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Advanced Liquid Metal Reactor Development at Argonne National Laboratory During the 1980s*

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ADVANCED LIQUID METAL REACTOR DEVELOPMENT AT ARGONNE NATIONAL LABORATORY DURING THE 1980's

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BACKGROUND

The AEC's earlier prediction of breeder reactor commercialization in the late twentieth century was invalidated in the late '70's by the low rate of growth of electrical demand, the increase in identified uranium reserves and the executive branch proscription on LWR fuel reprocessing which severed the historical tie between current LWR reactors and breeders. When combined with a degree of public disaffection with nuclear power in general, the public consensus in the U.S. was to defer the introduction of breeders until at least the 2020 time frame; this public consensus led, through the U.S. Congress, to a cancellation of funding for the Clinch River Breeder Reactor (CRBR) plant in late 1983.

The enforced hiatus in the historical path to breeder introduction forced the community in the U.S. advanced reactor program to rethink its rationale and to reformulate its goals and strategy in light of the then-existing situation. The decade of the 80's has hosted this process, and the U.S. LMR program currently in place at the start of the 1990's reflects the outcome of that reevaluation.

AN LMR RATIONALE FOR COMMERCIALIZATION IN THE EARLY 21st CENTURY

The fundamental long term rationale for the LMR (liquid metal reactor) remains unchanged -- to provide for resource extension by consuming the more abundant isotope of uranium. But the market penetration strategy no longer relies on a uranium shortage. Instead, the next generation LMR reactors are being developed to a set of design goals which include a concerted effort to provide engineering solutions which can positively impact on the technical issues and on the public perception issues which have been identified in the current generation of commercial power reactors in the U.S. Included among these issues are simplicity and reliability of operation, robust and highly assured safety performance, a demonstrated and publicly-acceptable waste management approach, affordable capital and operating costs, and an acceptable degree of protection against international proliferation. The current rationale for LMR commercialization is to exploit the unique properties of LMRs so as to successfully address the above public perception issues with valid technical solutions; the advanced LMRs can then be offered in the marketplace as an improved, second generation nuclear power source which will penetrate the market on their own merits -- not relying in an essential way on economic factors which derive solely from a shortage in the world uranium reserves.

ARGONNE NATIONAL LABORATORY CONCEPTION FOR THE INTEGRAL FAST REACTOR (IFR)

The work at Argonne National Laboratory since late 1983 has approached the above design goals for the next generation nuclear power enterprise as a whole (reactor and balance of plant, reprocessing, refabrication, waste management; construction, licensing, operation and decommissioning) -- looking at the impact of each design selection on all facets of the enterprise.[1]

The fundamental approach to LMR design has continued to rest on the low system pressure and large separation between operating and boiling temperatures which are the hallmarks of liquid metal cooling. The low primary system pressure facilitates thin-walled vessels which in turn allow for a pool plant layout which will provide for a large heat capacity thermal buffer between the balance of plant and the primary system. This tends to insulate primary system response from off-normal status of the BOP where the majority of accident initiators are shown to arise in PRAs conducted for current generation plants. The point of departure of the IFR concept from the breeder reactor concepts of the mid sixties onward is to employ a closed, fissile-self-sufficient, transuranic-self-consuming fuel cycle which is based on a uranium/plutonium metallic alloy fuel form. The metallic fuel form facilitates a radical departure in fuel cycle technology -- allowing for a compact, few-step pyrometallurgical-based reprocessing and remote injection casting fuel refabrication (sodium bonded pins) operation to close the cycle.[2,3] The metal alloy fuel form, with pyroprocessing, and injection casting refabrication comprises the basis on which the closed fuel cycle has a potential to provide low fuel cycle costs even if it must penetrate the market on an incremental basis with small, dedicated fuel cycle facilities.

Since uranium is not expected to be in short supply for three or four decades, high breeding ratio and short doubling time is not an immediate requirement, and the IFR closed fuel cycle is designed for fissile self sufficiency -- i.e., cycle breeding ratio equal to unity.[4] Initial fissile working inventory for the cycle is a component of plant capital cost, and the cycle is designed for startup on either uranium 235 or plutonium -- depending on availability and cost. In either case, however the IFR cycle subsequently relies on U^{238} feedstock only -- thus achieving the traditional goal of resource extension. The core design is laid out to allow for breeding ratio variations between 0.85 and 1.50, with only minor changes, and to thereby allow a high degree of flexibility in accommodating to future changes in economic environment over the life of the plant.

The IFR design approach to safety is to design in passive safety features which provide for the two essential safety functions (reactivity shutdown and decay heat removal) without a reliance on balance of plant (BOP) and a plethora of Engineered Safety Features equipment.[5] This approach is taken not only to meet the goal of rugged, and "perceivably reliable" safety performance but also to drastically limit the extent of safety related-equipment and construction so as to form the basis for reduced capital costs.

