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Prescription for the Planet

The Painless Remedy for our Energy & Environmental Crises

Tom Blees

My hope is that you, dear reader, can set aside for a moment your own fears, preconceptions, categorical thinking, and scientific and political biases to consider my proposal for a solution to the seemingly intractable problems that I promised to deal with in the beginning of this book. You will not be asked to make any great leaps of faith or technological fantasy. Amazing as it may seem, the technologies to solve some of the greatest challenges of our time are well in hand. First, though, you — and many like you — have to be convinced. Only then can our decision-makers possibly be persuaded to set aside their deadly inertia and take the bold steps necessary to implement real solutions.

CHAPTER FOUR

Newclear Power

"Mankind does have the resources and the technology to cut greenhouse gas emissions. What we lack is the political will."
— Dr. Paul Davies, Physicist

Of all the energy systems we've discussed (albeit briefly, of necessity), the one with the greatest potential for reducing the threat of global warming is arguably nuclear power. It's been surprising to see the range of individuals who have embraced this option, who have pronounced themselves willing to settle for more and more nuclear waste and the widely feared dangers of proliferation and possible (though unlikely) accidents. It is a measure of how deeply concerned they are about global warming. But there is still a vocal opposition to nuclear power by those who aren't ready to discount the negatives that seem to be an inextricable part of the package.

Opponents of nuclear power might assume that those who support it are being dismissive of such concerns either out of foolish heedlessness or desperation. But from the beginning of the nuclear power era the physicists, engineers and others who worked at the cutting edge of that research recognized both its promise and its shortcomings. Having identified the most serious problems, they set out to solve all of them, determined to leave no loose ends.

Argonne National Laboratory (whose western branch was recently rechristened Idaho National Laboratory) was the focus for America's nuclear power research and development since the beginning of the nuclear age. In 1964 a research reactor called the EBR-II was built to demonstrate a breeder reactor system with on-site fuel reprocessing and a closed fuel cycle. During the thirty years of its operation, many advances were incorporated into its design and proved eminently workable. The project was a resounding success. The advantages of such a system are so far superior to the light water reactors (LWRs) now in use that one might be forgiven for wondering why this technology has not completely supplanted current systems.

There is much here to wonder about. Why was the program suddenly terminated in 1994, just one step shy of its full demonstration of proof of concept, after thirty years of flawless performance? Cost was not an issue, especially since the Japanese had offered to chip in $60 million to finish the research. It seems especially ironic to see Al Gore today as the leading light in the climate change field when it was the Clinton administration (with Gore as vice president) that urged Congress to shut down the EBR-II. There were certainly no technical or economic reasons to do so.

There has been speculation that Clinton was bowing to antinuclear political pressure and that the shutdown was a payback for the support of environmentalists. Certainly Clinton and Gore's 1992 campaign stressed renewable energy development and a distinct lack of support for nuclear power. It has also been suggested that Clinton's choice as Secretary of Energy, Hazel O'Leary, would have been wary of the threat to the fossil fuel industry that the Argonne project represented, having previously been a lobbyist for fossil fuel companies. She and Senator John Kerry led an impassioned opposition to the project, arguing that it represented a proliferation threat. Since the

EBR-II's design was specifically intended to reduce proliferation risks, however, their opposition would seem to be a case of either ignorance or duplicity. It seems entirely believable that the shutdown of the program was ultimately due to misinformation and misunderstanding of the legislators who voted to kill it. It's been said that they didn't understand the difference between PUREX fuel reprocessing (which does present a proliferation threat because it isolates weapons-grade material, albeit of poor quality) and the proliferation-resistant fuel recycling that was intended to be an integral part of the new reactor system. The Senate, in fact, didn't go along with Clinton's recommended program termination, but the House prevailed in conference committee and the program was killed. (You can read the whole deplorable story in Chapter 12.)

If the Integral Fast Reactor (IFR) concept that the EBR-II represented was so far superior to current designs, you may wonder why the information hasn't made its way out into the public arena since 1994. When I first began to research this technology in 2001 I found even the people who worked at Argonne quite reticent to discuss it openly. After a considerable amount of communication I finally asked one day why the person who was my source of information there wasn't more forthcoming. It seemed I always had to pry information out of him a piece at a time. Finally he told me that the Department of Energy had issued a directive that the technology was not to be publicized. I could have specific questions answered, but I would have to figure out what those questions would be.

