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Advanced Nuclear Power Systems to Mitigate Climate Change

Tom Blees[1], Yoon Chang[2], Robert Serafin[3], Jerry Peterson[4], Joe Shuster[1], Charles Archambeau[5], Randolph Ware[3, 6], Tom Wigley[3,7], Barry W. Brook[1,7]

[1]Science Council for Global Initiatives, [2]Argonne National Laboratory, [3]National Center for Atmospheric Research, [4]University of Colorado, [5]Technology Research Associates, [6]Cooperative Institute for Research in the Environmental Sciences, [7]University of Adelaide

Abstract

Fossil fuels currently supply about 80% of humankind's primary energy. Given the imperatives of climate change, pollution, energy security and dwindling supplies, and enormous technical, logistical and economic challenges of scaling up coal or gas power plants with carbon capture and storage to sequester all that carbon, we are faced with the necessity of a nearly complete transformation of the world's energy systems. Objective analyses of the inherent constraints on wind, solar, and other less-mature renewable energy technologies inevitably demonstrate that they will fall far short of meeting today's energy demands, let alone the certain increased demands of the future. Nuclear power, however, is capable of providing all the carbon-free energy that mankind requires, although the prospect of such a massive deployment raises questions of uranium shortages, increased energy and environmental impacts from mining and fuel enrichment, and so on. These potential roadblocks can all be dispensed with, however, through the use of fast neutron reactors and fuel recycling. The Integral Fast Reactor (IFR), developed at U.S. national laboratories in the latter years of the last century, can economically and cleanly supply all the energy the world needs without any further mining or enrichment of uranium. Instead of utilizing a mere 0.6% of the potential energy in uranium, IFRs capture all of it. Capable of utilizing troublesome waste products already at hand, IFRs can solve the thorny spent fuel problem while powering the planet with carbon-free energy for nearly a millennium before any more uranium mining would even have to be considered. Designed from the outset for unparalleled safety and proliferation resistance, with all major features proven out at the engineering scale, this technology is unrivaled in its ability to solve the most difficult energy problems facing humanity in the 21st century.

Introduction

The global threat of anthropogenic climate change has become a political hot potato, especially in the USA. The vast majority of climate scientists, however, are in agreement that the potential consequences of inaction are dire indeed. Yet even those who dismiss concerns about climate change cannot discount an array of global challenges facing humanity that absolutely must be solved if wars, dislocations, and social chaos are to be avoided.

Human population growth exacerbates a wide range of problems, and with most demographic projections predicting an increase of about 50% to nine or ten billion by mid-century, we are confronted with a social and logistical dilemma of staggering proportions. The most basic human morality dictates that we attempt to solve these problems without resorting to forcible and draconian methods. At the same time, simple social justice demands that the developed world accept the premise that the billions who live today in poverty deserve a drastic improvement in their standard of living, an improvement that is being increasingly demanded and *expected* throughout the developing countries. To achieve environmental sustainability whilst supporting human well-being will require a global revolution in energy and materials technology and deployment fully as transformative as the Industrial Revolution, but unlike that gradual process we find ourselves under the gun, especially if one considers climate change, peak oil and other immediate sustainability problems to be bona fide threats.

It is beyond the purview of this paper to address the question of materials disposition and recycling[i], or the social transformations that will necessarily be involved in confronting the challenges of the next several decades. But the question of energy supply is inextricably bound up with the global solution to our coming crises. It may be argued that energy is the most crucial aspect of any proposed remedy. Our purpose here is to demonstrate that the provision of all the energy that humankind can possibly require to meet the challenges of the coming decades and centuries is a challenge that already has a realistic solution, using technology that is just waiting to be deployed.

<u>Energy Realism</u>

The purpose of this paper is not to exhaustively examine the many varieties of energy systems currently in use, in development, or in the dreams of their promoters. Nevertheless, because of the apparent passion of both the public and policymakers toward certain energy systems and the political influence of their advocates, a brief discussion of “renewable” energy systems is in order. Our pressing challenges make the prospect of heading down potential energy cul de sacs – especially to the explicit exclusion of nuclear fission alternatives – to be an unconscionable waste of our limited time and resources.

There is a vocal contingent of self-styled environmentalists who maintain that wind and solar power—along with other technologies such as wave and tidal power that have yet to be meaningfully developed—can (and should) provide all the energy that humanity demands. The more prominent names are well-known among those who deal with these issues: Amory Lovins, Lester Brown and Arjun Makhijani are three in particular whose organizations wield considerable clout with policymakers. The most recent egregious example to make a public splash, however, was a claim trumpeted with a cover story in *Scientific American* that all of our energy needs can be met by renewables (predominantly ‘technosolar’ – wind and solar thermal) by 2030. The authors of this piece—Mark Jacobson (Professor, Stanford) and Mark A. Delucchi (researcher, UC Davis)—were roundly critiqued[ii] online and in print.

An excellent treatment of the question of renewables’ alleged capacity to provide sufficient energy is a book by David MacKay[iii] called *Sustainable Energy – Without the Hot Air.*[iv] MacKay was a professor of physics at Cambridge before being appointed Chief Scientific Advisor to the Department of Energy and Climate Change in the UK. His book is a model of scientific and intellectual rigor.

Energy ideologies can be every bit as fervent as those of religion, so after suggesting Dr. MacKay’s book as an excellent starting point for a rational discussion of energy systems we’ll leave this necessary digression with a point to ponder. Whatever one believes about the causes of climate change, there is no denying that glaciers around the world are receding at an alarming rate. Billions of people depend on such glaciers for their water supplies. We have already seen cases of civil strife and even warfare caused or exacerbated by competition over water supplies. Yet these are trifling spats when one considers that the approaching demographic avalanche will require us to supply about three *billion* more people with all the water they need within just four decades.

