THE RENEWAL OF HTR DEVELOPMENT IN EUROPE

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ABSTRACT: The European HTR-Technology Network (HTR-TN), created in 2000, presently groups 20 organisations from European nuclear research and industry for developing the technologies of direct-cycle modular HTRs, which presently raise a large world-wide interest, because of their high potential for economic competitiveness, natural resource sparing, safety and minimisation of the waste impacts, in line with the goals of sustainable development of Generation IV. All aspects of HTR technologies are addressed by HTR-TN, from the reactor physics to the development of materials, fuel and components. Most of this activity is supported by the European Commission in the frame of its 5th Euratom Framework Programme. The first results of HTR-TN programme are given: the analysis of the reactor physics international benchmark on the commissioning tests of HTTR (Japan), the long term behaviour of spent HTR fuel in geologic disposal conditions, the preparation of a very high burnup fuel irradiation and the development of fabrication processes for producing high performance coated particles, etc.
Keywords: HTR, Europe, reactor physics, fuel, materials, safety.

1 Introduction

There has been in the last years a renewal of interest for the High Temperature Reactors (HTRs) in the world. One decade after the stopping of Fort Saint Vrain in USA and AVR and THTR in Germany, two high temperature test reactors started, HTTR in Japan in 1998 and HTR-10 in 2000 in China. Two industrial projects are progressing, with the objective of commissioning prototype reactors before 2010, the GT-MHR led by an international consortium (Minatom, General Atomics, Framatome ANP and Fuji Electrics) for burning Russian military plutonium and the PBMR, led by ESKOM (South Africa) with the participation of BNFL, Exelon and German institutes. In Europe several countries have significant activities in the field of HTRs and the European Commission is supporting a cluster of projects for the development of HTR technology in its 5th EURATOM Framework Programme [1].

2 Why a renewal of interest for HTRs?

The experience with reactors built in the past in England, Germany and United States, have shown that HTRs are reliable and can be operated on an industrial basis. But their economic competitiveness was penalised by a very low power density. During the last 2 decades, 2 major breakthroughs came out and restored the economic competitiveness of HTRs, bringing also some new safety features, which can make these reactors more acceptable for the public:

- the modular concept,
- the direct helium thermodynamic cycle (Brayton cycle).

Instead of trying to reach the competitiveness by the scaling up effect, the modular concept is based on the scaling down of the reactor size for the decay heat to be released only by thermal conduction and radiative heat transfer. For an HTR with a power not exceeding 200 to 600 MWth (depending on the reactor and fuel design), the fuel temperature can be kept below 1600°C without operating any active safety system in all plausible abnormal transients, even in very hypothetical accident conditions (see for example in Fig. 1, the evolution of the fuel temperature during a LOCA in GT-MHR). Therefore, also due to the exceptional robustness of the coated particle fuel (see Fig. 2 for a description of HTR fuel) which does not release significant quantities of fission products at least up to 1600°C (Fig. 3), redundant safety grade emergency systems can be eliminated from modular HTRs with a substantial simplification of the design, implying significant savings. Moreover the safety of a modular HTR, based on inherent physical properties of the system, which cannot break down or be bypassed by human actions, is a strong argument for the acceptation of this type of reactor by the public.

In former HTRs, electricity was generated by a steam turbine, with the steam produced in a steam generator heated by the helium cooling the core. Due to the advances in natural gas turbine technology, a direct cycle can be considered now, with a helium turbine directly driven by the primary helium. If such a helium cycle is optimised (recuperated and intercooled cycle, see Fig. 4) the thermodynamic efficiency of the system can be significantly improved: in the first modular reactor, the German Modul, with a steam cycle, the efficiency was not exceeding 39% and in GT-MHR, with direct cycle, it reaches 47%. This increase of the efficiency and the simplification due to the direct cycle are boosting the economic competitiveness the reactor. Moreover, in the direct cycle, there is no high-pressure water, contrary to the former reactors with a steam generator, where water ingress was responsible for many cases of unavailability and could also be a safety issue.

The most recent economic evaluations show that for a direct-cycle modular HTR, the costs of construction per kWe and of generation of electricity should be of the same order of magnitude as for commercial reactors of the present generation. Of course there are still some uncertainties in these evaluations, which is not surprising for innovative projects, but, as HTR technology is still far from maturity, there is a large potential for improvements and simplifications (design, materials, fuel), which will secure the competitiveness of HTRs in the long term.

