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# Considerations referring to materials types able to be used in gas-cooled fast reactors

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The demand for standard of living and population growth, in developing countries are asking for a considerable increase of energy supply. Nuclear energy is one way to provide it. In this context, an integrated R&D program was initiated: Generation IV reactors Program. Taking in account the operation conditions of these reactors types, it was necessary to find some materials with special characteristics. For exemplification, in this paper are presented aspects regarding the study and selecting modality of some adequate materials for Gas-Cooled Fast Reactor – GFR.

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*Keywords*: Nuclear energy, Nuclear reactor, Materials

## 1. Introduction

Share of nuclear energy to cover future energy needs is recognized worldwide and consequently thus have been developed and perfected several systems of nuclear reactors. Given that this global energy scenario is dynamic, it requires a periodic assessment [1]. The current level of maturity of the technology of nuclear materials involves both efforts to achieve high burn-up - energy production / unit quantity of fuel - as well as to reduce the cost of nuclear energy, these being the main objectives of advanced nuclear reactors [1]. The nuclear materials can be grouped into two broad categories as are located in or outside the core. The reactor components include:

- in-core materials comprising the fuel assemblies (bundles) and respectively channels from their vicinity in which circulates the primary circuit coolant;
- non-core materials, that are generally different types of steels, which are used at the execution of systems from the rest of Nuclear Power Plant (NPP), of which the most important is Steam Generator [1].

Determinant for the future of nuclear plants is the competitiveness between the cost of nuclear energy and other alternatives of electricity production. In the case of nuclear power plants, there is initially a very high cost of plant structure which subsequently became much smaller during its operation, resulting greater economic gains by maximizing the use of plants. This can be achieved through operational cycles as long, the reducing of the number of unplanned shutdowns and stopping periods as short possible. Currently, the load factor of a modern NPP is about 95% and a fuel cycle lasting is about 2 years. In addition, another factor which must to consider is the minimizing of the amount of radioactive waste, due to limited facilities for storing them in an initial period and the relatively high cost implied in their removal and respectively waste treatment.

Given the foregoing, it was necessary to pass from one old NPP generation at other top sites, the Generation IV. From the 100 proposed reactor systems, only six the most promising systems were selected [2]. Of these, two NPP types use thermal neutrons fluxes –Supercritical Water Reactors (SCWR) and respectively the Reactors operating at Very High Temperatures (VHTR) - and three types of reactors: Gas Cooled Fast Reactors (GFR), Lead (LFR) and Sodium Cooled Reactors (SFR), use fast neutron fluxes. The last type of reactor - that using molten salt for cooling - MSR - uses a circulating liquid fuel mixture, which offers a considerable flexibility in actinide recycling and can be an alternative for accelerators [2].

In Fig. 1[1] is presented synoptically the evolution of some several types of power reactors. The introduction of new types of fuel in nuclear reactors is, however, slowly taking great precautions as requiring by their safety in operation in radiation field. For example, it is necessary to test new fuels types in transient conditions, at the large degrees of burning to demonstrate whether or not an acceptable behavior of their in abnormal operating conditions and to define their limits of deterioration. Such tests are very expensive and require more time for experiments. They last, usually, about six years in the tests running on fuel bundles, which contain a new variant of fuel, so that it can achieve a sufficiently high degree of burning.