There is no avoiding the fact that the water for all these people—and even more, if the glaciers continue to recede, as expected—will have to come from the ocean. That means a deployment of desalination facilities on an almost unimaginable scale. Not only will it take staggering amounts of energy just to desalinate such a quantity, but moving the water to where it is needed will be an additional energy burden of prodigious proportions. A graphic example can be seen in the case of California, its state water project being the largest single user of energy in California. It consumes an average of 5 billion kWh/yr, more than 25% of the total electricity consumption of the entire state of New Mexico.[v]

Disposing of the salt derived from such gargantuan desalination enterprises will likewise take a vast amount of energy. Even the relatively modest desalination projects along the shores of the Persian Gulf have increased its salinity to the point of serious concern. Such circumscribed bodies of water simply won't be available as dumping grounds for the mountains of salt that will be generated, and disposing of it elsewhere will require even more energy to move and disperse it. Given the formidable energy requirements for these water demands alone, any illusions about wind turbines and solar panels being able to supply all the energy humanity requires should be put to rest.

Energy Density and Reliability

Two of the most important qualities of fossil fuels that enabled their rise to prominence in an industrializing world is their energy density and ease of storage. High energy density and a stable and convenient long-term fuel store are qualities that makes it practical and economical to collect, distribute, and then use them on demand for the myriad of uses to which we put them. This energy density, and the dispatchability that comes from having a non-intermittent fuel source, are the very things lacking in wind and solar and other renewable energy systems, yet they are crucial factors in considering how we can provide reliable on-demand power for human society.

The supply of fossil fuels is limited, although the actual limits of each different type are a matter of debate and sometimes change substantially with new technological developments, as we've seen recently with the adoption of hydraulic fracturing (fracking) methods to extract natural gas from previously untapped subterranean reservoirs. The competition for fossil fuel resources, whatever their limitations, has been one of the primary causes of wars in the past few decades and can be expected to engender further conflicts and other symptoms of international competition as countries like India and China lead the developing nations in seeking a rising standard of living for their citizens. Even disregarding the climatological imperative to abandon fossil fuels, the economic, social, and geopolitical upheavals attendant upon a continuing reliance on such energy sources demands an objective look at the only other energy-dense and proven resource available to us: nuclear power.

We will refrain from discussing the much hoped-for chimera of nuclear fusion as the magic solution to all our energy needs, since it is but one of many technologies that have yet to be harnessed. Our concern here is with technologies that we know will work, so when it comes to harnessing the power of the atom we are confined to nuclear fission. The splitting of uranium and transuranic elements in fission-powered nuclear reactors is a potent example of energy density being tapped for human uses. Reactor-grade uranium (i.e. uranium enriched to about 3.5% U-235) is over 100,000 times more energy-dense than anthracite coal, the purest form of coal used in power generation, and nearly a quarter-million times as much as lignite, the dirty coal used in many power plants around the world. Ironically, one of the world's largest producers and users of lignite is Germany, the same country whose anti-nuclear political pressure under the banner of environmentalism is globally infamous.

The vast majority of the world's 440 commercial nuclear power plants are light-water reactors (LWRs) that use so-called enriched uranium (mentioned above). Natural uranium is comprised primarily of two isotopes: U-235 and U-238. The former comprises only 0.7% of natural uranium, with U-238 accounting for the remaining 99.3%. LWR technology requires a concentration of at least 3.5% U-235 in order to maintain the chain reaction used to extract energy, so a process called uranium enrichment extracts as much of the U-235 as possible from several kilos of natural uranium and adds it to a fuel kilo in order to reach a concentration high enough to enable the fission process. Because current enrichment technology is capable of harvesting only some of the U-235, this results in about 8-10 kilos of "depleted uranium" (DU) for every kilo of power plant fuel (some of which is enriched to 4% or more, depending on plant design). The USA currently has (largely unwanted) stockpiles of DU in excess of half a million tons, while other countries around the world that have been employing nuclear power over the last half-century have their own DU inventories.

Technological advances in LWR engineering have resulted in new power plants that are designated within the industry as Generation III or III+ designs, to differentiate them from currently-used LWRs normally referred to as Gen II plants. The European Pressurized Reactor (EPR), currently being built by AREVA in Finland, France and China, is an example of a Gen III design. It utilizes multiple-redundant engineered systems to assure safety and dependability. Two examples of Gen III+ designs are the Westinghouse/Toshiba AP-1000, now being built in China, and GE/Hitachi's Economic Simplified Boiling Water Reactor (ESBWR), expected to be certified for commercial use by the U.S. Nuclear Regulatory Commission by the end of 2011. The distinguishing feature of Gen III+ designs is their reliance on the principle of passive safety, which would allow the reactor to automatically shut down in the event of an emergency without operator action or electronic feedback, due to inherent design properties. Relying as they do on the laws of physics rather than active intervention to intercede, they consequently can avoid the necessity for several layers of redundant systems while still maintaining 'defense in depth', making it possible to build them both faster and cheaper than Gen III designs—at least in theory. As of this writing we are seeing this playing out in Finland and China. While it is expected that first-of-a-kind difficulties (and their attendant costs) will be worked out so that future plants will be cheaper and faster to build, the experience to date seems to validate the Gen III+ concept. Within a few years both the EPR and the first AP-1000s should be coming online, as well as Korean, Russian and Indian designs, at which point actual experience will begin to tell the tale as subsequent plants are built.