HTRs are not an alternative to advanced reactors derived from the plants of the present generation, like the EPR or the SWR. They are complementary to these plants, because they answer the needs of different parts of the market and/or of different uses of nuclear energy, e.g.,

- the need of new industrial countries or of large countries with scattered energy consumption for medium size plants (a few hundreds of MWe), which is, for the time, being mostly satisfied by gas and nearly not at all by nuclear energy,
- the need of industry for co-generation or process heat (including for the high temperature production of hydrogen by water decomposition), which is again for the time being mostly satisfied by gas and coal and not at all by nuclear energy,
- the need for low temperature heat for district heating or seawater desalination, for which HTRs, with their relatively limited heat releases (a few hundreds MW), and the higher temperature of the releases (~120°C) are much more adapted than LWRs,
- the need for limiting the accumulation of plutonium generated by civilian and production reactors and for mastering the associated danger of proliferation, by burning the plutonium very efficiently so that a significant quantity of plutonium disappears and that the isotopic content of the residual plutonium is very much degraded (see in Fig.5 the potential of HTRs for destruction of weapon plutonium compared to that of LWRs).

3 The development of HTR technology in the European Union

As already mentioned, many European organisations are partners of one or the other of the two present projects of industrial prototypes, GT-MHR and PBMR.

Moreover, about 20 organisations from industry, research and higher education of 8 countries and the Joint Research Centre (JRC) of the European Commission joined forces and created the (European) HTR Technology Network (HTR-TN) in 2000, the objectives of which are

- to create the technological basis for an industrial emergence of HTRs in Europe by 2010,
- to prepare longer term evolutions of HTRs, which will appear necessary for keeping their competitiveness and satisfying more fully the requirements of sustainable development (optimisation of the product taking the benefit of advanced design or technological options and of the first industrial experience feed-back, increase of the operating temperature, possibly hardening of the neutron spectrum and finally extension of the fields of applications - co-generation applications, hydrogen production, actinide burning…).

The partners of HTR-TN presented 6 coordinated projects, which were selected for the 5th Framework programme with a total budget of about 15 M$ (50% funded by the European Commission), HTR-N, HTR-F, HTR-M, HTR-E, HTR-L and HTR-C. This last project deals only with the integration and the coordination of the whole cluster and each of the other projects covers a technical area. The programmes of work are presented in the following. HTR-N, HTR-F and HTR-M started in the second half of 2000 and already produced first significant results, which will also be presented. HTR-E and HTR-L just started in the last 2001 trimester. Moreover a task force on accident analysis and fission product transport have been created by HTR-TN in order to start the work in these fields, even though there is no related project funded for the time being by the European Commission, due to the limitations in the funding.

HTR-TN is also looking for the synergy and complementarity of its programme with the present world-wide R&D effort on HTR technology, through the development of international co-operation: some co-operation already started with JAERI (Japan), INET (China) and USDOE/General

Atomics, other international co-operative projects are considered.

3.1 Reactor physics and fuel cycle studies (HTR-N)

The following topics are addressed in the project:

- the qualification of tools and methodologies for HTR applications, by benchmarking the experimental results obtained from the beginning of operations of HTTR and HTR-10,
- the analysis of the physics of HTR cores and of possible HTR fuel cycles, mostly focused on the feasibility of cores fed only with civil plutonium from the 1^{st} or 2^{nd} generation,
- the comparison of the wastes from LWRs and HTRs,
- the behaviour of irradiated HTR fuel in the conditions of deep geological disposal.

An international benchmark of HTTR and HTR-10 reactor physics tests has been organised by IAEA. An important scattering of the different calculations and large discrepancies with measurements resulted from the exercise [2]. In HTR-N, only the results of HTTR benchmark have been fully analysed until now, both for the annular configuration of the first criticality (with central fuel positions loaded with dummy graphite blocks) and for the cylindrical configuration of the full core. The origin of the main discrepancies of the IAEA benchmark are understood (detailed modelling of the very heterogeneous geometry of the fuel and burnable poisons, streaming effect, impurities in graphite) [3]. New calculations were made both with a Monte Carlo (MC) code (TRIPOLI 4 [4]) and with diffusion codes (CRONOS 2 [5], CITATION [6]). With the MC code, the discrepancy is reduced to 1% $\Delta k/k$ in the annular configuration, which may be explained by the uncertainty on graphite impurities, the impact of which is very important in this configuration. For a fully loaded core, the agreement between the experiment and the calculation is rather good. With 3D diffusion calculations, the results were acceptable in the cylindrical configuration but discrepancies remain important in the annular one.

