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HTR FUEL RESEARCH IN THE HTR-TN NETWORK ON THE HIGH FLUX REACTOR

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ABSTRACT

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Foremost, this paper explains the economic and strategic reasons for the comeback of the HTR reactor as one of the most promising reactors in the future.
To study all the points related to HTR technology, a European network called HTR-TN was created in April 2000, with actually twenty European companies involved. This paper explains the organisation of the network and the related task-groups. In the field of fuel, one of these task-groups works on the fuel cycle and another works on the fuel itself in order to validate by testing HTR fuel possibilities. To this aim, an experimental loop is under construction in the HFR reactor to test full-size pebble type fuel elements and another under study to test compact fuel possibilities.
These loops are based on all the experience accumulated by the High Flux Reactor in the 70s-90s, when a lot of test were performed for fuel and material for the HTR technology and the facility design uses all the existing HFR knowledge.
In conclusion, a host of research work, co-ordinated in the frame of a European network HTR-TN has begun. and should allow in the near future a substantial progress in the knowledge of this very promising fuel.

1- INTRODUCTION: HTR – THE COME BACK

In the years 1960 to 1990 several HTR prototypes were built and tested in Europe and in the US with good results:

- Dragon – GB – 1964/1975
- AVR – Germany – 1966/1988
- Peach-bottom – USA – 1966/1974
- Fort-St-Vrain – USA – 1974/1989
- THTR 300 – Germany – 1983/1989

A commercialisation of HTR seemed to be promising in the 1980's for medium-sized or modular steam cycle HTR despite the fact that LRW allow larger power sizes due to high power density of about 100 MW/m^3 as compared to 3-6 MW/m^3 for the HTR.
But after the TMI and Chernobyl accidents, the two main countries working on this concept USA and Germany decrease their effort.
The commercial development of HTR in Europe was terminated around 1990 when the German HTR programme was stopped after the decision to decommission the 300 MWe demonstration plant (THTR 300).
But several facts show in the year 2000 the come back of the HTR on the market.

- In Japan a 30 MW prototype reactor HTTR has started operations 2 years ago.
- In China a 10 MW test reactor has reached first criticality in December 2000.
- In South Africa an industrial project on a 110 MWe modular HTR, with direct cycle gas turbine (PBMR) is under detailed design.
- In Russia, Russia, USA and other partners focus research on a project (GT-MHR) to burn military plutonium stock with modular HTR reactors.

2- HTR ADVANTAGES

The reasons of this comeback are many potential advantages for this type of reactor in comparison with the classical LWR high power reactors.
Modularity: All the advantages of modularity are well known. The idea to have a basic module, licensed, builded in industrial way, and with a short time installation planning is coming back with the ask for flexibility and quick response on the new market of energy.
Inherent safety: The refractory coated fuel allows to retain all fission products even in severe accident conditions and by inherent passive behaviour. To reach the same safety objectives, it was necessary for classical LWR to increase many dispositions (core catcher, containment under higher pressure, water injection, etc.). Therefore, the costs of LWR have increased a lot, year after year. This allows now to the HTR to be competitive again with LWR kilowatt cost.
Fuel cycle: Due to higher efficiency and higher burn-up possibilities, it needs to produce one kilowatt, 3 times less uranium that on a LWR.
Other time the actinide production is reduced by a factor of about 2.
So at the end, in terms of fuel supply and in terms of waste production, the HTR reactors have advantages.
You can add to that the possibility to burn plutonium or to burn thorium and various fuels. This flexibility on fuel cycles allows a lot of strategies and possibilities in the future.
Technology progress: The progress of technology, especially on the high temperature gas turbines, can be used now in the conception of HTR, with direct cycle gas turbine. This allow to increase the efficiency (to reach about 50%) and to consider suppression of the secondary system. This point contributes to decrease the kW cost of the HTR modular reactor.
Industrial use: The HTR modular reactor opens very interesting possibilities of industrial use, not only for electricity production, but also for a lot of various applications: water desalinisation, hydrogen production, high temperature chemical process, etc.

