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The Integral Fast Reactor (IFR): An Optimized Source for Global Energy Needs

Charles Archambeau[1], Randolph Ware[2,3], Tom Blees[1], Barry Brook[4],
Yoon Chang[5], Jerry Peterson[6], Robert Serafin[3], Joseph Shuster[1],
Evgeny Velikhov[7,8], Tom Wigley[3]

[1]*Science Council for Global Initiatives,*
[2]*Cooperative Institute for Research in Environmental Sciences,*
[3]*National Center for Atmospheric Research,* [4]*University of Adelaide,*
[5]*Argonne National Laboratory,* [6]*University of Colorado*
[7]*Kurchatov Institute,* [8]*Russian Academy of Sciences*

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Abstract

The new Generation IV nuclear power reactor (the IFR, "Integral Fast Reactor") can provide the required power to rapidly replace coal burning power plants and thereby sharply reduce greenhouse gas emissions, while also replacing *all* fossil fuel sources within 30 years. We conclude that this can be done with a combination of renewable energy sources, IFR nuclear power and ordinary conservation measures. We summarize the design and functionality of the primary component of this mix of sources, namely the IFR nuclear system, since its exposure to the scientific community and public at large has been limited. We consider the cost of replacing fossil fuels while utilizing renewable and nuclear sources to generate electricity, as well as the cost of meeting increasing national and global demand for electrical power. The amount of IFR fuel available is sufficient to supply world-wide needs for many hundreds of years without Uranium mining.

Basic IFR features:

- Closed-cycle IFR nuclear reactors extract 99% of the energy in Uranium fuel, whereas current reactors extract only 1%;
- IFR produces relatively small amounts radioactive waste with less than 300 yr toxicity, compared to much larger amounts of waste with toxicity periods >300,000 yr) produced by current nuclear power systems;
- An electrochemical "pyroprocessor" can be integrated with a fast reactor (FR) in a closed process that separates "spent" FR fuel into "fission product" waste and the new isotope fuel to be cycled back into the FR;
- This recycling process can be repeated until 99% of the original Uranium energy is converted to electrical power;
- Pyroprocessing does not separate highly radioactive isotopes produced during IFR recycling that can be used for nuclear weapons;
- If metal IFR fuel overheats for any reason, it expands and reduces its density and terminates the chain reaction, automatically shutting down the reactor -- an important passive safety feature.

Introduction and Overview

The threat of global warming and climate change has become a polarizing social issue, especially in the USA. The vast majority of informed scientists, however, are in agreement that the potential consequences of inaction are dire. Yet even those who dismiss concerns about global warming and 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% 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 draconian methods of human culling. 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 increasingly being demanded throughout developing countries. This will require a global revolution in energy and technology deployment fully as transformative as that during the Industrial Revolution but, unlike that gradual process, we now find ourselves under extreme time pressure, especially if one considers global warming and climate change to be immediate threats requiring immediate action.

It is beyond the purview of this paper to address the question of the social transformations that will necessarily be involved in confronting the challenges of the next several decades (however, see Blees, “Prescription for the Planet,” for a discussion which is helpful). But the question of energy supply is inextricably bound up with the global solution to our coming crises, and it may certainly be argued that energy production is the most crucial element of any proposed course of action. Our purpose here is to demonstrate that the provision of all the energy that will be required to meet the challenges of the coming decades and centuries is a challenge that already has a realistic solution using fourth generation nuclear reactors which are currently available, affordable and safe[1].

Our description of these new reactors will make heavy use of previous work on fast reactors and electrochemical processing ("pyroprocessing") by General Electric (see, for example, Lineberry et al., 2004) and Argonne National Laboratory, Department of Energy (see, for example, Y.E. Chang, 2002) and our summary incorporates results from this work which was completed during the period from about 1980 to the present. The books by Blees (Prescription for the Planet, 2008) and Shuster (Beyond Fossil Fools, 2008) discuss the role of the new Generation IV nuclear power systems in addressing the urgent global need for abundant/renewable and clean low-carbon sources to replace the current hydrocarbon sources. Their analysis includes comparisons among the variety of renewable energy sources that can contribute to future energy needs. We do not consider detailed comparisons with other sources in the present discussion, but confine our attention to nuclear systems alone. Therefore the reader may want to refer to these two books in particular, to get a wider comparative view of what mix of energy sources might best address both global warming and global energy needs.

Our objective here is to describe how the new Generation IV nuclear power reactor (IFR-Integral Fast Reactor) will be able to replace fossil energy sources as the principal global energy source and to also be able to supply the increasing energy demands of the future. The characteristics and capabilities of the IFR power systems which make it possible to expand the nuclear component of the global energy supply to such an extent include the following:

- IFR systems are closed-cycle nuclear reactors that extract about 99% of the available energy of the Uranium fuel (by repeated cycling of the fuel) in which the open-cycle, once-through, LWR and other open-cycle reactors, in current use, extract somewhat less than 1% of the available energy. Therefore, the IFR is more than 100 times as efficient in its use of Uranium fuel compared to any open-cycle reactor, like a LWR. This IFR capability is a consequence of electrochemical reprocessing ("pyroprocessing") of fast reactor waste material to produce new fuel for recycling.
- The waste produced by an IFR consists of a relatively small mass of "fission products" which consist of short half-life isotopes (about 30 years or less), while LWR reactors produce a large amount of "spent nuclear" waste (about 10 times the amount of an IFR) which is composed of both short and (very) long half-lived isotopes (actinides). This

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[1] Because of the necessary frequent use of specialized terminology we have added a glossary of terms at the conclusion of this report as an aid to the reader.

results in IFR waste that has rapidly declining toxicity which becomes less than that of naturally occurring Uranium ore after about 300 years, while LWR waste has radioactive toxicity levels above that from Uranium ore for a period of about 300,000 years. The large amounts of highly radioactive waste from LWR reactors require a very large facility to store even the currently accumulated waste in the U.S. To confidently ensure confinement of the LWR waste in a sealed underground repository over it's high toxicity period, which is of the order of 100,000 years[2], is not really possible given the large uncertainties in predicting the very long term behavior of a "hot repository" in a time-variable environment. On the other hand, the storage of the IFR waste, with its smaller mass and volume and much shorter toxicity time period (300 years) can be accomplished with a reasonably high confidence level in an underground repository which is open (unsealed) and has natural ventilation and water drainage outlets to help cool the whole repository, including waste canisters.

- The pyroprocessor unit can be used as a stand-alone system to process LWR waste from any open cycle reactor into fuel for IFR closed cycle reactors. The depleted Uranium produced by the enrichment of Uranium ore can also be processed to generate additional IFR fuel. The current amount of LWR waste, plus the amount of depleted Uranium in stock piles world-wide, is sufficient to supply fuel to all the IFR plants needed and in fact to supply the world's required energy for about *1000 years*.[3] The problem of storage of current LWR waste and depleted Uranium waste from refining of mined Uranium is therefore solved by pyroprocessor generation of IFR fuel, along with a relatively small mass of short-lived fission products which can be easily and safely stored. Uranium can also be extracted from sea water using IFR power sources (see, for example, Cohen, 1983). Because Uranium is constantly added to seawater by erosion processes, then the IFR fuel source is effectively unlimited. Therefore, IFR power plants do not require fuel from regular mining operations, as does a LWR powered plant, but can use pyroprocessor generated fuel essentially indefinitely. In this sense the IFR is a "renewable" energy source which can be expanded, essentially indefinitely, to meet demand.