For final disposal studies, the installation of experimental autoclave and dynamic systems for static corrosion and leaching measurements (Fig.6) have been finished. The leaching facility has been built up in a glove box in order to be able to make experiments with irradiated fuel. Preliminary corrosion results have already been obtained [7], both in the chemical conditions of a clay and salt geological environment, showing a minimum lifetime of about 10 000 years for the SiC coating of a HTR fuel particle, without taking into account the protecting effect of the graphite matrix of the fuel element and of the two other pyrolytic carbon (PyC) coating layers. This would provide the HTR irradiated fuel in a geological repository with a stability significantly higher than that of vitrified reprocessing wastes. In the following of the project these very promising trends will be confirmed with experiments on irradiated fuel.

3.2 Fuel technology (HTR-F)

The objectives of the HTR-F project are:

- to restore the state-of-the-art technology on HTR fuel fabrication,
- to develop a highly competitive HTR fuel, that is a fuel providing high performance in terms of very high burnup and high temperature capability with very low fission product release, together with a competitive fuel cycle cost,
- to verify the past preliminary tests (see for example Fig.7) on the ability of HTR fuel to reach the extremely high burnups (~ 700 GWd/tHM) needed in order to exploit the potential of HTRs for burning plutonium very efficiently.

The following topics are addressed in the project:

- the behaviour of the fuel under irradiation and its modelling,
- the technologies of the fabrication of coated particles.

The first step for the development of a fuel with very high performance is to explore the limits of the state-of-the-art fuel and to understand its failure mechanisms. This is what will be done in an experimental irradiation of different types of presently available HTR fuel (German pebbles and American compacts from old fabrications, pebbles from present Chinese fabrication) to very high burnup (200 GWd/tHM, 8×10^{25} n m^{-2}), now under preparation in HFR (Petten, Netherlands) [8]. The irradiation will start in October 2002 and last 2 years. After the irradiation, the fuel will be subject to post-irradiation examination and to a heat-up experiment (simulating accident conditions) in a facility (see Fig. 8) now being installed in the hot cells of ITU (Karlsruhe).

In order to be able to analyse the fuel behaviour under irradiation and to optimise the fuel design, a European HTR fuel code is being developed, with a combination of a 3-D deterministic calculation of the coated particle including the best state-of- the-art-material data and phenomenological models (creep, shrinkage, swelling, fission gas release, burnup and fast fluence effects, CO build-up) and a statistical computing of the behaviour of the thousands of particles in a fuel element. The first qualified version of the code will be operational in 2003.

The first steps of fabrication of coated particles are underway: two variants of a GSP sol-gel process are tested with uranium in ITU and CEA. ITU is also preparing the adaptation of the process for producing plutonium kernels. CEA (Grenoble centre) has restored two fluidised-bed chemical vapor deposition coaters, which were operated in its past HTR programme, and which are now used for recovering the coating know-how on dummy cerium kernels. The parameters for producing a buffer and an inner PyC layer fully complying the specifications are already mastered (see Fig.9) and tests for the elaboration of the SiC layer are progressing. In parallel control techniques for the two inner coating layers have been developed (weight, burn and laser scattering measurement). In the meantime CEA is developing a coater for real uranium fuel in Cadarache. The first uranium coated particles will be available for irradiation tests in 2004.

3.3 Material development (HTR-M)

The objective of HTR-M is to qualify the key materials for their use in the conditions of the modular HTR projects: the reactor vessel material, the high temperature (~ 850°C) materials for the reactor internal structures (e.g., control rod cladding) and for turbine blades and discs and the graphite. Due to the relatively short time perspective for the first industrial applications (no more than a decade) and to the very long time scale for developing a new type of material, no development of innovative materials is planned and only the qualification of existing materials for the specific conditions of their application in HTRs is targeted.

For the vessel, two design options exist:

- one option, which minimises R&D, keeps the temperature of the vessel at a similar value than in PWRs by means of a derivation of the coolant flow from a point of the power conversion system where the helium is at the appropriate temperature; this option allows the use of existing PWR vessel materials without collecting new irradiation data. This is the option, which have been selected for PBMR.
- in the other option, which maximises the thermal efficiency of the system, the vessel is kept at the coolant core inlet temperature, that is for GT-MHR, which takes this option, 450°C. PWR steels are not acceptable at such a temperature and another steel has been selected, the Modified 9 Cr 1 Mo steel (A3.18S material of the RCCMR code). This material is well known and has many records of industrial applications but few in nuclear industry, in particular in large thickness.

The programme concerning the vessel material is therefore focused on the qualification of Mod. 9 Cr 1 Mo. For this purpose, an irradiation test of thick welded joints of this material is being prepared and will start at the end of 2002 in the reactor HFR (Petten).

