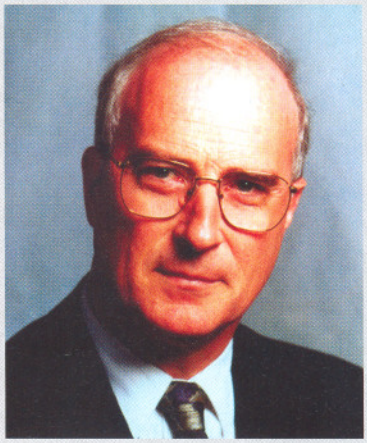
Generation IV Advanced Nuclear Energy Systems

By Jacques Bouchard, French Commissariat à l'Energie Atomique, France and Ralph Bennett, Idaho National Laboratory.

Generation IV first stepped on to the international scene in 2001 when nine countries joined together on a mission to develop and implement the next wave of safe and sustainable nuclear reactors, and created the Generation IV International Forum (GIF) to oversee it. Seven years of important changes in energy, environment and public acceptance have given the GIF a renewed sense of purpose. During those years an R&D program, with a framework covering technical and legal aspects, was created to meet the challenge of expanding nuclear energy throughout the 21st century.

The GIF countries' pledge to cooperate comes at a particularly urgent time. Worldwide greenhouse gas emissions grew 70 percent between 1970 and 2004, and if current energy practices remain unchecked such emissions will have a devastating effect on the planet. The dramatic effect on climate of increased carbon emissions poses a problem that transcends national borders and politics. Safe, efficient nuclear energy must be a part of a serious effort to stabilize greenhouse gas levels.

Making a significant difference in carbon emissions would require a large expansion of nuclear power. According to Princeton University's Carbon Mitigation Initiative, increasing the number of nuclear power plants to 1000 worldwide—more than double what it is today—could avoid one billion tons of carbon emissions per year by 2055. Generation IV aims to develop reactors and their associated fuel cycles that assure their long term sustainability and allow them to address more than just electricity generation, thereby setting the stage for sustained expansion through the century.



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A Framework for R&D Collaboration

The effort towards a new generation of nuclear energy systems started in July 2001, when nine countries signed the GIF Charter. In doing so, France, Argentina, Brazil, Canada, Japan, the Republics of Korea and South Africa, the United States and United Kingdom signaled their mutual interest in new nuclear systems. Since then, Switzerland, Euratom (representing the nations of the Euratom Treaty), China and Russia have all become members of the GIF.

To date, nine of the members have also acceded to a Framework Agreement,[1] which allows its signatories to formally participate in the development of Generation IV nuclear systems. Under that agreement, System Arrangements provide the framework for collaboration on each type of reactor. These arrangements allow for cooperation with industry, academia and even other governments to accomplish the R&D. Each member finances its own research and development, chooses which systems it will work on, and shares and protects the intellectual property they develop collaboratively.

Nuclear Power through the Generations

The conventional paradigm for the history of nuclear reactors has been to separate different types of nuclear designs into "generations." Generation I, dating from the 1950s and 60s, includes early prototypes in a number of countries. Generation II, the first commercial power plants, date from the 70s and 80s and include Pressurized Water Reactors and Boiling Water Reactors—designs generally utilizing water for coolant and slightly enriched uranium for fuel, almost all of which are still operating today. Most nuclear power plants being built now are categorized as Generation III—water-cooled reactors with more refined designs than their Generation II ancestors. This third generation has evolved to be both safer and more efficient, but

is nevertheless focused on electricity generation and only a limited recycle of the plutonium generated during one cycle through the core.

Worldwide projections of increased demand for electricity and new imperatives to reduce carbon emissions have lent special urgency to the promise of next generation systems. New markets, technical innovations and a rising acceptance of nuclear energy have produced the conditions needed for a revolution in nuclear technology. Economic competitiveness, improved safety, conservation of uranium resources and minimalization of waste, increased physical protection of the plants and added resistance to threats of nuclear proliferation are the new challenges posed to Generation IV reactors, which will ensure the sustainable development of nuclear energy.

