

Nuclear Reactors – Designs and Operations

So far, we have discussed the nuclear and atomic physics that forms the foundation of nuclear engineering. It is now possible to consider the way nuclear energy is utilized for practical purposes. We learned that if the required conditions are created to initiate the fission reaction and devise the means to control and sustain these reactions, we will have access to a useful source of energy. The engineering arrangements used to initiate, sustain, control, and utilize the nuclear energy are called nuclear reactors. Nuclear reactors are classified in many ways.

1. Classification based on the coolant
 - Light water Reactors (LWR)
 - Heavy water Pressurized Water Reactors (HPWR)
 - Liquid Metal Reactors (LMR)
 - Molten Salt Reactors (MSR)
 - Gas Cooled Reactors (GCC)

2. Classification based on neutron spectrum
 - Thermal reactors
 - Fast reactors

3. Classification based on the Conversion ratio
 - Breeders
 - Convertors
 - Burners

4. Classification based on moderator
 - water moderated reactors
 - Heavy water moderated reactors
 - Graphite moderated reactors

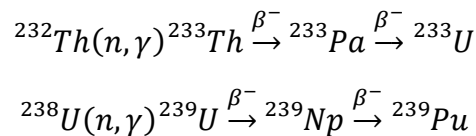
5. Classification based on fuel
 - Natural Uranium
 - Enriched Uranium
 - Plutonium plus Uranium
 - Thorium plus Uranium

Conversion and Breeding

Theoretically, the reproduction factor η must be greater than 1, so that the nuclear fuel would be able to sustain the criticality. However, we have seen in the six-factor formula, that η must be significantly greater than one in order to account for neutron losses (absorption, leaks) through out their life.

Review of fission data has shown that η is substantially greater than one for the fissile materials for all neutron energies. For fissionable materials, $\eta > 1$ only for neutron energies above the fission threshold. that means η must be multiplied by the fraction of neutrons with energies higher than the fission threshold. This number is regrettably always less than one. It follows that reactors can't be made critical with non-fissile material alone.

We also know that U-235 is the only naturally occurring fissile nuclide. With its abundance of about 0.71%, the natural resources available to sustain the utilization of nuclear energy is limited, and the nuclear era is short. Fortunately, fissile isotopes can be produced from non-fissile nuclei through a process called **conversion**. The two most important fissile isotopes produced in the reactors are U-233, and Pu-239 through the following reactions:



Thorium Th-232, and U-238 are available naturally. These reactions are realized by irradiation of Th-232 and U-238 inside a reactor. Quantitatively, the conversion process is described in terms of the "**conversion ratio C**" also called "**Breeding ratio**". It is defined as the average number of fissile atoms produced in a reactor per fissile fuel atom consumed. Nuclear reactors are therefore Called

1. Breeders if $C > 1$.
2. Convertors if $0 < C < 1$
3. Burners if $C = 0$

For Breeders, η must be substantially greater than 2. One neutron is available for fission, the other is available for breeding. Further, the reproduction factor η (The average number of neutrons produced per each neutron absorbed by the fuel) is a function of neutron energy. The value of η for the three attainable fissile nuclides U-235, Pu-239, and U-233 are 2.07, 2.14, and 2.29, respectively for thermal neutrons ($E = 0.025$ ev). Taking into consideration the neutron losses, a Thermal breeder is only possible, if it were fueled by U-233. Pu-239 and U.235 would not be able to sustain breeding in thermal spectrum. on the other hand η is adequately greater than 2 to permit breeding if the neutrons are within the fast spectrum. Therefore, with these fuels (U-235, U-233, and Pu-239) it would be possible to breed provided that most fission reaction take place with fast neutrons. These reactors are called "**Fast breeder reactors**".

Generation IV international forum (GIF)

The Generation IV international forum (GIF) was created in January 2000 by 9 countries. Today, It has 13 members, all of which are the signatories of the founding document, the GIF charter; The founding document of the GIF, a framework for international cooperation in Research and development (RID) for the next generation of nuclear energy systems, are set out in the GIF Charter which can be found in the following link:

https://www.gen-4.org/gif/jcms/c_40243/gif-charter

The charter identified in its technology road map eight technology goals for Generation IV systems in four broad areas:

1. Sustainability:

Gen IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long term availability of systems and effective fuel utilizations. Gen. IV will minimize and manage nuclear waste and there by improving protection for the public health and the environment.

2. Economics

Gen IV will have clear life cycle cost advantage over other energy sources. Gen II will have a level of financial risk comparable to other energy projects

3. Safety and reliability

Gen IV will excel in safety and reliability. Gen II will eliminate the need for off site emergency response Gen IV will have a very low likelihood and degree of reactor core damage

4. Proliferation resistance and physical protection

Gen IV will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials. They should also provide increased physical protection against malevolent acts.

These goals guide the cooperative R&D efforts undertaken by GIF members. Considering the ambitious goals involved, international cooperation is Considered essential for a timely progress in the development of Gen IV systems.