- The IFR fast reactor uses metal fuel rather than one of the oxide fuels which are used in LWR and other Generation II and III reactors. The metal fuel expands when heated, so in the event of accidental reactor core over-heating, the density of the metal fuel will rapidly decrease and cause a rapid drop in the number of neutron collisions with Uranium atoms per unit volume of fuel. This drop will result in a termination of the nuclear chain reaction. Hence reactor core overheating from any cause will result in a fuel density decrease followed by a termination of the chain reaction and the automatic shut down of the reactor. This whole reaction chain is called a passive shut-down because no operator action, or automatic electronic sensor driven feed-back system, is needed. This passive safety feature is an important and robust addition to fast reactor operational safety which is not found in LWR and other open cycle reactors. Consequently, the resistance to core melt-down in these IFR reactors is extremely high, with near vanishing probability of such an event occurring in the life-time of the reactor. As well as metal fuel use, the IFR uses metal

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[2] Initially the Nuclear Regulatory Commission (NRC) specified a 10,000 year integrity requirement for the repository at Yucca Mountain. Later it was raised to 50,000 years, and currently the repository has been abandoned altogether.

[3] The total global electrical energy probably will be about 100 Quads per year, or about 30 trillion kilowatt-hours per year, by mid-century.

coolant (sodium preferred) which allows safe operation at high output temperatures leading to greater efficiency and lower reactor fabrication costs. The IFR metal coolant pool is also a large heat sink which safely absorbs the excess heat in the reactor core after passive shut-down.

- The new features of the IFR systems with pyroprocessing are such that the cost of electrical energy production is estimated to be quite low, in the range below $.01 per kilowatt-hour for an IFR. (For comparison, natural gas fuel cost was at $.05 per kilowatt-hour, and coal was at about $.03 per kilowatt-hour, while LWR nuclear power was at $.02 per kilowatt-hour.) The G.E. estimated building cost of the S-Prism reactor (Fletcher, 2006) is $1300/kw, where this cost assumes some cost savings due to mass production and modular construction. For a commercial level gigawatt reactor (using 3 modular S-Prism reactors with 380 MW of power from each) the cost would total $1.3 billion dollars per one gigawatt plant. These nuclear plants are essentially carbon dioxide emissions free, and in general produce no atmospheric pollution. Further, all the Uranium fuel can be provided from processing the stock piles of spent and depleted Uranium fuel. Therefore, no Uranium mining and associated pollution will occur. Likewise, IFR waste material is minimal and short-lived so that no pollution will occur from this source. Consequently, significant reduction in greenhouse gases, and a variety of other dangerous pollutants, can be immediately achieved if these IFR plants are used to replace the furnaces in coal burning power plants which exist in profusion world-wide. Here the infrastructure at existing coal fueled plants, such as electric power lines, water sources and conduits, steam turbines, etc., can all be simply converted and used in the nuclear powered plant. Hence, costs of building complete power plants and their electrical connections to the grid can be minimized while the impact on global warming and pollution related diseases can be maximized by replacing the worst of the polluters. Further, it is urgent that we move quickly to strongly and immediately control CO_2 gas emissions to drastically slow global warming. Clearly, the costs are not prohibitive since construction of one large stand-alone pyroprocessing plant, at about 6 billion dollars, and only about 10 of the large IFR powered plants, costing under 20 billion dollars, will go a long way toward strongly dampening the massive production of CO_2 emissions from existing electricity power plants in the U.S.

In the following sections, we describe how the IFR is designed to have the functionality required to achieve these capabilities.

Nuclear Power Reactors: History and Status

The vast majority of the world's 400-odd nuclear power plants are light-water reactors (LWRs) that use so-called "enriched Uranium". Natural Uranium is comprised primarily of two isotopes: U-235 and U-238 with the former comprising only 0.7% of the total mix and U-238 accounting for the remaining 99.3%. LWR technology requires a concentration of at least 3.5% of U-235 in the Uranium mix in order to maintain the chain reaction used to extract energy. Consequently, Uranium enrichment is used to extract as much of the U-235 as possible from several kilos of natural Uranium and add it to a single fuel kilo in order to reach a concentration high enough to enable the fission process to proceed. Because current technology is capable of harvesting only a modest percentage of the U-235, this "enrichment" process 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, who've been employing nuclear power over the last half-century, also 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 Generation III+ designs, to differentiate them from currently-used LWRs which are normally referred to as Generation II plants. The European Pressurized Reactor (EPR), currently being built by AREVA (the French nuclear power agency) in Finland, is an example of a Generation III design. It utilizes multiple-redundant systems to assure safety and dependability. Two examples of Generation 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 Generation 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 using either operator action or electronic feedback to shut down. (The passive safety features of the Generation III+ are discussed in the following section that describes Generation IV, IFR Reactors.)

The first nuclear reactor of any type to produce electricity was the Experimental Breeder Reactor I (or EBR-I), located at what is now known as the Idaho National Laboratory, previously a western branch Argonne National Laboratory. This achievement occurred in 1951. 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 reactor in use around the world today.

But research had continued with the breeder reactors, which are now termed "fast (neutron) reactors". The first of these, the EBR-I, was shortly followed by the EBR-II, a larger and more sophisticated fast reactor that was fueled with metal fuel as opposed to the oxide fuel used in virtually every other reactor design in use today, including the few fast reactors currently online. In addition to the metal fuel, the EBR-II and later fast reactor designs used liquid metal coolants to achieve efficient high temperature operation.

Eventually the Generation III line of reactors led to the Generation IV "Integral Fast Reactor" (IFR) design. Here the term "Integral" refers to the integration of an electrochemical processing system in tandem with the Fast Reactor (essentially an EBR-II reactor). This "attached" processing system is designed to separate the fast reactor "waste" into reprocessed Uranium, metal fuel (MF) and waste fission products (FP). The reprocessed Uranium and the metal fuel are repackaged and recycled through the Fast Reactor, while the waste fission products are stored temporarily on-site as High Level Waste (HLW). This IFR design, which includes an attached electrochemical processing component (a "pyroprocessing unit"), is therefore a closed cycle system, while previous Generation II and III systems were open cycle systems.

Pyroprocessing of Spent Nuclear Fuel for Reactor Recycling

A schematic of the spent fuel pyroprocessing shows that used fuel rods, chopped into small pieces, are loaded in an anode basket (Figure 1). One type of cathode on the electro-refining unit of the pyroprocessor recovers Uranium, and a second cathode recovers all other actinide elements together. A photograph of the Electrorefiner component, along with a mockup of the entire Pyroprocessor system are shown in Figure 2.. The anode basket that contains cladding hulls and noble metal fission products is melted into a metallic high-level waste form. Electrolyte salts that contain most of the fission products are passed through zeolite columns. Fission products then get immobilized into the zeolite molecular structure through ion exchange and occlusion. The zeolite powder is then mixed with glass frits and melted at high temperature to form a ceramic waste form called sodalite.

