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Co-ordination and Synthesis of the European Project of Development of HTR Technology

(HTR-C)

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Project coordinator

Dominique Hittner (Framatome ANP)

Partners

Werner von Lensa (Forschungszentrum Jülich)
Mayeul Phélip (Commisariat à l'énergie atomique)
Derek Buckthorpe (National Nuclear Corporation)
Daniel Besson (Framatome ANP)
Jacques Pirson (Suez-Tractebel)

Abstract

In this report, a synthesis of the main results obtained by the coordinated cluster of HTR projects of the Euratom 5th Framework Programme (FP5) is presented and the prospects for industrial application of these results are assessed. The objective of the cluster for FP5 was to retrieve, master and develop the technologies developed in the past HTR European activities and to assess key feasibility issues of modern modular direct cycle HTRs.

The main results concern:

- The improvement of reactor physics modelling of HTR cores and the validation of the improved methods by benchmarking with relevant experimental data,
- The fabrication process for kernels and coating layers of TRISO fuel particles, the behaviour of these particles under normal irradiation conditions and in accident conditions (including the development of test facilities for that purpose and of techniques for on line monitoring of fission gas releases) and the modelling of the behaviour of these particles under irradiation (fission product release, failure probability),
- The identification and the validation in HTR operating conditions of appropriate materials for the vessel, the helium turbine of a direct cycle HTR and the internal structures,
- The feasibility of the key components and systems of this type of reactor (the turbine with its magnetic bearings , the recuperator, the helium purification system),
- A preliminary assessment of the waste production of HTRs and of the behaviour of irradiated HTR fuel in disposal conditions and the laboratory scale development of a process for decontamination of irradiated graphite,
- The development of a safety approach meant at an optimal application of the general safety goals used for designing any nuclear system taking into account the very unique inherent safety features of modular HTRs.

These results confirm the high potential of HTRs for producing electricity with a high thermal efficiency (nearly 50 %) or providing high temperature heat required by many industrial processes.

Executive summary

This report gives a global status of the achievements of the Euratom 5th Framework Programme (FP5) cluster on HTR technology development, emphasising on the most significant results obtained by the projects of the cluster, in the perspective of a strategy of industrial development aimed at the deployment of a first generation of modern modular HTRs within the next decade and at longer term improvements of this type of system in line with the goals of sustainable development.

The main technical areas are related to the improvement and the qualification of design computer tools for reactor physics and fuel performance, the recovery and development of fabrication processes for high performance HTR fuel, the exploration of the limits in performance of this fuel, feasibility studies on fuel cycle issues and waste management, the qualification of the key materials for high temperature (metallic materials for the vessel and the direct cycle helium turbine, graphite for internal structures and carbon fibre composites for control rod cladding), the development of the key components of a direct cycle modular HTR (turbine, magnetic bearings, recuperator) and the development of a safety approach adapted to modular HTR.

The analysis of the discrepancies between the physics measurements made for the first criticality of the test reactors HTTR of JAERI and HTR-10 of INET and the calculations performed in the frame of an international benchmark organised by IAEA resulted in important progress in reactor physics modelling for HTR core design (in particular concerning the double heterogeneity of the fuel and the neutron axial streaming). It improved significantly the HTR reactivity calculations, but there are still more efforts to be made for the qualification of reactor physics codes for HTR core design (e.g. qualification of physics / thermo-fluid dynamics coupling, of burn-up calculations for the very high burn-up aimed at in HTRs and of transient calculations). This programme will extend widely beyond FP5. For plutonium core calculations, no experimental data are available for validating the calculations, but a benchmark was organised between different codes provided by partners, which gave very convergent results.

The GT-MHR project demonstrated the feasibility of very efficient burning of weapon grade plutonium in HTRs in safe conditions (temperature coefficient always remaining negative). In FP5, this result was extended to reactor grade plutonium, both for 1st generation Pu (generated while burning U in an LWR) and for 2nd generation Pu (generated during a first MOX recycling in an LWR), which gives a very efficient solution for stopping the growth of the plutonium stockpile produced in LWRs, only marginally slowed down by standard MOX recycling in LWRs.

The analysis of the waste flow of HTRs allowed pointing out the need to focus R&D efforts for HTR waste minimisation on fuel fabrication wastes and effluents and on the management of irradiated graphite. As a first step for the management of irradiated graphite, preliminary tests on a gasification process for graphite decontamination gave promising results.

Concerning the behaviour of HTR fuel in disposal conditions, the first results of corrosion of SiC in representative geological environments (clay, salt, granite) show a better resistance of the SiC coated particles than that of vitrified wastes, but a significant sensitivity to

temperature and a large variability with the mode of fabrication (and therefore the composition and microstructure of SiC). The influence of irradiation was also tested. Tests should be repeated with actual non-irradiated and irradiated coated particles. Data were obtained also on matrix graphite behaviour (radionuclide diffusion and corrosion) and on kernel leaching.

