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POSSIBLE APPROACHS TO GENERATION IV REACTORS – A FEASIBLE CHOICE

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Abstract: World is changing in terms of pursuing new energy technologies, and nothing different happens with nuclear. The Generation IV initiative depicts a new revolution in terms of electricity supply for the future. The proof of concept originated in the Generation IV forum, which listed six possible technological routes for a future of nuclear generation based on fissile material, which includes safety requirements, nuclear energy efficiency and less waste generation, in terms of new reactors concepts. These are the very high temperature reactor (VHTR); supercritical water-cooled reactor (SCWR); molten salt reactor (MSR); gas-cooled fast reactor (GFR); sodium cooled fast reactor (SFR); and lead-cooled fast reactor (LFR). The present study explored the possibilities, the obstacles, as well as the challenges to be overcome, for the Very High Temperature Reactor (VHTR). Despite other technological paths have their benefits, VHTR technology seems to be versatile; it originates on the advancement of another type, the High Temperature Reactor (HTR). USA, Germany and UK were main countries in this avant-garde research. In addition to generating electrical energy, VHTR can provide heat for industrial sectors and other applications. Like any nuclear technology, challenges regarded to safety and the environment are key points in the implementation of the system. VHTR was here prospected, with its “pros and cons”; as a promising way to a safe nucleoelectric energy. Summarizing, VHTR is shown as a possible alternative, as long as studies of high-strength materials go ahead. In short, the reactor becomes a viable source of thermonuclear generation, also associated with hydrogen production.

INTRODUCTION

Specialized literature have brought nuclear power reactors mainly used to obtain electrical energy. There are several types of nuclear power reactors, which can be classified according to the fuel and other components of the system, such as the moderator and the refrigerant [1].

The Generation IV International Forum (GIF) was an initiative held in January, 2000, created by nine nations, with the objective of promoting the advance of nuclear energy through collaboration between countries. In 2002, six reactors were chosen that would compose the “Generation IV reactors” [2]; incorporating new concepts in generation.

The VHTR – Very High Temperature Reactor is one of the reactors chosen by GIF members, aiming to offer greater safety and reliability, in addition to reducing CO₂ emissions, contributing to the high future energy demand. The reactor is characterized by using helium as a refrigerant and graphite as a moderator, operating routinely in the temperature range of 700 to 850°C [3], and even more.

This work intends to present and describe the VHTR reactor in terms of historical context, proof of concept, advantages, disadvantages and its implementation effort. The approach comprises comparisons with other reactor types.

GENERATION IV – APPROACHES AND THE VHTR CONCEPT

Generation IV reactors (“Gen IV”) are a set of theoretical nuclear reactor projects, which are still being researched; most of the projects will be made available for commercial use, initially, with construction scheduled for the 2030s. Currently, reactors in operation all over the world are considered second or third generation systems; first generation systems have been discontinued some decades ago

and are no longer used. In relation to the nuclear energy currently used, the benefits of 4th generation reactors will be: sustainability; increased security; better use of nuclear fuel; high efficiency; greater savings; minimal waste in production; ability to consume existing nuclear waste in the production of electricity [4].

During the beginning of generation IV work, many reactors were speculated; however, the list was shortened; therefore, there is a focus on most promising technologies and those that had the potential to meet the initiative's objectives. Currently, research is focused on six types of reactors.

- 1) very high temperature reactor (VHTR);
- 2) supercritical water-cooled reactor (SCWR);
- 3) molten salt reactor (MSR);
- 4) gas-cooled fast reactor (GFR);
- 5) sodium cooled fast reactor (SFR);
- 6) lead-cooled fast reactor (LFR).

Some literature states the need for sustainability as an important role when searching for a new concept of reactors [5]. Generation IV systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems. Also is sought an effective fuel utilization for worldwide energy production [5].

Unlike the other IV generation reactors, MSR uses high temperature liquid salt as coolant and the fuel can be in liquid or solid form, or even a mixture of salts. The Sodium-cooled Fast Reactor would be aimed at energy production and management of high-level radioactive waste. Its main component is liquid sodium (NaO), used as a cooling material. Under atmospheric pressure conditions, its external temperature can reach 550 °C.