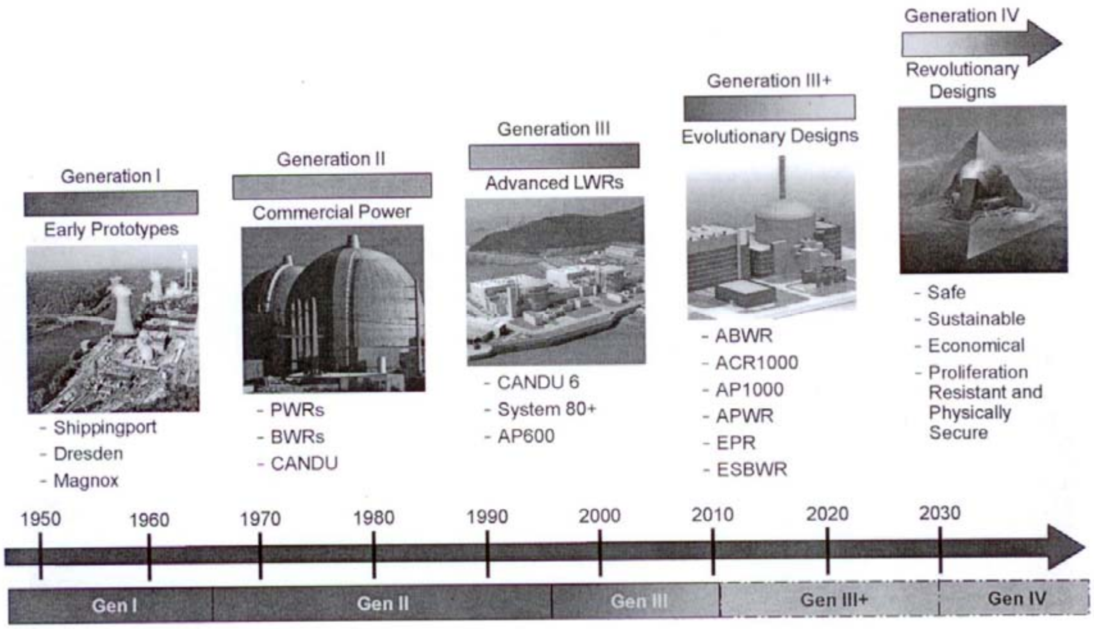

*Fig.1. Evolution of patterns of power reactors.*

Given the tough operating conditions laid down for the Generation IV reactors, including possible accident scenarios, had devised a database rich enough to demonstrate that the candidate materials for the components of these types of nuclear plants meet the following requirements:

- an acceptable dimensional stability that must not change significantly by fuel blowing, thermal creep, creep under irradiation, stress relaxation and dimensional enlargement;
- an acceptable ductility and toughness;
- an acceptable resistance to rupture under creep, fatigue cracking, interaction creep-fatigue and helium embrittlement;
- chemical compatibility and an acceptable corrosion resistance including SCC and SCC under irradiation in presence of coolants and other fluids participating in several processes [2].

The scrupulosity with which these tests were performed under irradiation was reflected in the rates of degradation of fuel, which showed a downward trend over the past 20 years. One way of fuel degradation can take place and when the sheath is cracking, allowing the coolant to come into contact with the fuel and thus the fission by-products are released into circuit. Generally, the NPP being provided with some adequate systems for removal and capture of fission products, it will produce a small number of fuel degradation that will not affect the plant operation and will not diminish its performance. However, a damaged fuel element will release the radioactive products in primary coolant circuit, which can cause some additional exposure doses to operators, representing an unwanted source of accidents.

The power plants have some strict limits referring to the radioactivity amount that can be tolerated in the circuit and in the case of a big enough fuel degradation, the plant will be stopped in view of removal of damaged fuel. Moreover, refueling with fresh fuel is not permitted until some proper investigations and repairs are made and sometimes some expenditure quite greatly with the pressure tube from which was discharged the damaged fuel. In addition, it will be necessary the developing of new models applicable to relations microstructure - properties in view to establish some long-term predictions about the behavior of materials in different Generation IV reactors [2]. Such models will serve in safe operation as of fuel and of finding of those materials for sheaths that can withstand at much higher temperatures existing in the Generation IV reactor core [2].