A programme of irradiation of HTR fuel (pebbles obtained from past German fabrications and from present Chinese fabrication), is taking place in HFR (Petten, the Netherlands). Its objective is to explore the capability of HTR fuel to keep its unique leak tightness properties in normal and accident conditions when operated at high or very high temperature and up to a very high burn-up, significantly above the performances demonstrated in past German and US programmes. A first irradiation started in September 2004 at very high temperature (corresponding to the Generation IV VHTR core outlet temperature objective of 1000 °C) with a delay of two years due to difficulties met in the preparation work. The target burn-up of 160 000 MWd/tHM will be reached early 2006. A second irradiation still under preparation, will start in 2005, at a lower temperature (corresponding to a core outlet temperature of 850 °C), but with the objective of reaching a burn-up of 200 000 MWd/tHM. There will be an on line fission gas release monitoring in that test.

A facility for simulating the heat-up transient of the fuel in a depressurisation accident has been installed in a hot cell of ITU and is ready to start tests, first with already irradiated pebbles recovered from the past German programme and then with pebbles from the above mentioned irradiations in HFR.

The recovering of the HTR fuel fabrication technology is finalised, the development of a sol-gel process for the fabrication of UO_2 kernels and a coating process for obtaining SiC TRISO coated particles. First ZrC coatings were also obtained as well as first plutonium kernels. Nevertheless in both cases, contrary to the cases of SiC TRISO coated particles and of UO_2 kernels, the properties of the obtained products are still far from the required specifications and therefore more R&D is necessary in order to improve the process.

The bases for the deterministic modelling of a single coated particle have been finalised. All the physico-chemical models simulating the phenomena that are significant for the particle behaviour during irradiation have been selected. The next step will be the modelling of the whole fuel element (pebble or compacts) with a statistical processing for describing the behaviour of thousands of particles which are part of each fuel element.

Concerning the development of vessel material, it has been decided to focus it on the hot vessel option, for which the selected material is modified 9Cr1Mo. Welded joints of mod. 9Cr1Mo have been produced. Hot micro-cracking was observed in the welds. Nevertheless there were sufficient sound zones in these welds to use them for samples to be irradiated in HFR. This irradiation (up to a fluence corresponding to a 60 years lifetime of the vessel) and the corresponding PIE took place in 2004. They led to a very important result of the programme: for the low level of dose reached by the vessel protected by a thick graphite reflector, there is no significant impact of the irradiation on the mechanical properties of the base mod. 9Cr1Mo and of a thick welding of this material. In parallel the industrial partner who met difficulties with the first welds, launched a programme that succeeded in establishing the industrial feasibility of thick welding of mod. 9Cr1Mo.

Materials have been selected for the turbine, but for the time being no solution exists for operating the turbine beyond 750 °C without cooling at least for the first discs. First mechanical tests have started (tensile and short term creep tests) on the selected materials as received. Further tests are planned on these materials after carburising/decarburising conditioning in order to study the impact of the impure helium atmosphere of the reactor on the materials properties.

Five different graphite grades have been selected for HTR applications and samples of these grades have been supplied for irradiation in HFR, which started early 2004. The programme on graphite and carbon fibre composite oxidation has been completed, showing in particular that the oxidation behaviour of all but one of the tested grades was acceptable.

Conceptual designs have been proposed for the turbine, magnetic bearings, and helium leak tight rotating seal. Several severe constraints to be put on the design of a helium turbine for the direct cycle have been identified: limitation in the diameter of the discs, need of disc cooling, limited load acceptable by catcher bearings, vertical axis of the turbine to be avoided. The consequences of these constraints on the feasibility and the competitiveness of direct cycle have to be assessed. Different recuperator designs (plate type and tubular type) are being assessed. The loop, in which thermo-mechanical endurance testing of these different types of recuperators will be performed, has been upgraded and the tests will start very soon.

The appropriate chemical conditions (concentration of impurities in helium) for operating an HTR have been explored. A preliminary definition of the target impurity content of helium atmosphere has been issued. This is the first important step for the study of chemical interactions of the impurities of the helium atmosphere with the materials of the reactor primary circuit, which is a key factor for the selection of the most appropriate high temperature materials.

A consensus has been found on the bases of the safety approach to be used for modular HTRs: methodology for event classification, for defining the requirements for confinement / containment and for the classification of systems, structures and components. A list of key licensing issues for modern modular HTRs have been defined.

Links have been established with the main actors of the development of HTR technology in the world and some co-operations already started (with INET in China, with USNRC). The European partnership is actively participating in the definition of the R&D programme for the VHTR of the Generation IV International Forum.

For FP6, a follow-up of the FP5 HTR European programme, the Integrated Project RAPHAEL, has been accepted by the European Commission. It will continue long-term actions which could not be finalised in the timeframe of FP5 (e.g. PIE of irradiations performed in FP5) and will explore ways to improve the performances of HTR towards VHTR objectives and to extend its use to high temperature heat applications. It will start during the first semester of 2005, in parallel with the last ongoing activities of FP5.