For the internal structures, the potential of carbon fibre composites (CFCs) [9] is evaluated. For the turbine, the most critical areas are the first stage discs and blades. Materials have been selected for these applications, but the HTR design and operating conditions, in terms of size, temperature (~ 850°C), stresses, chemical environment and long term endurance (~ 60 000 h without maintenance), are beyond the existing industrial experience. Manufacturing considerations are a major factor for discs: for the selected materials, producing the large ingots that are required, without porosity and segregation is a real challenge. Corrosion, which can cause a significant shortening of the material creep life and an acceleration of creep crack growth rates, is a major issue for blades. It will be addressed by optimisation of the alloy composition and/or application of suitable coatings. High temperature (≤ 1300°C) mechanical tests and medium term (10^{4} h) creep tests at 850°C on the selected materials are planned.

The graphite grades, which were used in the former HTR projects, are no longer available and the suitability for HTR applications of the products, which can be presently proposed by graphite manufacturers, is not known. Therefore a programme of selection of the appropriate grades is undertaken and in particular an irradiation test of samples from different manufacturers will start in the 2nd half of 2002 in HFR.

Moreover a study on graphite oxidation has been started on THERA and INDEX facilities in Jülich research centre and some early results in air are already available. Measurements have been made on the kinetics of graphite in oxygen for temperatures between 550 and 750°C and partial pressures of between 2 and 20kPa. Measurements in steam require some improvements of the test facilities to be incorporated in the test rig, which have just been completed.

Oxidation resistance of 3 selected CFC materials developed for fusion have been measured in air. Further tests in steam are expected before the middle of 2002 and results from the high flow rate facility will be obtained by the end of the year. Experiments are also being carried out to determine the thermal conductivity of these CFCs. So far reference measurements have been made on non-irradiated material. Tests on irradiated samples will be completed in 2002.

3.4 Key components of the power conversion system (HTR-E)

The objective of HTR-E is to assess the key feasibility issues related to the components and technologies of the power conversion system (PCS) and to make recommendations for further developments. So far no original PCS design is made in the project or individually by its partners and the key issues are identified from the existing industrial projects, GT-MHR and PBMR.

The first and probably most important issue, coupled to the high temperature materials issue, concerns the feasibility of a 300 MWe high-efficiency turbine operating at 850°C without internal cooling and with non-standard requirements in terms of long term endurance. A preliminary design will be made and a programme of tests on a mock-up for the validation of the performances of this design will be defined. The realisation of these tests will be proposed later for the follow-up of the project in the 6th Framework Programme.

The second challenging component is the recuperator, which is a key component for the thermal efficiency of the PCS, with quite heavy operating loads (temperature transients and differential pressure) and very stringent compactness requirements. A concept will be selected for this component and a prototype module will designed, fabricated and tested at CEA Grenoble, in order to validate the performances of the design in steady and transient conditions.

Active magnetic bearings (and the necessary related catcher bearings) is the solution proposed for the support of the turbo-machine, in order to avoid lubrication of bearings in a direct-cycle plant, with the related risks of water or organic liquid ingress. This is an existing technology, but the mechanical and thermal loads for one of the existing projects (GT-MHR) are above the levels usually met in industry in this field . Therefore a prototype of active magnetic bearing and catcher bearing will be designed, fabricated and tested on a test bench of the University of Dresden. Besides, a feasibility study of smaller size permanent magnetic bearings applicable for the turbo-machine design options of PBMR will be performed.

In order to release the loads on the magnetic and catcher bearings and therefore to make their design less challenging and also to facilitate the design and maintenance of the alternator, the feasibility of a leak tight rotating seal will be studied: this option would allow to keep classical bearings outside of the PCS vessel for the vertical support of the turbo-machine. Different concepts will be assessed (dry system, use of a liquid film, controlled leak rate, liquid film with electromagnetic confinement, magnetic transmission or canned bearings), the most promising concept will be identified and a programme of tests on a representative mock-up will be prepared for the follow-up of the project in the 6th Framework Programme.

For two technologies, which are necessary for the use of materials and the operation of components of HTRs, tribology and helium purification, an effort is made to recover the state-of-the-art from past projects and in the case of tribology, complementary tests adapted to the specific conditions met in the existing projects of direct-cycle plants are planned.

3.5 Safety approach (HTR-L)

The objective of HTR-L is to establish a common European safety approach for modular direct-cycle HTRs. A large consensus on an approach, which can take into account the specific safety features of modular HTRs and which leads thus to a simplification of the reactor design (e.g., suppression of engineered safety systems, limitation of the number of components with a safety classification, reduction of the loads on the third barrier…), is very important for consolidating the economic competitiveness of HTRs. Therefore the results of HTR-L will not only be presented to European safety authorities, but HTR-TN will also take initiatives to incite large international discussions on these results, in order to broaden the consensus.

