IV Generation Nuclear Reactors

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I. Introduction

An international working group shares R&D to develop six new reactor technologies for deployment between 2020 and 2030. Four of them are fast-neutron: they do not need to slow down neutrons like the current ones to fissure the fuel. *The Fourth Generation International Forum* **GIF** was initiated by the US Department of Energy in 2000 and formally founded in 2001. It represents the governments of 14 countries where nuclear energy is considered vital for the future. Most **GIF** countries are committed to the joint development of the next generation of nuclear technology. The original founding members of **GIF** are Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, the United Kingdom, and the United States. They were joined by Switzerland, the EU **Euratom**, China, Russia, and Australia.

The majority are part of the 2005 Framework Agreement, which commits them to participate in the development of one or more *IV Generation systems* selected by **GIF** to continue research and development. Argentina, Australia, and Brazil did not sign the Framework Agreement, and the United Kingdom withdrew from it. These four members remain as inactive members. Russia formalized its accession to the Framework Agreement in August 2009 as its tenth member, with Rosatom as the implementation agent.

- In 2011, the 13 members decided to modify and extend the GIF status indefinitely.
- Australia joined as the 14th GIF member in June 2016.
- 2015, the Framework Agreement was extended for ten years, with Rosatom signing the extension in June and Euratom in November 2016.
- 2005, the technical secretariat was transferred to the **OECD** Nuclear Energy Agency in mid-2015 also to the International Framework for Nuclear Energy Cooperation **IFNEC**. NEA in Paris provides the technical secretariat.

After two years of deliberation and review of around one hundred concepts, at the end of 2002, the **GIF** (which at that time represented ten countries) announced the selection of six reactor technologies that, in its opinion, represent the future form of the nuclear energy. These designs were selected based on being clean, safe, and profitable means to meet the growing demands of energy sustainably while being resistant to the diversion of material for the proliferation of weapons and terrorist attacks. Three of the six are fast neutron reactors and one can function as a fast reactor, one is epidermal (intermediate zone) and only two operate with thermal (slow) neutrons like current plants.

The effective section indicates the ability to collide with the core only one is cooled with light water, two are cooled with helium and the others have coolant with lead salt and bismuth, sodium, or fluorine. The last three operate at low pressure and the last one has the uranium fuel dissolved in the refrigerant. Temperatures range from 510°C to 1000°C, compared to 330°C for current light water reactors, and this means that four of them can be used for thermochemical hydrogen production, sizes range from 150 and 1500MWe, with lead-cooling optionally available as a 50–150MWe ”battery” with long service life (15–20 years with the same fuel) and with the possibility of replacing the complete reactor module. At least four of the systems have significant operational experience in most aspects of their design, which provides a good basis for increased R&D and can probably be in commercial operation before 2030.

In January 2014, a new update of the **GIF** technology roadmap was published, confirmed the choice of the six systems and focused on the most relevant developments to define the R&D objectives for the next decade GIF suggested that The IV Generation technologies that will most likely be used first are the sodium-cooled fast reactor, the lead-cooled fast reactor, and the very high-temperature reactor technologies. The molten salt reactor and the gas-cooled fast reactor were shown to be the furthest from the demonstration phase. The third GIF symposium took place in Japan in May 2015 and checked the progress of the six systems.

Although Russia was initially not part of GIF[1], it is developing the **BREST** reactor and is currently the main operator of the sodium-cooled fast reactor to generate electricity, one of the technologies presented by **GIF** India is a member but is developing its technology to use thorium as nuclear fuel A three-stage program with the first well established: pressurized heavy water reactors **PHWR** fed with natural uranium to generate plutonium. Second, fast breeder reactors **FBR** will use this plutonium-based fuel to reproduce thorium U-233, and finally, advanced reactors will use **U-233**. Used fuel will be reprocessed to recover fissile materials for recycling. The two main options for the third stage, although continuing with the **PHWR** and **FBR** programs, are an advanced heavy water reactor and subcritical systems driven by the accelerator. An important project related to several IV Generation designs is investigating the use of actinide-laden fuel elements in fast reactors as part of the sodium-cooled fast reactor program.

II. Sodium Refrigerated Fast Reactor **SFR**

Figure 1. Photograph of the Russian **BN-800** in operation since 2016.

The **SFR** uses liquid sodium as the reactor coolant, which allows a high power density with a low volume of low-pressure coolant.