Goals for Generation IV

Six different Generation IV nuclear reactor systems are currently being advanced. They were identified by an international group of over 100 experts who examined more than 130 proposals sent by specialists from around the world. The GIF took a top-down approach to choosing which designs were most promising versus the challenges of sustainability, safety, economics, proliferation resistance and physical protection. Further considerations included estimated R&D costs and time horizons. Though the final six systems selected have different strengths, each one was chosen for its unique potential to contribute to the new face of nuclear energy and advance toward the following eight goals:

Sustainability–1: Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

Sustainability–2: Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden in the future, thereby improving protection for the public health and the environment.

Economics–1: Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

Economics–2: Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

Safety and Reliability–1: Generation IV nuclear energy systems operations will excel in safety and reliability.

Safety and Reliability–2: Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

Safety and Reliability–3: Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

Proliferation Resistance and Physical Protection–1: Generation IV nuclear energy systems will increase the

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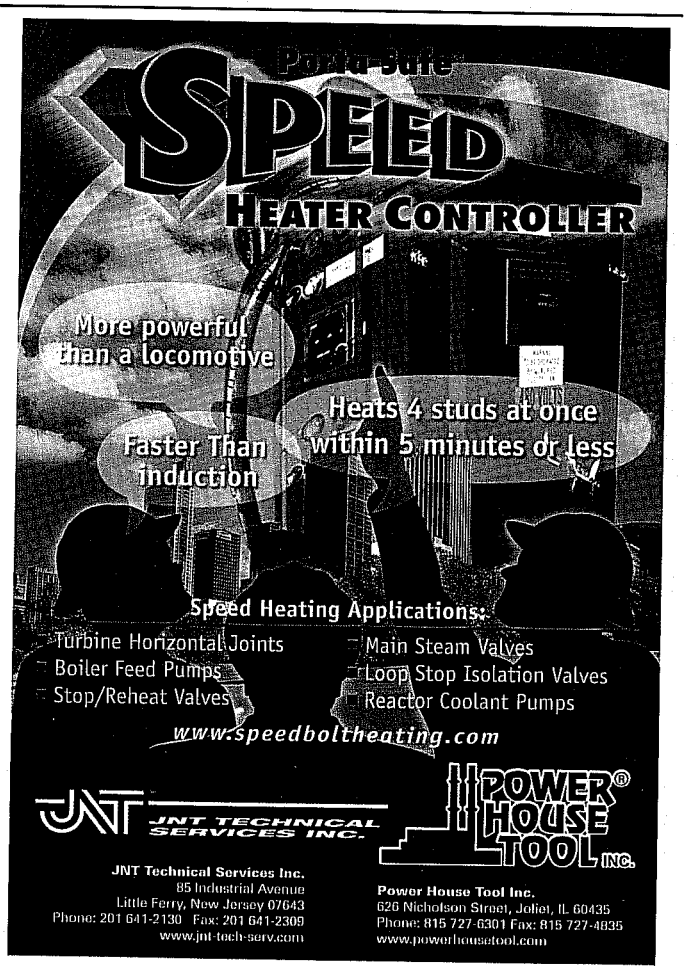

Generation IV...