What was doubly ironic is that the chief engineer for the EBR-II project, Leonard J. Koch, was awarded the prestigious Russian Global Energy International Prize by Vladimir Putin in June 2004 for his work on the project.[120] And this was

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[120] Argonne National Laboratory News Release, "Argonne Fast-Reactor Pioneer Receives International Prize," (May 7, 2004).

happening at a time when the Argonne people were under a virtual gag order to prevent free discussion of the project in their own country! What could have prompted the U.S. Department of Energy, then under the watchful eye of Spencer "I-never-met-a-gas-hog-I-didn't-like" Abraham, to squelch publicity about this promising technology? Why, indeed, have both Democratic and Republican administrations thrown bars in the wheels of their own scientists who'd worked for over thirty years — with stunning success — to develop and demonstrate an incredibly promising energy technology?

Rather than venture into areas ripe for speculation, I will leave my readers to draw their own conclusions and, hopefully, ask themselves and their political leaders some penetrating questions. In order to encourage that, a description of the technology, and what it could mean to our planet in its current dire straits, will be presented here. I will make every attempt to refrain from overly technical descriptions. Footnotes will be provided for those who wish to delve further into the details, and the glossary at the back of the book provides descriptions of the terminology and acronyms.

If you find this to be tough sledding despite my efforts to the contrary, please don't be dismayed. A cursory understanding of the basic concepts is helpful, but you need not be concerned if the details escape you. The salient points will be made quite clear regardless, as the book progresses. I would, however, mention one exception to this. If you happen to be a person for whom anything with the word "nuclear" in it is anathema and you still feel that way even after you get to the end of this book, then it would behoove you to make sure that you do, indeed, understand these principles. If not, I would submit to you that you don't have a sufficient basis upon which to espouse a dogmatic position. If you cling to the belief that nuclear anything is necessarily bad (excepting, perhaps, the nuclear family), and

yet don't understand how it works, then you're probably just accepting it on faith from someone who may be as ignorant about the facts as you are. Even worse, you may have placed your trust in someone who knows better but who preaches an anti-nuclear ideology for reasons that are either self-serving or willfully blind to the facts, in which case deliberate distortions and outright lies are unfortunately not at all uncommon. In any event, at this point I would implore you to withhold judgment until the evidence is presented. I suspect you may be both surprised and hopeful when all is said and done.

Nuclear Physics 101

The process that powers nuclear reactors today is termed fission, and uranium is the basic fuel. In a reactor, neutrons[121] are naturally released from fissioning atoms and collide with the nuclei of other atoms in their vicinity. The absorption of a neutron often causes the nucleus of the impacted atom to split apart (fission), thus creating *fission products* — isotopes[122] of two new elements of about half the mass. In the process of splitting, the impacted atoms themselves release neutrons, which continue the process by colliding with more atoms, causing a chain reaction that is harnessed for the heat it

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[121] A neutron is a subatomic particle with no net charge. Both protons (with a positive charge) and neutrons are found in the nucleus of all atoms (except for hydrogen's protium form). Electrons, carrying a negative charge, reside outside the nucleus.

[122] The number of protons in an atom's nucleus determines which element it is, but a variation in the number of neutrons in an element's nucleus is what the term isotope denotes. Thus an element is distinguished by its name or its chemical symbol, while a number following it designates its "mass number," the total number of protons plus neutrons. Thus U-238 denotes the most common isotope of uranium, which has 92 protons, with a total of 146 neutrons (238 – 92). U-235, with 3 fewer neutrons, is needed to fuel nuclear reactors and can also be used to build nuclear weapons.

produces. The reaction is controlled by materials that either slow down or safely absorb neutrons, keeping the heat within tolerable limits and thus preventing the fuel from melting. Fluid coolant is piped around the fuel to draw off the heat and harness it via a heat exchanger to run a steam turbine that powers an electricity generator.

This can be thought of as modern alchemy, where one element is transformed into others. But whereas the alchemists of old seemed intent on producing one particular element — gold — the fission process is considerably more random, producing a great variety of elements. (And fission works, while ancient alchemy didn't.) Some of the resulting isotopes are stable, but almost all of them are decidedly unstable at first, and spontaneously emit (or radiate) subatomic particles as they decay towards a stable condition.

In some of the fuel atoms, absorption of a neutron does not lead to fission, but to the creation of a slightly heavier isotope. Some of these newly created heavy elements are themselves good producers of neutrons when they split, and thus contribute to furthering the chain reaction. Many of the lighter elements that result from the splitting of atoms, however, impede the reaction by absorbing neutrons, thus acting as so-called nuclear poisons.

It is the buildup of the nuclear poisons that is the limiting factor in the usability of nuclear fuel. The types of nuclear reactors in commercial use today operate with relatively slow neutron speeds, which increases the cross-section for absorption of neutrons and thus the probability that fission will occur. The usual fuel of choice is uranium, with the concentration of the minor isotope, U-235, enhanced (the fuel is "enriched"). Virtually all current reactors use water to slow ("moderate") the neutrons (lowering their kinetic energy) and to carry off the heat. Hence such reactors are generically classified as "thermal" reactors. Nuclear poisons build up eventually and make further reactivity impossible. The fuel is then removed from the reactor and either discarded as nuclear waste or, in some cases (though not in the USA), destined for partial recycling.