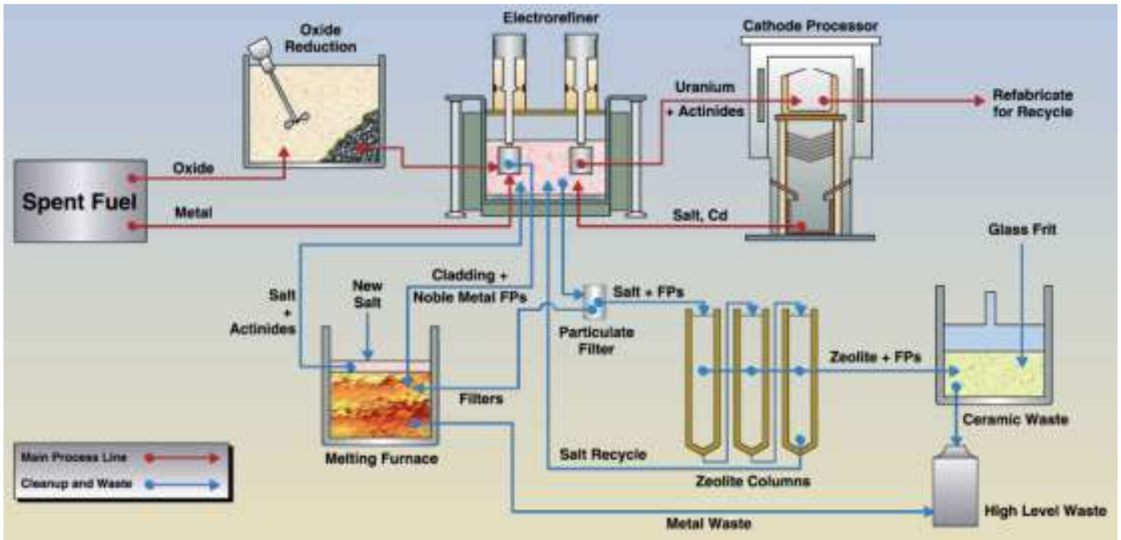

Figure 1 - Pyroprocessing methods developed and demonstrated at Argonne National Laboratory (Chang, 2002).

Figure 2 - Pyroprocessing system (mockup - left) and Electrorefiner component (photo - right).

Pyroprocessing was originally developed for integration with a fast reactor, but it can also be used in a stand-alone mode to treat spent fuel from today's commercial reactors with the addition of a front-end step to convert the used oxide fuel to metallic form. Pyroprocessing eliminates the ability to use the reactor's nuclear materials directly in weapons because it cannot separate out any

Plutonium (Pu). Instead, it keeps the major nuclear fuels, Uranium and Plutonium mixed, at all times, with other actinides and fission products. This mixture is protected against theft or unauthorized diversion because the mixture is extremely radioactive and must be handled remotely with sophisticated and specialized equipment.

As indicated by Figure 2, pyroprocessing involves compact equipment systems and the fuel cycle facility can easily be collocated with the reactor plant, eliminating the need for nuclear fuel transportation. In pyroprocessing, the actinides are easily recovered and recycled back into the reactor for fissioning.

As shown in Figure 3, the effective lifetime of the waste is reduced from hundreds of thousands of years to a few hundred years, at the same time generating energy by "burning" actinides. This does not obviate the need for a repository, but the technical performance requirements placed on the repository can be met much more easily without the long-lived actinides. Furthermore, the repository capacity can be increased substantially because the long-term radioactive heat source is eliminated.

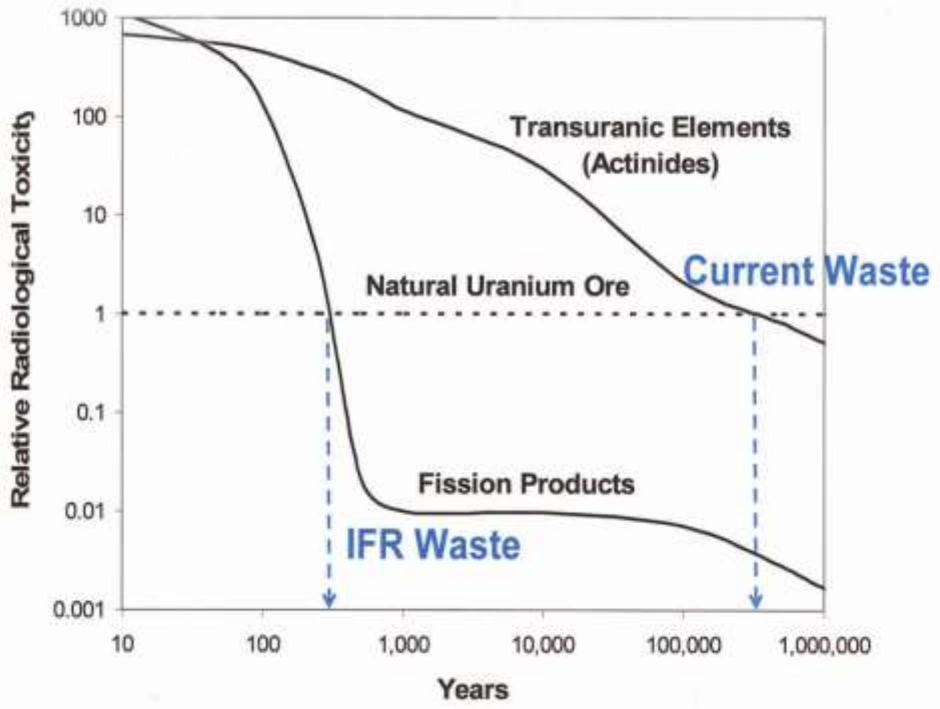

Figure 3 - Relative radiological toxicity versus time for IFR and LWR waste.

This fuel cycling technology, developed at Argonne National Laboratory, is an extremely important addition to the fast reactor design since it allows about 99% of the energy available in the Uranium fuel to be extracted. Further, it reduces the mass and toxicity life-time of the waste produced, by factors of 10 and 1000 (respectively), below that produced by the widely deployed Light Water Reactors (LWR's).

Pyroprocessors can also be designed to operate in a stand-alone mode capable of processing existing waste from LWR systems. Such high level waste is enormously plentiful (the world-wide amount is not accurately known) but it is the order of 600,000 tons in the U.S., not including weapons waste. Therefore, stand-alone pyroprocessing units can produce a very large Uranium fuel stockpile for use in fast reactors. Further, the volume and mass of the waste generated by the pyroprocessing is an order of magnitude less than that generated by LWR systems, which makes the IFR waste much simpler to store than is the case for LWR and other "open-cycle" nuclear waste. As show in Figure 3, the toxicity of the IFR waste is reduced to the level of naturally occurring Uranium ore after only about 300 years. The upper curve shows the time variation of the LWR waste toxicity, which does not reach the Uranium ore threshold level until about 300,000 years after its creation. Thus, the smaller IFR waste product is therefore far easier to store safely in a repository over its relatively short life-time than is the case with LWR reactor waste, given its large bulk and very long toxicity period.

Integral Fast Reactors: Basic Features

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 atom of Uranium and cause it to split, thereby perpetuating the chain reaction. In a fast reactor, the neutrons move at a considerably higher speed, and for this reason the fissile content of the fuel must be higher, so that more neutron-atom interactions will occur. In an IFR the fissile concentration is about 20% as opposed to the 3.5-5% concentration in a LWR.