## 2. Main characteristics of GFR

The Gas Cooled Reactor system with fast neutron spectrum (GFR) and having a closed fuel cycle is operating at 7MPa, with an inlet temperature of coolant of 858$^{o}$C. This system uses a cyclical turbine Brayton to produce electricity which can be used also in the process of thermo chemical hydrogen production. This type of reactor was chosen as reference design because of its resemblance with VHTR reactor. The main factors which will influence the structural properties of materials used in Generation IV reactors will be: the radiation effects, the period of high temperature exposure and the interaction with chemical species from gaseous environment in which they are exposed. For this purpose, a comprehensive program of testing and evaluation will be necessary to be developed to highlight the impact of these factors on the properties of potential materials to be used in GFR plants [3]. In Fig. 2[4] is presented schematically a GFR concept.

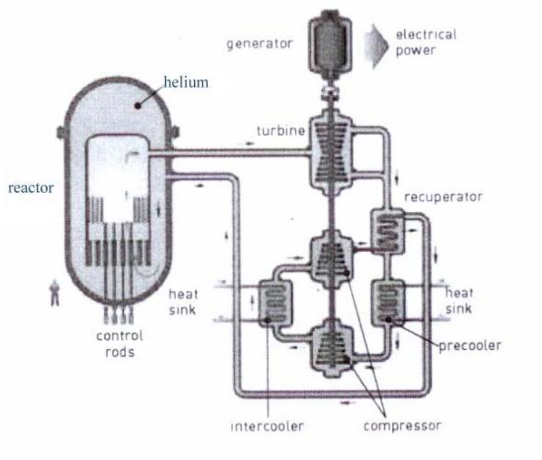

*Fig.2. Illustration of the GFR concept*

Combining the fast neutron spectrum with full actinide recycling, such reactors GFR will be able to minimize the production of radioactive isotopes of long life and contribute to closing of the nuclear fuel cycle.

While the GFR project is not done yet practical, two other options are routinely taken into account. A first alternative of project was a GFR plant cooled with helium, which used an indirect Brayton cycle for energy conversion. Another project alternative uses $CO_2$ in a supercritical state at 550$^{o}$C and 20MPa. This allows as the output temperature of coolant from primary circuit should be comprised between 600 and 650$^{o}$C, the fuel quantity and material requirements in the case of indirect cycle should be reduced comparatively with direct cycle, maintaining the same time a high thermal efficiency (~ 42%).

Another GFR alternative system is that cooled with $CO_2$ in supercritical state (550$^{o}$C and 20 MPa) and using a direct Brayton cycle. The main advantage of this design choice is a higher reduction in temperature of coolant coming out from primary circuit, maintaining at the same time a high thermal efficiency (~ 45%). The exit temperatures not too high (comparable with those from reactors cooled with sodium) conducted at the reduction of certain materials requirements referring to fuel, the fuel matrices/ metallic platings and, generally, at the need for materials that can withstand the high temperatures which relatively less complicated the compatibility issues related from materials compatibility.

The GFR plants being provided with the Generation IV reactors will use the materials tested or qualified specific to this type of reactor. The most important goal referring to the GFR materials will consist in materials selection and their authorization for the reactor core and internals. Instead the selection of materials normally used as structural materials will be severely restricted because of the difficult moderation of neutron spectrum in core. In this context, have been found some acceptable materials of neutronic point of view which can operate satisfactorily at high temperatures and intense neutron field exposure, expected to be used in the reactor core and that are compatible with the coolant agent (Fig.3[2]).