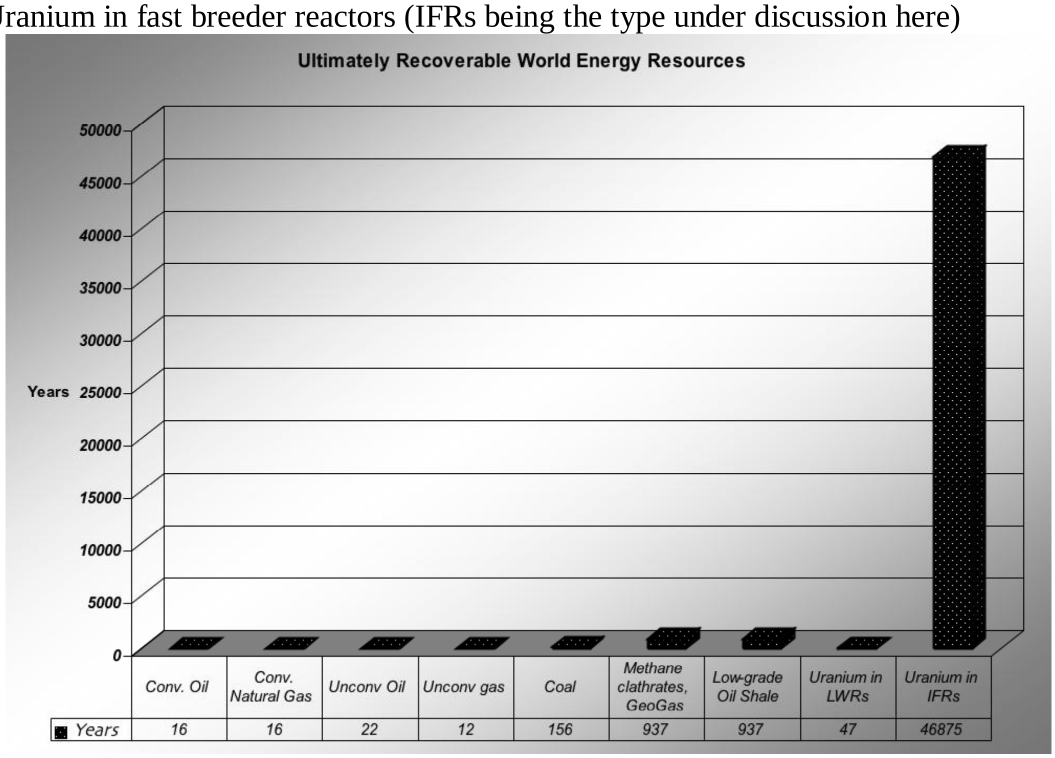
The safety and economics of Gen III+ plants seem to be attractive enough to consider this generation of nuclear power to provide reasons for optimism that humanity can manage to provide the energy needed for the future. But naysayers are warning (with highly questionable veracity) about uranium shortages if too many such plants are built. Even if they're right, the issue can be considered moot, for there is another player waiting in the wings that is so superior to even Gen III+ technology as to render all concerns about nuclear fuel shortages baseless.

The Silver Bullet

In the endless debate on energy policy and technology that seems to increase by the day, the phrase heard repeatedly is “There is no silver bullet.” (This is sometimes rendered “There is no magic bullet”, presumably by those too young to remember the *Lone Ranger* TV series.) Yet a fission technology known as the integral fast reactor (IFR), developed at Argonne National Laboratory in the 80s and 90s, gives the lie to that claim.

Below is a graph[vi] representing the number of years that each of several power sources would be able to supply all the world’s expected needs if they were to be relied upon as the sole source of humanity’s energy supply. The categories are described thusly:

- Conventional oil: ordinary oil drilling and extraction as practiced today
- Conventional gas: likewise
- Unconventional oil (excluding low-grade oil shale). More expensive methods of recovering oil from more problematic types of deposits
- Unconventional gas (excluding clathrates and geopressured gas): As with unconventional oil, this encompasses more costly extraction techniques
- Coal: extracted with techniques in use today. The worldwide coal estimates, however, are open to question and may, in fact, be considerably less than they are ordinarily presented to be, unless unconventional methods like underground *in situ* gasification are deployed.[vii]
- Methane Clathrates & Geopressured Gas: These are methane resources that are both problematic and expensive to recover, with the extraction technology for clathrates only in the experimental stage.
- Low-grade oil shale and sands: Very expensive to extract and horrendously destructive of the environment. So energy-intensive that there have been proposals to site nuclear power plants in the oil shale and tar sands areas to provide the energy for extraction!
- Uranium in fast breeder reactors (IFRs being the type under discussion here)



Integral fast reactors can clearly be seen as the silver bullet that supposedly doesn't exist. The fact is that IFRs can provide all the energy that humanity requires, and can deliver it cleanly, safely, and economically. This technology is a true game changer.

Integral Fast Reactors

Origins

At the dawn of the nuclear age in the late Forties and early Fifties, it was thought that uranium was quite rare. The scientists who pioneered nuclear power therefore thought it incumbent upon themselves to shepherd this resource as best they could. It soon became apparent that a type of nuclear reactor could be built that could transform U-238 into plutonium, and that the majority of the plutonium would be the isotope Pu-239, which like U-235 is a fissile material, i.e. it is capable of maintaining a fission reaction. If a reactor core were configured to do so, a properly designed "breeder reactor" could create more fissionable fuel than it consumed, and could be replenished by the occasional addition of the relatively abundant U-238.

The first nuclear reactor to produce electricity, in 1951, was the Experimental Breeder Reactor I (or EBR-I), located at what is now known as Idaho National Laboratory, previously a western branch of Illinois' Argonne National Laboratory. For reasons involving the leadership of Admiral Hyman Rickover in his quest to quickly develop nuclear power for naval vessels, the light-water reactor was created for that purpose, and when nuclear reactors began to be built for commercial land-based power generation, the path of least resistance led to the adoption of LWR technology, which is (with few exceptions) the type of reactors in use around the world today.

But research had continued with fast reactors, sometimes termed breeder reactors[viii] because they can "breed" new fuel. The EBR-I was followed by the EBR-II, a larger and more sophisticated fast reactor that was loaded with metal fuel (a ternary alloy of uranium, plutonium and zirconium) as opposed to the uranium oxide fuel used in virtually every other reactor design in use today, including the few fast reactors currently online and those that have been operated in the past.