The concept of a high temperature reactor, resulting in the nomenclature High Temperature Reactor (HTR), had proved that it would become viable in the United States,

United Kingdom and Germany, and at that time the operating parameter was reached with temperatures below 1000 °C. The VHTR concept, in turn, seeks to surpass this parameter in the future.

The VHTR set consists of a reactor, an external intermediate heat exchanger, a refrigerant gas circulation system with an external heat exchanger, operating as a source of heat for the hydrogen production plant and a gas turbine, for electricity generation [6]. Fig. 1 shows the scheme of the system.

The VHTR has graphite as a moderator and uses helium gas as a refrigerant. The outlet temperature provides its application in secondary industrial processes, such as the aforementioned production of hydrogen, desalination of sea water or producing heating for the population.

One possibility of organization for the reactor core is the design of a prism. The VHTR prismatic core consists of an arrangement, containing vertical columns of graphite blocks, with the fuel stored within them, guide control rods and replaceable reflective blocks.

Fig. 2 shows a radial section of the reactor core; red hexagonal blocks represent graphite blocks with axial holes (some for the refrigerant to pass and the rest to keep the small graphite cylinders that store the fuel) and the clear hexagons represent the graphite blocks without infiltration, with the function of returning neutrons that escape the nucleus.

AN ESTABLISHED PROOF OF CONCEPT

The HTR system was first proposed in Harwell, England, during the 1950s; the reference of the VHTR concept being a thermal system of operation in a single fuel cycle. HTR technology is well established and the requirements for its advancement are reasonable. The manufacture of the coating of

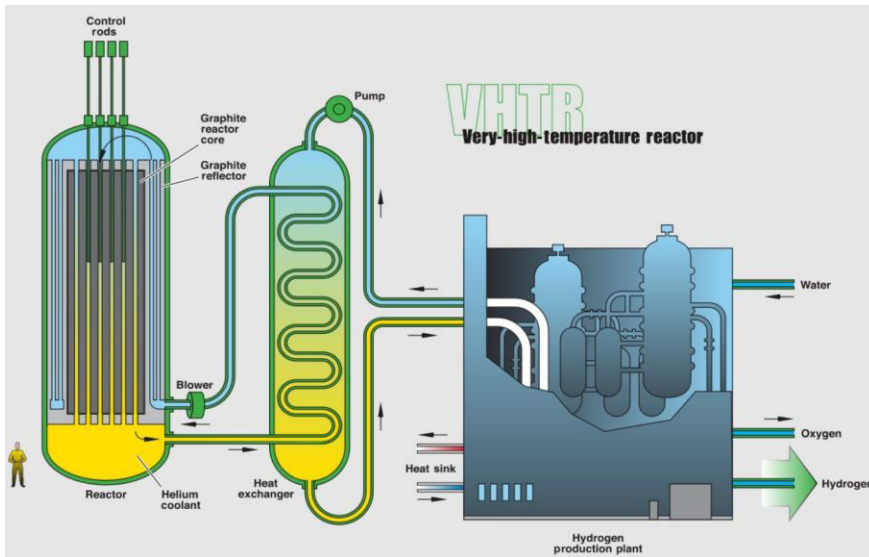


Figure 1: Schematic concept of the Very High Temperature Reactor (VHTR) generation-IV nuclear reactor (man size comparison).