Preapproved licensing based on standardized designs and modularized construction practices for NSSS and BOP form the basis for shorter and more predictable construction cycles.[6]

The IFR strategy for waste management is based on a unique property of pyrometallurgical reprocessing wherein all transuranics can be made to follow the plutonium rich-product stream thereby providing for the transuranics being recycled for consumption in the reactor. The fuel cycle then produces fission product waste streams for the repository which are essentially free of transuranics and so decay to levels below that of the original ore within 500 years.[7]

In the IFR closed, fissile self-sufficient fuel cycle, the delivery of the initial fissile working inventory is the only fissile shipment for the life of the plant. Incomplete fission product separation and incomplete uranium/plutonium separation of the product streams in pyroprocessing helps to provide a deterrent to subnational diversion -- inasmuch as the fissile materials remain highly radioactive at all stages of the fuel cycle.

REACTOR PHYSICS ASPECTS OF THE IFR CORE DESIGN

A principal focus of activities on core design and reactor physics for the IFR development for the past six years has been to produce core designs which can achieve open loop passive reactivity shutdown in response to unprotected accident initiators. Also, physics work has focused on developing designs which can accommodate to the neutronics conditions of a closed fuel cycle, with fuel composition containing recycled fission products and experiencing an isotopic spectra of transuranics which evolves to an eventual equilibrium as a result of repeated recycle.

The passive reactivity shutdown response to unprotected accident initiators[8] has been achieved by providing for a pool layout with large thermal inertia and designing the reactor for an inlet temperature coefficient of reactivity of such a size as to decouple the core's safe reactivity response from the state of the BOP. (Note is made of the fact that the knowledge of the state of the BOP in the open loop situation is coupled to the core primary system through the core coolant inlet temperature and in no other way). Also required is a power-to-flow coefficient of reactivity which is large enough to compensate -- within an acceptable core average temperature rise -- that reactivity which is vested in the incremental temperature rise of the fuel above the coolant, (since that reactivity would be introduced as a positive component when power is reduced to zero and the fuel temperature collapses to that of the coolant). A significant component of the power/flow feedback derives from radial core expansion. A systematic understanding of the core restraint design choices and core geometry and composition choices required to achieve this feedback has been gained,[9] and the models have been validated[10] against FFTF unprotected loss-of-flow tests from 50% power. Finally, passive safety response depends on a burnup control swing of nominally zero -- so as to preclude significant safety consequences of rod runout reactivity addition.[8]

The high thermal conductivity of the metallic fuel and its high density are physical features which have been exploited to provide core designs which simultaneously meet the above contradictory requirements. The achievability of passive reactivity shutdown response through use of metallic fuel in the core design was demonstrated in 1986 in a series of integral tests at the EBR-II power plant where passive reactivity shutdown of unprotected loss of flow and of unprotected loss of heat sink transients were conducted from full power with no core damage.[11]

The capability for passive reactivity shutdown response has been shown to be relatively insensitive to unavoidable uncertainties in the underlying reactivity coefficients and in the thermal and thermo/structural responses which drive them -- because of strong correlation between the reactivity addition and subtraction mechanisms.[12] ZPPR critical experiments[13] have been conducted and applied through formal data fitting methodologies to significantly reduce (up to factors of 4) remaining uncertainties.[14,15,16] Finally, recent work[17] has been directed at development and demonstration of non-intrusive monitoring methods which can be used on operating plants to provide assurance that those feedbacks required to achieve passive safety shutdown are indeed in place and operating. Such testing for assurance of passive safety features in advanced LMR plants will be the equivalent of periodic testing of Engineered Safety Features on current generation power plants.

The design strategies for passive safety performance were applied first to the modular sized PRISM and SAFR reactor concepts[6] and more recently to large-sized designs (1250 MWe) to produce design concepts which can achieve open loop passive reactivity shutdown for all classes of whole core Anticipated Transient Without Scram initiating events taken one at a time.[19,20] A Level 1 PRA is currently being generated for EBR-II with explicit treatment of the passive safety response features.[21] When completed, this PRA will provide a quantification of the risk reduction benefits of passive safety response.

In the closed cycle, wherein transuranics are stripped from the fission product wastes and returned to the reactor (with unavoidable carry-over of a fraction of the lanthanide fission products), repeated recycle with cycle breeding ratio equal to one leads eventually (~20 cycles) to equilibrium levels of the transuranics and of the fission products. Even with repeated recycle, however, the resulting isotopic mass distribution is more "plutonium rich" than is the LWR discharge initial working inventory. This is a result of the hard neutron spectrum which reduces α for all transuranics and of the short out-of-reactor cooling and reprocessing/refabrication time intervals which reduce the fraction of Pu^{241} decay to Am. The carry over fission products (primarily the lanthanides) build up to a few percent of the heavy metal mass, but cause only minor changes to the neutronics performance of the core,[7] again because of the IFR's hard neutron spectrum.