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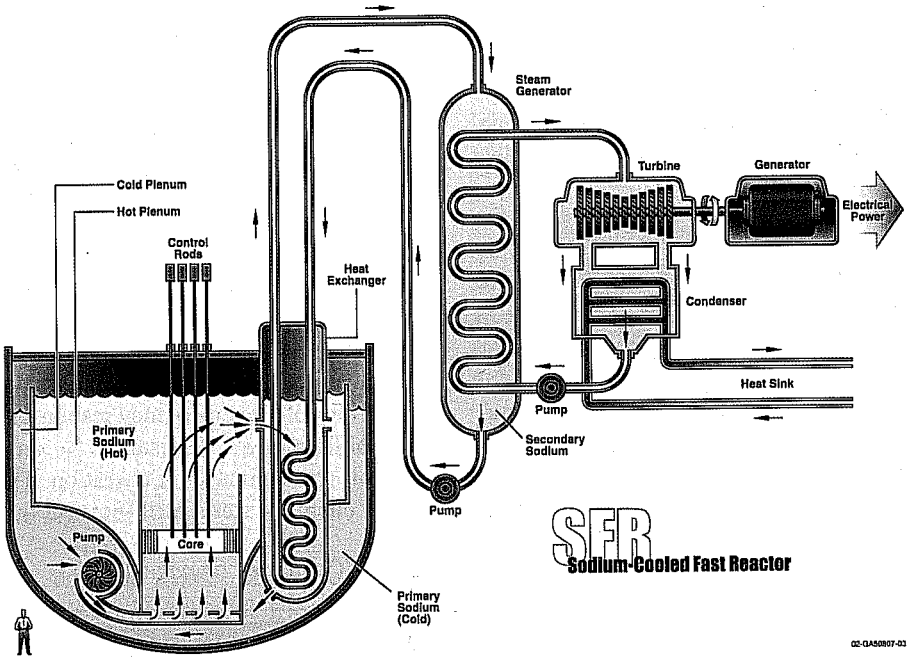
assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

A short overview of each system follows:

Sodium-Cooled Fast Reactor (SFR): The GIF is currently devoting much of its effort to this system. It uses liquid sodium for coolant, thereby gaining a high power density and lower coolant volume fraction. It features a closed fuel cycle, which is needed for fuel breeding and/or actinide management. The layout is flexible, with a pool layout (shown) or a compact loop layout. Either could be adjusted to produce a small-, medium- or large-sized reactor. The SFR can be economically competitive in electricity markets with innovations to reduce capital costs. The SFR is more efficient than thermal-spectrum reactors with open fuel cycles, with its potential to use both fissile and fertile isotopes of uranium. GIF has been taking a streamlined approach to developing SFR, by building upon technologies that are already being deployed throughout the world and advancing their performance. Progress in developing the SFR is well underway, with advances being made in fuel technology in France, compact heat exchangers in the United States, and design innovations underway in Japan[2].

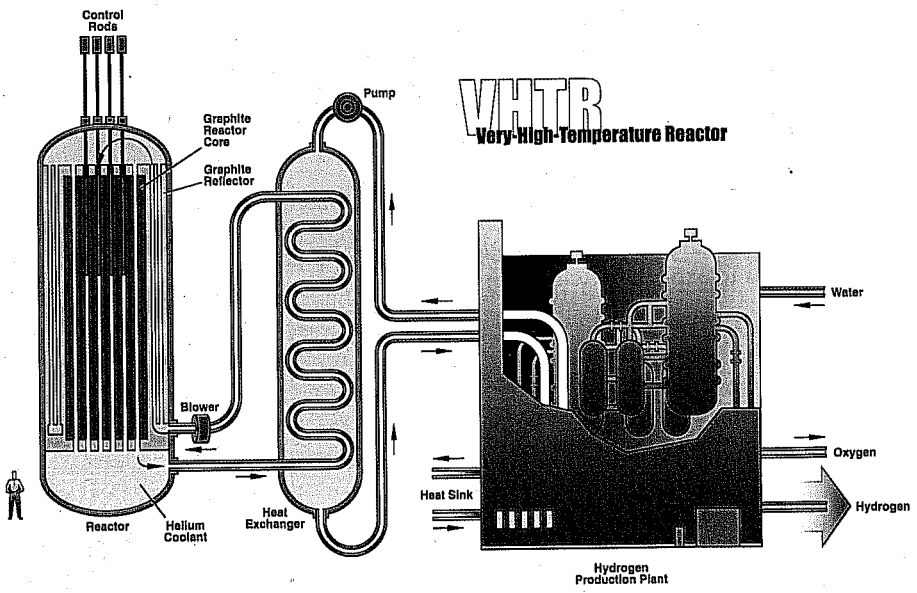
Very High Temperature Reactor (VHTR): The GIF is also devoting much of its effort to this system. It is a helium-cooled thermal reactor that can achieve an outlet temperature approaching 900 degrees Celsius. The ceramic fuel of the VHTR has a high degree of passive safety, and the high temperature gives it a high thermal efficiency approaching 50%. The high temperature also allows the VHTR to be applied to hydrogen production and other high temperature process heat applications, as well as low temperature heat applications such as water desalination, thereby addressing non-electric energy needs. The primary areas of research involve fuels, high temperature materials, and hydrogen production processes, and virtually all of the GIF members are collaborating on this system.



