Report of the first Meeting of
The IAEA Coordinated Research Project (CRP) on
"Advances in HTGR Fuel Technology Development"

Vienna International Center, Dec. 9 - 12, 2002

IAEA Co-ordinated Research Project on Advances in HTGR Fuel Technology Development

The IAEA has initiated a coordinated research project (CRP) on Advances in HTGR fuel technology. An organization meeting for the CRP was held in Vienna in December 2002. The background for this CRP, information presented by participating Member States, and future plans are briefly discussed below. For additional information regarding the CRP, including mechanisms for participation, please contact Mabrouk Methnani (m.methnani@iaea.org).

Background

A great deal of experience has been accumulated over the past half century in the production and testing of coated particle fuels in support of High Temperature Gas Cooled Reactor (HTGR) technology development. Most of the experience has been with pyrocarbon and silicon carbide coatings on UO_2 and UC_2 kernels, but other materials have also been investigated on a smaller scale. The production of large quantities of high quality coated particle fuel, capable of retaining fission products over a wide range of operating and accident conditions, as well as for disposal of spent fuel, has been demonstrated for UO_2 particles with combined isotropic pyrocarbon and silicon carbide coatings (referred to as a TRISO particle). The state of the art for PyC/SiC TRISO coated UO_2 particles is well advanced, and sufficient to support modular HTGR development and deployment projects in the near term, but additional development is needed to expand the capabilities of HTGRs.

Between 1993 and 1996, the IAEA conducted a CRP on HTGR fuel performance and fission product behaviour, the results of which have been published in IAEA TECDOC 978. Since then, there has been growing global interest in HTGR technology and currently programs related to fuel development, irradiation, testing and modelling are being planned and implemented in China, Europe (EU countries), the Republic of Korea, the Russian Federation, Japan, South Africa and the US. Potential gains can arise from advanced fuel design and production technology, which could enhance the economics and range of applicability of HTGRs. Examples of current interest include the development of advanced coatings, fabrication methods and quality control, and the use of HTGRs for burning stockpiles of Plutonium. Another issue warranting further investigation is the behaviour of HTGR fuel under high burnup. The data currently available for high performance UO_2 fuel covers burnup up to 10-14 % FIMA and plans are in place to investigate the range to 20% FIMA in future irradiation programs. Plans are underway for development and testing of UCO prismatic block fuel intended to achieve 26% FIMA. There is also a desire to qualify HTGR fuel integrity above the temperature safety limit currently set at ~1600 ºC, possibly using a ZrC coating. Fuel performance model development work is proceeding in parallel to predict the behaviour of HTGR fuel under normal and abnormal operation. Validating the resulting analytical models with experimental data is necessary before use in plant licensing analysis.

In response to increasing interest and activity among Member States, the IAEA has initiated a new CRP on advances in HTGR fuel technology development. Proposals for participation have been received from seven Member States and an organizational meeting was held in Vienna in December, 2002. Representatives from China, Germany, Japan, the Republic of Korea, the Russian Federation, and the United States participated, providing information on current status of their fuel development activities and topics of interest to the CRP as summarized below. Additional Member States are expected to join the CRP in 2003.

Previous work, current issues & planned activities

China – R&D activities for HTR fuel started from the middle of 1970's in China, and have begun to be a part of China High Technology Program since 1986. R&D work of HTR fuel was carried out in experiment scale before 1991. Since 1991 R&D activities have been focused on fabrication technology for the HTR-10 first core fuel. During long-term R&D activities, INET has successfully developed its own fabrication technologies for HTR-10 fuel. Up to May 2002, 20,000 spherical fuel elements have been fabricated. The performance of the fabricated fuel elements met the design requirement of HTR-10 fuel. At present and in the future, INET will make efforts to advance the development of HTR fuel technology. The HTR fuel with high performance will be the main objective of INET R&D activities for HTR fuel in the future.