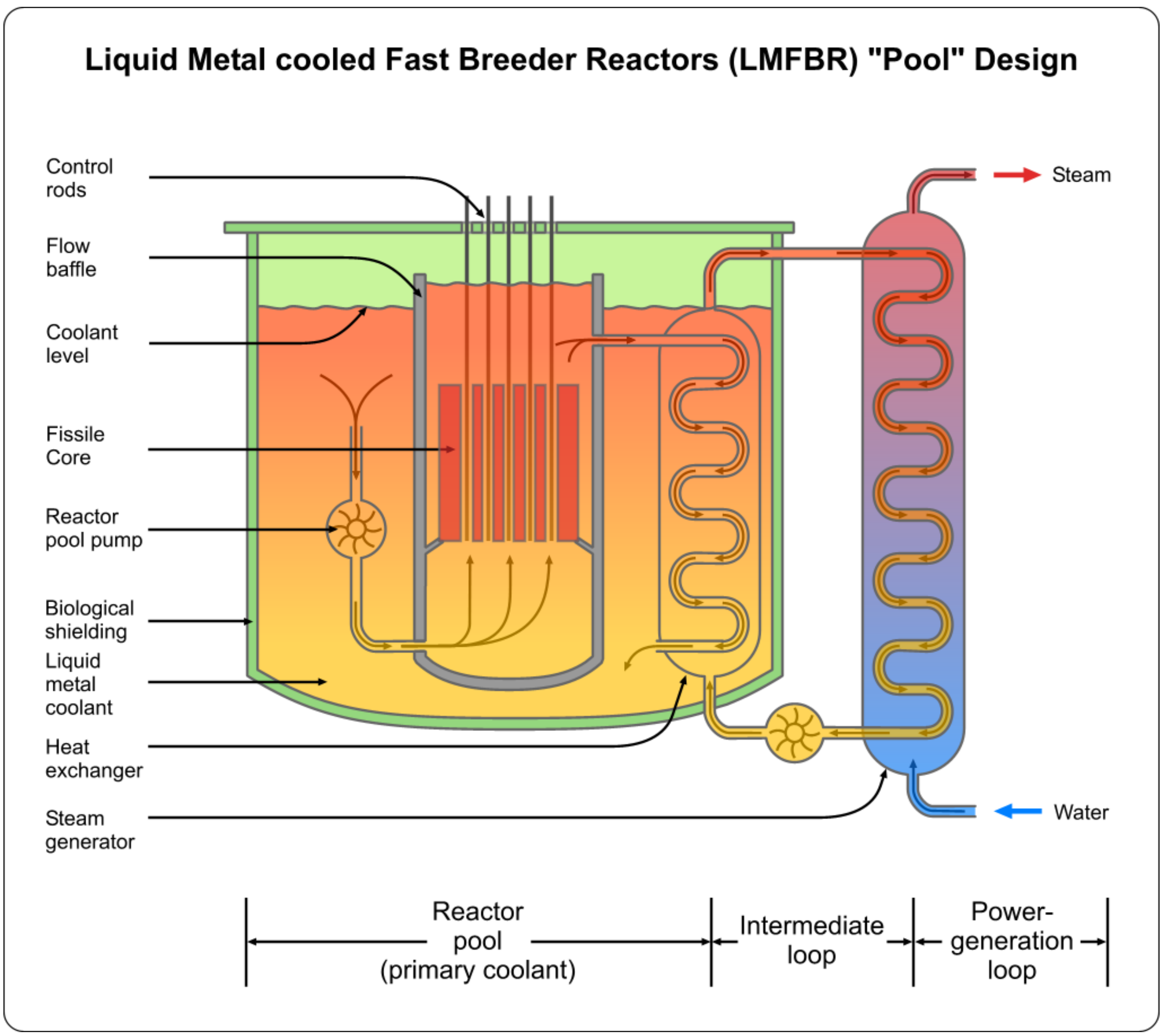
By 1984, the resistance to nuclear power in the USA, stoked by the accident at Three Mile Island in Pennsylvania and rising costs due to regulatory ratcheting,[ix] had reached such a pitch that orders for nuclear power plants were not only stopped but were being canceled. The scientists at Argonne could see that unless the public's concerns about nuclear power were satisfactorily addressed and solved, the political pressure would trump scientific and engineering considerations and make it politically impossible for nuclear power to provide the energy that the USA, and the world at large, demanded. It was at this point that the integral fast reactor project achieved its focus, building on the foundation that had been ably laid by the EBR-I and the early operations of the EBR-II.

An impressive team of scientists were assembled at Argonne under the leadership of Dr. Charles Till, who coordinated his exceptionally talented group in a multi-faceted project to solve all the issues of public concern over nuclear power generation simultaneously: safety, nuclear waste, proliferation, economics, fuel supply and fabrication, and construction. By the time a woefully shortsighted administration shut down the IFR project in 1994, all the problems had been successfully solved and all that was left was to demonstrate the commercial-scale fuel recycling system that would be an integral part of each power plant (hence the "I" in IFR).

IFR Basics

The main difference between a fast reactor and a light-water reactor is the speed at which the neutrons move when liberated by the splitting of an atom. In LWRs, water acts as a moderator, slowing the neutrons and thus increasing the chance that they'll encounter another fissile atom and cause it to split, perpetuating the chain reaction. In a fast reactor, the neutrons are allowed to move at a considerably higher speed, and for this reason the fissile content of the fuel must be higher (in an IFR it would be about 20% as opposed to the 3.5-5% in a LWR).

LWRs operate with water under pressure, hence the concern about pressure vessel leaks, coolant system leaks, etc, as well as the industrial bottleneck of only a single foundry in the world (though more are being built) capable of casting LWR pressure vessels. Fast reactors, on the other hand, usually use liquid sodium metal as the coolant, at or near atmospheric pressure, thereby obviating the need for pressure vessels. Because the boiling point of sodium is quite high, fast reactors can operate at a considerably higher temperature than LWRs, with outlet temperatures of about 550ºC as opposed to the 320ºC of Gen III reactors. Here is a simplified rendering[x] of a sodium-cooled fast reactor to convey the design features:



As can be seen from the picture, the heat exchanger loop, immersed in the reactor pool, contains *non-radioactive* sodium, which is piped to a heat exchanger in a separate structure where it gives up its heat to a water/steam loop that drives a conventional (Rankine cycle) turbine. This system assures that in the unlikely event of a sodium/water interaction caused by undetected breaching of the double-walled heat exchanger, no radioactive material would be involved and the reactor vessel itself would be unaffected. Such an event, however unlikely, could result in the cessation of flow through the intermediate loop and thus an inability of the system to shed its heat. In a worst-case scenario where such an event happened with the reactor at full power and operators, for whatever reason, failed to insert the control rods to scram the reactor, the passively-safe system would nevertheless shut itself down safely due to inherent properties of the metal fuel (see below), with the large amount of sodium in the reactor vessel then allowing the fission product decay heat from the core to dissipate.