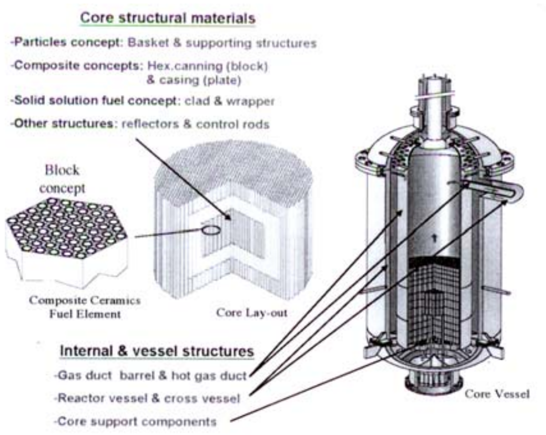

*Fig. 3. Main components of a GFR plant cooled with helium.*

The GFR energy conversion systems are very similar to those associated with next-generation nuclear reactors (NGNP) and absolutely identical in terms of pressure and temperature values. The temperature of helium cooling circuit at the turbine entry is 850$^{o}$C and that at the entry in recuperator is 500$^{o}$C. The maximum temperature in high and low pressure compressors and intermediary coolers respectively precoolers is very low (lesser than 150$^{o}$C). The two alternative projects use $CO_2$ in supercritical state at 20MPa in their energy conversion systems. In one project, the helium cooling circuit is operating at a temperature of 600-650$^{o}$C, transferring the heat through an intermediary heat exchanger at secondary circuit which uses supercritical $CO_2$. The advantages of power conversions in reactors type GFR, MHR and advanced PHWR are illustrated in Fig 4 [4].

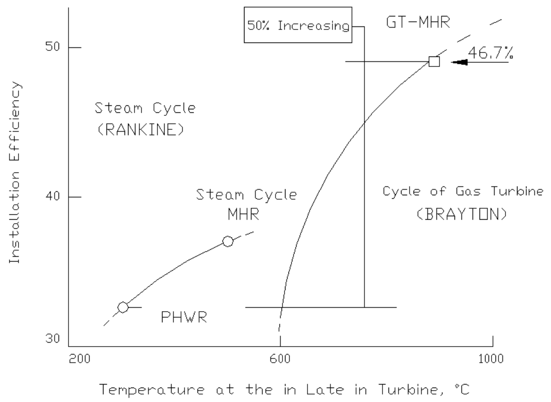

*Fig.4. Comparison of conversion degree of power in several advanced types of reactors.*

A brief presentation of operating parameters specific to GFR is shown in Table 1.

*Table 1. Target design parameters for the reference GFR system.*

| Reactor Parameters | Reference Value |
|---|---|
| Reactor power | 600 MWt |
| Net plant efficiency (direct cycle helium) | 42% |
| Coolant inlet/outlet and He pressure/flow rate | $490^oC/850^o/$ at 7 MPa, 312.4kg/s |
| Core structures temperatures (normal operations) | $500\text{-}1200^oC$ |
| Transient temperature in accident conditions | $1600\text{-}1800^oC$ |
| Out-of-core structures | $400\text{-}850^oC$, low irradiation exposure, mechanical loading <(50-60)MPa and high useful life (400000h) |
| Average power density | (50-100)$MWt/m^3$ |
| Reference fuel compound | UPuC/ SiC (50/50%) with about 20% Pu content |
| Volume fraction, Fuel/Gas/SiC | 50/40/10% |
| Conversion ratio | Self-sufficient (BR~0) |
| Burnup, Damage (initial values) | 5% FIMA; 80 dpa |