The core neutronics design takes into account not only the equilibrium levels of the transuranics and fission products but also the changing compositions during the transition from the initial working inventory over many recycles to the final asymptotic conditions. Both static performance (e.g., rod worth, power peaking) and dynamic performance (e.g., passive reactivity shutdown feedback coefficients) at each stage of the transition have been factored into the design. The limiting example of design for the transition phase occurs in the case of startup on enriched uranium with subsequent fissile-self-sufficient transition over a ~20 year period to the equilibrium plutonium cycle.[22] The evolving buildup of plutonium in the refabricated fuel at the expense of the burnout of the initial U^{235} charge requires a continuing reduction in overall fissile enrichment. Changes in passive safety response are found to be remarkably small in view of the change in sign of sodium density coefficient between U^{235} and Pu^{239} dominant loadings and in view of the factor of two change in delayed neutron fraction which influences the peak overshoot in unprotected loss of flow sequences.

A remarkable feature of pyroprocessing is that all transuranics naturally follow the plutonium-rich product stream. This facilitates return of >99% of all transuranics to the reactor -- where they act as fuel in the hard neutron spectrum. When the normal processing is combined with a final scrubbing step on the fission product waste stream to recover the remaining 1% of transuranics for recycle to the core, it leads to waste streams from the IFR closed cycle to the waste repository which are essentially free of transuranic content; such waste forms decay within 500 years to radioactivity levels which are below that of the original uranium ore which supplied the initial cycle working inventory. This feature of the IFR cycle, when coupled with its flexibility in cycle breeding ratio, is being explored[7] as to its waste management potential. The fissile self sufficient cycle maintains a non-increasing transuranic mass burden while generating an increasing energy release from fission power. A BR <1 design will reduce the global mass burden of transuranics while yielding useful energy. Both options are a contrast to current LWRs.

The material accountancy aspects of the closed cycle are being approached as a physics issue;[23] detailed modeling of all out-of-reactor processing steps is in progress,[24] and the formal methods for variance propagation at the several points in the process where homo-geneous samples can be taken are relied on to set meaningful control limits.[23] A multi-user interactive operations support code has been created to track all transuranic isotopic masses as they proceed through the batchwise out-of-reactor processing steps of the IFR cycle.[25]

Demonstration of a closed IFR fuel cycle, using near commercial-scale pyroprocessing and refabrication equipment, will commence in 1992 at EBR-II/FCF.[26] Physics activities in support of this demonstration have included equipment sizing trade studies wherein criticality and heat load considerations are paramount, ZPPR critical experiments in support of batch size criticality issues, development of fast neutron based non-destructive interrogation techniques for waste stream fissile assay, and an ongoing program of validation of calculational predictions of burnup and transuranic mass isotopic spectrum against measurements of EBR-II spent fuel.

FUTURE DEVELOPMENT

Areas of technology development for advanced Liquid Metal Reactors which will receive priority attention in the physics effort at ANL currently and in the future include the following:

Efforts will be made to exploit the innate load following characteristics of a reactor designed for open loop passive reactivity shutdown so as to simplify the control system and to make reactor safety less dependent on operator action and less vulnerable to automatic control system fault and/or operator and maintenance crew errors.[27] The underlying notion is to reduce reliance on control rod motion for reactor power control and to replace it with primary and secondary pump speed control; in this way, the core power can always be relied on to self-adjust to the local safe heat rejection capability -- irrespective of any misactions of the automatic control system, the operators, or the maintenance crews -- inasmuch as this safe heat rejection capacity is totally specified by the primary flowrate and the coolant inlet temperature.[28] If this can be achieved, it will extend the open loop passive safety response to all whole core ATWS initiators taken one at a time over to the closed loop case as well.

Efforts will continue on the goal to find core designs which reach a proper balance between the value of positive sodium void worth and the value of burnup control swing (i.e., BOL reactivity excess vested in the control rods.) The tradeoffs between sodium void worth and burnup control swing, have already been codified in an extensive trade study[29] which has shown that U^{238}/Pu^{239} based core designs cannot simultaneously achieve zero values for both performance parameters. This is physically impossible in a U^{238}/Pu^{239} fueled core because the latter requires good neutron economy in the core to achieve unity internal conversion ratio while the former requires poor economy in the core to reduce the importance of fission emission neutrons. Moreover, the tradeoffs impact essentially all of the crucial performance parameters including not only safety-related performance, but economic issues such as vessel size and fissile working inventory. The goal for reduction of the value of the positive sodium void worth to a "suitably-small" value has timely technical aspects (e.g., the issues of non-boiling mechanisms for voiding such as entrainment of cover gas bubbles or ferritic-cladded pin rupture with fission gas blanketing) and also has high visibility public perception aspects (e.g., positive coolant coefficient connection with Chernobyl). The result is that the selection of the optimal design point must find a rational and communicable balance of all facets of the enterprise including engineering elements, tangible nontechnical elements such as capital and operating costs and intangible elements like licensing judgements concerning relative likelihoods of alternative accident initiating events and public perceptions of the robustness of the risk reduction.

