Advanced Fast Reactor:
A Next-Generation Nuclear Energy Concept

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There is a growing international consensus that to be broadly acceptable for the 21st century and beyond, the next-generation advanced reactor system must meet these five criteria:

1. It must provide a long term energy source not limited by resources.
2. It must be passively safe, based on characteristics inherent in the reactor design and materials.
3. It must reduce the volume and toxicity of nuclear waste.
4. It must keep nuclear materials unsuitable for direct use in weapons.
5. It must be economically competitive with other electricity sources.

The only currently known concept that can meet all five requirements simultaneously is the Advanced Fast Reactor (AFR), a system that includes a closed fuel cycle based on pyroprocessing.

The AFR concept is being developed at Argonne National Laboratory, as an extension of earlier work done on the Integral Fast Reactor (IFR).[1] That work was undertaken specifically to resolve some pressing technical issues in safety, waste management, nonproliferation, and economics. Also important, however, was the fundamental fact that the efficient utilization of uranium resources is crucial to the long-term sustainability of nuclear energy.

Energy is the engine of the economy, and hence of prosperity. Figure 1 shows that in North America, we enjoy a very high per-capita GDP and a very high electricity generating capacity. The per-capita electrical energy consumption in other OECD[2] countries is only half of ours, but it is very important to note that it is still an order of magnitude higher than that of more than three quarters of the world=s population.

As we start the new millennium, growth in energy demand will become an acute problem, particularly outside North America. To meet the energy challenge, we have to exploit all energy options, including

[1] The AFR concept incorporates many of the features of the IFR, whose development was nearing completion when the program was terminated in 1994.

[2] *OECD*: Organization for Economic Cooperation and Development, consisting of 30 member statesC26 from the West, plus Australia, New Zealand, Japan, and Korea.

renewable energy sources. But the potential contribution of renewables is inherently limited. Fossil energy sourcesCcoal, oil and natural gasCare the most readily available, but they raise concerns about global climate change and other forms of environmental pollution.

Nuclear energy today contributes almost 20% of the electrical energy around the world. Over the past decade, nuclear plants have improved their operational reliability, safety records, and economic competitiveness, and nuclear energy is now recognized as the only power technology that can generate large amounts of electricity without producing greenhouse gases and other atmospheric pollutants. It is the technology of choice to meet the ever-expanding demand for electrical energy.

But today=s commercial thermal-spectrum reactors do not have the characteristics necessary to make nuclear a long-lasting energy source. Even with reprocessing, as is done in Europe and Japan, such reactors can utilize little more than one percent of the total energy potentially available from the mined uranium.[3] The U.S. once-through mode extracts considerably less than one percent. The unused energy is discarded as tailings in the enrichment process or as spent-fuel Awaste.@

On the other hand, fast-spectrum reactors can utilize essentially all of the uranium resources through recycling (and breeding, when called for in the future), making nuclear energy resources comparable to all fossil energy sources combined.

Uranium resources. To explore the uranium resources issue, let us look at the potential scenario for nuclear energy expansion that is depicted in Figure 2. The figure assumes a nominal growth in the next 10 years, followed by one-third of new demand to be met by nuclear, which translates to growth by about a 5% per year, through 2030, then a linear growth of 50 GWe/yr. This is a conservative assumption, to illustrate the resource implications.

The current total world-wide nuclear capacity is 350 GWe. We assume that life-extension of current reactors and 560 GWe of new LWRs will be the second-generation providers of nuclear energy. The AFRs that can be started up with actinides recovered from LWRs are shown by the dotted line; the remaining demand will have to be met by breeding in AFRs.

It is widely believed that there is a lot of cheap uranium, but this is illusory. Most utilities have long-term uranium supply contracts. When there are gaps in these long-term contracts, small quantities are purchased in the spot market. At present five hundred tonnes of highly enriched uranium from excess Russian weapons material are being blended down, flooding the uranium spot market. But the entire 500 tonnes represents only about a year and a half=s-worth of uranium for the reactors currently operatingCwhich has no significance in the global context, as a glance at Fig. 2 reveals.

[3] It is impractical to recycle the fuel for thermal reactors more than two or three times, mainly because buildup of the higher actinide isotopes seriously degrades reactor performance.