The **SFR** is not a new technology: it is based on about 390 reactor-years experienced with sodium-cooled fast neutron reactors for five decades in eight countries and is the main technology of interest to the **GIF** The **SFR** uses depleted uranium as a fuel base and has a coolant temperature of 500–550°C that allows the generation of electricity through a secondary sodium circuit, the primary being almost at atmospheric pressure, currently, the country most Advanced in this type of reactors is Russia with two industrial-scale operating (**BN-600** and **BN-800**, 600 and 800MW) and is finishing the design of a commercial reactor intending to also allocate it for export **BN-1200**. China operates an experimental 20MW **SFR** reactor **CEFR** and builds a 600MW demonstration **CFR600**[2] that will culminate with a 1000 MW commercial **CFR1000**. India plans to put the 500Mwe Kalpakkam **PFBR** into operation this year 2018.

III. Quick Reactor Refrigerated by Plomo **LFR**

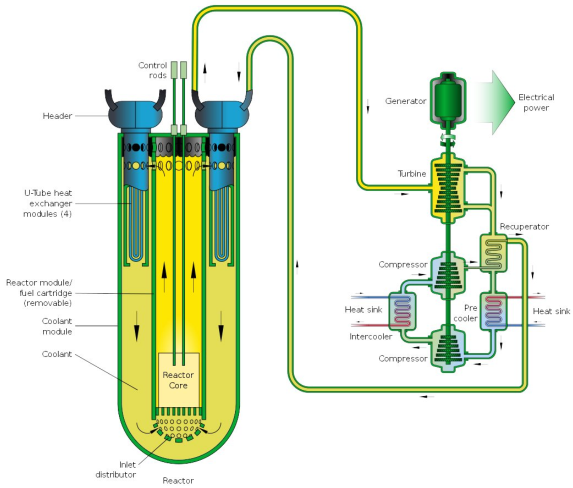

Figure 2. LFR

The **LFR** is a flexible fast neutron reactor that can use fuel with depleted uranium or thorium and burn the actinides of the LWR fuel, that is, recycle waste from current reactors. The cooling of the liquid metal (Pb or Pb-Bi eutectic) is carried out at atmospheric pressure by natural convection. The fuel is metal or nitride, with complete recycling of actinides, a wide range of unit sizes is expected, from a ”battery” with 15–20 years of life for small networks or developing countries to modular units of 300–400MWe and large individual plants of 1400MWe. The operating temperature of 550°C is easily attainable, but 800°C with advanced materials is provided to provide corrosion resistance of lead at high temperatures that would allow the production of thermochemical hydrogen.

IV. Water-Cooled Supercritical Reactor **SCWR**

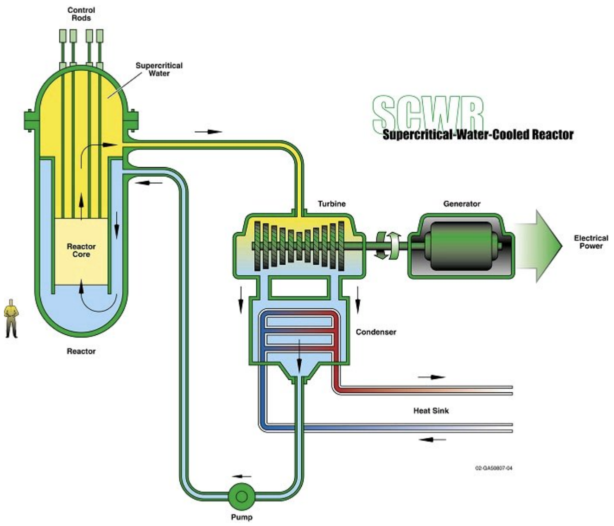

Figure 3. Supercritical water-cooled reactor

Very high-pressure water-cooled reactor that operates above the thermodynamic critical point of water 374°C, 22MPa to provide a thermal efficiency 1/3 higher than that of current light water reactors, supercritical water 25MPa and 510–550°C directly drives the turbine, without any steam generator, simplifying the plant. The passive safety features are similar to those of simplified boiling water reactors. The fuel is uranium oxide, enriched in the case of the option to open the fuel cycle, the core can use thermal neutron spectrum with light or heavy water moderation, or be a fast reactor with complete actinide recycling based on conventional reprocessing Since the **SCWR** is based on the experience of **BWR** and hundreds of fossil fuel-powered plants operated with supercritical water, it can be easily developed and the operation of a 30 to 150MWe technology demostration reactor is planned for 2022.