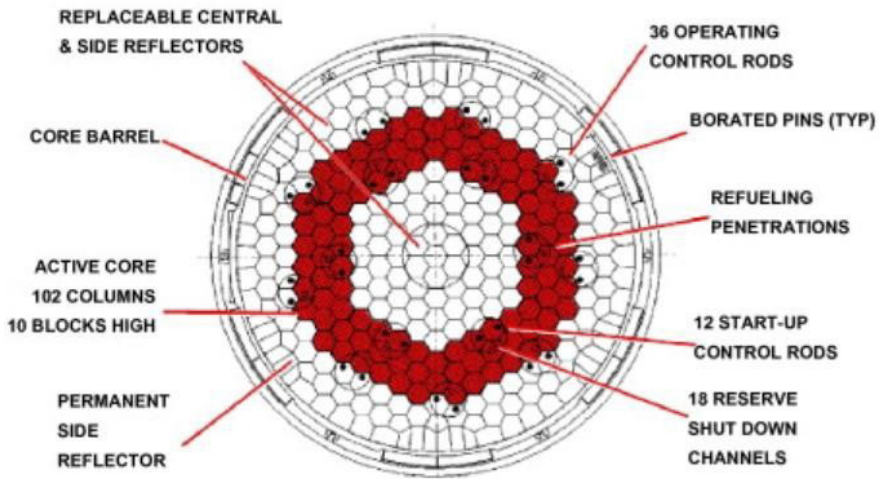


Figure 2: Prismatic core of a VHTR reactor.

the fuel particles is achieved by the deposition of chemical vapor and is dependent on established recipes, which present an acceptable production of fuel performance under the same conditions as the HTR [7].

Because of their high operational temperature, some of the concepts (as GFR, MSR) can be used for the cogeneration of hydrogen. VHTR also plays this role. The SCWR enables high thermal efficiency; around one-third higher than current light-water reactors, as well as a simplification in the plant, because the water can directly be used to drive the turbines [5]. The helium coolant at high temperatures used in the GFR system makes it possible to deliver electricity, hydrogen, or process heat with high efficiency, in a direct-cycle helium turbine for electricity generation [5].

While other concepts have a closed fuel cycle, the VHTR, due to its high temperature operation, has an open fuel cycle [5]. Basic technology for the VHTR has been established in the High Temperature gas-cooled reactors as in the US Peach Bottom and Fort Saint-Vrain plants, as well as the AVR and THTR prototypes in Germany, plus the HTTR test reactors in Japan and the HTR-10, this one in China. Such reactors present the two basic concepts for the VHTR core, respectively: the prismatic (Prismatic block-type) and pebble or spheres (Pebble bed-type) [8][9].

The experimental reactors in Japan and China, mentioned above, contribute to the advancement of the concept developed for the VHTR reactor. They provide important information for the demonstration of safety and operational analyses, such as the HTTR, which will promote a platform to couple advanced hydrogen production technologies with the nuclear source of heat above 950 °C.

And also in terms of Chinese concepts, the Institute of Nuclear Energy Safety Technology, in China, has been actively participating in LFR

activities. Its contribution to the development of LFR remains to 2013. Considering widely involving of Chinese institutions in R&D of this reactor type, China was interested in acceding to GIF LFR program [9].

Material technology can be one of the keys to the success of Generation IV reactors. HTR fuels have demonstrated that the combination of silicon carbide (SiC) with layers of pyrolytic carbon (PyC) can present excellent performance. For the future development of the VHTR, higher temperatures and alternative coatings are foreseen, such as zirconium carbide (ZrC) [7]. Table 1 shows the potential structure and coating materials for the different Generation IV systems.

Material integrity and nuclear safety for all reactors are strongly interconnected concepts. The operating conditions of this new generation will be more demanding and, therefore, knowledge of the material's behavior and its integrity during operation is essential. Safety analysis are based on technological assessment, where the integrity of the material is critical to the decision.

ADVANTAGES AND DISADVANTAGES OF VHTR – CHALLENGES

The analysis of advantages and disadvantages will enable actions to guide a VHTR project. The concept presents challenges - in terms of its disadvantages - as well as promising possibilities.

ADVANTAGES

The European Sustainable Energy Technology Platform (SNETP) aims to reduce greenhouse gas emissions through the participation of renewable energies in the total energy matrix. It understands that nuclear energy is a key technology to meet the goal of reducing CO₂ by 2050 [10].