Germany and the EU HTR-F program – The Institute for Safety Research and Reactor Technology (ISR) of FZJ consists of two departments, one dealing with safety research, the other one dealing with nuclear waste treatment and disposal. Future work will concentrate on the avoidance and control of nuclear accidents, and on nuclear waste reduction, conditioning of remaining waste, and development of improved treatment methods. FZJ is a partner in the EU Project HTR-F focusing on fuel. The project consists of 4 working packages (WPs). WP1 deals with a computer based collection of data and documents. WP2 concentrates on the preparation and conduction of the HFR-EU irradiation experiment with German, Chinese and USA fuel. WP3 comprises fuel modeling and the development of the finite-element method (FEM) based computer model ATLAS. WP4 treats the fabrication of coated particles.

Japan – Japanese research and development on HTGR fuel has been conducted under the HTTR Project. An outline of the HTTR Project and recent R&D status of HTGR fuel were introduced. The 1st loading HTTR fuel of about 1 ton, was fabricated and fission gas release data are being accumulated through the operation. Irradiation tests up to 9% FIMA were carried out to extend burnup of the HTTR fuel. Also development of ZrC-coated fuel is being carried out including a new deposition test and irradiation test up to 4.5% FIMA.

Republic of Korea – Korea Atomic Energy Research Institute (KAERI), as a dedicated research institute in nuclear energy in Korea, started its 2-year feasibility study on HTGR Technology Development in 2002. The presentation included a brief introduction of the project and current status, previous works and near-term future activities as well as strategy for the development in the area of coated fuel technology development. KAERI is currently evaluating the technology and establishing the fundamental knowledge on HTGR fuel technology through collecting and analyzing technical information in the form of a database and performing basic experiments in the fabrication technology.

Russian Federation – HTGR fuel development activities were conducted in Russia (USSR) since the early 70s. More than 100,000 fuel balls, 60mm in diameter, were manufactured. The design of coated particle was: UO2 kernel 500 µm diameter with TRISO 4-layer coating. The development of GT-MHR fuel was started in 1999. Basic fuel design parameters include: fuel compact 50mm length, 12.5 mm diameter, coated particle made of PuO2-x, 200 µm diameter of kernel, TRISO 4-layer coating.

United States – The key technical areas in the US Department of Energy Advanced Gas Reactor Fuel Development and Qualification Program include fuel fabrication, fuel irradiation, accident testing and postirradiation examination, fuel performance modelling, and fission product transport and source term. In fuel licensing reviews key issues and expectations involving fuel fabrication, performance analysis, modelling, fission product transport, irradiation testing and accident condition testing are being examined.

Fuel design, fabrication, QA/QC & licensing

China – The design of HTR-10 fuel is based on the present HTGR fuel element with high quality and the requirements of HTR-10. Fabrication technology for HTR-10 fuel has been established through a long term R&D activity. Fabrication of HTR-10 includes UO_2 kernel preparation by modified gel precipitation, SiC and PyC coating on the UO_2 kernels with the CVD process and spherical fuel element manufacture by a quasi-isostatic press process. The quality of HTR-10 fuel improved gradually as production experience accumulated. The free uranium fraction of fuel measured by the burn-leach method was $4.6x10^{-5}$ in a total of 20,000 fuel balls, but in first 10 lots was 1-1x10-4 and subsequent 34 lots was $2.7x10^{-5}$.

Germany – In the German fuel development program, the coated particle design has undergone various changes, from BISO to TRISO fuel in the 1970's, and from HEU to LEU fuel in the 1980's. For the fabrication of particles at NUKEM, a 400mm diameter coating furnace has been used with a continuous process for all layers. The sphere fabrication included the steps of materials mixing, CP overcoating, molding and waste treatment. The fuel development led to a steady increase in the CP quality. Burn-leach results from 1985-88 for the fuel element production of LEU-1, AVR 19 and the proof test fuel has shown free uranium fractions between 8 and 49 ppm. The free uranium was also found to be mainly existent as defective particles rather than as contamination of the matrix graphite.

Japan – JAERI established safety design criteria for licensing of the HTTR fuel. The inspection standard (items, methods, sampling rates) was also established. The as-fabricated failure fractions were 2x10-6 and 8x10-5 for through-coatings and SiC – failure fraction.