3- THE HTR-TN NETWORK

Under this background, an initiative to launch the High-Temperature Reactor Technology Network (HTR-TN) was undertaken by the partners of the INNOHTR Concerted Action and especially by the European Joint Research Centre (JRC) that already operates a number of European Networks with great success like PISC, AMES, ENIQ, NESC, EPERC, etc.
The HTR-TN could benefit from this experience and also adopt the proven structures with a Steering Committee as decision-making organ and different specific Task Groups all being supported by JRC as Operation Agent, Network Manager and Network Secretary.
The network members are bound together by a Multi-Partner Collaboration Agreement that does not involve cash flow between the members. All contributions are made in kind.
Fifteen companies have initially signed the network protocol: Ansaldo, Belgatom, BNFL, CEA, Framatome, Empresanos Agrupados, FZJ, NNC, NRG, Siemens, FZR, JRC and several universities. The kick-off meeting of the Steering Committee was held in April 2000, at JRC Petten (The Netherlands). Six technical task groups were created: components technology, system and applications studies, material performance

evaluation, safety and licensing, fuel testing, physics and fuel cycle including waste. In addition, three horizontal task groups on strategy, telecommunication and international collaboration are supporting the technical programmes. Meanwhile Balcke-Duerr, COGEMA, VTT, Ciemat and Slovenic Research Centre joined HTR-TN that is still open for further partners or associates from Europe and elsewhere.

4- THE HTR-TN PROGRAMME

The final goal is the development of advanced technologies for modern HTR in order to support the industry for the design of these reactors. Actually a lot of HTR-TN propositions have been accepted and funded in the Euratom 5th R&D Framework Programme (FP5). It gives to the task groups of the HTR-TN, an actual operating budget of about 17 Meuro.

5- FUEL RESEARCH

One of the six technical task groups is HTR-F, related to fuel research. The main objective of this research is to validate the irradiation of existing available fuel (pebbles or compacts) to a maximal burn-up. This irradiation will be provided on the High Flux Reactor, located in Petten (The Netherlands). This reactor owned by the European Commission and operated under contract by NRG, has already extensively be used in the past as a test bed for fuels and materials of HTR, The table in Annex 1 gives a survey of all the irradiation experiments already performed in the past at the HFR (Petten) in support to HTR research for Germany and USA.
All this experience gives to HFR a lot of knowledge to this type of experiments.

6- BASIC DESIGN OF HTR FUEL IRRADIATION FACILITIES

The major test objectives of the in-pile tests that are mentioned in Table 1 were the demonstration of the integrity and the retention capability of the particle coating against fission product and fission gas release and the irradiation stability of full size spherical fuel elements fabricated on a production scale under power plant conditions with respect to temperature history, correlation of fast fluence and burn-up and power history. The irradiations were not only conducted at normal, but also at off-normal operating conditions, e.g. simulating core water ingress and temperature transients.
Unique irradiation facilities have been developed by IAM and the design has continuously evolved to meet the extensive range of requirements for HTR fuel testing [ref. 1, 2, and 3].
Typical for all HTR fuel testing rigs at HFR are the multi-capsule designs, which allow loading of independent experiments into one core position. Small samples with diameters up to 30 mm can be loaded in rigs (type TRIO or QUATTRO) that provide 3 or 4 parallel and independent channels. The inserts of each channel can independently be loaded and unloaded. Larger samples with diameters of up to 63 mm can be loaded in multi-capsule rigs (type BEST or REFA) that can accommodate up to four independent superposed capsules. Each individual capsule is connected with an independent sweep loop that enables automatic control of temperature, gas pressure and purge gas mass flow. Surveillance of gas quality and the release of volatile fission products are provided as well. Furthermore, the capsules are fully instrumented with thermocouples, fluence detector sets, gamma scan wires and self- powered neutron detectors. Those containments, which contain fuelled specimens, are continuously purged with pure helium.
The irradiation temperature can be controlled between 870 and 1770 K with an accuracy of less than 10 K by means of gas mixture technique and vertical adjustment of capsules in the flux profile. Modelling by means of FE computer codes enable the design of required temperature fields by tailoring the appropriate dimensions of capsule components. The downstream of the purge gas of each capsule is continuously monitored on-line on the release of gaseous fission products. The fractional fission gas release R/B (Release rate to Birth rate) can be determined by means of intermittently taken gas samples. The release rate is measured and the birth rate is calculated.
The multi-capsule design features the possibility to perform parametric studies at identical nuclear conditions with a large variety of specimens. The required burn-up-fluence correlation can be adjusted by flux tailoring, by which the material of the direct environment of the in- pile sections can be adequately selected.