The Integral Fast Reactor (henceforth IFR), as might be deduced from the word "fast" in its name, is a type of reactor that allows the neutrons to move at higher speeds by eliminating the moderating materials used in thermal reactors. The greater velocity of the neutrons results in more energetic splitting and thus a greater number of neutrons being liberated from the collisions. The result is that the fuel is utilized much more efficiently. Whereas a normal nuclear reactor utilizes less than one percent of the fissionable material that was in the original ore, with the rest being treated as waste, a fast reactor can burn up virtually all of the uranium in the ore.

That quantum leap in efficiency is only the tip of the iceberg, though. For the fuel can then be recycled on-site in a process that removes the fission byproducts and incorporates the actinides[123] from the used fuel into new fuel rods, which are then reloaded into the reactor. The fission products, being the ashes of the process, if you will, are not usable as fuel (or as weapons). They can be stabilized by vitrification, a process that transforms them into a glasslike and quite inert substance for disposal. In this form they can be stored for thousands of years without fear of significant air or groundwater contamination.[124]

Yet the waste coming from an IFR doesn't have to be stabilized for anwhere near that long. Unlike the "waste" from the thermal reactors in use today, the waste elements from an IFR

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[123] The 14 chemical elements that lie between actinium and nobelium (inclusively) on the periodic table, with atomic numbers 89-102. Only actinium, thorium, and uranium occur naturally in the earth's crust in anything more than trace quantities. Plutonium and others are heavier, man-made actinides resulting from absorption of neutrons.

[124] D. H. Bacon & B. P. McGrail, "Waste Form Release Calculations for the 2005 Integrated Disposal Facility Performance Assessment," (Pacific Northwest National Laboratory, July 2005).

have much shorter half-lives[125] than the actinides that have been retained in the reprocessing and subsequently reloaded into the IFR's core for further fissioning. The nuclear waste problem, probably the most common concern about nuclear power, is seen as serious primarily because of its long-lasting radioactivity, for some of the actinides remain appreciably radioactive for thousands of years. With the actinides removed from the spent fuel, dealing with this new type of nuclear waste becomes quite manageable. Though very radioactive (a shorter half-life means more intense radioactivity), the vitrified IFR waste can be placed in lead-lined stainless steel casks and safely stored on-site or transported for storage elsewhere. Within a few hundred years — millennia before there is any degradation of the vitreous mixture that locks it in — the radioactivity will have diminished to below the level of naturally occurring ore. And unlike the actinide-containing waste, no weapons-usable materials are involved.

Yet there is an even better feature of IFR fuel than its relatively benign waste. For the new actinides used to augment the spent IFR fuel during its reprocessing can come from the nuclear "waste" from thermal reactors, which we are all so concerned about. Plutonium and uranium from decommissioned nuclear weapons can also be incorporated into fast-reactor fuel. Thus we have a prodigious supply of free fuel that is actually even better than free, for it is material that we are quite desperate to get rid of. Uranium, plutonium, and other actinides, both weapons-grade and otherwise, will go into the IFR plants. Only non-actinides with short half-lives will ever come out. We will eliminate the problems of both radioactive longevity and the potential for nuclear proliferation.

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[125] Half-life refers to the amount of time required for a radioactive substance to decay to half its original quantity. As radioactive elements decay toward a stable state their radioactivity decreases, eventually passing below the harmless levels of normal background radiation.

Which brings us to one likely reason why fast reactor technology has been ignored all these years. Because fast reactors are capable of creating more fissile material than they burn, they are known as breeder reactors. And because breeder reactors create plutonium, they have been a special target of anties and politicians concerned about proliferation. As in so many issues having to do with nuclear power technology, most of the resistance is due to ignorance of the technology and a generalized fear of all things nuclear.

Let's be clear about one thing: all uranium-fueled nuclear reactors create plutonium. Here's how it works: When uranium ore is extracted from the ground and milled, it contains about seven-tenths of one percent uranium 235 (U-235). This is a fissile material, meaning that it is so prone to splitting when it absorbs a neutron that it will maintain a fission chain reaction if enough of it is brought together in the same place. The other 99.3% of the uranium is made up almost entirely of U-238, which is not fissile but fertile. Fertile materials are those that do not readily fission in a neutron flux, but which, upon absorbing a neutron, are transmuted into fissile isotopes. A handy rule of thumb when discussing actinides is that if the mass number is even, they're fertile. Odd numbered actinides, on the other hand, are fissile.