Figure 3 shows that, with the AFR introduced, the uranium requirements can be capped well below the Aestimated additional resources@ category, which is, in effect, the limit of uranium resources that could be economically recovered to feed a fuel cycle based on thermal reactors. But if we continue with that type of reactor, the uranium requirements rise even beyond the Aspeculative resources@ category, which consists of uranium that is thought to exist mostly on the basis of indirect evidence and geological extrapolations. As the term implies, the existence, size, and recovery cost of such resources are guesses. (There is also a great deal of uranium in sea water, but it is so dilute that it is economically out of reach for use in the very inefficient thermal reactors.)

Safety. Today=s reactors are very safe, but if there are going to be thousands of reactors around the world, they should have a higher level of *passive* safetyCthat is, safety should be inherent in design and materials, and not dependent on engineered safety systems or operator actions. The AFR can be designed for such, as was demonstrated in two landmark tests conducted with the EBR-II experimental reactor in 1986.

Those tests showed that even most the severe accident-initiating events would not lead to reactor damage or release of radioactive material. In one test, we shut off the power to the pumps that circulate coolant through the core, and in the other we cut off all active heat removal. In both tests the reactor safely shut itself down without human or mechanical intervention. In any other type of reactor, either of these occurrences would initiate a reactor-disabling accident.

Passive safety is uniquely achieved in the AFR by combining three factors:

$ *Sodium coolant*. Because sodium has a very high boiling temperature, the cooling system can operate at essentially atmospheric pressure. Sodium is also non-corrosive to structural materials used in the reactor. These unique characteristics of a sodium-cooled system result in superior reliability, operability, maintainability, and long lifetime, all of which contribute to low life-cycle costs.

$ *A Apool@ type of cooling configuration*. The AFR core sits in a large pool of liquid sodium, combining high thermal inertia with convective removal of decay heat in the event of loss of forced coolant flow. Most of the previous fast-reactor designs used a cooling Aloop,@ which does not have those safety advantages.

$ *Metal fuel, rather than oxide*. This is a major safety advantage. In all reactors there is a ADoppler reactivity effect,@ which causes the reactivity to increase if the temperature rises. Metal=s high thermal conductivity means that there is only a small temperature gradient along the radius of the pin, so that there is much less heat stored in the fuel. In the AFR, as a result, there is only a small temperature rise upon loss of coolant, limiting the Doppler reactivity rise.

The fact that the fuel is metallic is what makes it practical to use pyrometallurgical processing (Apyroprocessing@ for short, discussed next).

Pyroprocessing. The most innovative feature of the AFR is pyroprocessing, which promises revolutionary improvements in waste management, nonproliferation characteristics, and economics. With oxide fuel, reprocessing is done by the PUREX process, which produces chemically pure plutonium. Pyroprocessing not only does not do that, it cannot. This is a big part of the AFR=s overriding non-proliferation advantage.

Figure 4 is a simplified pyroprocessing flow sheet. The key element of pyroprocessing is electrorefining. Spent fuel rods chopped into small pieces are loaded into the anode basket. One type of cathode recovers uranium and the other one recovers all other actinide elements together: Pu, Np, Am, Cm, and also some U.

The anode basket, which retains the cladding hulls and noble-metal fission products, is melted to produce high-level waste in metallic form.

The electrolyte salts, containing most of the fission products, are passed through zeolite columns where the fission products are immobilized by incorporation 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 stable ceramic waste form called sodalite.

Originally developed for the IFR, pyroprocessing works with metallic fuel. However, with the addition of a front-end step to reduce the oxide to metal it can treat spent fuel from today=s commercial reactors.

Waste. The radioactive isotopes in spent fuel are of two types: fission products and actinides. The fission products as a group have an effective half-life of about thirty years. As shown in Fig. 5, it take only about 500 years for their toxicity to drop below that of the natural uranium ore from which their parent atoms came.

The actinides, on the other hand, have long half-lives, and their toxicity level is orders of magnitude greater for millions of years. In pyroprocessing, the actinides are easily recovered and recycled back into the reactor. This reduces the effective lifetime of the waste from tens of thousands of years to a few hundred, and meanwhile energy is generated by fissioning the actinides.