V. Very High-Temperature Gas reactor **VHTR**

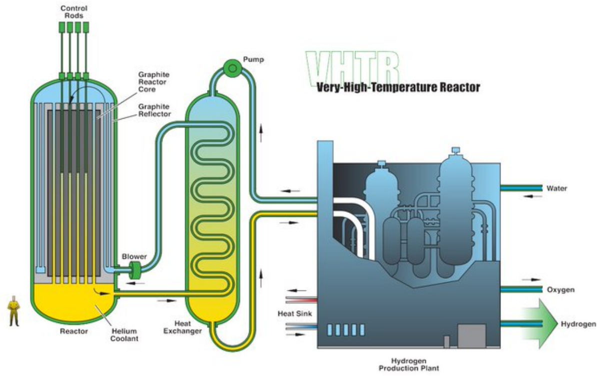

Figure 4. Very High Temperature Reactor

The reactor cooled by helium and moderated with graphite. The core can be constructed with prismatic blocks such as the Japanese HTTR and the General Atomics **GTMHR** and others in Russia, or as the HTR-10, the Chinese **HTR-PM**, and the South African **PBMR**. The output temperature of more than 900°C and the target of 1000°C. It allows the thermochemical production of hydrogen through an intermediate heat exchanger, with electricity cogeneration, or the high-efficiency direct conduction of a gas turbine (Brayton cycle). At low outlet temperatures, the Rankine steam cycle can be used for electricity generation, and this is the approach for demonstration projects. 600MW thermal modules are expected, the fuel is in the form of **TRISO** (tristructural-isotropic) particles less than one millimeter in diameter.

Each has a core (approximately 0.5mm) of uranium oxycarbide (or uranium dioxide) and enriched uranium up to 20% of *U-235*, the fuel core is surrounded by layers of carbon and silicon carbide, giving a containment for fission products that is stable at more than 1600°C. The particles can be incorporated into spheres the size of billiard balls, or in prismatic graphite blocks, the **VHTR** has a high combustion potential (150–200GWd/t), completely passive safety, low operation and maintenance costs, and modular construction. A **VHTR** of 600MWt dedicated to hydrogen production could produce more than 2 million cubic meters per day.

VII. Cast Sales Reactor **MSR**

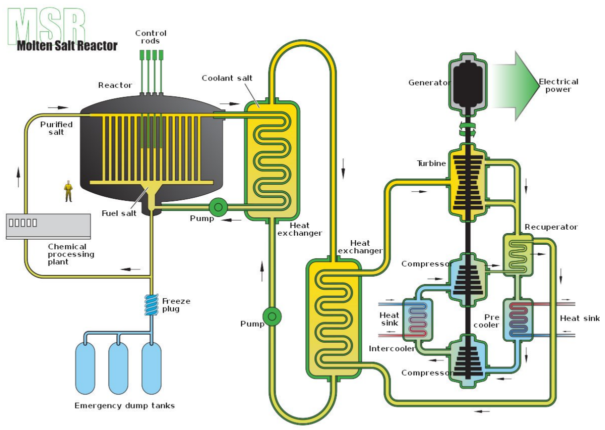

Figure 5. Molten Salt reactor

It has two variants: a fast reactor with fissile material dissolved in the form of a salt of fuel in the circulation water and the other with solid particle fuel in graphite and the salt operating only as a refrigerant in an **MSR**, the uranium dissolves in the refrigerant of salt that circulates through the central channels of graphite to achieve some moderation and a spectrum of epidermal neutrons, the reference plant is up to 1000MWe. Fission products are continuously removed and actinides are completely recycled, while plutonium and other actinides can be added together with **U-238**, without the need for fuel manufacturing the coolant temperature is 700°C at very low pressure, with 800°C provided.
A secondary refrigerant system is used for electricity generation, and thermochemical hydrogen production is also feasible. Compared to solid fuel reactors, **MSR** systems have lower inventories of fissile material, without the restriction of radiation damage in fuel burn and a homogeneous isotopic composition of fuel in the reactor, attractive features of the fuel cycle concept MSR's include: high activity waste containing only fission products, therefore, shorter life radioactivity, low fuel consumption and safety due to passive cooling. The 2014 **GIF** roadmap said it was necessary to do a lot of work on the salts before the demonstration reactors were operational, and suggested that 2025 be the end of the feasibility R&D phase.