In most thermal reactors, uranium must have a higher concentration of fissile material than its natural concentration of 0.7%, so it is put through an enrichment process to boost its percentage of U-235 to about 4%. Once this concentration is attained the fuel can be assembled into a critical mass, the amount necessary to maintain a fission reaction. The U-238 that makes up the other 96% of the fuel is then bombarded with neutrons as the fission proceeds since it is, of course, in the neighborhood.

When a neutron hits an atom of U-238, one of two things can happen. Either the atom fissions (unlikely) or it absorbs the neutron in a process known as neutron capture. You'll remember that neutrons have no charge, whereas protons (their companions in the atom's nucleus) have a positive charge and electrons have a negative charge.

Once U-238 absorbs a neutron it would be expected to become the radioactive isotope U-239, and it does. But U-239 has a half-life of just minutes, so it quickly undergoes beta decay,[126] becoming a different element, neptunium 239. But Np-239 has a half-life of only 2.35 days, so it also soon undergoes beta decay. Now the atom of U-239 has gone from having uranium's 92 protons to 94 protons (through 2 consecutive beta decays). Since the number of protons determines the identity of an element, it is no longer uranium, nor neptunium. It is plutonium (Pu-239).[127]

So now you have two fissile elements in the reactor core: what's left of the original 4% of U-235, plus some Pu-239, which itself begins to fission. The neutrons being liberated from both these elements continue to not only produce fission products, but also to create more plutonium from the remaining U-238, thus sustaining the reaction longer than would be the case without the creation of plutonium. By the time the buildup of nuclear poisons necessitates the removal of the nuclear "waste" there's a considerable amount of plutonium that's been created. A normal-sized nuclear power plant of one gigawatt capacity — sufficient to power about a half million European homes, but only about half that many in the more power-hungry USA — will expel nearly 500 pounds of plutonium in its spent fuel over the course of a year.

In both thermal and fast reactors, the plutonium produced is intimately mixed with a large amount of U-238 and other elements, and the spent fuel would have to be reprocessed in order to get pure plutonium. This can be done as easily with irradiated fuel from an ordinary thermal reactor as it can from the "breeder blanket" of a fast reactor. So the hue and cry about the proliferation dangers of breeder reactors is actually much ado about nothing special. The danger of nuclear proliferation isn't an issue of thermal reactors vs. fast reactors; it's an issue of maintaining tight control over the entire nuclear fuel cycle, regardless of the type of reactor. One of the great benefits of the IFR over thermal reactors is that the reprocessing facility is located in the same complex as the reactor itself — hence the "Integral" in "Integral Fast Reactor" (IFR). In an IFR plant, all actinides — including plutonium — are kept sequestered in an extremely radioactive environment while they are repeatedly sent through the fast reactor until they are transformed into energy.

The so-called pyroprocessing that occurs at an IFR site is quite unlike the PUREX (**P**lutonium and **U**ranium **R**ecovery by **EX**traction) reprocessing, which isolates weapons-purity plutonium from a thermal reactor's spent fuel. During the entire relatively simple pyroprocess within the confines of the IFR, the plutonium is always in combination with elements that make it impossible to use for weapons without further, PUREX-type processing, and is so radioactive that the entire operation is done remotely behind heavy shielding. Once the new material that we want to dispose of is added from outside, it too is removed from possible weapons use once and for all. Thus all the actinides in spent fuel from thermal reactors, as well as weapons-grade material we wish to get rid of, can be sent to IFRs. Instead of being a plague on future generations, the energy potential of the actinides is fully utilized in the production of electricity.

Consider, if you will, what this means in terms of energy

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[126] In beta decay, a neutron is converted into a proton while emitting an electron and an anti-neutrino. Don't worry, there won't be a quiz on this. The point is, a proton replaces a neutron, thus changing one element into another.

[127] Since uranium had been named after the planet Uranus, the discoverers of the next two elements named them in ascending order after the last two planets of the solar system. That was back in the good old days, of course. (Sorry about your recent demotion, Pluto!)

availability. Nuclear "waste"—which in today's terms can now be seen to be a gross misnomer—from LWRs[128] still contains about 95% of the fuel's original energy. IFR plants can burn, in time, *all* of the actinides that have been mined, not just those that make it into the LWR's fuel. None of the actinides that enter the site will ever leave it, until the time comes that all the plutonium from thermal reactors has been used up, and excess fissile material must be bred and transported to new reactors that need an initial loading. As we'll see later on in the book, for all the worry about the long-lived nuclear waste building up all over the world, we can easily use it all up in IFRs. And once it's all used up, all we'll need to keep the then-existing IFRs operating is U-238, the principal component of depleted uranium (DU), which is a byproduct of uranium enrichment and the main component of all reactor fuels.[129] We have so much of this already available that it could provide all the power needs of the entire planet for hundreds of years before we need to mine any more uranium. This is the same depleted uranium that is currently being used in both defensive and offensive weaponry, primarily by the United States. It would be a great improvement if we'd use it for generating electricity instead of shooting it at people.