*Table 2. Normal and off-normal conditions for GFR vessel, core and internals.*

| *Component* | *Design Option* | *Normal Conditions* | | *Off-Normal Conditions* | *Notes* |
|---|---|---|---|---|---|
| | | *Temperature* $(^oC)$ | *Peak Dose* | *Temperature* $(^oC)$ | |
| Fuel Matrix-Cladding | He direct | 1200 | 15-20 dpa/yr, total 60 dpa | Up to 1800 | |
| | He/S-$CO_2$ indirect | 1000 | | Up to 1600 | |
| | S-$CO_2$ direct | 900 | | 1100-1500 | It may be possible to use metals in the core, depending on configuration |
| Spacers/Wire Wrap | He direct | 490-1000 | 15-20 dpa/yr, total 60 dpa | Up to 1600 | |
| | He/S-$CO_2$ indirect | 300-800 | | Up to 1400 | |
| | S-$CO_2$ direct | 400-700 | | 900-1300 | |
| Fuel Subassembly | He direct | 490-1000 | 15-20 dpa/yr, total 60 dpa | Up to 1600 | |
| | He/S-$CO_2$ indirect | 300-800 | | Up to 1400 | |
| | S-$CO_2$ direct | 400-700 | | 900-1300 | |
| Fuel Subassembly Duct | He direct | 490-1000 | 15-20 dpa/yr, total 60 dpa | Up to 1600 | |
| | He/S-$CO_2$ indirect | 300-800 | | Up to 1400 | |
| | S-$CO_2$ direct | 400-700 | | 900-1300 | |
| Reflector | He direct | 480-850 | Up to 150dpa | Up to 1100 | Normal operating temperatures are conservative; the high end may be less |
| | He/S-$CO_2$ indirect | 300-650 | | Up to 900 | |
| | S-$CO_2$ direct | 400-550 | | Up to 800 | |
| Control Rod Guide | He direct | 490-1000 | Up to 200dpa | Up to 1600 | |
| | He/S-$CO_2$ indirect | 300-800 | | Up to 1400 | |
| | S-$CO_2$ direct | 400-700 | | 900-1300 | |
| Upper Support Plate | He direct | 850 | Up to 100dpa | Up to 1200dpa | Normal operating temperatures assume the gas is well mixed at the core exit |
| | He/S-$CO_2$ indirect | 650 | | Up to 1000dpa | |
| | S-$CO_2$ direct | 550 | | Up to 900dpa | |
| Lower Support Plate | He direct | 490 | Up to 100 dpa | Up to 750dpa | |
| | He/S-$CO_2$ indirect | 300 | | Up to 550dpa | |
| | S-$CO_2$ direct | 400 | | Up to 600dpa | |
| Core Barrel | He direct | 490-850 | 80-100 dpa | Up to 1100dpa | |
| | He/S-$CO_2$ indirect | 300-650 | | Up to 900dpa | |
| | S-$CO_2$ direct | 400-550 | | Up to 800dpa | |
| Pressure Vessel | He direct | 490-850 | <1dpa to 40 dpa | Up to 1100dpa | Dose is dependent on shielding used, and off-normal temperatures can be significantly reduced if insulation is used |
| | He/S-$CO_2$ indirect | 300-650 | | Up to 900dpa | |
| | S-$CO_2$ direct | 400-550 | | Up to 800dpa | |

One of the objectives of R&D plan referring to GFR reactor materials will be the examination and prevalent testing of those materials which can limit the viability of the entire system. For example, it is still unclear whether some special materials are available for operation of GFR core. The characteristic temperatures reached by different components during operation of various types of reactors GFR, cooled with different gases, are presented in Table 2 [2].

It must achieved the materials evaluation acceptable from neutronic point of view, that must operate at very high temperatures in presence of relative high neutron fluxes and the possible interactions of materials with coolant agent. The candidate materials for operation must be identified using profound studies of their properties to allow a continuous perfecting of preliminary projects in view of selecting and classification of candidate materials. Considering that many of the materials used in the execution of GFR plants excepting the core are similar to those for reactors of Generation IV, the R&D plan will be available to providers referring to materials used at the execution of plants and especially reactors belonging to this generation.

## 3. Main materials used at the execution of GFR plants

### 3.1. Ceramic insulators used in some main GFRs

It is known that in GFR reactor core are mainly used the ceramic materials due to their outstanding resistance at high temperature. The main components executed from ceramic materials are: reactivity control rods, upper and lower support plates, etc. The nonmetallic materials used in the execution of GFR core components, of some internal components, structures-support and of assemblies of support bares and reflector, can be classified into the following categories: insulators and structural ceramics and structural composites.

The class of ceramic insulators is used in applications that require low mechanical performance (for example: stress lesser than 1MPa) and therefore require a short period of these qualification tests of materials. The non-structural ceramic materials can be used as spacers, electrical insulators and/ or thermal insulator in a reactor. The ordinary commercial ceramic materials, such as CaO and MgO, are hygroscopic and therefore are not good candidates for applications requiring an exposure at various impurities present during maintenance such as the water vapor.