The adaptation of the usual internationally accepted safety guidelines and principles to modular direct-cycle HTRs will be examined, taking into account the unique safety features of modular HTRs (exceptional robustness of the first barrier (the fuel envelopes), large negative temperature coefficient, very large thermal inertia and inherently safe design).

The design basis operating conditions to be considered in the safety analysis will be determined and a classification of these conditions will be proposed.

The requirements for the function of confinement/containment provided by the third barrier will be re-assessed considering the properties of the first barrier of HTR fuel, the nature of the design basis accidents to be considered for licensing modular HTRs and the practical exclusion of core melting situations for this type of reactor.

The safety classification of components will be adapted to the specific HTR safety features.

Finally the specific safety issues related to the different applications considered for HTRs, apart from electricity generation (co-generation, desalination, district heating, hydrogen production, plutonium burning…), will be identified and assessed.

Besides the programme of work of the project funded by the European Commission, the task force on accident analysis and fission product transport will start its work with a benchmark of the results the transient experiments of HTTR and HTR-10 and of the operation data of the helium loop, which has been coupled to the natural gas heater of the power station of Oberhausen in Germany. The analysis of the results of the benchmark will allow the group to make an evaluation of the ability of existing codes to calculate properly direct-cycle modular HTR transients and to make recommendations for future developments.

4 Conclusion

It is most likely that HTRs will emerge on the world industrial scene in the next 10 years.

The present HTR-TN programme of development of HTR technology is the first step of an ambitious programme, which associates industrial partners (manufacturers and energy producers) and research centres from different countries in a close partnership, and which is also open to international co-operation. This programme is aimed at giving to the European nuclear industry, by the end of the present decade, the tools for being present in this emergence of a new generation of reactors, which has the potential for opening new markets for nuclear energy. In the longer term, the objective is to develop a whole family of reactors based on gas technology, approaching step-by-step the fulfilment of the goals of sustainable development. Technical proposals are already prepared for the next step (6^{th} Framework programme of the European Commission) for continuing the development of the technologies, which will be needed by industry by the end of the decade, for going toward higher temperatures, for enlarging the scope of applications of HTRs (e.g., hydrogen production), for minimising the waste production and for burning high- level, long-lived wastes.

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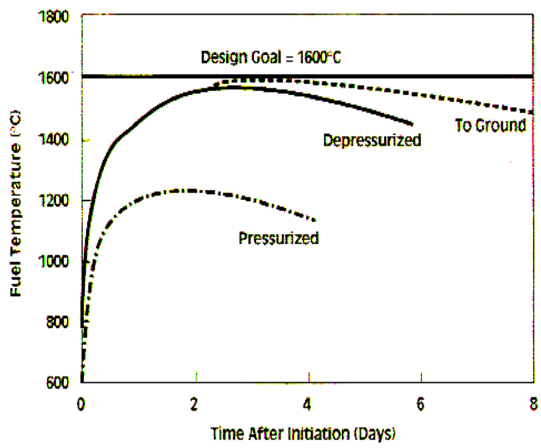


Figure 1: Evolution of the maximum GT-MHR fuel temperature during conduction cooldown events (by courtesy of General Atomics)

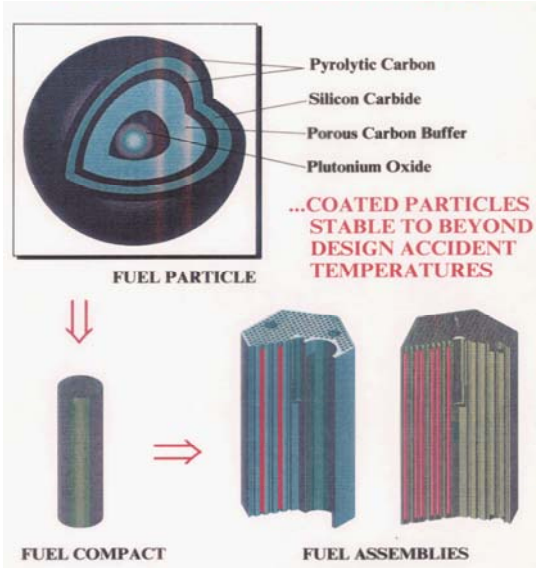


Figure 2: The HTR fuel (GTMHR fuel element design).