Let us not forget the hazards and environmental insult of uranium mining and milling, which is a constant and ever-growing requirement of thermal reactors. Once all the thermal reactors reach the end of their useful lifetimes and are all replaced with IFRs, the world's uranium mining and milling operations can be completely shut down for centuries. Likewise all uranium enrichment facilities will be obsolete, as will large, centralized plants for reprocessing spent fuel from thermal reactors.

Once that point is reached, all it would take to keep a one-gigawatt reactor running would be about a milk-crate quantity of depleted uranium every three months. And if the stuff wasn't so ungodly heavy (1.6 times as dense as lead), it's safe enough that a person could just carry it into the plant by hand. Except for weapons-grade plutonium possessed by nations in the "nuclear club," none would ever be in existence outside the IFR plants.

But whereas nuclear waste and proliferation are serious problems that can be rectified with IFR technology, what about the possibility of nuclear accidents? Once again the IFR design has proven to be a stellar solution. One of the major problems with thermal reactors is the fact that they use pressurized systems for their coolants. Both the Three Mile Island and the much more serious Chernobyl accidents were due to coolant problems, faulty readings from monitoring devices, and operator error. In addition, the antiquated Chernobyl didn't even have a containment building, thus allowing the release of radioactive substances that was prevented in the case of Three Mile Island.

The physicists and engineers who designed the IFR wanted to eliminate even the remote possibility of accidents by using passive safety, which relies on the inherent physical properties of the reactor's components to shut it down in even the most adverse situations. And once again they figured out how to do it.

The reactors in an IFR complex are often referred to as LMRs, meaning Liquid Metal Reactors (or sometimes ALMRs, Advanced Liquid Metal Reactors). The Argonne project used a large vat of liquid sodium in which the reactor vessel itself

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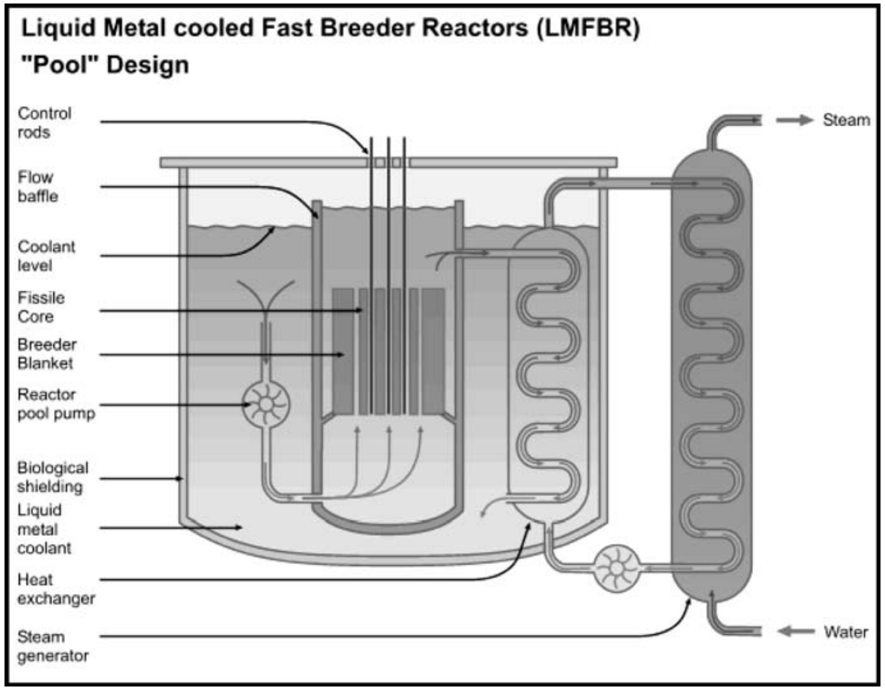
[128] LWR: Light-Water Reactor. A thermal reactor that is moderated and cooled by ordinary water, which must be fueled with uranium that has been enriched to about 4% U-235. Most of the world's power reactors are LWRs, but by no means all. Some, moderated by heavy water or graphite, can use natural uranium. In fueling LWRs, some 85% of the ore's energy is left behind in the tailings from the enrichment process, and only about 5% of what makes it into the fuel gets consumed.