Of monolithic ceramic materials that have a moderate resistance at radiation, it can be mentioned: $Al_2O_3$, $MgAl_2O_3$, $Si_3N_4$, AlN, SiC, ZRC, etc. Other ceramic materials, type alkaline halides, shows a high susceptibility to radiolysis, they tending to crake and peel slightly during operation and/ or maintenance.

Therefore, for these reasons, the ceramic materials susceptible at radiolysis cannot be used in these conditions. In view of their using in GFR reactors, the specific tests will be focused on filling gaps in the existing database on the variation of thermal conductivity and dimensional stability under irradiation. A number of composite materials have been designated in view of their using at the execution of the control bars and other structural components of GFR plants. In Table 3 [2] are presented some of these candidate components and materials used in GFR plants.

*Table 3. Main structural composite materials used in GFRs.*

| **Component** | **Graphit** | **C-C** | **SiC-SiC** |
|---|---|---|---|
| Hot ducts | | X | X |
| Core support | X | | |
| Core | X | | |
| External/ internal interchangeable blocks of reflector | X | | |
| Upper/ lower isolator blocks | X | | |
| Upper monolithic block | X | | |
| Floor block | X | X | X |
| Structural lining/ isolation | | X | X |
| Control and guiding bars | | X | X |

The main criterion that constituted the basis of their selection was their strength at temperatures above 1000°C, temperature at which the most metallic materials are not resistant.

### 3.2. Main metallic materials used in GFRs

From the metallic components used at high temperature in GFRs it can be mentioned the ducts, heat exchangers, turbines, compressors and recuperators. From the main candidate metallic materials used at the execution of these structures we remember some more important materials such as: alloy 617, 800H, X and XR, 602CA and 230[2]. In table 4[2] are presented main candidate metallic materials used at the execution of above-mentioned GFR components. There are a number of outstanding potential candidate that have not been included in Table 4[2]; their inclusion depends to a large extent on which option is under consideration.

*Table 4. Primary and secondary potential candidate materials for high-temperature metallic GFR components.*

| Primary/ secondary candidates | Nominal composition | Maximum temperature (°C) | Helium or other gas Experience |
|---|---|---|---|
| Primary candidates<br>Inconel 617 | 45Ni-22Cr-12Co-9Mo | 1100 | Yes |
| Inconel 800H | 33Ni-42Fe-21Cr | 1100 | Yes |
| 316FR | 16Cr-12Ni-2-Mo | 700 | No |
| Gr91 | 9Cr-1Mo-V | 650 | No |
| Cr22 | 21/4Cr-1Mo | 650 | Yes |
| Secondary candidates<br>Hastelloy X | Ni-22Cr-9Mo-18Fe | 1000 | Yes |
| Hastelloy XR | Ni-22Cr-9Mo-18Fe | 1000 | Yes |
| CCA Inconel 617 | 45Ni-22Cr-12Co-9Mo | 1100 | No |
| Alloy 230 | 53Ni-22Cr-14W-Co-Fe-Mo | 900 | No |
| Steel Gr92 | 9Cr-1.5W-Mo-V-Nb | 650 | No |
| Steel Gr23 | 21/4Cr-1.5W-V-Nb | 650 | No |

### 3.3. Materials compatibility considerations to establish the feasibility of GFR plants

Among the components that operates at high temperatures in GFR plants, remember mainly the pipes and heat exchangers. Other materials that operate at elevated temperature, for components that convert the power, are: turbines, compressors, coolers and recuperators. The main coolant agents in GFR plants are helium and supercritical $CO_2$.

#### ***3.3.1. Helium***

It is expected that the materials performance needs for the GFR in He will be largely covered by the work needed for the NGNP and data generated in previous He-cooled reactor work. Tests are needed to demonstrate that under the appropriate He flow rate and atmospheric ingress, the composition of the He can be maintained within the compositional range of previous testing range. These tests will require an appropriate sized pumps loop with associated chemistry measurement and side stream gas cleanup equipement.

