of the metal fuel lead to the availability of large design margins. In pool systems, the large primary system heat capacity buffers the primary system so that no reactor scram is required for any combination of balance-of-plant BOP faults. In metal-fuelled reactors, very little reactivity variation need be involved in changing power level (~0.1$ for a 50% power change with metal, compared to ~1$ with oxide). These basic characteristics and the availability of large margins are being used to develop simplifications in the PPS/PCS (plant control system) configuration and a new optimum control strategy for the IFR that could lead to reductions in event frequencies and scram demands.

Important reductions can be achieved in the number of PPS safety channels by taking advantage of the inherent response to the loss of heat sink (LOHS) for modular sized designs. Upsets in the balance of plant essentially need no waterside PPS signals due to the decoupling between the primary system and the BOP with the mild LOHS inherency response. Significant reductions in the number of safety channels appear to be achievable. With the availability of large margins, a decrease in scram frequency may be possible through the use of a controlled runback by the plant control system. Current work is focused on exploiting the alternative of raising setpoints from "traditional" settings, thus reducing the number of spurious scrams and thereby further lowering the scram frequencies. Modifications to the control strategy for certain modular sized designs through the use of inherent operability, the scheme proposed by Sackett et al. [2], appears to be feasible. For a modest increase in operating temperatures reactor power control can be affected through the usage of primary pumps and balance of plant swings rather than through the active movement of control rods. Work is currently being performed to examine further ramifications of this control strategy which would reduce the time at risk for transient overpower events.

Anticipated Transients Without Scram

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 one or more inserted control rods are 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 protection 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 the control rod worth, to limit the inserted reactivity in the TOP accident. This is achieved in the IFR by maximizing the breeding potential and conversion of fertile uranium into fissile plutonium. This reduces the total burnup reactivity swing, the control reactivity requirement, and thus the available insertion reactivity.

In all three of the 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 the reduced positive Doppler reactivity feedback associated with the small radial temperature gradient in the fuel (high thermal conductivity).

For the LOF accident, the assumed initiator is loss of power to the primary and intermediate coolant pumps without scram. As the flow decreases, the core outlet temperature rises. The heating and expansion of the core radially and axially causes negative reactivity feedback that reduces the reactor power. As the power falls, the coolant outlet temperature peaks and then also begins to decrease. Analysis shows that coolant boiling is avoided with substantial margin in the short-term transient. In the long term, system temperatures remain below levels at which load-stress-induced creep could result in structural failures.

For the TOP accident, the assumed initiator is an uncompensated withdrawal of a single, maximum-worth control rod. In the IFR metallic-fueled core with its high breeding gain and low cycle burnup reactivity swing, this amounts to an insertion of less than ten cents of reactivity. In the resulting transient, the reactor power rises above nominal, followed by a very slight heating of the coolant which introduces sufficient negative reactivity to return the reactor power gradually to equilibrium with the assumed nominal heat rejection at the steam generators. Analyses show that the low control rod worth made possible by the high breeding gain in the metallic core results in only slight over-temperature conditions.

For the LOHS accident, it is assumed that feedwater supply to the steam generators is lost, yielding a gradual heating of the intermediate and primary coolant systems and an increase in the core inlet temperature. Heating of the core support grid spreads the core radially, introducing negative reactivity which reduces the reactor power. In the long term, the reactor power equilibrates to any available heat sink with the inlet temperature elevated above the initial state. Analyses show that for the metallic-fueled IFR design, the negative reactivity feedbacks reduce the reactor power as the core inlet temperature rises, with peak temperatures only slightly elevated above nominal conditions.

Local Faults

Loss of cladding integrity of a single fuel element during normal steady-state full power operation should not occur during the design lifetime of the fuel because of the margins included in the design of the fuel and cladding. However, stochastic fuel element failure must be anticipated, due to a random cladding defect which goes undetected during manufacture and inspection or due to random localized thermal, hydraulic or mechanical conditions within the fuel assembly.

Loss of fuel element cladding integrity will allow mass transport to occur across the fuel element boundary, releasing fission gas, bond sodium, and/or fuel and solid fission products from the fuel element into the coolant, or permitting ingress of primary sodium into the element. Local fuel failure implies a failure that is initiated within a single fuel assembly.