[129] All current reactors, that is. Thorium is another possible reactor fuel, but as yet the technology is not mature.

was immersed. Sodium has the advantage of being an excellent conveyor of heat, as well as innate characteristics that prevent it from interfering in the fission process. A closed loop of sodium passes through this pool, transporting heat from it into a separate area where it boils water in a second heat exchanger. The (non-radioactive) water, as with thermal reactors, is thus converted to steam for generating electricity with the plant's turbines. The now-cooler sodium in the heat-transfer loop circulates back through the reactor pool heat exchanger in a continuous process.

Unlike thermal reactors, however, this is all done at atmospheric pressure, or nearly so. The closed loop utilizes a low-pressure pump just sufficient to maintain the sodium flow, moving cooled sodium from the heat exchanger back into the reactor area. There is also a small circulating pump immersed in the main tank to transfer heat more efficiently from the reactor core to the sodium pool. The diagram[130] shows an IFR that incorporates a breeder blanket of fertile material (U-238) that is being converted to fissile material, to "breed" more nuclear fuel. In the beginning of the conversion to IFRs, new reactors would be fueled with actinides from used thermal-reactor fuel. For the most rapid growth of nuclear power, IFRs would be loaded to breed the maximum possible amount of new fissile material, using the excess to start up new IFRs. Should the time come when no more generating capacity is needed, the reactors could be operated in the "break-even mode," to simply maintain the plant's own operation with the breeding reduced to a subsistence level.

The IFR concept considerably simplifies the entire nuclear power system, utilizing far fewer valves and pumps than even the most advanced thermal reactors and avoiding the potential problems of high-pressure coolants. The metal fuel, unlike the ceramic pellet fuel of thermal reactors, conducts heat much more efficiently and is thus able to dissipate it far more effectively. The fuel pins' unique composition is such that if they begin to overheat the resulting expansion decreases their density to the point where the fission reaction simply shuts itself down.


Liquid Metal cooled Fast Breeder Reactors (LMFBR)
"Pool" Design

> The passive safety characteristics of the IFR were tested in EBR-II on April 3, 1986, against two of the most severe accident events postulated for nuclear power plants. The first test (the Loss of Flow Test) simulated a complete station blackout, so that power was lost to all cooling systems. The second test (the Loss of Heat Sink Test) simulated the loss of ability to remove heat from the plant by shutting off power to the secondary cooling system. In both of these tests, the normal safety systems were not allowed to function and the operators did not interfere. The tests were run with the reactor initially at full power.

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[130] Illustration courtesy of Andrew Arthur

> In both tests, the passive safety features simply shut down the reactor with no damage. The fuel and coolant remained within safe temperature limits as the reactor quickly shut itself down in both cases. Relying only on passive characteristics, EBR-II smoothly returned to a safe condition without activation of any control rods and without action by the reactor operators. The same features responsible for this remarkable performance in EBR-II will be incorporated into the design of future IFR plants, regardless of how large they may be.[131]

These worst-case scenario trials were meant to account for the most serious possible circumstances such as devastating earthquakes or meteor strikes, though since that date the possibility of airliner strikes might also be added to the list of conceivable disasters. The potential problem to be prevented is overheating due to the sodium coolant being drained or lowered to the point where the fuel would be exposed. In order to avoid this, the containment structure can be built with no openings whatsoever below the level of the top of the sodium vessel. The primary vat is half-inch-thick stainless steel. A second stainless steel vessel surrounding that is designed to contain the sodium in the highly unlikely event that the primary one should spring a leak. Outside that second vessel is a six-inch thick sodium-resistant hardened concrete barrier, resting against the solid wall of the containment building, which forms the fourth level of assurance. Outside, the containment building can be banked with earth at least to that level, forming even a fifth level of redundancy. By supplying sufficient sodium to allow for maximum leakage all the way to the earthen barrier while still keeping the reactor covered, a loss of coolant accident would be a virtual impossibility.

But sodium is known to be a somewhat dangerous substance in its own right, subject to easy combustion in air and explosive combustion if it comes into contact with water. In order to prevent contact with air the entire covered pool area is itself covered with a blanket of argon gas, which is nonreactive with sodium and forms an effective barrier. Being heavier than air, it is unable to escape from such an area since there is no egress below the top of the tank. Argon is also used in the pyroprocessing facility where the fuel is recycled, though in that process sodium is not involved. The only other possible contact with air or water for the sodium is in the unlikely event of a breach of the water side heat exchanger loop, which is constructed of double-walled stainless steel. Should a leak occur, sodium would at most flow out at a low rate because of the unpressurized system. To get an explosive reaction in air you need atomization, which isn't an issue in an unpressurized system.