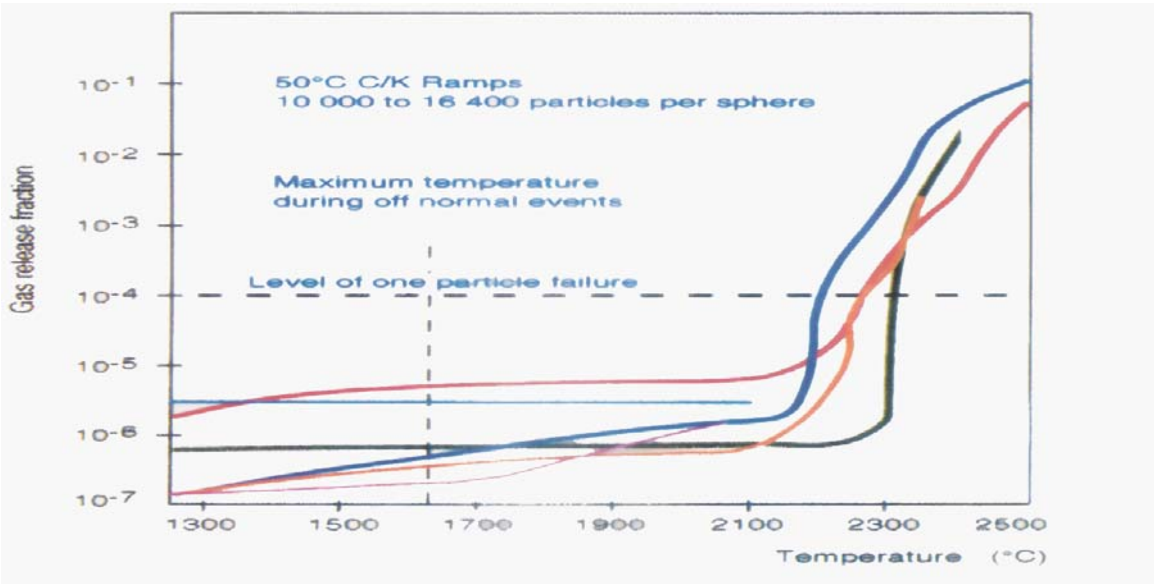


Figure 3: Temperature ramp tests to 2500°C with AVR TRISO fuel.

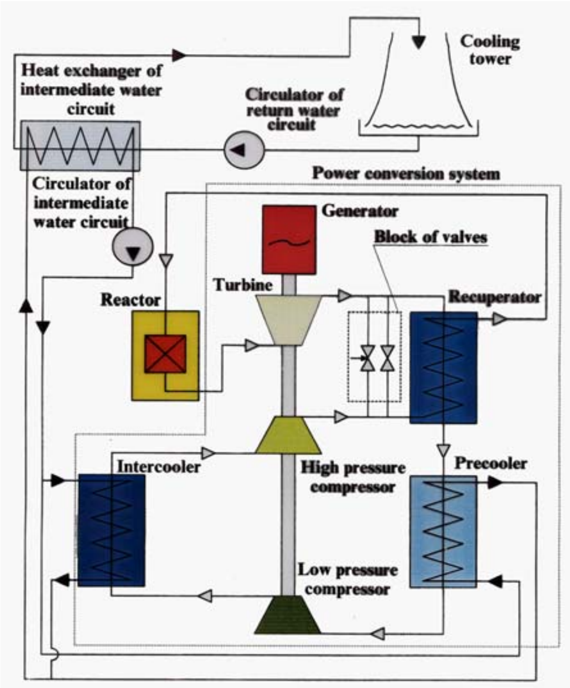


Figure 4: GT-MHR schematic flow diagram.

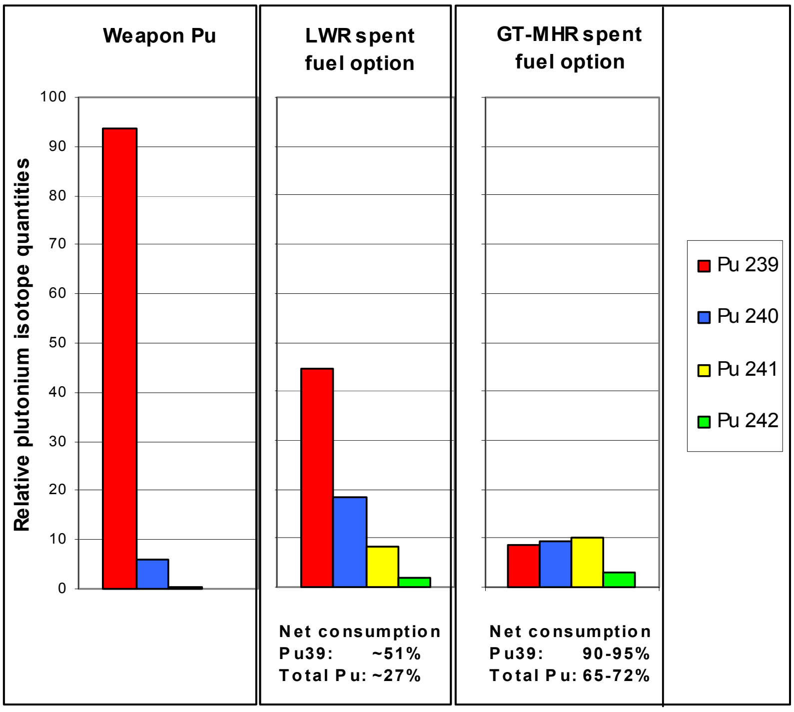


Figure 5: Plutonium destruction capability of disposition options (once-through reactor cycle).