7- THE HFR-EU1 TEST WITHIN HTR-TN

The HFR-EU1 irradiation at HFR Petten is the first fuel test that will be conducted within the new European network HTR-TN as the Shared Cost on project "HTR-F" of EU's 5th FP. A consortium of 6 contractors participates in the HFR-F project, i.e., CEA as co-ordinator and Framatome, NRG, FZJ, JRC-ITU and JRC-IAM. The HTR-F project has been approved under the contract no. FIKS-CT-2000-00099 [ref. 4].
The new European HTGR fuel program of the 5th Framework Program of the European Union is based on previous experience and plans to explore the potential for high-performance and high-burn-up fuel for next generation of inherent safe nuclear plants (4th generation).
The HFR-EU1 irradiation experiment will be carried out at the High Flux Reactor (HFR) Petten in close co-operation between FZJ, NRG and JRC Petten. Post-irradiation examination (PIE) will be performed both at NRG Petten and at JRC-ITU. Accident simulation tests will be done at JPC-ITU.
The main objective of the HTR-EUI irradiation test is the demonstration of the feasibility of high burn-up for the existing German LEU fuel with TRISO coated particles. It will include in particular:

a) the irradiation up to a burn-up of 20% FIMA, to be achieved within 2 years;
b) the evaluation of fuel performance at such ultra-high burn-up to explore the real limits of the existing CP that have formerly been designed for operational conditions of the HTR- Modul;
c) the extension of the existing data base for the EOL metallic fission product release, particularly the silver isotope Ag-110m for an improved assessment of the particle choice for the gas turbine HTGR concept;
d) the demonstration of the ability of the LEU-TRISO CP for fission product retention at accident scenarios, e.g. post-irradiation heating beyond 1600°C. These PIE tests, which will be performed in the KUFA facility at JRC-ITU, are the main goal of the HFR-EU1.

The irradiation samples of the HFR-EU1 test will be four spherical fuel elements with 60mm outer diameter. These spheres exist and are of the type AVR GLE-4 (AVR reload 21-2) with 16.7% U^{235} enrichment. These FE's have been irradiated earlier in the AVR. They have reached a calculated average burn-up of 8.6% FIMA with a maximum burn-up of about 20% FIMA. No particle defects were observed during the on-line gas release measurements. This excellent result indicates a certain potential of the LEU-TRISO particles for the application in FE's with a prospective extreme high burn-up.
Excellent results have also been obtained from a large variety of tests on LEU-TRISO fuel at the HFR Petten. As before mentioned, these tests (Table 1) have been conducted under conditions beyond nominal conditions of HTR concepts. These tests comprised spherical fuel elements and a large variety of compacts and loose coated particles. The experience of three decades of fuel testing resulted in optimised design and instrumentation of the facilities and irradiation under well-controlled conditions.
The proposed facility for the HFR-EU1 test will be designed for the simultaneous irradiation of four spherical fuel elements. The in-pile section will consist of a sample holder with two independent and superposed capsules, which will be inserted into a thimble that forms the second controlled containment. The thimble is a standard facility, code-named REFA-172. The useful diameter of the REFA is 72 mm. Each capsule will contain two spheres, which are held in position by cylindrical half-shells. Figure 1 shows the schematic design of the in-pile section. The capsules will be instrumented with thermocouples, fluence monitors and flux detectors. Each capsule and the second containment will be connected with an independent sweep loop circuit that allows continuous purging with an inert carrier gas under controlled conditions. The purge gas of the second containment will be composed of an adjustable helium-neon gas mixture and serves for automatic temperature control. The purge gas of the two capsules will basically be pure helium and serves for continuous surveillance of the fission gas release rate of the specimens. The fractional release of the main Kr and Xe isotopes will be determined quasi on-line. Further features of the HFR-EU1 test are the feasibility to tailor the neutron spectrum for proper burn-up-fluence correlation and a vertical displacement unit that allows a fine tuning of fluence/burn-up and temperature, and the cycle-wise turning by 180° to realise a homogeneous azimuth fluence/burn-up distribution in the large specimens. Design of the structural part of the capsules ensures that the total amount of solid fission product released from the fuel elements can be measured by leaching this part after irradiation. The required burn-up level should be reached after irradiation of about 2 years in a peripheral in-core position of the HFR.
The HFR-EU1 test shall be conducted such that the central temperatures of all fuel specimens be held constant at about 1100°C. This will require a gradual increase of the initial surface temperature of 800°C to compensate for the reduction of the fuel central temperature with increasing burn-up.

