THE INTEGRAL FAST REACTOR CONCEPT --
TODAY'S HOPE FOR TOMORROW'S ELECTRICAL ENERGY NEEDS

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ABSTRACT

Acid rain and the greenhouse effect are getting more attention as their impacts on the environment become evident around the world. Substantial evidence indicates that fossil fuel combustion for electrical energy production activities is a key cause of those problems. A change in electrical energy production policy is essential to a stable, healthy environment. That change is inevitable, it's just a matter of when and at what cost. Vision now, instead of reaction later, both in technological development and public perception, will help to limit the costs of change. The Integral Fast Reactor (IFR) is a visionary concept developed by Argonne National Laboratory that involves electrical energy production through fissioning of heavy metals by fast neutrons in a reactor cooled by liquid sodium. Physical characteristics of the coolant and fuel give the reactor impressive characteristics of inherent and passive safety. Spent fuel is pyrochemically reprocessed and returned to the reactor in the IFR's closed fuel cycle. Advantages in waste management are realized, and the reactor has the potential for breeding, i.e., producing as much or more fuel than it uses. This paper describes the IFR concept and shows how it is today's hope for tomorrow's electrical energy needs.

FOSSIL FUEL DILEMMA

Recent measurements of carbon dioxide, chlorofluorocarbons, and other trace greenhouse gases in the environment indicate substantial increases over the last century. At a 1987 meeting in Villach, Austria, international scientists and technical experts in the World Meteorological Organization discussed how climatic change resulting from increasing atmospheric concentrations of greenhouse gases could affect various regions of earth. In the judgment of this working group, there is a 90% chance that the average global temperature will increase at a rate between 0.06°C and 0.8°C per decade for the next century. Temperature increases of this magnitude would raise the sea level between 30 centimeters and 1.5 meters within 50 years as a result of thermal expansion of seawater and ice melting. In coastal areas, where one-half of the world's human population resides, a rise in sea level of this magnitude would mean the loss of wetlands and an increase in the frequency and severity of flooding damage.[1]

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The impacts of acid rain are clearly evident in the lakes and forests of Europe and North America. Nearly one quarter of the Adirondack's lakes and ponds are too acidic to support fish, and half the streams of the mid-Atlantic coastal plain are threatened. In Canada, the Department of Environment reports some 14,000 lakes almost fishless and another 150,000 in peril. Half of southern Norway's fish population has been destroyed; over 17,000 of Sweden's lakes have been damaged.[2]

Fossil fuel combustion is largely responsible for acid rain and global warming due to emissions of sulfur dioxide and carbon dioxide. In 1987, 72% of electricity in the U.S. was produced by the combustion of fossil fuels (i.e., coal, petroleum, and natural gas). Statistics show that electricity use grows as the economy grows. Since 1973, electricity use in the U.S. has increased over 40%, and growth is expected to continue.[3] Fossil fuel combustion must be reduced, or at least its rate of growth controlled, to mitigate impending environmental consequences.

Besides environmental concerns, continued fossil fuel combustion poses another dilemma: exhaustion of the earth's limited natural resources. Resource estimates vary widely among sources, but there is a reasonable consensus regarding the relative order-of-magnitude amount of energy available from known reserves and economically recoverable resources.[4-8] In general, uranium via the ^{235}U once-through cycle and coal are about equivalent, and could provide roughly 10 times more energy than petroleum (which includes crude oil, oil shale, peat, tar sands, and natural gas). However, uranium if used in a breeder cycle (i.e., a cycle which converts non-fuel to fuel, for example, ^{238}U to ^{239}Pu) can provide approximately 100 times more energy than coal or the ^{235}U once-through cycle. Therefore, from the perspective of environmental consequences and natural resource utilization, development of a safe nuclear breeder option is a sound research objective. Not only is the conversion of nuclear energy to electricity clean, it can be the most reasonable use of available resources. These characteristics are paramount to a stable environment and growing economy.

THE INTEGRAL FAST REACTOR CONCEPT

Argonne National Laboratory (ANL) is developing an advanced nuclear reactor concept -- the Integral Fast Reactor (IFR). The IFR program consists of development and demonstration of an entire reactor system including development of fuel cycle and waste disposal processes. The IFR concept offers advantages over past and current nuclear technology in safety, security, waste management, and effective use of natural resources.