Design approaches which provide for extremely high reliability of passive decay heat removal and simultaneously for containment function must be found. The USNRC staff pre-reviews[30] of the recent advanced LMR concepts have stressed the desirability of containment function to provide a mitigative line of defense for those classes of accident initiators which do not benefit from the whole core passive reactivity shutdown. On the other hand, the natural circulation decay heat cooling of the core by the sodium in the pool, with the subsequent natural draft air cooling of the guard vessel which provides for a totally passive decay heat removal path from the fuel pins to an ultimate heat sink has been shown to provide an extremely high reliability release prevention line of defense. The geometrical layouts required to achieve the two lines of defense appear to be topologically inconsistent. Design conceptions which can retain both features must be found.

Work will be initiated to attempt to structure the closed cycle concept in a way which will provide increased assurance of proliferation resistance by exploiting the unique properties of a fissile self sufficient, transuranic-self-consuming, closed fuel cycle collocated at one side. These unique properties include the following: First, shipments are avoided in the fissile self sufficient design since the initial working inventory is the only required shipment. Second, the working inventory is innately self- protecting because of pyroprocessing's incomplete fission product separation from heavy metal, incomplete separation of transuranics from uranium, and the common reporting of the transuranics to the plutonium-rich stream. While these two features are strong deterrents to diversion by subnational groups, they provide only a weak proliferation barrier. However, additional unique features of the system could potentially be used to provide for timely detection of manufacture and diversion of fissile material by sovereign states. Specifically, the attractiveness level of the working inventory fissile material is innately low at every point in the closed cycle, thereby requiring time-consuming steps to achieve materials suitable for weapons. And when the site is regarded as a control volume, the inflowing steel, U^{238}, and chemical reagent mass flow rates are coupled to the outflowing electrical current, waste heat, and transuranic-free waste steams through immutable conservation equations involving energy release and refueling interval. Because the inflowing and outflowing streams are regular (nonfissile) commodities which are amenable to non-intrusive monitoring via standard commercial publications, the application of the known conservation equations to the closed fuel cycle site as a whole may prove to be sufficient for identification of manufacture of excess fissile material and its subsequent diversion on a time scale which, while relatively long, may still be timely in view of the low attractiveness of the material.

CONCLUSION

The hiatus in the early 1980s of the effort to commercialize the breeder in the U.S. based on the CRBR demonstration plant -- and the concomitant vast reduction in publicly-funded monetary commitment to the breeder development program has forced the advanced reactor community to rethink the rationale for LMR introduction in the U.S. The result of that re-evaluation has been to abandon the U^{235} shortage rationale of earlier years, and while not altering the fundamental goal of resource extension by use of U^{238} for fuel, to put the focus on using the LMR's favorable coolant properties and new innovations to provide technical solutions for those issues (including public perception issues) which have been identified for the current generation of power reactors in the U.S. (i.e., to "produce a better mousetrap.") If a "better mousetrap" is indeed achievable through exploitation of the LMR's characteristics, then it will penetrate the market on its own merits in the early 21st century.

ANL's effort to pursue this rationale has given rise to the Integral Fast Reactor (IFR) concept, and has produced substantial technical advancement in concept implementation which includes demonstration of high burnup capability of metallic fuel, demonstration of injection casting fabrication, integral demonstration of passive safety response, and technical feasibility of pyroprocessing. The first half decade of the 90's will host demonstration of the IFR closed fuel cycle technology at the prototype scale. The EBR-II reactor will be fueled with ternary alloy fuel in HT-9 cladding and ducts, and pyroprocessing and injection casting refabrication of EBR-II fuel will be conducted using near-commercial sized equipment at the Fuel cycle Facility (FCF) which is co-located adjacent to EBR-II. Demonstration will start in 1992.

The demonstration of passive safety response achievable with the IFR design concept, (already done in EBR-II in 1986) will be repeated in the mid 90's using the IFR prototypic recycle fuel from the FCF. The demonstration of scrubbing of the reprocessing fission product waste stream, with recycle of the transuranics to the reactor for consumption, will also occur in the mid 90's.

Such demonstrations of engineering solutions for the technical and public perception issues of nuclear power will be a step toward the introduction of the LMR as a second generation nuclear power source for the 21st century.

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