Research on IV generation reactors is part

System	Materials		
	Cladding	Core regions	Out of core regions
Gas-Cooled Fast Reactor System (GFR)	Ceramics Matrices of SiC, ZrC & TiN, ODS (Oxide Dispersion-Strengthened)	Ceramics Carbides SiC, ZrC Nitrides ZrN, TiN Oxides MgO ZrYO ₂ Zr ₃ Si ₂ ODS	Coated or non coated ferritic-martensitic or austenitic steels Nickel based super alloys ODS
Lead-Cooled Fast Reactor System (LFR)	Austenitic, ferritic-martensitic steel Coated cladding e.g. FeAl	Graphite Nickel-based alloys Ceramics Advanced austenitic steels	→
Molten Salt Reactor System (MSR)	-		
Sodium-Cooled Fast Reactor System (SFR)	ODS (Metallic fuel) Ferritic-Martensitic steels (MOX-fuel)	→	→
Supercritical –Water-Cooled System (SCWR)	Austenitic, Ferritic-Martensitic steels ODS		
Very-High-Temperature Reactor System (VHTR)	ZrC	Graphite Ceramics	Ni-Cr-W super alloys High temperature metal alloys

Table 1: Materials for coating and core of the different Generation IV reactor systems.

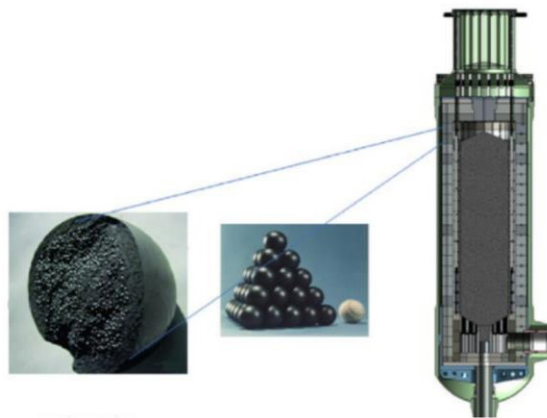


Figure 3: Core with spheres bed (pebble-bed).

of the activities of SNETP, which cites the VHTR reactor as a representative of a modern and highly developed version of the original design of the HTR reactor. Nuclear energy is cited by the platform as a versatile technology, through reactors such as the VHTR. The technology designed for the VHTR concept, using processes without emission of greenhouse gases and with production of carbon-free hydrogen [8][9][10], leads to the possibility of obtaining this important source. Hydrogen is used as a raw material in industry and is considered as fuel, instead of fossil ones. The production of nuclear hydrogen is perceived, then, as a valuable technology for complementing renewable energies.

The VHTR is indeed a thermal reactor; therefore, it has the ability to apply heat in industry processes, used as a thermal source in processes for refineries, petrochemicals and metallurgy, replacing fossil fuel applications [8][11].

The other possible arrangement for the core of the VHTR reactor is the deposition of spheres (see fig. 3). In this case, fuel of the sphere is coated with TRISO (TRistructural-ISotropic coating). The spherical coated fuel form is the main barrier in terms of releasing fission products. The coatings, in particular the silicon carbide layer, effectively retain most of the radionuclide stock, maintaining its structural integrity under conditions of high temperature and chemical attack [10][12]. Spherical fuel coated with TRISO retains fission products within the coated sphere, under normal operating conditions and could also support accident conditions.

The graphite used as a moderator in the VHTR reactor, in addition to having great thermal inertia, absorbs additional heat, even in the hottest fuel element. It also offers the advantage that it can be recycled [11][12]. The reactor has the potential for inherent safety, high thermal efficiency, the ability to apply

process heat, low operating/maintenance costs and modular construction.

The VHTR also has a negative temperature reactivity coefficient, which serves to suppress fission power in the event of accidents. There is flexibility in fuel usage [10][13]; the VHTR can support alternative fuel cycles, such as U-Pu, Pu, MOX, U-Th. The VHTR also has versatility, not only in the use of fuel, but also in the energy conversion unit.

DISADVANTAGES

What determines the operating temperature of nuclear reactors are alloys and metallic components. With the technology and materials available today, the VHTR reactor can provide heat and electricity in a core outlet temperature range between 700 and 950°C [8][10][12]. The materials available today would make the reactor limited in terms of power, considering the degradation of these materials.