The IFR concept employs fast neutron-induced fissioning of heavy metals in a sodium cooled reactor to generate electricity. The fuel is a metallic alloy of uranium, plutonium, and zirconium. Upon neutron absorption by plutonium-239 (^{239}Pu), it fissions (i.e., splits into lighter elements), producing heat. High energy (fast) neutrons are emitted in the fission process. These neutrons are absorbed by the uranium-238 (^{238}U) in the fuel which then transmutes to ^{239}Pu. Depending on the fuel configuration and the conditions at which the reactor is operated, more ^{239}Pu fuel can be created from ^{238}U than is required to sustain the fission reaction. This phenomena, called "breeding," uses the natural uranium resources in the most efficient manner.

The reactor core and primary heat exchanger are submerged in a large pool of sodium which flows through the core as coolant. Heat generated by the fission process is transferred to the sodium coolant. The heat is then transferred in the primary heat exchanger to a separate sodium loop, which in turn transfers the heat to water in the secondary heat exchanger. This produces steam to drive turbines and generate electricity. This process is shown schematically in Figure 1.

Spent fuel from the reactor is pyrochemically reprocessed and returned to the reactor, constituting a closed fuel cycle. Pyrochemical reprocessing entails separation of usable fuel atoms from waste fission products in high temperature (500°C) reactions driven by electrolytic chemical properties of the materials. This is a radical departure from the traditional PUREX process, wherein oxide fuels are dissolved in nitric acid and subsequent operations involve complex chemical processing of dilute aqueous and organic-phase solutions through a series of large tanks and hundreds of feet of connecting pipes.

In the pyrochemical process, the primary separation of accumulated fission products from the metallic fuel occurs in a single compact vessel. The basic process steps consist of: dismantling fuel assemblies to remove the individual fuel elements; chopping the elements into segments; electrorefining the fuel segments to electrolytically separate the uranium, plutonium, and zirconium from the fission products and cladding; processing the cathodes from the electrorefining step to separate the refined fuel from cadmium and salt; injection casting new fuel pins from the refined fuel and make-up materials (^{238}U and zirconium); and assembling new fuel elements and assemblies for return to the reactor. These basic process steps are shown schematically in Figure 1.

The word integral in the IFR acronym refers to the fact that the program is integrated to include all aspects of the nuclear cycle from reactor design to waste disposal. Also, because of the small number of steps and the high fuel density in the pyrochemical process, only a small facility is required for reprocessing, making it economically and logistically feasible to co-locate reactors and reprocessing at one integral site.

The basic principles of the IFR concept are not new. Seven liquid metal fast breeder reactors have operated in the U.S., two of which are still operating -- the Experimental Breeder Reactor-II (EBR-II) at the Idaho National Engineering Laboratory (INEL) near Idaho Falls, Idaho, and the Fast Flux Test Facility (FFTF) at the Hanford Engineering and Development Laboratory (HEDL) near Richland, Washington. Table 1 gives a brief description and status of these reactors.[9] Not only have the basic reactor concepts been used before (e.g., sodium coolant in a pool configuration with metallic fuel), but similar reprocessing of EBR-II metallic fuel was demonstrated from 1964 to 1969 by Argonne at the Fuel Cycle Facility adjacent to EBR-II. The IFR pyrochemical process corrects deficiencies of the earlier process, primarily through the electrorefining step. The electrorefining step is a process similar to that used in industry to purify metals such as copper and nickel. The IFR concept is the first to apply this process to refining nuclear fuel.

The IFR concept incorporates desirable features of earlier liquid metal fast breeder reactors that have proven advantageous, with new features that offer improvement in safety, security, waste management, and effective use of natural resources. This combination makes the IFR concept the logical nuclear option for meeting the electrical energy needs of tomorrow while at the same time maintaining a stable environment. Before discussing specific advantages of the IFR concept, it is prudent to summarize current nuclear energy production technology.

LIGHT WATER REACTORS

All but one of the 109 commercial nuclear reactors operating in the U.S. are light water reactors (LWRs). LWRs employ fissioning of ^{235}U induced by low energy (slow) neutrons. Water, used as the coolant, slows down the neutrons so they may be absorbed by ^{235}U to cause fission. In LWRs, the water must be kept under high pressure to maintain the appropriate thermodynamic properties for cooling and energy conversion from heat to electricity.

LWR fuel is generally uranium oxide enriched to approximately 3% ^{235}U. Today's LWR commercial fuel cycle is a "once-through" cycle; i.e., when spent fuel is discharged from the reactor it is not reprocessed. It is stored at the reactor sites in water pools until it can be disposed of permanently. Current U.S. disposal plans for LWR spent fuel call for transportation of the spent fuel from the reactor sites to a deep geologic repository to be located in Nevada.