VII. Gas Refrigerated Fast Reactor **GFR**

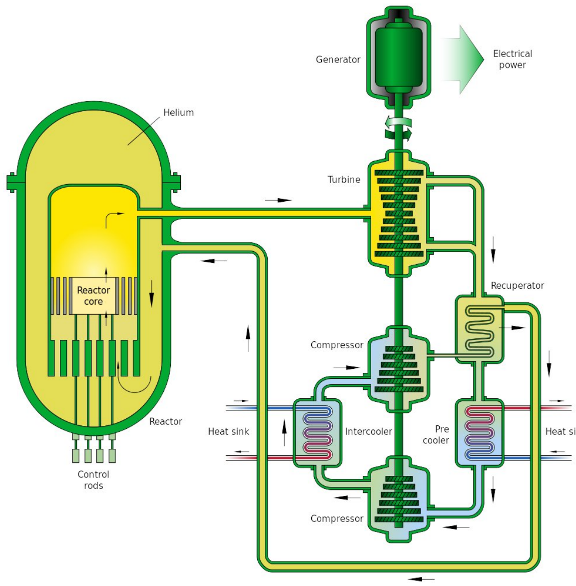

Figure 6. GFR

Like other helium-cooled reactors that have operated or are under development, GFRs will be high-temperature units: 850°C. GFRs use a reactor technology similar to VHTR, suitable for power generation, thermochemical hydrogen production or other types of process. The reference **GFR** unit is 2400MWt and 1200MWe with three 800MWt loops. The primary will be cooled with helium, the secondary will use helium in a gas turbine (Brayton cycle) and a steam cycle will comprise the tertiary circuit would have a self-generating core (reproductive reactor) with a fast neutron spectrum. Nitride or carbide fuels would include depleted uranium and any other fissile material, with plutonium content of 15 to 20% as with the **SFR**, the fuel used would be reprocessed at the plant itself and all actinides would be recycled repeatedly to minimize the production of long-lived radioactive waste. It is the only Generation IV design with no operational history, so a prototype is not expected before 2022. However, Euratom plans a 75MWt experimental technology demonstration **GFR** that will be built from 2018.

Generation IV reactor designs under development by GIF

	Neutron spectrum (fast/thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel cycle	Size (MWe)	Use
Gas-cooled fast reactors	fast	helium	850	high	U-238 +	closed, on site	1200	electricity & hydrogen
Lead-cooled fast reactors	fast	lead or Pb-Bi	480-570	low	U-238 +	closed, regional	20-180** 300-1200 600-1000	electricity & hydrogen
Molten salt fast reactors	fast	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Molten salt reactor - advanced high-temperature reactors	thermal	fluoride salts	750-1000		UO_2 particles in prism	open	1000-1500	hydrogen
Sodium-cooled fast reactors	fast	sodium	500-550	low	U-238 & MOX	closed	50-150 600-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-625	very high	UO_2	open (thermal) closed (fast)	300-700 1000-1500	electricity
Very high temperature gas reactors	thermal	helium	900-1000	high	UO_2 prism or pebbles	open	250-300	hydrogen & electricity

* high = 7-15 MPa
\+ = with some U-235 or Pu-239
** 'battery' model with long cassette core life (15-20 yr) or replaceable reactor module.

Figure 7. Generation IV reactor desings under development by GIF

VIII. European Programme

[3] The European Commission launched in 2010 the European Sustainable Nuclear Industrial Initiative **ESNII**, which will support three Generator IV rapid reactor projects as part of the EU plan to promote low carbon energy technologies. Other initiatives that support biomass, wind energy, solar energy, electrical networks, and carbon sequestration are in parallel with nuclear energy. **ESNII** promotes three nuclear projects: the **Astrid** sodium-cooled fast reactor **SFR** proposed by France, the Allegro **GFR** gas-cooled fast reactor supported by central and eastern Europe, and the **ALFRED LFR** lead-cooled rapid reactor in Romania. The objective of **ESNII** is to demonstrate IV Generation technologies to close the nuclear fuel cycle, provide waste management solutions and expand the applications of nuclear fission, with the production of hydrogen, industrial heat, and desalination. The **ALFRED LFR** technology demonstrator, the European Advanced Lead Fast Reactor, of approximately 300 MWt is considered a prelude to an industrial demonstration unit of approximately 300–400 Mwe.

ALFRED will use mixed oxide fuel **MOX**, with approximately 17% plutonium, and will be able to recycle minor actinides. The construction of ALFRED could begin in 2020 and the unit could begin operating in 2025.

IX.

References

[1] World Nuclear Association, "Nuclear Power Reactors," 2019.

[2] Foundation Museum Andrew W. Mellon, "Climate Museum Mellon Post-Doctoral Fellowship," 2019.

[3] J. E. Kelly, "Generation IV International Forum - Overview Presentation." 2014.