

THE VHTR FUEL AND FUEL CYCLE PROJECT: STATUS OF ONGOING RESEARCH AND RESULTS

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I. INTRODUCTION

The VHTR Fuel and Fuel Cycle project is intended to provide demonstrated solutions for the VHTR fuel (design, fabrication and qualification) and for its back-end management.

TRISO coated particles, which are the basic fuel concept for the VHTR, need to be qualified for relevant service conditions (Figure 1). Furthermore, its standard design UO₂ kernel surrounded by successive layers of porous graphite, dense Pyrocarbon (PyC), silicon-carbide (SiC) then Pyrocarbon (PyC) could evolve along with the improvement of its performance through the use of UCO kernel or ZrC coating for enhanced burn-up capability, minimized fission product release and increased resistance to core heat-up accidents (above 1 600°C). Fuel characterization work, post irradiation examinations, safety testing, fission product release evaluation, as well as the measurement of chemical and thermomechanical material properties in representative conditions will feed a fuel material data base, applying strict QA enforcement. Further development of physical models enables assessment of in-pile fuel behavior under normal and off-normal conditions.

Fuel cycle back-end encompasses spent fuel treatment and disposal, as well as used graphite management. An optimized approach for dealing

with the graphite needs to be defined. Although a once-through uranium cycle is envisioned initially, the potential for deep-burn of plutonium and minor actinides in a VHTR, as well as the use of thorium based fuels will be accounted for as evolutionary steps towards a closed cycle.

To answer these questions, an international collaborative program has been set up between the US, Japan, Korea, the European Union and France, under the GIF umbrella. The “VHTR/Fuel and Fuel Cycle” (VHTR/FFC) Project Arrangement (PA) became effective January 30, 2008, although the collaborative work had already started somewhat earlier (Figure 1). The present paper outlines the current status of the collaboration.

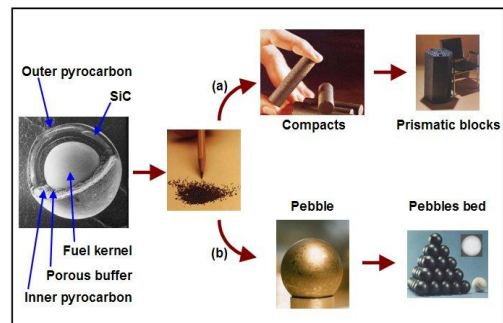


Figure 1: The VHTR particles fuel and the two types of fuel elements [a – Compact (courtesy of General Atomics), b - pebble (courtesy of JRC)].

II. THE VHTR/FFC PROGRAM AND ORGANIZATION

The VHTR/FFC research plan has been edited in 2007 and undergoes revisions as necessary. [2] For its elaboration, inputs from major industrial HTR and VHTR projects, such as PBMR, GTHTR300C, ANTARES, NHDD, GT-MHR, NGNP and HTR-PM, led by several plant vendors and national laboratories, have been considered.

The R&D plan is structured in work-packages and tasks as described in Table I.

Work package	Task
Irradiations and PIE	1.1 - Irradiation devices and procedures
	1.2 - Shared irradiation tests
	1.3 - PIE protocol and procedures
	1.4 - Irradiation and PIE results
Fuel Attributes and Material Properties	2.1 - Critical material properties
	2.2 - Fuel material property database
	2.3 - Characterization techniques
	2.4 - Fuel performance modeling
Safety testing	3.1 - Pulse irradiation testing
	3.2 - Heating test capabilities
	3.3 - Heating test
	3.4 - Source term experiments
Enhanced and Advanced Fuel	4.1 - Process development
Waste Management	5.1 - Head-end processes
	5.2 - Graphite management
	5.3 - Disposal behavior and waste package
Other Fuel Cycle Options	6.1 - Plutonium burning and transmutation
	6.2 - Thorium cycle

Table I: Structure of the VHTR/FFC research program.

In order to preserve the partners' intellectual property rights, there will be no open collaborative work on fabrication processes. For the time being, the process development to fabricate innovative TRISO fuels (such as ZrC coating process) remains out of the scope of the program as well.

From this research plan, the parties derive a bi-annual "action plan" that contains detailed

descriptions of contributions and a list of deliverables with due date. The main milestones are:

- Irradiation and PIE (post-irradiation examination)
 - 2015: irradiation PIE results
- Fuel attributes and material properties
 - 2009: Establishment of fuel material property database
 - 2009: Characterization techniques of fuel attributes and fuel performance modeling
- Safety testing
 - 2012: Pulse irradiation testing, establishment of heating test capability, and source term experiments
 - 2015: Heating tests
- Waste management
 - 2010: Disposal behavior and waste package
- Other fuel cycle options
 - 2010: Plutonium burning and transmutation and thorium cycle assessment.

The Project Management Board (PMB), which meets twice a year, keeps track of the plan with the help of the OECD/NEA who, in particular, maintain a dedicated web site archiving all documents including the deliverables. The tracking includes budget and cost elements for each party both for current contribution and background information shared in the frame of the project.

III. STATUS OF ON-GOING ACTIVITIES

During 2008, the first "Action Plan" has been established covering the period 2007-2009, and identifies more than one hundred deliverables with the vast majority of which are associated with the two first work packages.