ADVANTAGES OF THE IFR CONCEPT

The technological merits of the IFR concept are many. However, public acceptance of the concept is just as important to it's viability as a long-term solution as the technological feasibility. History has shown that public perception plays a vital role in policy making.[10-12] Therefore, issues which are of great concern to the public, such as safety, nuclear waste, and transportation, must be a consideration in future energy policies. This section addresses some of the issues most commonly raised by the public.

Safety

The IFR concept possesses many desirable safety features. The physical properties of the sodium coolant and the metallic fuel allow for efficient heat removal. This is important as heat and cooling imbalances are the root of serious nuclear reactor accidents. The pool configuration of the sodium coolant gives it a large thermal inertia, i.e., the ability to absorb large amounts of heat with only a small temperature increase. Pool configuration promotes natural convective flow through the reactor providing a completely passive means (i.e., no actions are required from operators or mechanical devices) to remove heat. This safety feature was demonstrated in EBR-II in 1986 in two experiments. The experiments simulated heat and coolant imbalances similar to those which caused the Three Mile Island and Chernobyl accidents. In both cases, EBR-II cooled itself without any intervention from operators or mechanical safety systems resulting in no damage to either the reactor or fuel.[13]

Other safety benefits of the sodium coolant result from its low melting point, high boiling point, and low vapor pressure. These properties mean that the reactor system does not have to be pressurized. This reduces stress to the system and decreases the driving force for the escape of radioactive materials from the fuel in the event of an accident. In the latter case of an accident where fission products are released from the fuel, sodium provides the benefit of combining with gaseous iodine (considered the most dangerous gaseous fission product from a radiological health standpoint) to form a solid. In LWR systems, iodine is available for release to the atmosphere in the unlikely event of an accident. Another benefit of the sodium coolant is that it is noncorrosive to the stainless steel components of the reactor system.

Finally, public concern over safety in transportation of nuclear materials should not be overlooked. Because of the closed fuel cycle, the IFR concept could be economic on a small scale and its facilities co-located. Transportation of nuclear materials and the associated risk of transportation accidents would, therefore, be greatly reduced.

Security

The IFR concept offers two main advantages from the perspective of security (i.e., the protection of materials which could be used for nuclear weapons). Fission products from the spent IFR fuel are not completely removed when it is reprocessed leaving it too radioactive for human contact. Secondly, if the co-location option for siting the reactor and reprocessing facility is chosen, no transportation of weapons-grade materials would be required after the initial reactor fuel delivery. Hence, the diversion potential would be largely eliminated.

Waste Management

A major benefit in waste management is possible with the IFR concept. The waste products in LWR spent fuel and oxide fuel reprocessing waste streams require isolation for up to millions of years due to the actinide element content. With the unique IFR reprocessing concept, it appears that the actinides will be retained with the recycled fuel. If further reseach proves this to be correct, they will be recycled back to the reactor where they would be fissioned instead of discharged as a waste stream. Therefore, the isolation period required for the IFR concept wastes is reduced by orders of magnitude to hundreds rather than millions of years.

Effective Use of Natural Resources

Most importantly, effective use of uranium is the feature which makes the breeding option the only nuclear option for providing a significant long-term environmental benefit and the IFR concept the logical choice for meeting tomorrow's electrical energy needs. Uranium-238 is the most abundant isotope (about 99.3%) in natural uranium. Uranium-235, however, which makes up only 0.7% of natural uranium, is the only isotope of value in LWRs. The nuclear physics of the IFR allow much more efficient use of the earth's natural uranium resources because ^{238}U is changed to fissionable ^{239}Pu by breeding. More plutonium can be produced in an IFR than is needed to fuel itself. This is analogous to driving a car and having more fuel when you arrive than when you leave.

IFR PROGRAM STATUS

The complete IFR concept will be demonstrated by Argonne at EBR-II, which is Argonne's small prototype of the IFR. Fresh IFR fuel has been fabricated and is being irradiated in EBR-II. A hot cell facility located adjacent to EBR-II is being refurbished, modified, and equipped to conduct a prototypic demonstration of the IFR fuel cycle. Current plans call for the fuel reprocessing demonstration to begin in 1990. A successful demonstration will open the doors to commercial deployment of the IFR concept.