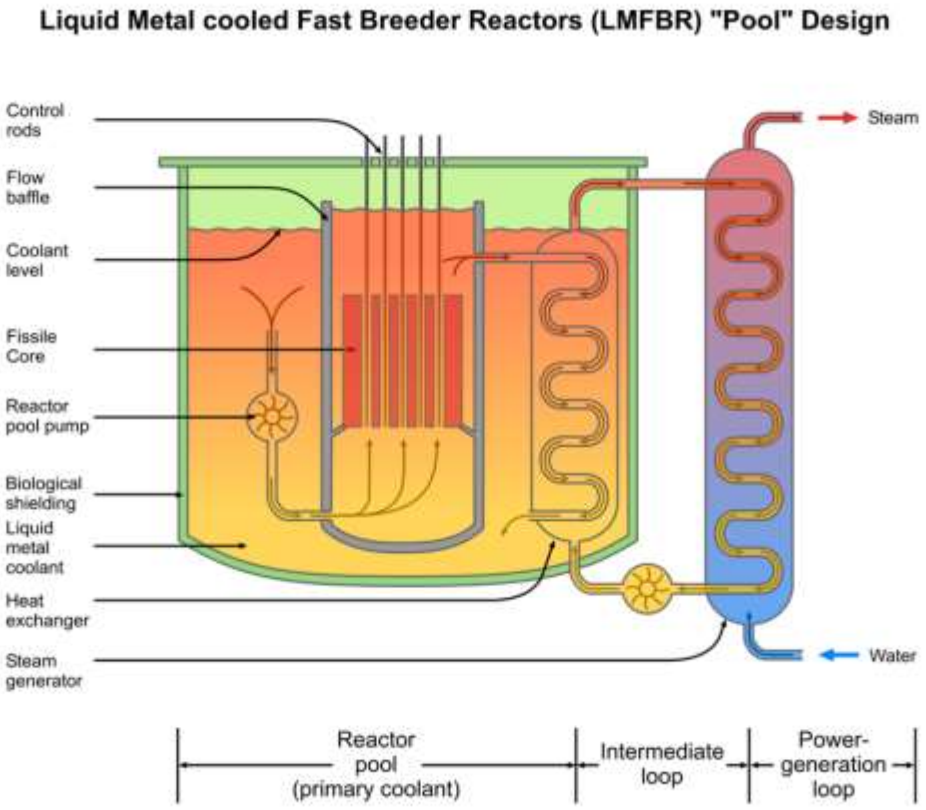

Figure 4 - Sodium cooled fast reactor schematic.

LWRs operate with water under pressure, hence the concern about pressure vessel leaks, coolant system leaks, and steam explosions. There is also 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 at or near atmospheric pressure, 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 which is also much higher than the 320ºC of Generation III reactors. Figure 4 shows a simplified rendering of a sodium-cooled fast reactor which illustrates the basic design features employed in an IFR.

As can be seen from the figure, the heat exchanger loop contains *non-radioactive* sodium which is piped to a heat exchanger, in a separate structure, where it gives up its heat in a water/steam loop that drives a conventional 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 released and the reactor vessel itself would be unaffected. Such an event, however unlikely, would probably 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 where operators, for whatever reason, failed to insert the control rods to scram the reactor, the passively-safe system, involving the active features of metallic fuel, would nevertheless shut the reactor down safely. Further, the large amount of sodium coolant in the reactor vessel would allow the heat from the core to be dissipated. The shut-down happens because overheating of the reactor core also overheats the metal fuel and results in neutron leakage which rapidly terminates the chain reaction. Therefore, a reduction in neutron-atom interactions due to a fuel density decrease from heating produces an effective passive shut-down response without operator action or electronic feedback from external sensors.

The passive safety characteristics of the IFR were tested in an EBR-II reactor on April 3, 1986. Two of the most severe accident events postulated for nuclear power plants were imposed. 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, the EBR-II smoothly returned to a safe condition. The same features responsible for this performance of EBR-II are to be incorporated in the design of all future IFR plants.

While the IFR was under development, a consortium of American companies, led by General Electric, collaborated with the IFR team at Argonne 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 MW) is called the S-PRISM. As with all new nuclear reactor designs, probabilistic risk assessment studies were conducted for the S-PRISM. These studies produced very low failure probabilities, well within the range acceptable for commercial licensing. The S-Prism fast reactor is therefore the reactor system of choice for the IFR.

The closed cycle processing of fast reactor fuel (Uranium plus about 11% of other actinides) is illustrated in the mass-flow diagram of Figure 5. This example is appropriate to a commercial sized IFR. The stand-alone pyroprocessing of Light Water Reactor (LWR) waste is indicated at the top of the mass flow column and produces the initial inventory (90 tons) of fuel for the IFR, a one gigawatt reactor, from a stock pile of 700 tons of LWR waste which will supply the processed fuel to last for the lifetime of the reactor. The output from pyroprocessing of the spent fuel results in 35 tons of fission product waste, which can be stored on site for the lifetime of the reactor and then moved to a permanent repository site.[4] In addition 575 tons of Uranium is produced and stored separately in a "used Uranium reserve" from which used Uranium is to be withdrawn for additional fuel to the IFR reactor.

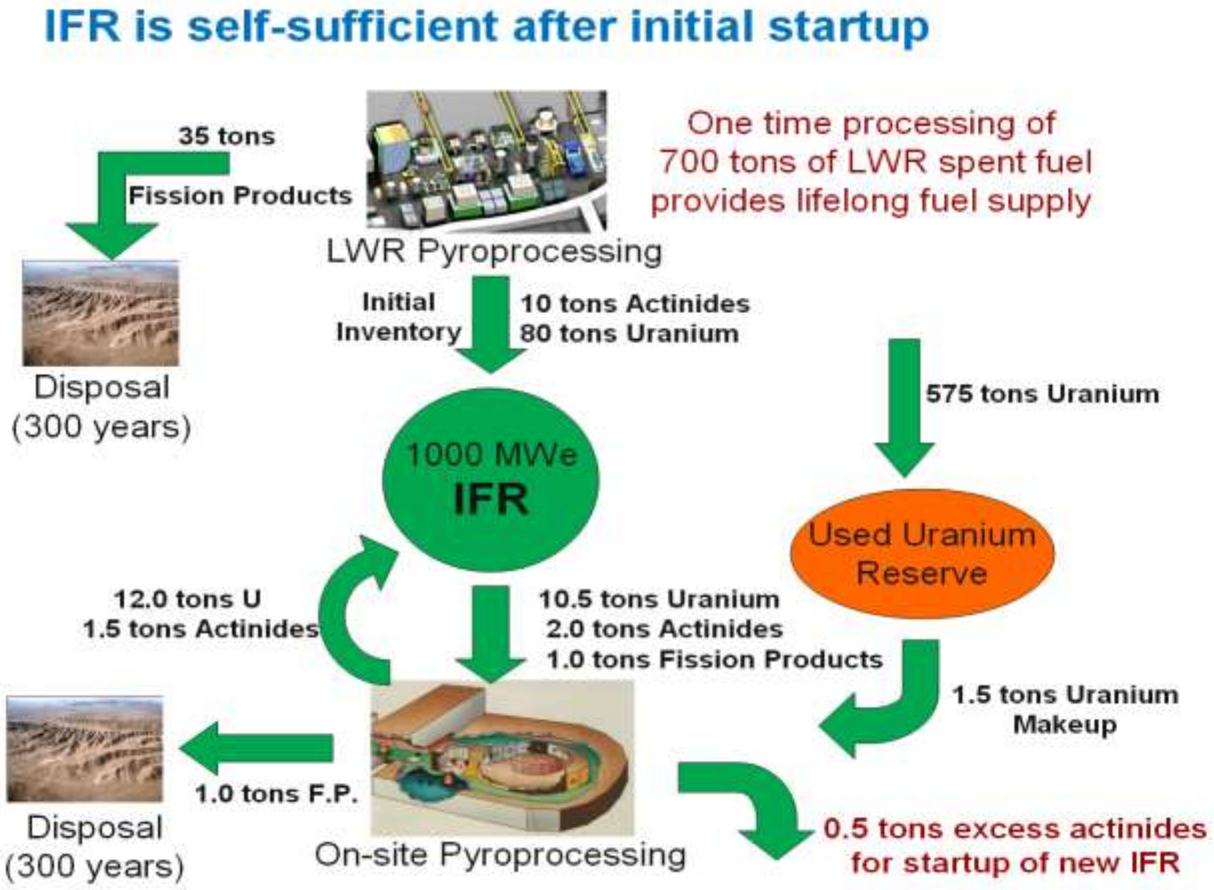

Figure 5 - Mass flow diagram for off-line stand-alone pyroprocessing facility using LWR waste to provide fuel for a gigawatt IFR operating in the closed cycle mode.