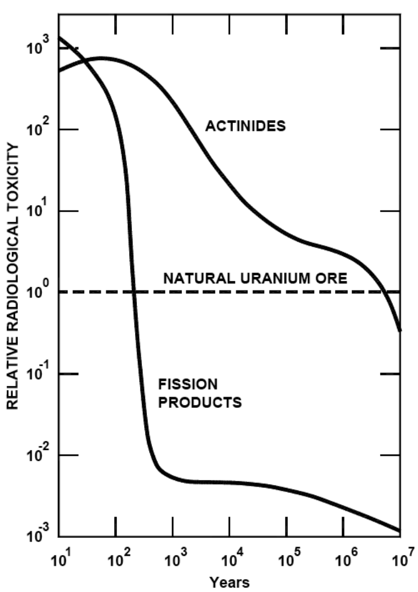
<u>Metal Fuel: The Ultimate Safety Valve</u>

One of the most important of the many superlatives of the IFR is its use of a metal fuel comprised of uranium, plutonium and zirconium, and the ingenious manner in which the Argonne team solved the problems of fuel expansion and fuel fabrication, as well as the potentially dangerous overheating scenario. Unlike the fuel fabrication of oxide-fueled reactors that requires the dimensions of the fuel pellets to be uniform to very exacting tolerances, the metal fuel for the IFR can be simply injected into molds and then cooled and inserted into metal tubes (cladding) with a great deal of dimensional tolerance, with a sodium bond filling any voids. If an accident situation occurs that would cause the core to overheat, such as a loss of coolant flow accident, the metal fuel itself will expand, causing neutron leakage to terminate the chain reaction, relying on nothing but the laws of physics.

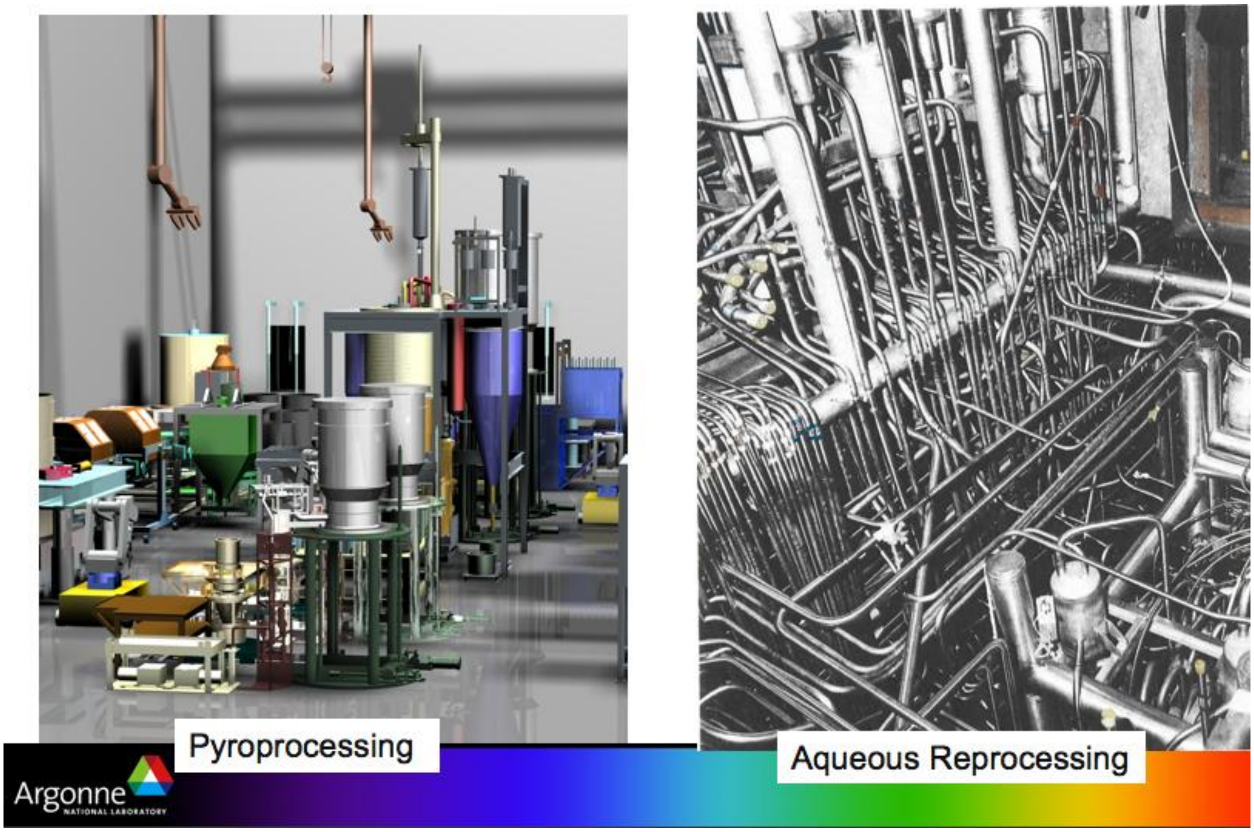
> The passive safety characteristics of the IFR were tested in EBR-II on April 3, 1986, against two of the most severe accident events postulated for nuclear power plants. The first test (the Loss of Flow Test) simulated a complete station blackout, so that power was lost to all cooling systems. The 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.
>
> 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.[xi]

While the IFR was under development, a consortium of prominent American companies led by General Electric collaborated with the IFR team to design a commercial-scale reactor based upon the EBR-II research. This design, currently in the hands of GE, is called the PRISM (Power Reactor Innovative Small Module). A somewhat larger version (with a power rating of 380 MWe) is called the S-PRISM. As with all new nuclear reactor designs (and many other potentially hazardous industrial projects), probabilistic risk assessment studies were conducted for the S-PRISM. Among other parameters, the PRA study estimated the frequency with which one could expect a core meltdown. This occurrence was so statistically improbable as to defy imagination. Of course such a number must be divided by the number of reactors in service in order to convey the actual frequency of a hypothetical meltdown. Even so, if one posits that all the energy humanity requires were to be supplies solely by IFRs (an unlikely scenario but one that is entirely possible), the world could expect a core meltdown about once every 435,000 years.[xii] Even if the risk assessment understated the odds by a factor of a thousand, this would still be a reactor design that even the most paranoid could feel good about.