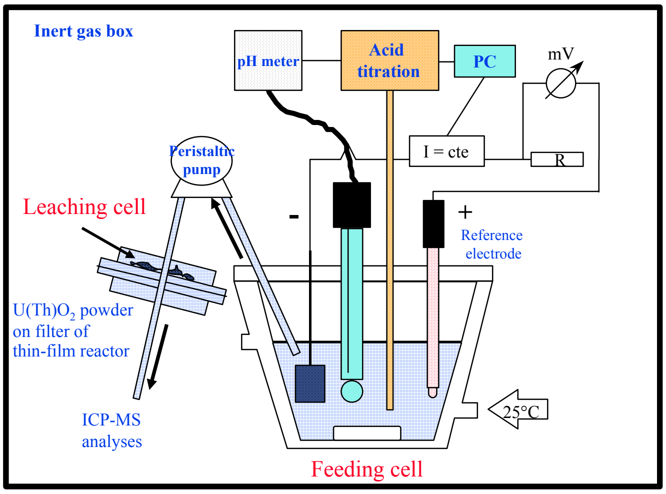
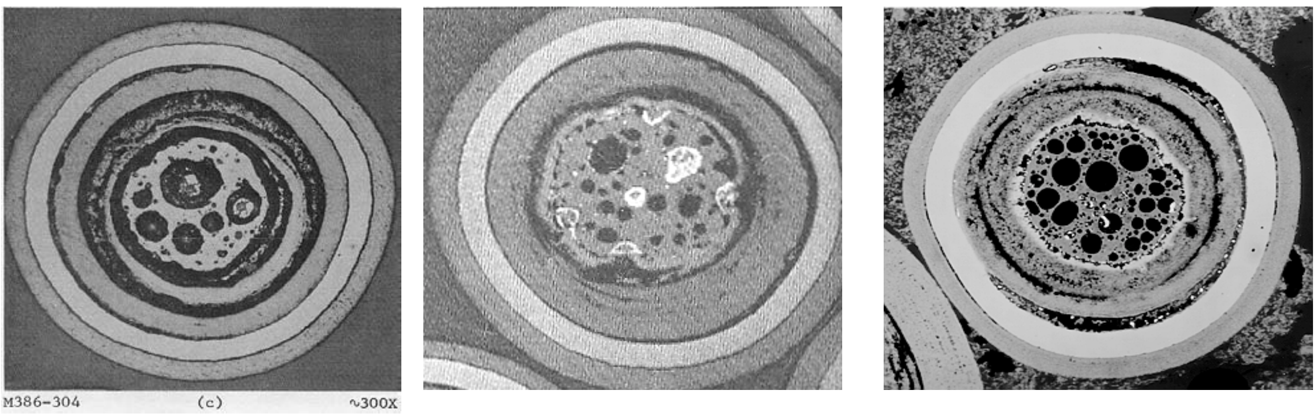


Figure 6: Experimental setup for the measurement of dissolution rate of HTR coated particles in the conditions of a deep geological repository.



1275°C ***1450°C***

UO_2 TRISO particles irradiated to 7.8 x 10^{25} n m^{-2}, 750 GWd/tHM

$PuO_{1.68}$ TRISO particle irradiated to 2.3 x 10^{25} n m^{-2}, ~ 750 GWd/tHM temperatures up to 1450°C

Figure 7: Behaviour of TRISO coated particles with a high fissile content irradiated at ultra high burnup (Data presented by General Atomics at the HTR-TN International HTR fuel seminar, Brussels, 1-2/2/2001).