The procedure involves for the accompanying calculation inherent uncertainties such as power profile and material properties as a function of temperature and fluence. Temperature transients will not be performed. The fission power of a single particle should remain < 250 mW. The irradiation shall be conducted until a maximum burn-up of the highest loaded FE of approximately 20% FIMA is achieved. Fast neutron fluence shall not exceed $8*10^{25}$ M^{-2} (E>0.1MeV).

8- HFR-EU2 TEST WITHIN HTR-TN

The HFR-EU2 test is the second fuel test that will be performed in the frame of HTR-TN.
This device is devoted to the test of compact fuel from USA (GA).
Figure 2 gives a schematic view of the proposed HFR-EU2 test, where the compacts are tested in one leg of a classical TRIO loop.
Same mode of operation is followed as for the HFR-EU1 test.
Discussions are also engaged with JAERI, to test Japanese compact elements on these test possibilities.

9- CONCLUSION

The HTR remain one of the most serious candidates for applications of nuclear reactors in the future.
With the HTR-TN network, Europe has shown a recognised organisation to develop and co-ordinate technology around HTR in the future. This organisation has today a budget of about 17 Meuro in several task-groups. For the fuel research, the four possible providers – in 2001 – of HTR fuel in the world should be tested in the near future (first test in 2002) on the HFR reactor, that has a large knowledge in this field. The investment made today in the frame of HTR-TN, on devices and gas circuits for these pebbles and compact tests, will also be useful to test other new promising HTR fuel in the future.

Project name	Contractor	Characteristics of specimens	Irradiation performance data					
			Irradiation period	Irradiation time [fpd]	Temperature [°C]	Burn-up [% fima]	Fluence E>0.1 MeV [10^{25} m^{-2}]	EOI fractional fission gas release [R/B Kr^{85m}]
HFR-K 3	FZJ, NUKEM, HRB	4 spherical fuel elements 60 mm UO_2 LEU reference particle	1982 – 1983	359	1210 central	10.6	6.0	2.2 10^{-7}
HFR-P 4	FZJ, NUKEM, HRB	36 small spheres 20 mm diameter UO_2 LEU reference particle	1982 – 1983	351	1000 and 1200 central	14.5	8.2	8.5 10^{-8}
HFR-P 5	FZJ, NUKEM	116 coupons UO_2 LEU reference particle	1983	142	1450	7.2	5.5	1.1 10^{-4}
HFR-K 4	FZJ	2 spherical fuel elements 60 mm UO_2 LEU	1985 – 1986	667	600<T<1150	13	10.0	Defective coated particles due to drilled holes for thermocouples
HFR-K 4	FZJ	2 graphite spheres 60 mm A3-27	1985 – 1986	667	800	-	8.5	-
HFR-K 5	FZJ, NUKEM, ABB, HRB	4 spherical fuel elements 60 mm UO_2 LEU reference particle	1991 – 1994	564.28	800/1000 cycle 3x 1200 for 5 h	6.7 – 9.1	2.85 – 4.25	3.0 10^{-7}
HFR-K 6	FZJ, NUKEM, ABB, HRB	4 spherical fuel elements 60 mm UO_2 LEU reference particle	1990 – 1993	633.55	800/1000 cycle 3x 1200 for 5h	7.2 - 9.7	3.2 – 4.83	3.0 10^{-7}
HFR-B 1	General Atomic FZJ	36 fuel rods in 3 capsules UCO LEU & ThO_2 Segments of block design	1988 – 1989	445	900 880<T<1230 820<T<1040	15.4 17.0 14.2	6.1 6.7 5.3	10^{-3} 10^{-3} 10^{-3} and 16 H_2O injections
HFR-K 9	FZJ	6 SiC coated graphite spheres 60 mm and without fuel	1995	93.89	550 - 680	-	1.0 – 1.95	-
HFR-K 10	FZJ	5 SiC coated graphite spheres and 3 SiC samples 60 mm and without fuel	1998	98.01	600 - 770	-	1.6 – 1.9	-
HFR-K11	FZJ	Six SiC coated graphite spheres and 6 SiC samples 60 mm and without fuel	1999	95.88	620 - 760	-	1.0 – 1.7	-
HFR-EU1	EU Contract FIKS-CT-2000-00099	4 spherical fuel elements 60 mm UO_2 LEU reference particle	2002-2004					