Though sodium is highly reactive with air and water, it is completely nonreactive with stainless steel. When cameras were run into the double-walled sodium loops after thirty years of use in the EBR-II to check the extent of corrosion, the welders' original markings were still visible on the joints that had been welded, as they were in the tank itself when the pool was drained. In point of fact, sodium is frequently used in industrial processes because of its superb heat transfer characteristics, and one would be hard-pressed to find an incidence of a serious sodium fire. The room where the heat exchanger brings the sodium loop and the water loop together could also be filled with argon as a precautionary measure, argon being noted for its fire extinguishing (or in this case, preventive) properties. The chances of a water/sodium contact are extremely remote, considering the lack of corrosion between the sodium and stainless steel and the well-known minimal interaction between stain-

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[131] From "The Unofficial IFR Home Page," which served to bypass the DOE gag order for years to keep the story of the IFR available on the internet. It disappeared in 2007. Sorry, DOE, the cat is out of the bag.

less steel and water. Keeping the water reasonably clean and nonreactive would be sufficient to deal with any sort of corrosion issues preemptively. During the lifetime of a plant it is unlikely that anything would have to be replaced. Based on past experience with nuclear plants (and other industrial facilities), however, the wisest course of action will be to make sure that the plant design will allow for replacement of any components that might become compromised, even if the chances of such contingencies are slim. And in a worst case scenario where the sodium and water met, it would happen in a separate building, isolated from the reactor core and its pool of sodium. No radioactive material would be involved, and the argon would smother any fire.

Though terrorism had always been a safety consideration even before its recent prominence in the public consciousness, there are several design features that can be utilized to make the reactor complexes essentially terrorist-proof. As with the EPR, the containment building can be built to withstand a direct hit from a fully fueled jetliner. A web of heavy cables can be suspended like a net above the containment and control structures, which would preemptively shred any incoming aircraft even before it made contact. But even better than that would be to simply mound earth over the critical structures once they're built, effectively keeping them above the water table but nevertheless taking advantage of the structural impregnability of massive amounts of earth.[132] Building such a structure with its sole ingress being via blast doors would make it virtually impervious to terrorism of any kind.

This tub within a tub redundant safety system provides a perfect opportunity for multiple sets of shock absorbing mounts in the event of a major earthquake. One could hardly envision a scenario under which the three levels of primary containment would be breached, much less the earth itself outside them. If theoreticians and statisticians and materials scientists feel that the system as described here is still too risky (highly unlikely, but then again I'm not a statistician), how many layers of containment would be needed to make it acceptably safe, to make it one in a million safe, or one in a billion? A third stainless tub? A thicker or completely separate additional reinforced concrete barrier? Fine, no problem. Build it in. The safety factor built into the fuel rods themselves is based on the laws of physics, which are fairly immutable at this level. Eventually it gets down to the point of irrational paranoia, beyond which nothing would ever be built and we'd still be living in caves (Look out, a stalactite might fall on your head!).

Just as an incredibly improbable thought experiment let's imagine the earth suddenly yawning open and swallowing the entire complex, the sodium pouring out and catching fire in an onrushing flood that just happened to occur after the earth crushed the reactor pool to pop its top. Such yawning, gulping, then crushing scenarios are favorites of cheesy disaster movies, but unknown in real life. Of course the chance of any such event occurring anywhere, much less precisely at a reactor core, is astronomically improbable. Nevertheless, imagine tons of uranium and even some plutonium being thus inexplicably liberated in a scenario as unlikely as Elvis and Marilyn rising together from the dead. If all the earth's electrical supply were provided by IFRs and this happened by some miraculous event, the damage to humanity would still be far less serious than what our current energy systems are doing every day, with tons of polluting gases pouring from coal-fired power plants, while their soot alone kills well over half a million people per year.[133] The safety factors that would be built into the IFR plants as a

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[132] It might be advisable to make sure that the reactors are built at least 50 meters or so above sea level, just in case the most pessimistic global warming scenarios come to pass despite our best efforts.

[133] Jeff Barnard, "Researchers Track Dust, Soot from China," *Boston Globe* Jul 13, 2007.

matter of course will most certainly provide a level of safety that will be a vast improvement over current energy systems, be they coal, oil (with its long list of disasters both large and small), gas (likewise), or even hydro power.

No matter how safe a system is, those who seek to find fault with it will often contend that a disaster is only one human error away, and that there's no way around it. That same argument will undoubtedly be leveled at the IFR system, yet it would be wildly off the mark. One of the wonders of the passive safety of IFRs is that they substitute the very laws of physics in place of human competence and mechanical performance. Rather than relying on pumps never failing (or on redundant backup pumps and systems), or on the competence of the plant operators, IFR design relies on unchanging physical laws. The boiling point of sodium is not going to change. And the temperature beyond which the fission reaction cannot sustain itself — less than the aforementioned boiling point of sodium — is likewise a function of the laws of physics. Human error cannot change these immutable conditions.