The "Initial Fuel Inventory" of 10 tons of actinides and 80 tons of Uranium produced by the off-line pyroprocessor is then used to initiate the first cycle of the IFR's fast reactor and on-site pyroprocessor. The IFR produces 10.5 tons of Uranium, 2 tons of actinides and 1 ton of Fission Products (short-lived isotopes) after the first "burn cycle" and all remaining cycles. The fission products are sent to a high level waste repository or are stored temporarily at the plant site. The Uranium and actinides are sent back to the fast reactor, after adding 1.5 tons of Uranium from the

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[4] Note that the small picture labeled “Disposal” in Figure 5 is a photograph of the Yucca Mountain site at the Nuclear Test Site (NTS) in Nevada. This site was proposed as a high level waste (HLW) repository for LWR waste. The site has not, however, been approved for future consideration and a DOE panel has been formed to evaluate other methods of LWR waste disposal. The Yucca Mountain site could nevertheless be safely used for the much shorter lived IFR waste, provided a few modifications are incorporated into the repository design.

reserve to the pyroprocessor output, to begin the next reactor cycle. Note that after each cycle an excess of actinides is sent from the pyroprocessor as fuel for a new IFR start-up.

The important features here are the small mass of waste produced and the relatively short time (300 years) required for containment in a repository, as well as the very high efficiency achieved by closed-cycle operation which burns all actinides and extracts 99% of the energy available from the original Uranium fuel.

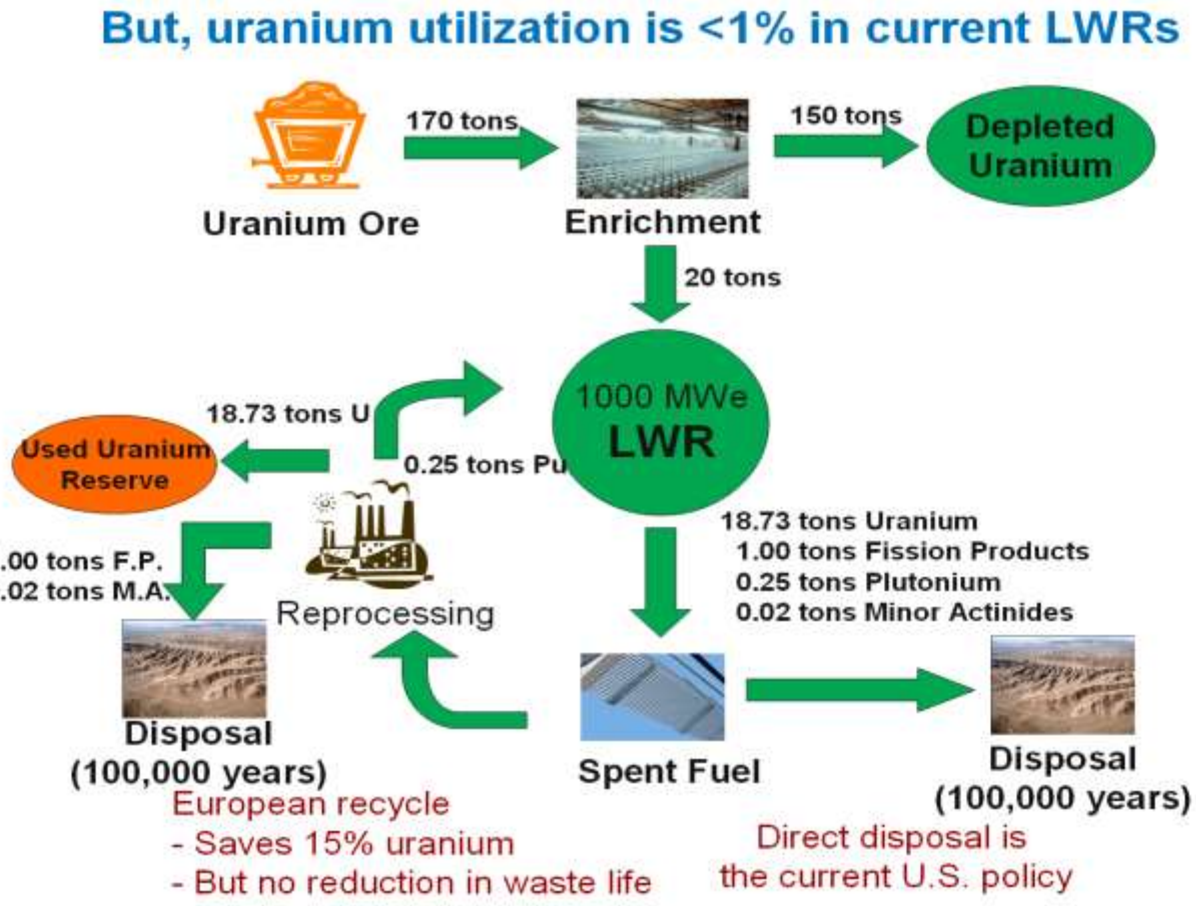

Figure 6 - Mass flow diagram for an off-line enrichment of mined uranium ore to provide fuel for a gigawatt LWR operating in the open cycle mode.

Figure 6 shows the mass flow for Generation II light water reactors, with and without an off-site reprocessing system that separates the LWR spent fuel into its chemical parts. In particular, it separates out .25 tons of plutonium which is "burned" by the reactor, and 1 ton of fission products and .02 tons of minor actinides, both to be stored in an off-site repository. This reprocessing system is used in Europe, while the U.S. policy is to package the waste ("spent nuclear fuel") in steel and concrete containers suitable for transportation and safe storage in a national repository. However, none of the U.S. high level waste has ever been stored in such a repository, as the only proposed repository at Yucca Mountain has not been licensed by the Nuclear Regulation Commission to accept HLW. Currently power plant waste is stored on site and has grown to constitute a hazard which must be addressed very soon.

The European recycle option produces waste which still has actinides with long half-lives, so that the radioactive waste high toxicity duration is still on the order of 100,000 years. Further, the separation of plutonium for recycling can be subverted for weapons development by militants. Therefore, without on-site pyroprocessing the accessibility to plutonium from chemical reprocessing presents nuclear weapons proliferation problems, and the actinides in the reactor waste present long-time storage problems.

On the other hand, the LWR plants are wide-spread and growing in number. Their use creates large stockpiles of "Depleted Uranium (DU)" from Uranium enrichment, as indicated in Figure 6, as well as large amounts of "Spent Nuclear Fuel" obtained directly from the LWR reactor. Both of these are sources of IFR fuel, after the LWR waste and DU have been pyroprocessed. Therefore shipping the LWR waste, both that stored on site and that continuously generated, along with DU to a stand-alone pyroprocessing facility for IFR fuel generation will solve all the LWR waste problems and allow the current LWR reactors to be used over their normal lifetimes. Of course this requires that the IFR waste, which is much less massive and has a relatively short life time, presents no difficult storage problems. Based on our previous analysis and experience, we do not foresee any insurmountable containment problems involving IFR waste at a well-designed repository.