Russian Federation – Construction of the Bench Scale Facility at VNIINM to develop process operations and fabricate GT-MGR test fuel was started in 2002. Design documentation for process equipment to be installed inside glove boxes is being developed and updated now. The first batch of fuel compacts will be manufactured by the end of 2004.

United States –The planned fuel fabrication activities will focus on the advanced QA/QC techniques that will be examined, the evaluation of the quality of fuel produced from both lab scale and production scale coaters as compared to German fuel, and the eventual irradiation of this fuel. The fuel related results of any US licensing review will be made available to the CRP to help understand the needs of the regulator and hopefully find a way for these issues to be resolved in the different programs that are underway on coated particle fuel

Fuel irradiation, testing, operation performance, & spent fuel disposition

China – The irradiation testing of HTR-10 fuel started on July 3, 2000 in the Russian IVV-2M reactor. Up to October 6, 2002, the maximum burnup and fast neutron fluence of the irradiated fuel elements reached 90,000 MWd/t(U) and 1.1x1021 n/cm2, respectively. All release rate curves show small fluctuations under 1000ºC average fuel temperature conditions. Heating the fuel element in capsule No.3 from 1050ºC to 1200ºC for 200 hours at a burnup of 38,000 MWd/t, and from 1050ºC to 1250ºC for 200 hours at a burnup of 57,300 MWd/t caused an increase of about one order of magnitude in Kr85m release. When the temperature returned to 1050ºC, the release rate was restored to the initial value.

Germany – A whole variety of irradiation tests in different MTRs has been conducted within the German Program both comprising loose particles and complete fuel spheres. It also included a large-scale demonstration in the AVR reactors. The MTR tests covered a burnup range up to 14% FIMA and a fast neutron fluence range up to $8x10^{25}m^{-2}$. The measured R/B for different fission gases were always found to be on a very low level indicating no particle failure in the LEU TRISO tests. Metallic fission product release at end-of-life has shown a significant silver release at irradiation temperatures >1000ºC reaching a level of several %. In contrast, cesium release was in the order of 10-5 to 10-4. Temperature measurements in the AVR with melting wires have given the surprising result that a significant portion of these spheres have seen a gas temperature higher than 1280ºC.

Japan – After R&D for the first-loading fuel of the HTTR, JAERI has conducted capsule irradiation tests for higher burnup fuel development. The results show that a few additional particle failures were found. Through the SEM and EPMA observations of the particles, it was concluded that the failure occurred by internal pressure. JAERI is trying to reproduce the result with the fuel performance model.

Russian Federation – UO2 fuel balls were irradiated in the former USSR up to burn up of about 15% FIMA. Gaseous fission products release was on the level <10-4 at 1250ºC and on the level ~10-5 as a rule. The in-pile tests of GT-MGR fuel will start in NIIR (Russia) research reactors RBT-6 and SM-3 in 2005.

United States –The irradiation, accident testing, and postirradiation examination (PIE) plans include eight different irradiation capsules. The Advanced Test Reactor where the irradiations will be performed, has the ability of the irradiation locations to reasonably mimic a gas reactor spectrum and capability to control and monitor the experiment. Accident testing and PIE techniques will be used in the later phases of the program.

European Commission, Joint Research Centre, Institute for Transuranium Elements - The Cold Finger Device, (KÜFA), developed in the 70's in the Research Centre of Jűlich to test the high temperature performance of irradiated HTR fuel elements, has been re-installed in the Hot Cell installation of the Institute for Transuranium Elements (ITV) of the JRC of the European Commission. The cold testing has been finalized and the installation in the α-box will be terminated by the middle of January 2003. First hot testing is scheduled for March 2003. Twenty one irradiated HTR-FE, coming from irradiations in DIDO reactor in Jűlich (3), HFR- Petten (8) and in AVR- Jűlich (10), have been transferred from FZJ to ITV in November 2002.