In order to develop the full potential of application and possible uses of the VHTR reactor, which are the supply of electricity, work as a thermal source and produce hydrogen, research and development of alloys and metals, as well as their manufacture, is still necessary. R&D is demanded, both for materials in the reactor itself, as well as for coupling materials for heat transfer and hydrogen production [12]. There is initially no recycling of the TRISO-coated sphere type fuel; there are needs for research and development for the treatment and disposal of such spent fuel [9][13].

The expansion of nuclear energy in India, China and other countries will soon lead to a substantial increase in the rate of global uranium use [14]. The concern about future fuel shortages is consistent, according to the Idaho National Laboratory, as the current known reserves of uranium, which are economically viable for mining, are

approximately 5,500,000 tons.

At the current usage rate of 65,000 tonnes U/year, known uranium resources will last for around 85 years. Not a disadvantage in essence of the VHTR, it is a consideration about fissile fuel. In addition to the issue of fuel shortages, non-proliferation is a concern. The burning of plutonium and smaller actinides would be an important support for the closed cycle of nuclear fuels and the waste reduction in repositories [9][14].

Although the ball type fuel coated with TRISO is the main barrier for the release of the fission product, its qualification is still necessary [10][13]. It is necessary to validate and verify system analysis and computational fluid dynamics models [12], for the concept. Finally, industries with the potential to take advantage of the thermal source need to have their plants operating close to the nuclear facilities.

CHALLENGES FOR IMPLEMENTATION

In addition to the challenges inherent in the processes involving fourth generation nuclear reactors, safety control issues arise when thermal behavior is taken into account. In this regard, two points must be considered: (1) maintaining the pressure limit of the reactor core; (2) preventing explosions and contamination [15]. The temperature above 1000 °C at the gas outlet, by itself, poses a great technological and safety challenge [5][16].

Reactors that work with the High Temperature concept - HT, in general, must follow the safety protocols, using low power of the core, with heat being passively released to the environment, without harming the fuel or even radioactive material during accidents. The reactor size and core configuration are designed to ensure that the core has a relatively small diameter, to assist in the shortest path from the core to the vessel [17]. So engineering

challenges lie there either.

Metal components exposed to core conditions may be susceptible to failure. Valves, rods, tubes and connectors would be the most vulnerable, which can cause core depressurization, which does not represent great damage in relation to the fuel; however, it can provide the circulation of fission products.

The metal alloys used in the construction of high temperature reactor plants, currently available, determine the maximum temperature limit of the VHTR (700-950 °C), which implies a demand for research and superalloy projects, which are more resistant and less subject to failures [18].

The project also requires other materials that operate at higher temperatures and neutron fluxes than experiments in previous nuclear processes. The high temperatures and neutron fluxes of a VHTR represent a complex interaction between radioactive damage, diffusion phenomenon and direct chemical reactions. The development of structural components and refrigeration systems are essential for the operation of a VHTR [15].

Considering the long-term implementation, some challenges and R&D keys for an operational VHTR system, in the next 10-15 years, are here mentioned [19].

- Completion of the fuel test and qualification capacity (including manufacturing, irradiation, safety test and PIE (Post-Irradiation Examination)).
- Qualification of graphite; hardening of graphite against air and water ingress; also waste management of this material.
- Coupling technology and related components.
- Establishment of design codes and standards for new materials and components.
- Advanced manufacturing methods

(cross cutting challenge).

- Cost reduction.
- Licensing and location.
- Integration of the system with other energy carriers in hybrid systems.
- Exchange with several startups, private investors and new programs.
- Safety demonstration tests and coupling to the hydrogen production plant.

Fig. 4 brings the contribution, for the Generation IV Forum, in terms of countries intending to provide knowledge and technical support for this initiative [9]

CONCLUSIONS

The study sought to map the perspectives of nucleoelectric generation in terms of a new paradigm of its production; obtaining a new disruptive technological concept.

Generation IV became known as a scientific forum, which seeks advances in terms of economically viable technologies to scale production. In this context, routes have been studied, in order to establish, in years to come, which ones will be more promising.