Therefore, it is eminently reasonable to use LWR power plants for their full life expectancy, along with IFR plants established in large numbers. One option is to first replace all fossil burning power plants (coal, gas and oil as fuels) and then add new IFR plants to meet the expanding demand for electric power due to population growth and rapid economic growth world-wide. (This must take place globally rather in just some "wealthy" countries, so that replacing plants in India is as important as it is in the U.S. since, for example, global warming and its causes, do not respect national borders.)

Applications and Costs

Nuclear power development, in the U.S. at least, has followed a long and rocky road,[5] with both real and imagined problems slowing and sometimes stopping what probably could have been a more rapid evolution into a mature technology which is both very safe and very powerful. This technology, as embodied in its current form as an IFR, Generation IV closed-cycle nuclear reactor system, is capable of near continuous operation and a remarkably efficient extraction of energy from its Uranium fuel. Further, its built-in safety features including the passive safety properties of the metal fuel to overheating, make the IFR systems inherently safe, with very low failure probabilities, over their entire life-time of operation. A major addition to the fast reactor unit has been the "pyroprocessor", which processes "spent fuel" from the reactor into new reactor fuel, plus a small amount of short-lived "fission product" waste. Consequently, this allows cycling of the fast reactor-pyroprocessor combination (i.e. an IFR) to form a closed-cycle power unit which can extract over 99% of the accessible energy stored in the original Uranium fuel. The waste material produced during the fuel recycling in an IFR is a small fraction of the input mass (about 5% of the origin fuel mass) and can be temporarily stored on site and later transported to a repository for safe long-term (200-300 years) storage. Finally, pyroprocessing can be used in a stand-alone mode to process current nuclear power plant (LWR) waste in order to generate IFR fuel and a much reduced amount of short-lived radioactive waste, and also rid us of the highly radioactive, long-

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[5] See Blees (Prescription for the Planet, 2008) for a more compete description of this rocky road.

lived, nuclear waste that has accumulated in huge amounts world-wide. The IFR fuel which can be produced is estimated to be enough to provide fuel for a global distribution of IFR power plants which can provide enough electrical energy for the world's needs for hundreds of years. Consequently, mining uranium fuel for a large network of IFR power plants is not necessary (not now or probably ever). Clearly, costs of operation of IFR power plants will be significantly reduced because of this accessibility to large stockpiles of low cost fuel.

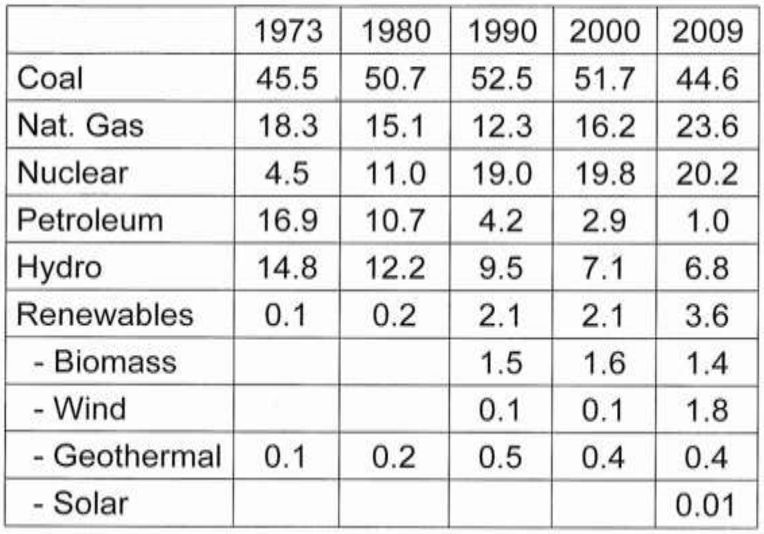
Given all this capability and functionality, it seems that the only critical question at this point is one of cost. That is, we can and should build these nuclear power plants to address specific important problems, but do we have the resources to do so? To find out, we need to specify the problems which should be addressed. Two that are most time-critical are: (1.) mitigation of global warming and climate change by replacement of coal burning power plants, and (2.) meeting the need for increased energy production in the near future in order to deal with world population growth and the rapid expansion of economies in developing countries.

To gauge the size and cost of these problems we need to see where we are now since we want to modify (in [1.] above) and next expand (in [2.] above) the national and world-wide energy output. The current mix of sources for U.S. electrical output, from 1973 to 2009, is shown in Table 1. This table shows the rapid increase in use of nuclear power from the middle 1970's to the middle 1980's, followed by the long plateau from the mid 80's to the present. Coal on the other hand, has increased slowly, in keeping with the population increase, and only recently has had a sharp decline, during 2000 to 2009. This decline might likely be attributed to concerns over coal plant pollution along with the increased use of renewable energy sources rather than coal derived power.

In any case the modification to the use of coal fired plants would replace coal plants by IFR powered electrical plants, so that in a relatively short time, say 10 years, the 44.6% coal contribution could be absorbed by a mix of nuclear, renewables and natural gas sources. In the following 20 year interval (2020-2040) the remaining fossil fuel driven energy production could be reduced, with only a modest (about 10% of the total) use of natural gas remaining by 2040. During this 30 year period, from roughly 2010 to 2040, the total energy requirement is expected to increase in the U.S. by a factor of almost two (from 14 Quads to 25 Quads, (where 1 Quad = 294 billion kWh) and the world increase in electrical energy use is roughly from about 40 Quads to about 100 Quads.

To be able to estimate the cost of such an undertaking we need to know not only the cost of the IFR power plants, including costs of electric grid expansion, etc., but also the operational costs of producing the electric power, including costs of pyroprocessed fuel and waste disposal. Figure 7 shows the direct electrical energy production costs per kilowatt-hour for coal, natural gas, nuclear (LWR power plants) and petroleum. Notice the high and erratic costs for petroleum, no doubt reflecting oil price fluctuations, also probably the origin of the rapid decline in the use of petroleum as a fuel for generating electricity, as shown in Table 1.

Table 1 - Trend of U.S. electricity by fuel type (% total)



	1973	1980	1990	2000	2009
Coal	45.5	50.7	52.5	51.7	44.6
Nat. Gas	18.3	15.1	12.3	16.2	23.6
Nuclear	4.5	11.0	19.0	19.8	20.2
Petroleum	16.9	10.7	4.2	2.9	1.0
Hydro	14.8	12.2	9.5	7.1	6.8
Renewables	0.1	0.2	2.1	2.1	3.6
- Biomass			1.5	1.6	1.4
- Wind			0.1	0.1	1.8
- Geothermal	0.1	0.2	0.5	0.4	0.4
- Solar					0.01

The cost curve in Figure 7 nuclear plant (LWR) production has been close to that for coal since 1995, although recently somewhat lower. The current nuclear cost will be higher than those for IFR power plants, largely because of the much lower Uranium fuel costs for pyroprocessed IFR fuel and the much higher efficiency of the IFR compared to an LWR power plant, as well as the much lower IFR waste storage costs. Therefore, it seems conservative to assume that an IFR power plant would produce a cost curve lower than that for a LWR plant, by at least a factor of two. Therefore, for 2010 and beyond, a production cost of $.01 per kilowatt hour seems a reasonable upper limit production for IFR units. But, in any event, the direct operational costs for an IFR power plant are likely to be well under the costs for fossil burning plants.