Table 1: survey of irradiation experiments performed at the HFR Petten in support of R&D for German modular HTR and US HTGR

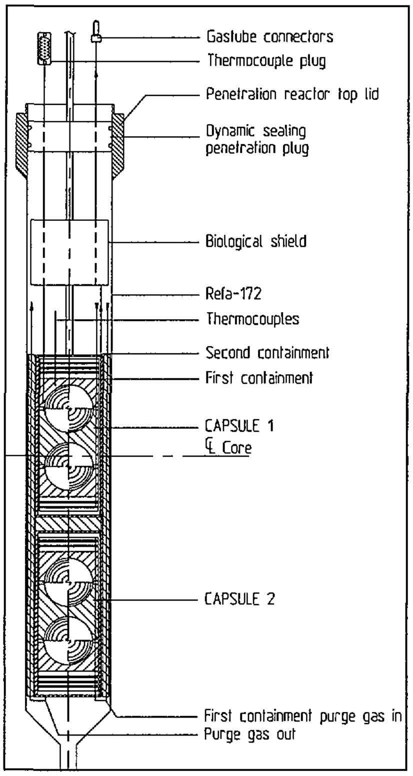

Figure 1: schematic design of in-pile section of HFR-EU1

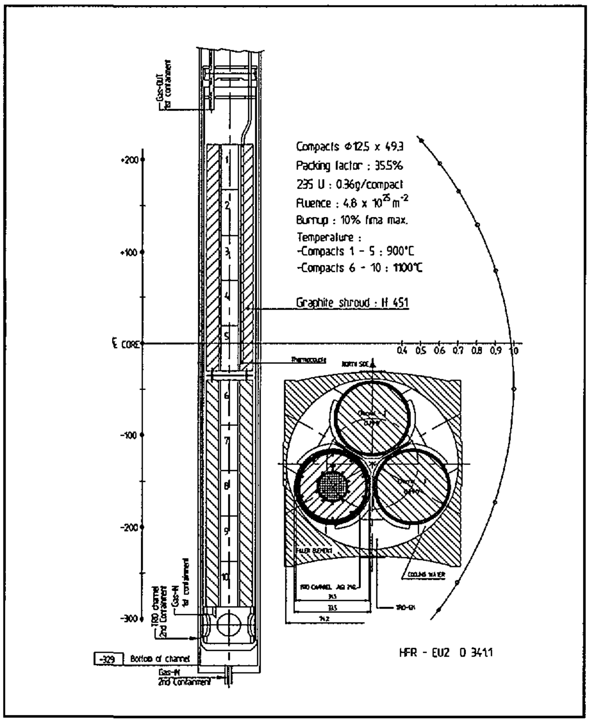

Figure 2: schematic design of in-pile section of HFR-EU2

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