A repository is still needed, but its performance specifications can be much less stringent without the long-lived actinides. Furthermore, the repository=s capacity is increased substantially because the long-term heat source is eliminated. And the disposal site does not become a geological plutonium deposit, waiting to be mined by a would-be bomb-maker in the distant future, when the isotopic suitability of the plutonium for weapons will have improved considerably.

Nonproliferation. The nuclear materials in the AFR=s closed fuel cycle cannot be used directly in weapons, because pyroprocessing is unable to separate pure plutonium. Instead, the plutonium is mixed at all times with uranium, other actinides, and fission products. The mixture is protected against theft or unauthorized diversion because it is dauntingly radioactive and must be handled remotely with sophisticated, specialized equipment.

Pyroprocessing systems are compact, and the fuel-cycle facility can easily be collocated with the reactor, all but eliminating the need to transport nuclear fuel.

Further, AFRs could be used to eliminate the existing stockpile of separated plutonium as well as the huge and growing amount of plutonium Aarisings@[4] that are in spent fuel now in storage. Figure 6 shows that the plutonium arisings can reach thousands of tons. With enough AFRs in service, the entire plutonium inventory could be put into the reactors and their collocated fuel cycle facilities, generating more energy in the process.

Economics. The economic competitiveness of the AFR has not yet been established. While the plant operating costs might be somewhat higher than for today=s LWRs and cheap uranium, there are a number of offsetting factors:

$ The unique properties of the sodium coolant, mentioned above, help lower the life-cycle costs.

$ Improved fuel-pin design permits much higher burnup per fuel cycle, an important economic benefit.

$ A major long-run economic advantage of the AFR is its ability to exploit essentially all of uranium=s natural energyCabout a hundred times as much as is possible with today=s commercial reactors, even with recycling (see footnote 3).

$ Because the AFR is so efficient and can use all the actinides for fuel, the large quantities of spent fuel and depleted uranium that are already on hand eliminate the need for further mining of uranium for many decades.

$ With no uranium mining, there is no need for uranium milling.

$ Even when resumed mining of uranium eventually becomes necessary, the need to identify and exploit high-cost uranium resources will be pushed far into the future.

$ As observed above, waste disposal will be markedly cheaper.

[4] *Plutonium arisings*: the plutonium that is inevitably created in today=s thermal-spectrum reactors.

$ A non-economic factor that deserves some weight is the nonproliferation value of the AFR, notably its ability to consume plutonium rather than create it. It can eventually create a world where the only existing plutonium is sequestered behind barriers and shielding in a highly radioactive power plant.

What=s new and different? The idea of sodium-cooled fast breeder reactors has been around for many years, and so has elementary pyroprocessing. What=s innovative in the AFR is a combination of technological advances and integration of techniques into a coherent system.

The fast reactor was passed over, early on, for reasons that were not always technical, and its technical problems were not fundamental, but part of the development process. More than twelve fast reactors of various types have been built and operated, with varying degrees of success. Standouts have been EBR-II in Idaho (a low-power, experimental reactor that ran for thirty years), Phenix and Superphenix in France, and BN-600 in Russia. Of those four, two are still running (Phenix and BN-600), and the other two were shut down for non-technical reasons.

Past breeder designs did not necessarily fail all of the five desiderata listed at the beginning of this piece. However, they did fall somewhat short on the second (passive safety) and the fourth (proliferation resistance), in both of which the AFR excels.

The novel proliferation-resistance features of the pyrometallurgical fuel cycle deserve emphasis:

$ The collocation of reactor and reprocessing virtually eliminates, eventually, commerce in plutonium and transportation of spent fuel. In time, the only existing plutonium can be what is sequestered in AFR plants.

$ The plutonium never has the chemical purity needed for weapons.

$ The plutonium is extremely inaccessible, being at all times in an extremely radioactive environment behind thick shielding.

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Encouragingly, the near-term, high-priority benefits of pyroprocessingCnonproliferation and waste reductionChave been recognized by Vice President Cheney=s National Energy Policy Development Group, which makes this recommendation: AIn the context of developing advanced nuclear fuel cycles and next-generation technologies for nuclear energy, the United States should reexamine its policies, to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance.@