The surveys carried out here prospect the VHTR as a challenging and feasible alternative, in terms of cycle, engineering structuring, or in terms of efficiency. Therefore, a relevant aspect is pointed out: the search for new materials that can withstand extremely high temperatures. Undoubtedly, the possibilities are many and reflect innovative horizons; both in terms of a new energy concept itself and its consequent applications (where electricity generation is the main one), as well as in hydrogen generation - also converging towards the reach of clean energy matrices, not to mention spin-offs, such as research into new super resistant alloys.

The future will show the convenience of adopting, as a source of energy, a proposal

overcoming challenges and the possible scale of a project that, in conceptual terms, proved its viability. Future works in terms of Gen IV reactors are fostered.

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Contributions to the Generation IV International Forum



<i>VHTR</i>	◆	◆	◆	◆	◆	◆	◆	◆	◆
<i>GFR</i>		◆	◆	◆		◆			
<i>SFR</i>		◆	◆	◆	◆		◆	◆	
<i>SCWR</i>	◆	◆		◆					
<i>LFR</i>		◆		◆					
<i>MSR</i>		◆	◆						

Figure 4: International contribution to Gen IV Forum

REFERENCES

1. L. A. A. Terremoto “Disciplina TNR5764 - Fundamentos de Tecnologia Nuclear – Reatores” *Instituto de Pesquisas Energéticas e Nucleares* (2021).
2. “Technology Roadmap Update for Generation IV Nuclear Energy Systems” https://www.gen-4.org/gif/jcms/c_60729/technology-roadmap-update-2013 (2014).
3. “Annual Report 2017” https://www.gen-4.org/gif/jcms/c_102083/gif-annual-report-2017-210918 (2017).
4. R. V. Nieuwenhove, B. Lauritzen, B. Nonbøl “Nordic Forum for Generation IV Reactors, Status and activities in 2012” *Nordic-Gen4 Seminar*, Risoe, Roskilde, 29-31 october (2012).
5. P. Anzieu, “Generation IV Concepts and International Frames”.
6. V. C. Konigame, T. N. Conti, “Estudo do Reator Nuclear de 4ª Geração Very High Temperature Reactor” *Revista Engenharia e Tecnologia Aplicada*, v. 1, pp. 47-68, (2017).
7. T. Abram, S. Ion. “Generation-IV nuclear power: A review of the state of the science” *Energy Policy*, v. 36, pp. 2-7 (2008).
8. “Preparing the Future through Innovative Nuclear Technology: Outlook for Generation IV Technologies” https://www.gen-4.org/gif/upload/docs/application/pdf/2019-01/preparing_the_future_through_innovative_nuclear_technology_web.pdf (2019).
9. “Very-high-temperature reactor” https://www.gen-4.org/gif/upload/docs/application/pdf/2020-08/gif_2019_annual_report-final_-_chap4_vhtr.pdf (2019).
10. “Sustainable Nuclear Energy Technology Platform” <https://sh1.sendinblue.com/afxj4x8gs5t7e.html?t=1614684205> (2021).
11. “Very-High-Temperature Reactor (VHTR)” https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr (2020).
12. F. L. Chen, H. D. Gougar, “On behalf of the VHTR System Steering Committee” The Generation IV International Forum (2018).
13. “Generation IV Nuclear Reactors” <https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx> (2020).
14. M. F. Simpson, J. D. Law, “Nuclear Fuel Reprocessing” *Idaho National Laboratory, INL*, Idaho Falls, Idaho, February (2010).
15. D. Chapin, S. Kiffer, J. Nestel, “The Very High Temperature Reactor” *MPR Associates, Inc.*, Alexandria, Virginia, June (2004).
16. H. D. Gougar, *et al.*, “Assessment of the Technical Maturity of Generation IV Concepts for test or Demonstration Reactor Applications” *Idaho National Laboratory. INL*, Idaho Falls, Idaho, October (2015).
17. R. Bratton, T. D. Burchell, W. E. Windes, “Generation IV Reactors Integrated Materials Technology Program Plan: Focus on Very High Temperature Reactor Materials” (2008)
18. “2017 NEA Annual Report” https://www.oecd-nea.org/jcms/pl_15076 (2017).
19. GIF-RDTF: “Generation-IV Systems’ Experimental Infrastructure Needs”, *VHTR R&D INFRASTRUCTURES*, (2021).