CONCLUSION

Planning for the future is imperative to meet the challenge of accommodating the continuation of lifestyles grown accustomed to, the limitations of finite resources, and the byproducts of technological evolution. Issues which receive vast public attention quickly become political issues. Unfortunately, political pressures tend to produce short-term tradeoffs rather than attention to long-term solutions.[14] Perhaps not enough is known now to dramatically change energy policy. However, it is clear that research and development which address these issues are essential.

The IFR is a visionary concept which will meet tomorrow's electrical energy needs. However, because the role of public perception is extremely important, demonstration of the technological feasibility of the IFR concept alone will not be sufficient to guarantee its success as a long-term solution to continued economic security and environmental stability. ANL is taking responsibility for not only developing the technical merits of the concept, but for nurturing public understanding and acceptance. The public and the policy makers must, however, accept the responsibility to understand the facts and act accordingly.

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FIGURE 1

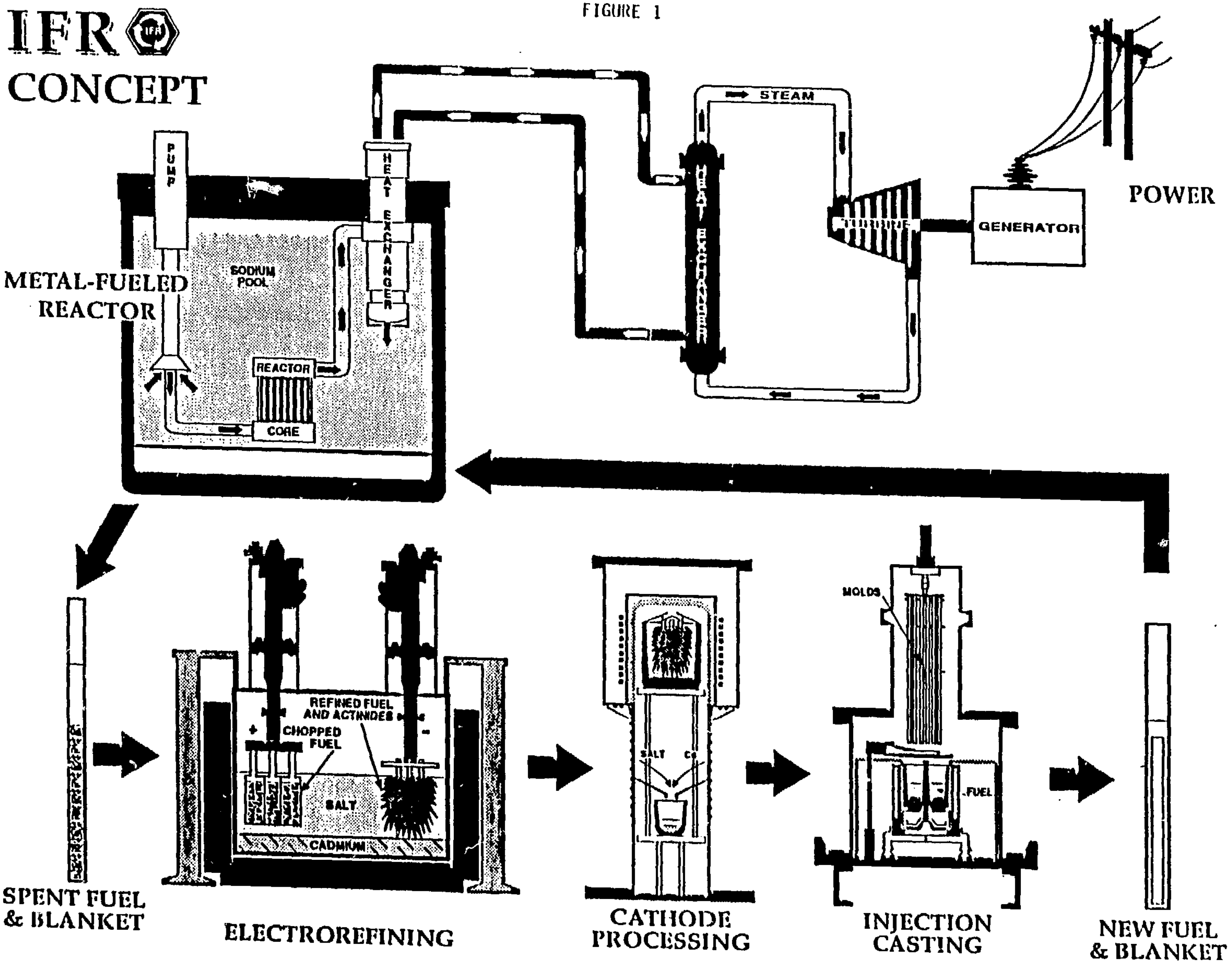
IFR
CONCEPT
PUMP
HEAT EXCHANGER
SODIUM POOL
METAL-FUELED REACTOR
REACTOR
CORE
STEAM
HEAT EXCHANGER
TURBINE
GENERATOR
POWER
SPENT FUEL & BLANKET
REFINED FUEL AND ACTINIDES
+
-
CHOPPED FUEL
SALT
CADMIUM
ELECTROREFINING
SALT
Cd
CATHODE PROCESSING
MOLDS
FUEL
INJECTION CASTING
NEW FUEL & BLANKET