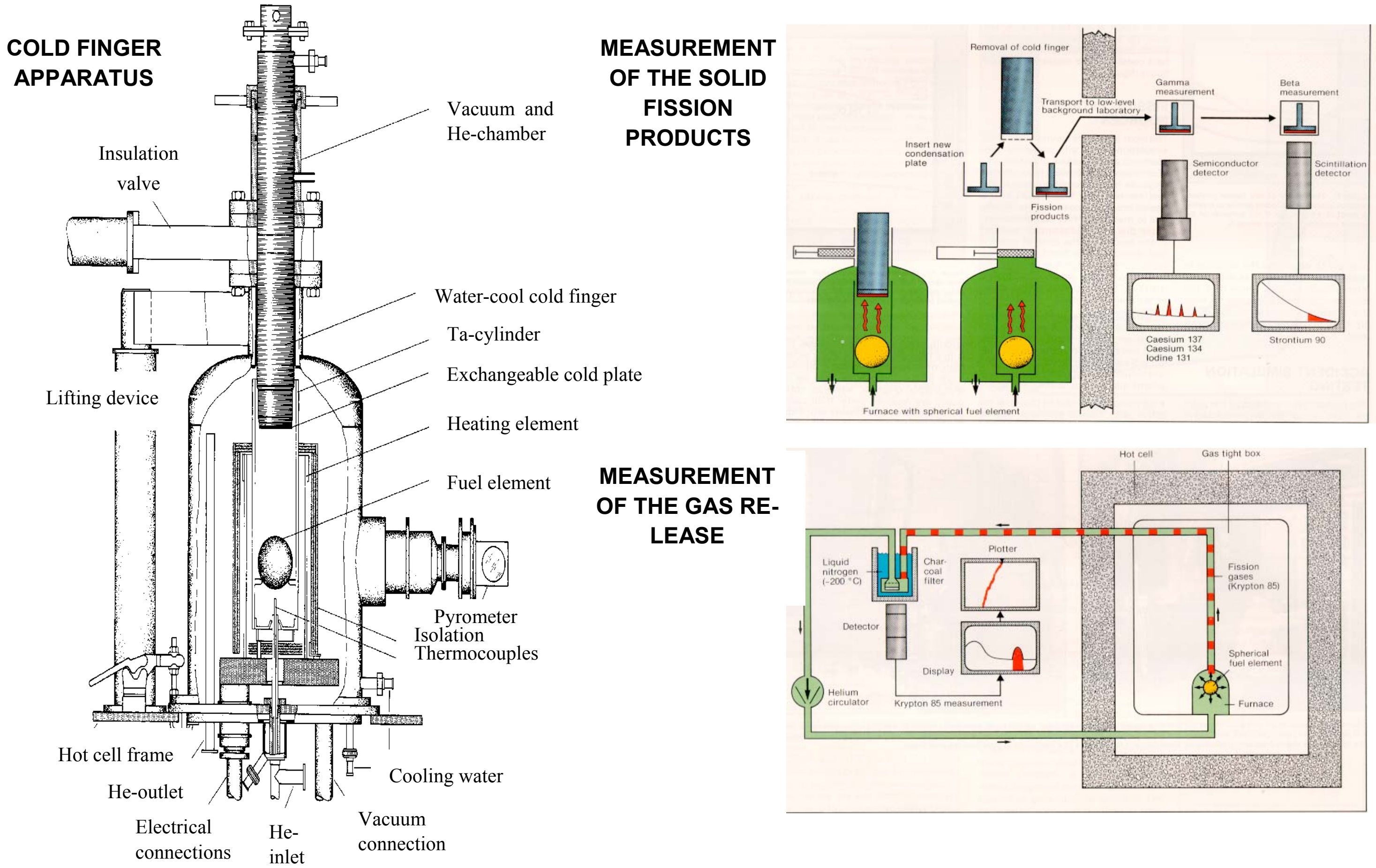


Figure 8: KÜFA facility for post-irradiation heat-up experiments.

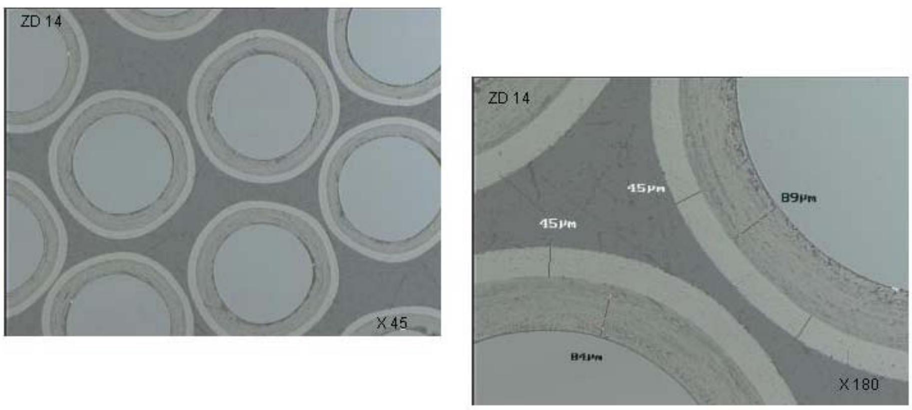


Figure 9: first coatings in CEA Grenoble (buffer and inner PyC layer).