Proposing a complete replacement of fossil fuel power plants worldwide with a massive building project of IFR reactors would seem outlandish if it were to be based on the single experience at Argonne, however spectacular that program may have been (and it was). But the Americans were not the only ones experimenting with breeder reactors in the latter half of the twentieth century.

> For three decades, several countries had large and vigorous fast breeder reactor development programmes. In most cases, fast reactor development programmes were at their peaks by 1980. Fast test reactors [Rapsodie (France), KNK-II (Germany), FBTR (India), Joyo (Japan), DFR (United Kingdom), BR-10, BOR-60 (Russian Federation), EBR-II, Fermi, FFTF (United States of America)] were operating in several countries, with commercial size prototype reactors [Phénix, Superphénix (France), SNR-300 (Germany), Monju (Japan), PFR (United Kingdom), BN-350 (Kazakhstan), BN-600 (Russian Federation)] just under construction or coming on line.[134]

A combination of factors led to the termination of these programs, not the least of which was the political pressure brought to bear by antinuclear activists. There were also a few accidents which, while not resulting in any danger to the populace, were seized upon by nuclear power foes to create political calamities. The accidents that did occur resulted from designs flaws that were eliminated in Argonne's EBR-II.

Those who conceived and built these plants understood full well that the future might present a very different political landscape and that someday this type of reactor might be necessary, whether from a diminishing supply of uranium or because of unforeseen developments. Global warming, of course, is probably the most surprising development, at best only dimly imagined in the early days of nuclear power research. Fortunately, the commitment to advancing this technology resulted in an international effort to create a shared pool of knowledge. Over forty years of fast reactor development worldwide represents a total of 300 reactor-years of operation. In the view of nuclear experts from around the world who know it from experience, this technology has reached a mature stage and is fully ready for commercial application. In fact, a fast reactor is currently under construction in India at the time of this writing, with others on the drawing board in various countries.

I once asked one of the directors at Argonne National Laboratory how the physicists and engineers felt about being ordered to essentially keep their work out of the public eye.

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[134] IAEA, "Operational & Decommissioning Experience with Fast Reactors," (Cadarache, France: Mar 11-15, 2002).

He told me that from what he could tell most of them seemed surprisingly sanguine about it, assuming that global warming politics and energy supply realities would eventually trump fossil fuel politics, at which time their system would become the obvious choice. It seems that time has arrived. A first step must be a revelation of the existence of such technology to the public at large, for the implications of a worldwide conversion to IFRs are staggering. Tremendous pressure will have to be brought to bear on our political leaders in order for them to abandon the current state of affairs and strike out on a path that puts the earth, and their constituents' interests, before the interests of the giant corporations that today have a stranglehold on energy production—and, to an appalling degree, on politicians—around the world.

Before we go down that road though, there are other roads to consider: the roads we drive on. Even if all the nations of the earth agreed to rely on the far superior IFR technology for their electrical generation, we still need energy carriers of some kind for use in our automobiles and other applications where electricity is inconvenient or unavailable. Virtually every discussion I've seen of fast reactors envisions using them to produce hydrogen for the supposed future "hydrogen economy." Indeed, the recent direction of nuclear power research has been directed toward the development of high-temperature reactors specifically for the production of hydrogen for transportation. Yet we've seen that hydrogen has immense technological hurdles to surmount before it can be economical and safe. Joseph Romm, earlier mentioned as the former Clinton administration energy official and author of *The Hype About Hydrogen,* comments:

> People view hydrogen as this kind of pollution-free elixir. That all you have to do is put hydrogen in something, and it's no longer an environmental problem, which is just absurd. In fact, if you take hydrogen from fossil fuels and run them in an inefficient internal-combustion engine vehicle, you end up with a vehicle that just generates a great deal of pollution.
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> People need to get out of their heads {the idea} that there is something that is inherently good for the environment about hydrogen. If you run it through a fuel cell, you have zero tailpipe emissions. We all would like zero tailpipe emissions. If you burn it, however, you don't get zero tailpipe emission, in fact. You get a lot of nitrogen oxide, because it tends to burn at a high temperature…
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> …The current costs of the fuel cells are about 100 times the cost of internal-combustion engines. Right now, they cost hundreds of thousands of dollars apiece. And getting them, frankly, to be within a factor of 2 of a regular car will be a stunning scientific achievement. I'm not expecting that to happen for at least two decades.[135]

If the Cal Tech researchers who predict ozone layer destruction are correct, even if all these challenges are met hydrogen may still be too hazardous to our planet to deploy as a worldwide source of fuel or, more precisely, as our primary energy carrier. But don't despair. There is a far better idea than hydrogen.

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[135] Romm, "Just Say No, to Hydrogen."