The initial manufacturing and subsequent recycling of the fuel pins themselves is accomplished with a well-understood and widely used electrorefining process, similar to one that is employed every day in aluminum foundries. The simplicity of the system and the small amount of material that would have to be recycled in any power plant—even one containing several reactor modules—is such that factory-built components could be pieced together in a small hot cell at each power plant site. Every 18-24 months, one third of the fuel would be removed from the reactor and replaced by new fuel. The used fuel would be recycled. Approximately 10% of it would be comprised of fission products, which in the recycling process would be entombed in vitrified ceramic and probably stored on-site for the life of the plant. If the reactor core were configured to breed more fissile material than it consumes, then during the recycling process some quantity of plutonium would be removed and fabricated on-site into extra fuel assemblies that could then be used as the primary core load of a new reactor. The long-lived actinides that remain would be incorporated into the new fuel rods, replacing the quantity of fission products removed (and any plutonium that had been extracted for startup fuel for new reactors) with an equal amount of either depleted uranium or reprocessed uranium from LWR spent fuel.



Thus we solve multiple problems at once. The quandary of long-lived nuclear waste is a non-issue since the fission products will decay below the radioactivity level of uranium ore within a few hundred years, (see diagram[xiii]) yet they will be embedded in a stone/glass matrix that won't leach anything into the environment for thousands of years. The long-lived actinides that cause so much consternation to the public when considering spent nuclear fuel will never leave the site of the IFR power plant (except in the case where new fuel is moved to start up a new IFR), but will instead be recycled back into the reactors, repeatedly, to produce prodigious amounts of clean energy, gradually all being transmuted into either electricity or fission products that pose no troublesome disposal problems. Moreover, all of the spent fuel that has accumulated from operation of past, present and future LWRs can also be consumed as fuel in an IFR; in short, they 'eat' nuclear waste.



The relative simplicity and small size of pyroprocessing systems vs. aqueous systems is graphically illustrated above. The entire recycling system for an IFR power plant could be contained in a hot cell about the size of a large garage, while aqueous reprocessing systems are extensive, complex, energy intensive and costly industrial enterprises.

Fuel Supply

We saw in the first graph how IFRs can create a virtually unlimited fuel source. Our discussions on energy density raise the question of just how much energy can be extracted from uranium using IFRs. Given the fact that enriched uranium in LWRs is 100,000 – 250,000 times as energy-dense as various grades of coal, one might be understandably amazed to discover that IFRs can extract 150 times as much energy from uranium ore as an LWR can. Not only that, but IFRs are also capable of using spent LWR fuel and weapons-grade uranium and plutonium as fuel. Once these bothersome products are disposed of, IFRs can begin to consume the millions of tons of depleted uranium that are ever increasing around the world. There is so much material that IFRs can use for fuel already out of the ground that even if humanity were to rely *only* on IFRs for all the final energy (not just the electricity) we need, we wouldn't have to mine any more uranium for nearly a thousand years. And the energy-intensive process of uranium enrichment will be a thing of the past once all the LWRs reach the end of their service lives.

The energy density of uranium when used in IFRs is so great that the entire amount of energy an American would expect to use in a lifetime—not just for electricity but for transportation, heating and cooling, and all the energy that goes into food and other consumables—could be derived from a piece of depleted uranium the size of half a ping-pong ball. It's over 2.6 *million times* the energy density of the best grade of coal. It is darkly ironic that about the only use for depleted uranium these days is in warfare, often in wars instigated by competition over fossil fuels.

Economics

The economics of nuclear power in the public debate has only the most tenuous connection with reality in many cases. Consider the example of the AP-1000 reactors currently being built in China. Even the first-of-a-kind plants (FOAK)—normally overly expensive compared to later ones for obvious reasons—that are well along in their construction are expected to be completed at a cost of about $1,760/kW.[xiv] China expects that once their supply chains are in place to mass-produce such plants, they will be able to produce them for $1,100/kW or less.[xv] Yet even when the exact same reactor is planned for construction in the United States, the price escalates to three times the Chinese cost or more, as when Florida Power & Light testified before the Florida Public Service Commission on October 16, 2007 about their planned construction of two AP-1000s.[xvi]

It is in this collision of actual data vs. cost projections that we find ourselves when attempting to credibly determine the costs of building commercial-scale IFRs. In Senate testimony in late 2006, GE estimated the building cost of the S-PRISM reactor at just $1,300/kW.[xvii] China's current project and Japan's construction of the first two GE-designed Advanced Boiling Water Reactors (ABWR) in the Nineties (built in only 36 and 39 months)[xviii] demonstrate the cost advantages of standardization and modular construction that will be a hallmark of PRISM reactors. Based on the ABWR experience, GE estimated in 2000 that they would be able to build ABWRs in the USA for as little as $1,200/kW (if regulatory and other risk-inflation problems could be resolved).[xix] Considering that the PRISM will operate at near-atmospheric pressures, obviating the costly fabrication of a pressure vessel, and employ cost-saving passive safety design concepts (and ultimately factory-built mass production), simple logic and manufacturing experience would indicate that IFR construction can be expected to be economically competitive with virtually any other power production system. Even if GE's 2006 estimate were doubled, the cost would still make it competitive, especially considering that the fuel to run it for many decades would be essentially free except for its fabrication costs, which we've already seen will be quite low due to the simplicity of pyroprocessing.

When it comes to the economics of nuclear power, experience of the last couple of decades has shown that there is nothing inherently cost prohibitive about nuclear power *per se*. While some will argue that China can build power plants inexpensively because of cheap labor, that argument is proven hollow by Japan's modest construction costs for the first two ABWRs, since Japan imports virtually all their construction materials and Japanese workers are among some of the highest-paid in the world. If nuclear power plants cost 4-5 times as much in the USA as the same plant costs in the Far East, it's the fault of American politics and economics, not the fault of the technology. With the construction of natural gas-fired power plants recently moving past the $1,000/kW range, the substantial added cost of the fuel needed to run them during the course of their service lives (already over 40-60% of the levelized cost of gas-fired electricity) makes nuclear power look like a bargain by any reasonable analysis, even before the introduction of a carbon tax.[xx]

How Fast Can We Build Them?