#### ***3.3.2. Supercritical $CO_2$ (S- $CO_2$)***

The materials proposed for various components of supercritical $CO_2$ cooled reactor will be evaluated over the expected temperature range. As a minimum, the corrosion performance and mechanical properties of proposed materials in S-$CO_2$ and the lift-off and plating characteristics of the corrosion products must be determined.

Because choices of materials are still to be modified, the proposed test matrix contained in Table 5[2] will be identified by materials application rather than the specific materials.

*Table 5. Environment materials test matrix.*

| Materials application | Environment |
|---|---|
| High dose tolerant metals | Helium |
| Ceramic internal | Supercritical $CO_2$ |
| Inert fuel matrix ceramics | Supercritical $CO_2$ |
| Metallic internal | Supercritical $CO_2$ |
| Pressure vessel cladding | Supercritical $CO_2$ |
| Lift-off/ plating experiments | Supercritical $CO_2$ |
| Ceramic internal | In-reactor supercritical $CO_2$ |
| Metallic internal | In-reactor supercritical $CO_2$ |
| Pressure vessel cladding | In-reactor supercritical $CO_2$ |

The expected temperatures in GFR projects are relatively lower than those envisaged in other future nuclear reactors of Next Generation Nuclear Plants (NGNP). In the frame of helium cooled reactor project, it operates at a temperature of 850°C and 7MPa, and in He/ S-$CO_2$ indirect version, the exit temperature is 600-650°C at 7MPa in secondary circuit. For any option, the cobalt-bearing alloys should be avoided to be used where the radiation field may be present because this metal can become radioactive with a half-period very great. Thus, the alloys 617 and 230 can be used to execute the components from the immediate vicinity of the reactor vessel and Hastelloy XR alloy having a low content in cobalt, can be successfully used in reactors cooled by helium. To assess the radiation effects on the candidate materials exposed in a testing reactor, in a weak flow of radiation, special facilities have been built to execute the testing under irradiation. Such facility was also equipped with testing devices under load, for the resistance to fracture and fatigue, the Charpy test, etc. All results of these tests will be inserted into the surveillance program of the system in view to optimize the execution of Generation IV nuclear reactors.

## 4. Conclusions

The competitiveness between the energy cost produced in nuclear power plants and respectively in other alternative electricity generation installations being a key factor in stimulating of technological progress, it passed at one superior reactors generation-Generation IV.

Of the 100 proposed reactor systems belonging to this generation, only five systems were selected, the most promising being: two types of reactors using thermal neutrons - with Supercritical Water Reactors (SCWR) and reactors operating at very high temperatures (VHTR) - and three types of reactors: gas cooled fast reactors (GFR), Lead (LFR) and Sodium (SFR) reactors using fast neutron fluxes.

In this paper are reviewed, for purposes of illustration, some features of the gas cooled fast reactor (GFR) and the main materials used in the implementation of facilities for this type of reactor.

## References

[1] “A Technology Roadmap for Generation IV Nuclear Energy Systems” (2002) http://www.gen-4.org/PDFs/GenIVRoadmap.pdf.

[2] Corwin W.R., etc, “Updated Generation IV Reactors Integrated Materials Technology Program Plan” Rev.2 ORNL/TM-2003/244/R2 (2003)0

[3] Baldev Raj, et al., „Challenges in Materials Research for Sustainable Nuclear Energy” MRS Bulletin **33**, 327 (2008).

[4] “Current trends in nuclear fuel for power reactors” . http://www.iaea.org/About/Policy/GC/GC51/GC51InfDocuments/English/gc51inf-3-att5_en.pdf.

[5] B.Slalaby "CANDU Technology for Generation III and IV Reactors" presented at Win Global Conference Waterloo, Ontario (2006).

[6] S. Banerjee "Better Materials for Nuclear Energy" IAEA Science Forum (2005).