Fuel characterization data & performance modeling

Germany/EU – Germany is using the computer codes PANAMA for fuel performance modeling under accident conditions and FRESCO for the fission product release behaviour from the fuel during normal operation and under accident conditions. PANAMA is using a simplified pressure vessel model comparing the internal gas pressure against the tensile strength of the SiC layer and including the effects of SiC corrosion and strength reduction due to fast neutron fluence. FRESCO is using the classical diffusion approach with one effective diffusion coefficient for each fission product species and each material. Both codes have been applied to all available heating tests for comparison with the measurements and validation of the codes. There are many tests with a good reproduction of the observed gas release with predicted failure probability and also for the transient release of cesium and strontium from the fuel sphere. Calculations with poor agreement with the diffusion model have initiated the development of the statistical model of Goodin and Nabielek based on an empirical relationship between cesium release and the parameters irradiation temperature, fast fluence, and fission density.

Japan – JAERI has developed analytical models for pressure vessel failure, kernel migration, Pd-SiC corrosion, thermal decomposition of SiC, oxidation failure, fission product (FP) gases release and FP metals release. The fission gas release model is revised through comparison of release-over-birth ratios (R/B) obtained in the HTTR operation. The pressure vessel failure model is under development through comparison of recent irradiation tests. Material data, such as coating layer strength as a function of fast neutron fluence, are important to model development.

Russian Federation – The code GOLT-v1 was developed for modeling the thermo-mechanics performance of coated particles at the normal operation mode of GT-MHR. The model of coated particles was presented. As basis criterion of serviceability, the preservation of integrity of the SiC layer is accepted. On the basis of the GOLT-v1 the development of an integrated code is begun in Russia (VNIINM).

United States – Model development and material properties measurements are currently funded. Activities include expanding the capability of the model, comparing the model results to experiments to date, studying the influence that key material properties have on the predicted behaviour, and benchmarking of the codes. It was recommended that benchmarking problems from simple analytic formulations to past and present full scale irradiations be performed under this CRP.

CRP deliverables, plans & schedules

Following the presentations and discussions in the above topical areas, participants discussed activities which could be conducted within the framework of the CRP. The table on the following page lists the activities identified and the participants expressing preliminary interest in taking part in each activity (indicated by an x). A lead participant for each activity is indicated by an X. In the coming months, the lead participant will further define the activity and interact with other participants to establish a final list of participants agreeing to take part.

The IAEA provided a brief demonstration of the Business Collaborator software, which will be made available to the CRP participants and supported by the Agency to facilitate communications and the exchange of information. It was agreed that a research coordination meeting for the CRP would be held in China in conjunction with the international conference on HTRs to be held in the spring of 2004. The CRP is expected to continue through 2007.

Preliminary Identification of CRP Activities and Participation[1]

Activity	China	Germany	France[2]	Japan	Korea	Russia	USA	EC-JRC
1. Definition and basis of plant concept fuel designs (gas turbine, process heat, transmutation)	x	X		x		x	x	
2. Advanced fuel designs	x		x	x	x	X	x	x
3. Characterization techniques (e.g., round robin measurements of BAF for standard material specimens)			x	x	X		X	
4. Methods for operational monitoring of fuel performance	X	x		x				
5. Large scale fuel production, characterization, irradiation testing, in-reactor performance (AVR, HTTR, HTR-10)	X	x		x				
6. Materials (matrix graphite, block graphite)	x	x		x		X		
7. Irradiation testing & PIE (HFR, ATR, IVV-2M, SM-3, RBT-6, JMTR)	x		x	x		x	x	X
8. Accident testing & PIE (KUFA, CCCTF)	x	x	x	x			x	X
9. Spent fuel disposition		X		x				
10. Advanced QA/QC methods						x	X	x
11. Benchmarking of fuel performance & fission product behaviour models under normal operation & operational transients	x	x	x	x	x	X	x	x
12. Benchmarking of fuel performance & fission product behaviour models under accident conditions	x	X	x	x		x	x	x
13. Fuel related licensing issues & status	x			x			X	

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[1] Marks indicate preliminary interest in participation in task, lead participant for each activity is identified by a capital X

[2] Participant not present, preliminary areas of interest were the based on CRP proposal from France.