During France's nuclear building boom they built an average of six nuclear power plants per year, culminating in a situation that provides them with about 80% of their electrical needs while making electricity their fourth-largest export earner. Gross Domestic Product (GDP) can be used as a rough guide to what a given country can financially bear for such a project, keeping in mind that France proceeded without the sense of urgency that the world today should certainly be ready to muster. There are six countries with higher GDPs than France, all of whom already possess the technology to build fast reactors: USA, China, Japan, India (they're building one now), Germany, and the United Kingdom. Add Canada and Russia (which already has a commercial fast reactor running and is planning more), then tally up the GDP of these eight countries. At the rate of 6 plants per year (~ 1GW each) at the equivalent of France's GDP, these countries alone could afford to build about 117 power plants per year, even without any greater urgency than the French brought to bear on their road to energy independence.

Consider that there are about 400 nuclear power plants in the world today. At this entirely feasible rate of construction we could more than double the planet's nuclear capacity in just four years. Remember, the French accomplished their transformation with non-modular, albeit standardized, Gen II designs. Modular construction, passive safety systems, and factory fabrication, divided among companies all over the planet, could realistically convert the planet's electricity production to virtually all nuclear in a couple decades, with abundant surplus electricity for ancillary uses such as desalination and the production of liquid fuels such as ammonia.

Proliferation

One of the arguments that was used to politically kill the IFR project, just as it was ready to demonstrate its last step, was the allegation that it was a proliferation risk. Yet the IFR system of pyroprocessing and metal fuel had been specifically designed to be proliferation resistant. Unlike aqueous reprocessing and chemical separation of the actinides, which is the type used in France and Japan, plutonium is never isolated at any stage of the IFR fuel cycle, nor is uranium. The mix of actinides and trace fission products is too hot to handle—and useless for weapons (except for a dirty bomb, assuming it could be assembled remotely)—at all times. Yet pyroprocessing is repeatedly conflated with aqueous systems by those who seek to squelch this technology, whatever their motivation, and the false allegation that pyroprocessing involves the separation of plutonium is used to claim that it is a proliferation risk. Because most people are unaware of the critical differences in the two reprocessing technologies, such spurious arguments too often carry the day, even though such isolation of weapons-usable material is technically impossible with pyroprocessing.

In point of fact, the isotopic composition of the plutonium extracted from spent power reactor fuel would be lousy for making weapons anyway, but pyroprocessing doesn't even go there at all. There is nothing inherently more proliferation-prone in a closed fuel cycle using pyroprocessing and fast reactors than there is in the once-through system used today. And since aqueous reprocessing equipment *is* what's used for extracting plutonium for weapons (from U-238 that's been irradiated for a short time specifically for that purpose), anyone who argues against pyroprocessing while still condoning aqueous has their facts backward.

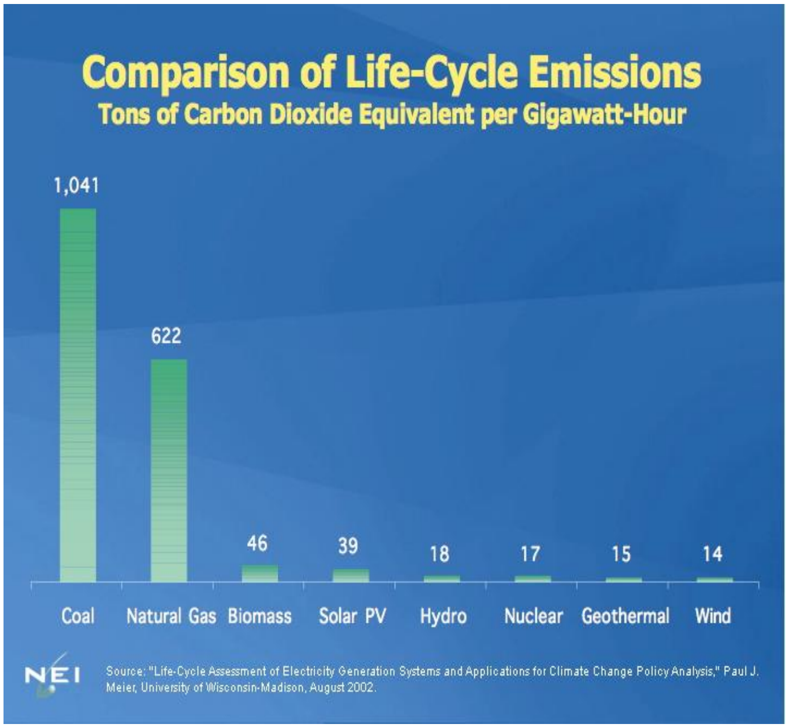
A Word About Load-Following

Nuclear power is sometimes criticized for being poor at load-following—the ability to quickly ramp up and down to match electricity demand. The fact that such criticism is usually leveled by advocates of notoriously skittish wind and solar power is beyond ironic. Even though IFRs would be pretty good at load-following, this is really a non-issue anyway. With all the uses we have for excess electricity and heat (the aforementioned desalination, for one), there is no reason not to constructively utilize the vast amounts of extra power available given the fact that nuclear power plants run fine at full power around the clock. As we've seen, the fuel in IFRs is essentially free, so all the more reason to make good use of it. Certainly the creation of hydrogen (via electrolysis or catalytic/heat reactions) can be beneficial not only for secondary synthesis of ammonia for use as a fuel, but also for its use in agriculture. Virtually all of the ammonia used in that industry today is derived from natural gas: all the more reason to displace it with ammonia derived from off-peak nuclear power. Likewise, the hydrogen could be used for manufacturing hydrazine, not exactly the first choice for fuels due to its instability, but a valuable commodity in several industrial processes.[xxi]