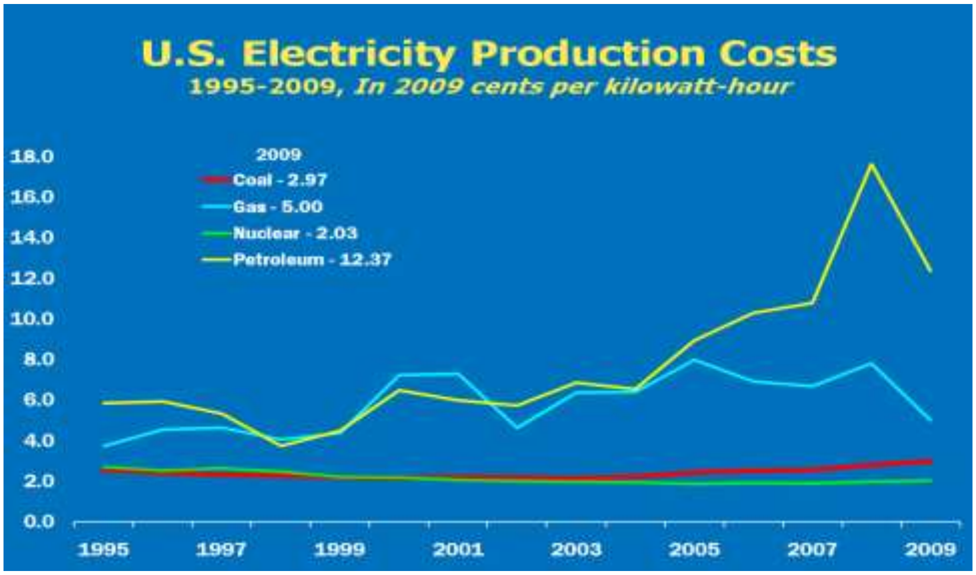


Figure 7 - Electricity production costs for coal, gas and petroleum fired power plants and for LWR nuclear plants for 1995-2009, in 2009 cents per kilowatt-hour[6].

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[6] The electricity production costs are only for the costs of operating the power plant and do not include grid costs and losses associated with transmission, waste disposal costs, etc.

While not shown here the direct costs for renewables (wind, solar, etc.) turns out to be close to the nuclear cost curve, when they are actually operating and generating electric power. However, if the sunless or windless "down-time" is accounted for by using an average energy production which includes times when there is no production, then, with this adjustment, the cost efficiency of renewable energy sources drops and the average cost per kilowatt hour increases. This increase is large and consequently the average cost curves for the renewable sources are much higher than those for nuclear power plants. These higher costs are to some extent misleading however, since the renewable energy sources will be used with nuclear sources which can fill-in the gaps in the generation of electricity by the renewable sources, so that viewed together the combination has a cost curve that is at about the same cost level as that for nuclear alone. Therefore, since we propose to use both nuclear and renewable sources to eliminate fossil sources (coal, natural gas, petroleum) in the future, for our purposes we can regard them as having nearly the same cost curve. This makes estimating the total costs of a mixed nuclear-renewable global energy system a much easier task.

In this regard, Shuster (2010) has estimated the cost of building and operating a network of IFR and renewable energy sources to eliminate coal and oil fueled power plants entirely by 2040. The replacement of gas fired plants (only 12% of the total in 2040) could take place in the years following 2040, so that all hydrocarbon based fuels would be eliminated from the U.S. and global energy source mix by about 2050, provided the rate of fossil fuel replacement is continued beyond 2040.

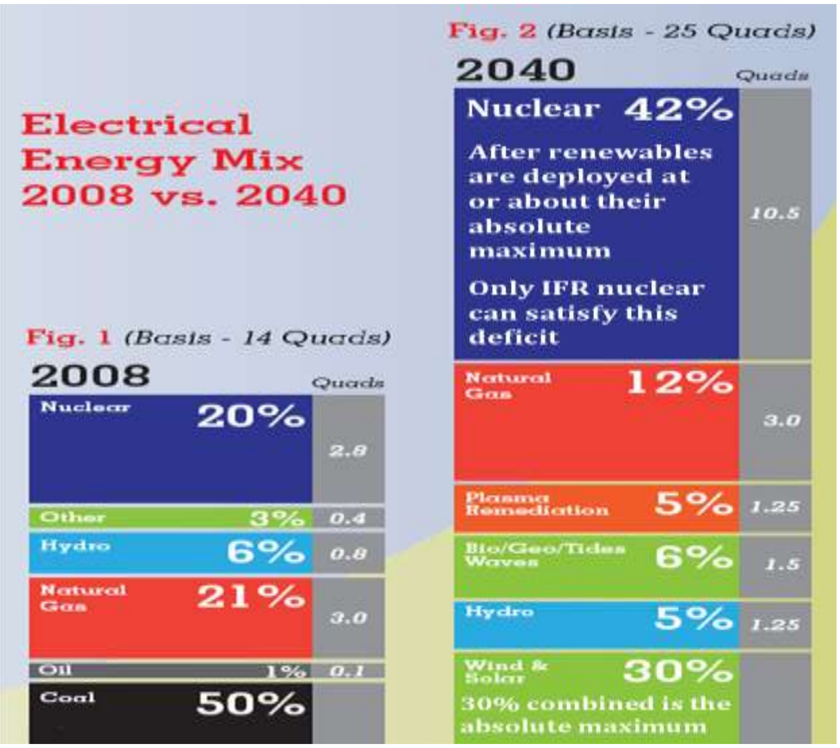
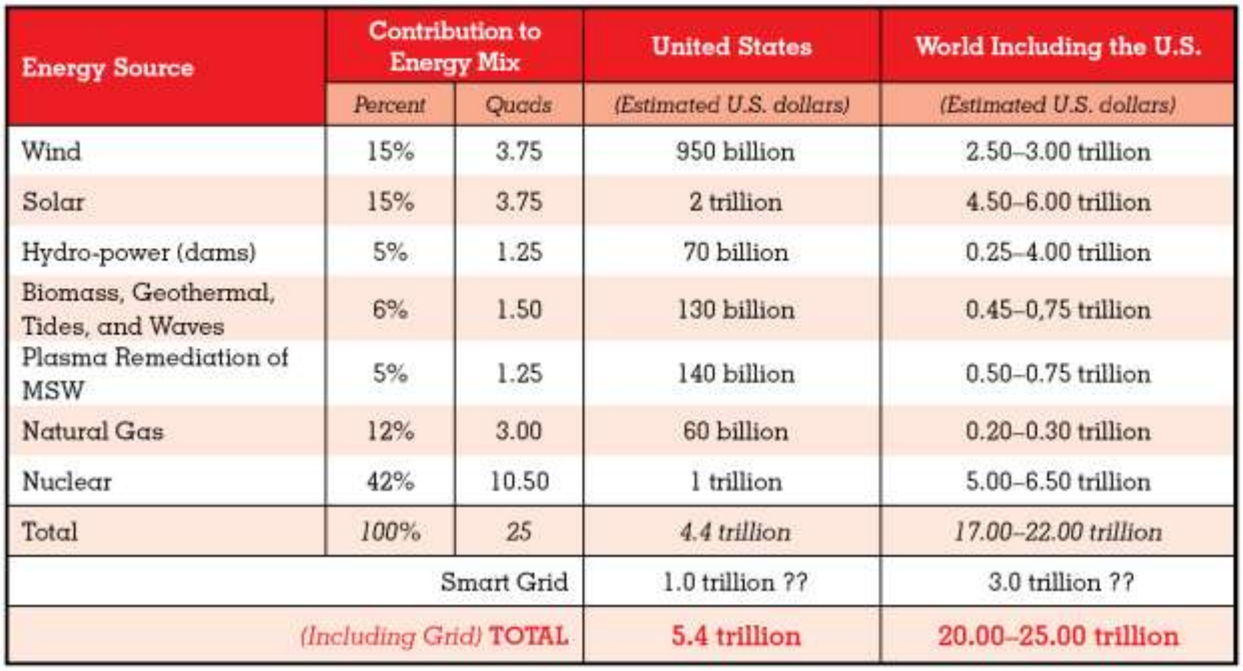


Figure 8 - Electrical energy mix 2008 vs. 2040.