Gas-Cooled Fast Reactor (GFR): A fast-spectrum thermal reactor using helium coolant with an outlet temperature of 850 degrees Celsius. It is attractive because of its high efficiency and minimization of transuranic waste.

Supercritical Water Reactor (SCWR): The SCWR design uses water above its critical point condition (374°C, 22.1 MPa) as the coolant. This avoids the need for steam generators and considerably reduces the size of the turbine generator. It is a flexible design, configurable as a fast or thermal reactor. Its thermal efficiency may exceed 45%, and its lower capital cost favors the economical production of electricity.

Lead-Cooled Fast Reactor (LFR): This fast reactor uses molten lead or lead/bismuth as a coolant and has a high degree of safety since the coolant is less chemically reactive than sodium. It operates at a temperature higher than the SFR, which may allow its use for



hydrogen production as well as electricity. It has a closed fuel cycle.

Molten Salt Reactor (MSR): This is an epithermal reactor design in which the fuel is actually dissolved in the coolant. Specifically, it uses liquid fluorides of uranium and plutonium for fuel, dissolved in fluorides of lithium, beryllium, sodium or other elements. The system provides for processing the wastes and adding new fuel online, which greatly reduces the fissile material inventory and avoids the development and qualification of fuel and cladding.

The Future

Generation IV designs improve upon current reactors in several ways. Four of the designs are fast reactors, allowing the reactors to potentially exploit the full energy potential of uranium—both fissile and fertile isotopes. Generation III reactors extract energy from a much smaller fraction of uranium in the fuel, where as Generation IV reactors can extend the uranium resource by about a factor of 50 beyond this. Another option for Generation IV is to improve on current designs by recycling all actinides—not only the bred plutonium-239, but the other actinides found in the waste as well. This revolution in fuel utilization would also dramatically reduce the radiotoxicity and heat generated by the waste by transmuting it to shorter-lived fission products, thus making it easier to dispose.

Several of the Generation IV designs are high-temperature reactors, which can generate not only electricity but also provide process heat for industrial purposes. Process heat has good potential for application to a wide range of industries, from petroleum refineries and chemical plants to large-scale hydrogen production potentially for revolutionizing transportation.

One of the overarching goals of Generation IV technology, and one that is most appealing to the international community, is its potential to reduce carbon emissions. This will only be accomplished through considerable R&D, and for example, the GIF members collaborating on the SFR and VHTR have already jointly committed over $500M for the next five years. The GIF believes that Generation IV, through improved safety, economics, safety and proliferation resistance and physical protection, can help ensure nuclear energy's long term expansion and sustained contribution to the world's energy security.

References

[1] Generation IV International Forum, "Framework Agreement," available at: http://www.gen-4.org/PDFs/Framework-agreement.pdf, 28 Feb 2005.

[2] Generation IV International Forum, "GIF Annual Report 2007," available at: http://www.gen-4.org/PDFs/annual_report2007.pdf, Mar 2008.

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