Carbon Footprint

It is sometimes alleged by anti-nuclear campaigners that nuclear power's life-cycle carbon costs are so high as to render it little better than the use of coal. The IPCC has studied this and put nuclear in about the same category as wind and solar in their Fourth Assessment Report section entitled Climate Change 2007: Mitigation of Climate Change.[xxii] On page 293 of this report there is a chart that describes both non-biomass renewables and nuclear in terms of their carbon output simply as "small amount." The text of the report (on page 269) states: "Total life-cycle GHG emissions per unit of electricity produced from nuclear power are below 40 g CO2-eq/kWh (10 g C-eq/kWh), similar to those for renewable energy sources. Nuclear power is therefore an effective GHG mitigation option…" Cynics may point out that they mention a thoroughly debunked report[xxiii] that claims much higher life-cycle emissions, but the IPCC clearly found it unpersuasive. A recent meta-review published in the journal *Energy* reinforced this result.[xxiv]

It's important to note that the vast majority of CO2 emissions in the nuclear life cycle arise from uranium mining and enrichment. Deployment of integral fast reactors, however, will eliminate the need for both mining and enrichment for nearly a millennium, so the life-cycle carbon cost will be virtually nil, especially if the concrete used in the new plants is of the magnesium silicate variety that actually is carbon negative.[xxv] While it is sometimes hard to envision a world powered by abundant nuclear energy, the fact is that the vehicles that are used in constructing a power plant can all be zero-emission, the smelting of the steel that goes into building the plant will be done with clean nuclear power, and even the cement plants can be powered by nuclear heat.



Conclusions and Recommendations

There are many compelling reasons to pursue the rapid demonstration of a full-scale IFR, as a lead-in to a subsequent global deployment of this technology within a relatively short time frame. Certainly the urgency of climate change can be a potent tool in winning over environmentalists to this idea. Yet political expediency—due to widespread skepticism of anthropogenic causes for climate change—suggests that the arguments for rolling out IFRs can be effectively tailored to their audience. Energy security—especially with favorable economics—is a primary interest of every nation.

The impressive safety features of new nuclear power plant designs should encourage a rapid uptick in construction without concern for the spent fuel they will produce, for all of it will quickly be used up once IFRs begin to be deployed. It is certainly manageable until that time. Burying spent fuel in non-retrievable geologic depositories should be avoided, since it represents a valuable clean energy resource that can last for centuries even if used on a grand scale.

Many countries are now beginning to pursue fast reactor technology without the cooperation of the United States, laboriously (and expensively) re-learning the lessons of what does and doesn't work. If this continues, we will see a variety of different fast reactor designs, some of which will be less safe than others. Why are we forcing other nations to reinvent the wheel? Since the USA invested years of effort and billions of dollars to develop what is arguably the world's safest and most efficient fast reactor system in the IFR, and since several nations have asked us to share this technology with them (Russia, China, South Korea, Japan, India), there is a golden opportunity here to develop a common goal—a standardized design, and a framework for international control of fast reactor technology and the fissile material that fuels them. This opportunity should be a top priority in the coming decade, if we are serious about replacing fossil fuels worldwide with sufficient pace to effectively mitigate climate change and other environmental and geopolitical crises of the 21st century.

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[i] Tom Blees, "Prescription for the Planet," (Create Space, 2008).
[ii] Barry Brook, "Critique of 'a Path to Sustainable Energy by 2030′," in *http://bravenewclimate.com/2009/11/03/wws-2030-critique/* (11/3/2009).
[iii] *SCGI - David Mackay* (2010 [cited); available from http://thesciencecouncil.com/index.php/david-mackay.
[iv] (Available as a free download from http://www.withouthotair.com/).
[v] "Energy Down the Drain: The Hidden Costs of California's Water Supply," *Natural Resources Defense Council* (2004).
[vi] Blees, "Prescription for the Planet." pp. 169
[vii] David Strahan, "The Great Coal Hole," *New Scientist* Jan 19,2008.
[viii] Also called fast neutron, fast spectrum, or liquid metal fast breeder reactors
[ix] Bernard L. Cohen, "The Nuclear Energy Option," ed. University of Pittsburgh (Plenum Press, 1990).
[x] Illustration courtesy of Andrew Arthur
[xi] Blees, "Prescription for the Planet." pp. 131-132
[xii] Ibid. pp. 217
[xiii] Yoon I. Chang, "Advanced Nuclear System for the 21st Century," in *Workshop on Nuclear Cycle Systems for the 21st Century* (Karlsruhe, Germany: 2002).
[xiv] "Milestones in Construction of Chinese Plants," in *World Nuclear News* (July 20, 2009).

[xv] "China Leverages the Learning Curve Cost Savings for Energy and the Us Attempts at Energy Research Leapfrogging," in *Next Big Future* (Aug 19, 2010).
[xvi] Korea has focused attention on its APR-1400 design, with domestic overnight costs of $2,333/kW. A recent contract for $20.4 billion has been signed with Korean consortium KEPCO to build four APR-1400 reactors in the United Arab Emirates, at $3,643/kW. This price is notable because it is under near-FOAK conditions, because these will be the UAE's first nuclear plants.
[xvii] "Testimony of Kelly Fletcher of GE," in *U.S. Senate Energy & Water Subcommittee*, U.S. Senate Appropriations Committee (Washington, DC: General Electric, Sep 14, 2006).
[xviii] John Redding, "GE's ABWR - Key Features & an Update," *Nuclear Plant Journal* (Sep-Oct 2000).
[xix] Ibid.
[xx] Biegler & Brook Nicholson, "How Carbon Pricing Changes the Relative Competitiveness of Low-Carbon Baseload Generating Technologies," *Energy* doi:10.1016/j.energy.2010.10.039 (2010).
[xxi] Barry Brook, "Sne 2060 – Assessment of Energy Demand," in *Brave New Climate* (Nov 14, 2010).
[xxii] IPCC, "Climate Change 2007: Mitigation of Climate Change," (2007).
[xxiii] *Energy Payback Times for Nuclear* (Apr 4, 2008 [cited); available from http://neinuclearnotes.blogspot.com/search?q=Leeuwen.
[xxiv] Nicholson, Biegler & Brook "How Carbon Pricing Changes the Relative Competitiveness of Low-Carbon Baseload Generating Technologies."
[xxv] Alok Jha, "Revealed: The Cement That Eats Carbon Dioxide," in *The Guardian, UK* (Dec 31, 2008).

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