Figure 8 shows the mix of electrical energy sources for the U.S. in 2008. The present one, for 2010, is expected to be close to that shown for 2008. The energy supplied to the electrical grid by the various sources is shown on the right side of the figure (in the grey colored stripe). The electrical energy amounts are specified in Quad units, where one Quad is equal to 294 billion kWh. The desired mix of sources is shown for 2040 and is quite different than that shown for 2008, where 50% of the energy from the total mix is from coal, which is replaced along with the small contribution from oil, by additions from the renewables and nuclear (IFR) sources. The approach taken in replacing coal-oil from the mix is first to expand the renewable energy contribution to the maximum contribution that is considered to be feasible by 2040. This expansion is to 30% (15% wind, 15% solar power) of the total estimated energy needs in 2040. The remainder of the 2008 coal contribution is replaced by 22% increase in the nuclear source contribution, to a 42% level.

It should be noted here that the electrical energy used in 2008 (14 Quads) and that expected to be used in 2040 (25 Quads) are partitioned by the percent to be supplied by each energy source type. It is assumed, in specifying an estimation of 25 Quads as the yearly electrical energy consumption by 2040, that there has been a 30% reduction in the consumption level through conservation measures.

Table 2 - Additional capital estimates needed to increase 2008 electrical energy output to the amount required in 2040.



Energy Source	Contribution to Energy Mix		United States	World Including the U.S.
	Percent	*Quads*	*(Estimated U.S. dollars)*	*(Estimated U.S. dollars)*
Wind	15%	3.75	950 billion	2.50–3.00 trillion
Solar	15%	3.75	2 trillion	4.50–6.00 trillion
Hydro-power (dams)	5%	1.25	70 billion	0.25–4.00 trillion
Biomass, Geothermal, Tides, and Waves	6%	1.50	130 billion	0.45–0,75 trillion
Plasma Remediation of MSW	5%	1.25	140 billion	0.50–0.75 trillion
Natural Gas	12%	3.00	60 billion	0.20–0.30 trillion
Nuclear	42%	10.50	1 trillion	5.00–6.50 trillion
Total	*100%*	*25*	*4.4 trillion*	*17.00–22.00 trillion*
		Smart Grid	1.0 trillion ??	3.0 trillion ??
		(Including Grid) **TOTAL**	**5.4 trillion**	**20.00–25.00 trillion**

Table 2 turns all the increases between 2008 and 2040, as given in Figure 8, into estimates of additional capital needed to increase the 2008 electrical energy output to the amount required in 2040. These additional costs for the U.S. are over 5 trillion for the U.S. and in the range of 20 to 25 trillion for the world. These are certainly very large amounts that can, of course, be spread out over 30 years so that, for example, 5 trillion for the U.S. would average about 170 billion per year which is still very large but possible under the right conditions.

The threat of global warming and climate change might be enough to push a funding program of this magnitude forward, but added delay, of any significant length, would endanger the effectiveness of reduced greenhouse emissions. This could then easily lead to a runaway heating of the planet's atmosphere, without a chance to damp it down by strongly limiting CO_2 emissions. As was observed in the Introduction, the consequences of inaction (in funding in this instance) would be dire.

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Glossary

Actinide: 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 man-made actinides resulting from neutron capture and are produced mainly in fission reactions.

AP-1000: A Generation III light water reactor from Westinghouse that utilizes modular construction and passive safety systems similar to those that are employed in IFRs.

AREVA: France's nuclear power agency that oversees all aspects of the process, from mining to waste disposal.

Beta decay: In beta decay, a neutron is converted into a proton while emitting an electron and an anti-neutrino. Because the number of protons in the nucleus is different for each element, beta decay changes one element into another.

EBR-II: The experimental Breeder Reactor that demonstrated the feasibility and safety of the IFR concept, successor to the earlier EBR-1.

Fast Neutron Reactor (FNR): Also called Fast Reactor (FR). In a fast neutron reactor, the fission chain reaction is sustained by energetic neutrons. A fast neutron reactor can extract energy via fission from all types of Uranium, including depleted Uranium. Through conventional thermal reactors also produce excess neutrons, fast reactors can produce enough of them to breed more fuel than they consume. Such designs are known as fast-breeder reactors.

GW: gigawatt, equal to a thousand megawatts. A typical large power plant would produce about one gigawatt of electric power.

Half-life: The amount of time for a radioactive substance to spontaneously decay to half its initial amount.

HLW: High level nuclear waste, where high level means high radioactive toxicity for humans and animals. There are also low level waste repositories which are licensed to store materials with low radioactive toxicity which are only toxic for humans after long and close exposure.

IFR: Integral Fast Reactor: A fast reactor plant that incorporates a pyroprocessing system on site for closing the fuel cycle, assuring that weapons-grade material will never be separated out and that actinides will never leave the power plant unless needed as startup fuel for new fast reactors.

Joule: A unit of electrical energy equal to the work done when a current of one ampere passes through a resistance of one ohm for one second. One joule per second equals one watt of power.

Kilowatt hour (kWh): Commonly used unit of electrical energy production or consumption equivalent to power in units of kilowatts times the time, in hours, of output from the power source.

Kilowatt: A unit of power equal to 1000 watts.

LMR: Liquid Metal Reactor: A fast reactor cooled by a liquid metal, such as sodium, lead or a lead-bismuth alloy.

LWR: Light Water Reactor: A nuclear reactor using regular water (as opposed to "heavy water") as a moderator to slow down the neutrons during the fission process. Most reactors in use today are LWRs.

Moderator: A substance used to slow down ("moderate") the neutrons in a thermal reactor. The most commonly used moderators are light water, heavy water and graphite.

MW: Megawatt, equal to one million (10^6) watts, or a thousand kilowatts.

NRC: U.S. Nuclear Regulatory Commission tasked with design, certification and oversight of all civilian nuclear power plants in the U.S.

Power: Work done or energy transferred per unit of time expressed in units of watts or joules per second.

PRISM: Power Reactor Innovative Small Module. An advanced liquid reactor designed by General Eclectic, the type of reactor that would be coupled with pyroprocessing facilities to make up an IFR system.

Pyroprocessing: A generic term for several kinds of pyrometallurgical reprocessing. In a fast neutron reactor this term refers to a process that recycles spent fuel at the reactor site.

Quad: One quad equals one quadrillion BTU or about 294 billion kWh.

Repository: An underground storage facility usually consisting of a network of tunnels and/or rooms designed to isolate and store sensitive or dangerous materials, particularly radioactive materials.

S-PRISM: Super-PRISM. The scaled-up version of GE's PRISM reactor at 380 Megawatts operational power.

Terawatt. A unit of power equal to one trillion (10^{12}) watts.

Thermal reactor: A nuclear reactor that uses ordinary "light" water, heavy water, or graphite to slow the neutrons emitted from its fuel in order to increase their odds of fission.

Watt: Unit of power equal to one joule per second.