Selection of Gen IV systems

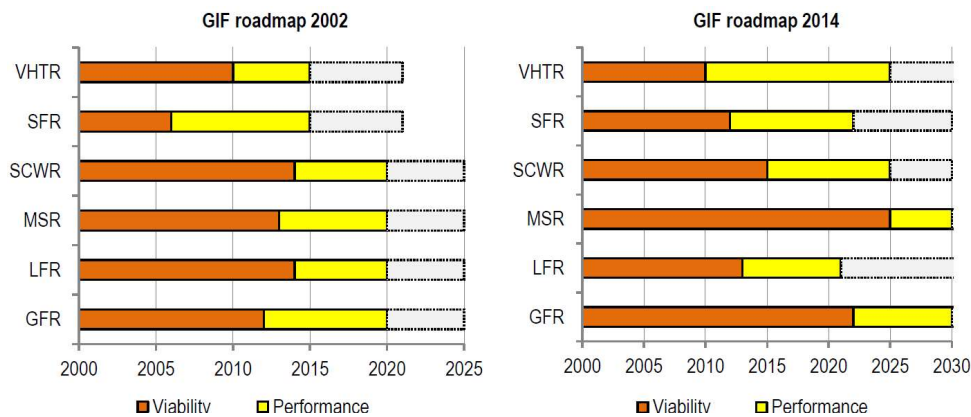
With these goals in mind some 100 experts evaluated 130 reactor concepts (systems) before they selected six systems for further R&D in 2002. These systems are deemed to have the potential to meet the Gen IV technology goals:

1. Gas-cooled Fast Reactor (GFR)
2. Lead-cooled Fast Reactor (LFR)
3. Molten Salt Reactor (MSR)
4. Sodium-cooled Fast Reactor (SFR)
5. Super Critical Water-cooled Reactor (SCWR)
6. Very High Temperature Reactor (VHTR)

For further details consult the “*Technology Roadmap Update for Generation IV Nuclear Energy Systems*” which can be downloaded from the following link.

<https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf>

The technology roadmap of 2002 defined and planned the necessary R&D and projected timelines to make these technologies available for commercial deployment by 2030. The roadmap is updated in 2014. The following chart shows the System development timelines as defined in the original Roadmap in 2002 (left) and in the 2014 update.



Viability Phase: Basic concepts, technologies and processes are tested under relevant conditions, with all potential technical show-stoppers identified and resolved

Performance Phase: Engineering-scale processes, phenomena and materials capabilities are verified and optimised under prototypical conditions.

Demonstration Phase: Assuming the successful completion of viability and performance R&D, a demonstration phase of at least 10 years is anticipated for each system, requiring funding of several billion U.S. dollars. This phase involves the licensing, construction and operation of a prototype or demonstration system in partnership with industry and perhaps other countries. The detailed design will be completed and licensing of the system will be performed during this phase.

In this class we are going to talk about one example of Gen IV technology; that is the sodium-cooled fast reactor (SFR):

SFR is a breeder reactor operates on uranium-plutonium fuel cycle. The blanket is usually natural or depleted uranium. For plutonium fuel the average number of neutrons emitted per fission increases monotonically with the neutron energy. It follows that the breeding ratio increases with increasing fission-induced neutron energy. Therefore, we should make sure that the neutrons do not slowdown, i.e. light weight nuclei must be excluded from the core.

Sodium has been the coolant of choice for SFR For its following advantages

1. $A=23$ for sodium, i.e. it does not substantially slow down neutrons by inelastic scattering
2. Excellent heat conductor with high heat capacity. It follows that SFR can operate at high power density.
3. Sodium has very low vapour pressure $T_{\text{Boiling}}=882^{\circ}\text{C}$ at atmospheric pressure. This means SFR can operate at high temperatures, precluding the need for the costly and heavy pressure vessels.
4. The high sodium temperature leads to a high temp. and high pressure steam in the secondary side, which means higher efficiency.
5. Unlike water, sodium is not corrosive to structural material (iron-based alloys).

Sodium also has some undesirable characteristics:

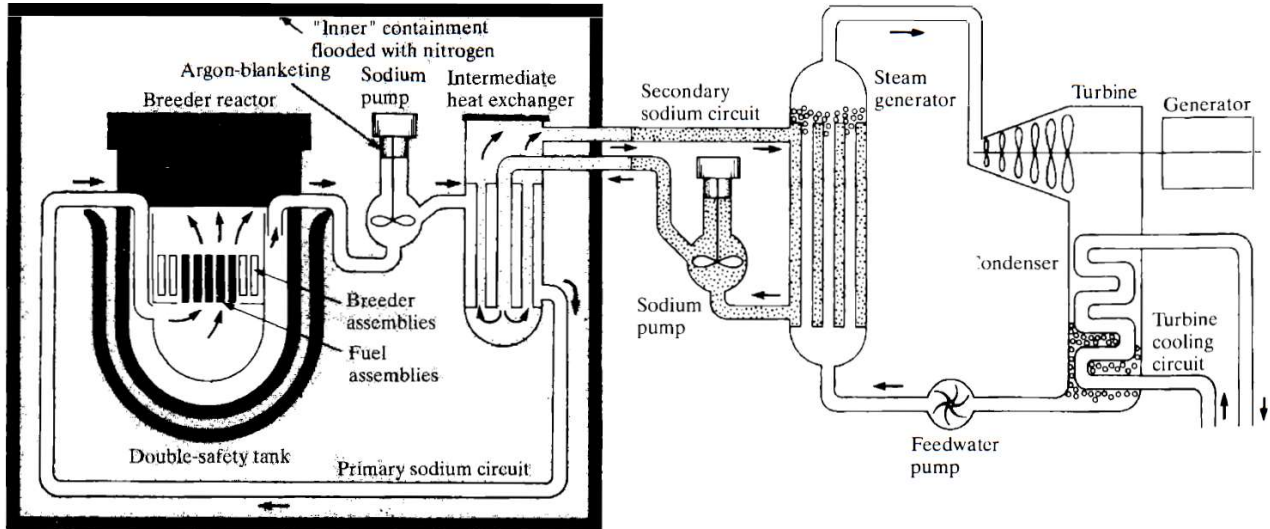
1. Melting point of sodium is 98°C that means the sodium loop must be kept heated even during shutdown
2. Sodium is highly reactive chemically. Hot sodium reacts violently with water and catches fire.
3. Sodium absorbs neutron leading to the formation of beta-gamma emitter (Na-24 $T_{1/2}=15\text{hrs}$). Therefore, sodium that passes through the core becomes radioactive.

Because sodium reacts violently with water and becomes radioactive, All SFR's use two sodium loops; primary loop carrying the radioactive sodium and intermediate loop carrying non radioactive sodium.

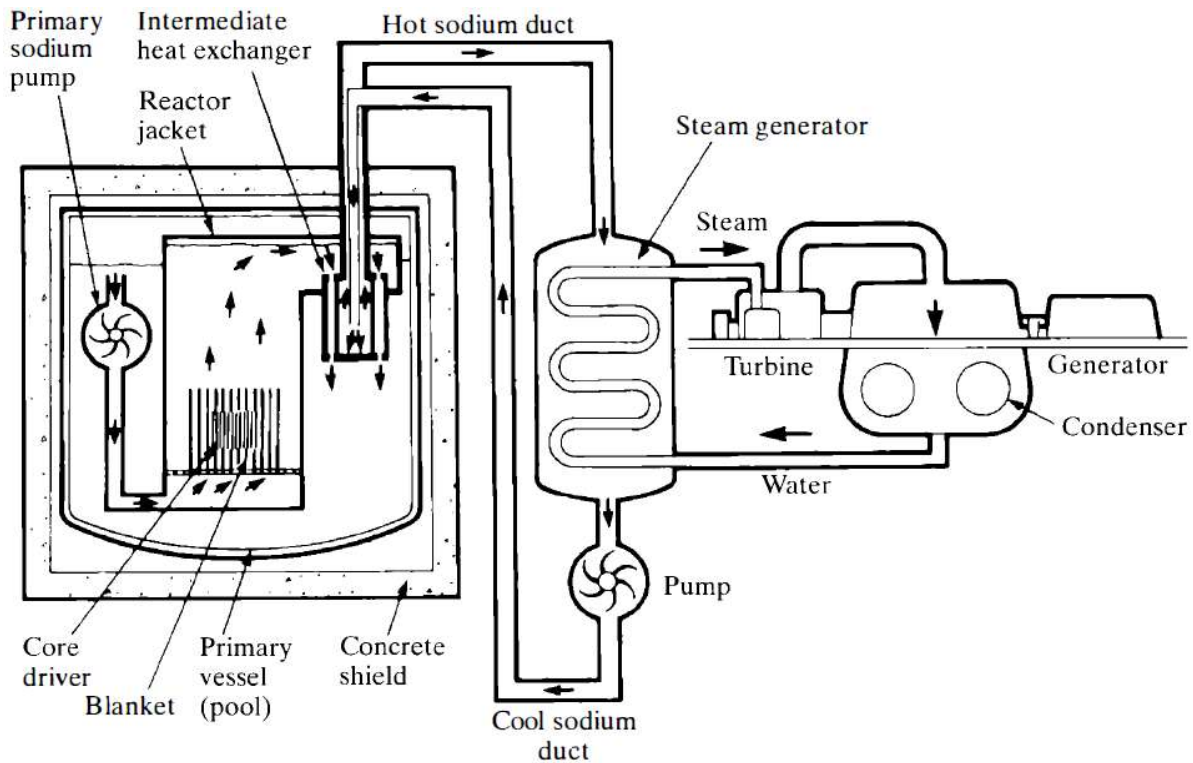
There are two arrangements for SFR design:

1. Pool type SFR
2. Loop type SFR

The pool type is more complicated, and no primary sodium goes out of the vessel makes it safer in case of accident, while the loop type is less complicated, the intermediate heat exchanger is outside the vessel, and primary sodium flows outside the vessel leading to higher risk of leak.



The loop type SFR



The pool type SFR