TABLE 1. Summary of U.S. Liquid Metal Fast Breeder Reactors

Reactor, Location	Design, Construction, Owner/Operator	Purpose	Heat Tran. Sys, Power Output (th/electrical)	Fuel Type	History/Status
Clementine LASL Los Alamos, NM	LASL DOE LASL	Neutron Physics Research	1°: Mercury 2°: H_2O 25 kW	Pure metallic Pu core, nat. U reflector	1945 - Start of design 1946 - Initial criticality 1949 - Full power operation 1952 - Shutdown, dismantled
EBR-I INEL Idaho Falls, ID	ANL DOE ANL	Engineering physics & safety studies & breeder demo	1°: NaK 2°: NaK 3°: H_2O steam 1.2 MW/0.2 MW	Cores 1-3: highly enriched U alloy, nat. U blanket; Core 4: Pu alloy DU blanket	1946 - Start of construction 1951 - Initial criticality, full power operations, first electricity produced 1963 - Final shutdown 1966 - Declared national landmark
LAMPRE LASL Los Alamos, NM	LASL DOE LASL	Molten Pu reactor core experiment	1°: Na 2°: Air 3°: H_2O 1 MW	Molten Pu-Fe alloy in capsules, SS reflector	1957 - Start of R&D 1961 - Initial criticality, full power operations 1965 - Shutdown, dismantled
E. Fermi Fast Breeder Reactor Laguna Beach, MI	Atomic Power Dev. Assoc. Power Reactor Dev. Corp. Detroit Edison	Demo of large scale LMFBR, electricity generation	1°: Na loops(3) 2°: Na 3°: H_2O steam 200 MW/60 MW	25% U enriched alloy, DU blanket	1955 - Conceptual design 1963 - Initial criticality 1966 - Electricity generated, partial fuel melt incident 1970 - Continued operations, reached design pwr output 1972 - Shutdown, converted to irradiation facility
EBR-II INEL Idaho Falls, ID	ANL DOE ANL	FBR closed fuel cycle demo; fuels & materials testing; IFR demo	1°: Na pool 2°: Na 3°: H_2O steam 65.2 MW/16.5 MW	U-Pu alloys DU blanket	1955 - Start of design 1961 - Initial criticality 1970 - Full power operations 1980 - Cogeneration capability added 1989 - Operating

TABLE 1. Summary of U.S. Liquid Metal Fast Breeder Reactors (cont'd)

Reactor, Location	Design, Construction, Owner/Operator	Purpose	Heat Tran. Sys, Power Output (th/electrical)	Fuel Type	History/Status
Southwest Exp. Fast Oxide Reactor Fayetteville, AK	GE DOE,SAEA,GE KFK SAEA	Demo of FBR safety	1°: Na loop(1) 2°: Na 3°: Air 20 MW	U-Pu mixed oxide (20% Pu), Ni reflector	1964 - Conceptual design 1969 - Initial criticality 1972 - Shutdown, decommissioned
Fast Flux Test Facility HEDL Richland, WA	Westinghouse Hanford DOE Batelle PNL	Fuels & materials testing	1°: Na loop(3) 2°: Na 3°: Air 400 MW	U-Pu mixed oxide, SS reflector	1965 - Conceptual design started 1980 - Initial criticality 1989 - Operating
Clinch River Breeder Reactor Clinch River, TN	Project Mgmt. Corp. Breeder Reactor Corp. Breeder Reactor Corp.	Prototype-scale LMFBR	1°: Na loop(3) 2°: Na 3°: H_2O steam 975 MW/380 MW	U-Pu mixed oxide	1969 - Plant design started 1975 - Conceptual design complete 1977 - President Carter postponed construction, banned reprocessing 1981 - President Reagan endorsed project 1983 - Congress abandoned funding killed project

DISCLAIMER