Metallic fuel elements have a range of features that enhance their tolerance to local fuel failure events. These features include:

1. Fuel alloy compatibility with sodium. Although there may be some limited interaction with trace oxygen in the coolant, this is significantly different from the chemical reaction that occurs between oxide fuels and sodium. This compatibility is the reason a sodium bond can be added to the fuel element to provide a high thermal gap conductance from the fuel to the cladding during the low burnup stage when a large gap exists.
2. High thermal conductivity of metal fuel. This results in very low fuel centerline temperatures, and reduces hot-spot temperatures for distorted geometries.
3. Predictable fuel irradiation behavior. For EBR-II Mark II fuel elements fabricated to achieve a 75% smear density, the dominant fraction of the generated fission gas is retained within the fuel structure at low burnup (less ~ 2 at %). The fission gas in the closed porosity causes volumetric expansion of the low burnup

fuel. At a volumetric expansion of 25-30% a fraction of the induced fission gas porosity becomes open porosity and the generated fission gas is transferred to the fuel element gas plenum.

4. Low fuel-induced cladding loading stresses. At low burnup with closed porosity, the compression strength of the material at nominal fuel temperatures is dominated by the gas pressure in the closed porosity with high cladding loading stresses possible if only fuel/cladding contact occurs. Such contact is made impossible by the relatively low fabrication smear density. At high burnup, after the formation of open porosity, the compressive strength of the fuel is severely reduced and consequently the cladding loading stresses remain low.

The major fraction of EBR-II experience is with uranium-fissium alloy. The reasons for expecting similar performance with the U-Pr-Zr alloy are: (a) anticipated similar structural properties, (b) a higher cladding-fuel eutectic temperature, and (c) similar fission gas release and fuel swelling characteristics. Recent preliminary experiments with ternary alloy fuel are confirming the anticipated excellent performance. These physical characteristics combine to give the ternary IFR fuel design superior local fuel failure performance, both in terms of reduced failure frequency and diminished failure consequences.

Severe Accidents

The possibility of widespread core melting and disruption in LMRs historically has been made exceedingly low by designing and constructing essential equipment to be highly reliable and by providing redundant and diverse scram systems. This practice is continued in the IFR concept. In addition, because of their unique reactivity feedback characteristics, IFR systems can be designed to avoid core meltdown under anticipated transient conditions (loss of flow, loss of heat sink, and transient overpower) without scram by maintaining a balance between the reactor power and the available heat rejection rate. Further, because of the low stored energy in IFR fuel, these systems can survive a sudden and complete rupture of any part of the high pressure core coolant supply system if a normal scram is accomplished. The probability of core meltdown in IFR systems therefore is exceedingly and uniquely remote.

The strategy for demonstrating a low risk of core disruption in the IFR design concept has been threefold: 1) provide reactor design features to enhance passive safety response and to mitigate the consequences of core disruption accident initiators, 2) provide scoping quasi-static analyses and detailed transient analyses of accident scenarios with experimentally-validated analysis techniques to quantify margins to core disruption, and 3) provide estimates of uncertainties associated with the frequency of accident initiators and the reliability of passive safety mechanisms. This strategy has been successfully applied for the ATWS events described earlier to show that the probabililty of failure of inherent shutdown is very small [3]. The likelihood of core disruption is even smaller, because of the presence of additional mechanisms (e.g. in-pin fuel motion prior to cladding failure) to terminate the accident prior to core distruction.

However, despite all possible design measures taken, a theoretical possibility of core meltdown (e.g. from complete and sudden loss of flow without scram or from complete, long-term loss of all decay heat removal systems) remains. Work to date has revealed three characteristics of particular importance to reduction of risk for these extreme scenarios: 1) the adiabatic Doppler feedback rate for metal fuel is equal or greater (more negative) than for oxide fuel, and 2) metallic fuel disperses upon melting giving rise to a powerful reactivity shutdown mechanism, and 3) resolidified molten metal fuel debris beds are highly porous and are coolable. Therefore, the energy in an IFR meltdown transient is expected to be modest and the debris bed is expected to be coolable by natural circulation.

Summary

The Integral Fast Reactor concept currently in development at Argonne National Laboratory embodies design principles that enhance both operational and public safety. The design features that form the basis for this heightened level of safety are 1) the liquid metal coolant, 2) the pool-type primary system arrangement, and 3) the advanced ternary alloy metallic fuel design. In the IFR concept, these features provide naturally corrective responses to plant and reactor upset conditions as a result of their inherent hydraulic, thermal, neutronic, and mechanical properties. The potential effectiveness of these design concepts has been demonstrated with full scale experiments and integrated analyses.

Reference

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