III.A. Irradiation and PIE

Numerous fuel irradiation tests had been conducted in Europe since the 1970s, in particular

in support of the German HTR program. After a pause of about 10 years, such irradiations were resumed in the HFR Petten in 2004. Results from these most recent irradiations will be made available to this project as background proprietary information. It laid the foundations to more detailed (as opposed to systemic) experiments aiming to better seize specific material properties which are crucial for the understanding and correct modeling of fuel performance.

In this sense, the PYCASSO-I (*PY*rocarbon *irradiation for Creep And Shrinkage/Swelling of Objects*) test is intended to generate basic thermo-mechanical properties of pyrocarbon under irradiation. Samples were provided by Japan, Korea and France. Samples from the US could not yet be included for scheduling reasons. The irradiation started on April 18, 2008, in the Euratom/JRC HFR reactor of Petten. It has proceeded without unexpected transients or changes observed. However, due to technical problems with the HFR reactor, the irradiation was suspended for several months in August 2008. It was resumed in February 2009 and is on track for completion in the second quarter of 2009. The PYCASSO-II experiment targets a higher fluence, up to 3×10^{25} n.m⁻², and is expected to begin irradiation in the second quarter of 2009 for 9 cycles of irradiation. Results from these irradiations will be part of work package 2 (Fuel attributes and material properties).

Because of technical problems with safety instrumentation and extended HFR downtime, the HFR-EU1 irradiation will continue into 2009. HFR-EU1 consists of 3 GLE4 pebbles and 2 pebbles produced by INET, and is intended to test high burn-up fuel performance in particular with respect to fission gas release.

The AGR-2 experiment is part of the general US/DOE VHTR fuel development program and is planned for the Advanced Test Reactor of Idaho National Laboratory. It will follow the AGR-1 irradiation which was the first one to test, in representative NGNP conditions, US fabricated fuels. Due to very good behavior of these fuels, the AGR-1 irradiation is being extended beyond plan so as to achieve a burn-up of 19.6% FIMA. Thus, the AGR-2 program has been delayed by a few months. It will carry both

UCO (uranium oxycarbide) based TRISO fuel elements and classical UO₂ (uranium oxide) ones. Design work and fuel fabrication activities have been done with fuel being fabricated by the U.S., France and South Africa (as an invited partner). The irradiation experiment is anticipated to start in late 2009.

In parallel and following several workshops on this topic, intense work is being performed by all partners to provide procedures for post-irradiation examinations and to set up the equipment. The sharing of these procedures and methods ensures improved comparability, replicability and quality of the result.

III.B. Fuel Attributes and Material Properties

The objective is to compile material property needs, to appreciate their importance in regard to known fuel failure mechanisms and to obtain state-of-the-art material properties data. A prioritization of the properties to obtain an optimized testing/measurement plan with the objective to define the details of the proposed analytical irradiation (such as PYCASSO), and potential other irradiations has been defined. Workshops have been held for discussing details of the experiments and the samples that will be provided.

Dedicated experiments have been set-up to measure basic properties of the materials used in the TRISO fuel concept (Figure 2). Reports on specific issues (SiC under irradiation, thermal diffusivity measurement etc...) have been completed and have been issued in early 2009.



Figure 2: Equipment used at DOE/ORNL to measure strength of SiC and PyC.

Regarding fuel performance modeling (illustrated in Figure 3), a round robin test has

been run in the frame of the IAEA CRP (-6) (Coordinated Research Program). Modeling mainly focuses on failure fraction determination and fission product release. All FFC members have participated in this work and the results are expected to be made available to the project after 2009 as the CRP-6 is extended to the end of 2009.

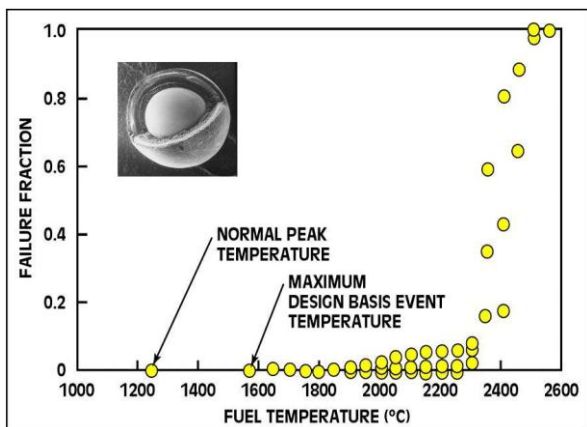


Figure 3: Influence of temperature on TRISO fuel failure fraction.

III.C. Safety testing

Safety testing comprises two types of tests on irradiated fuels: pulse irradiation and high-temperature (up to 2 000°C) heating experiments.

Post-irradiation heating tests can be performed in either of two ways:

- In a furnace/autoclave with a sweep gas transporting the effluent downstream to a thermal gradient tube in which condensable fission products are deposited, and to a final filter/gas trap to capture the non-condensable fission products. This approach has been used historically with LWR fuel. The advantage of the thermal gradient tube is that with precise measurements, the chemical form of the fission products can be inferred by the deposition profile.
- In a furnace with a sweep gas transporting the effluent to a cold finger that traps all fission products. The cold finger apparatus is then assayed using gamma spectroscopy to determine the fission product content.

This approach has historically been used in the gas reactor community. No inference about fission product chemical form is possible with this approach.

Some parties (EURATOM, Japan, France) have already the equipment and, eventually, have run several tests (EURATOM, Japan). Reports are expected to be issued shortly. The current work of other parties focuses on establishing or up-grading heating test capabilities as well as the definition of test protocols.

III.D. Enhanced and Advanced Fuel

Although innovative processes has to be developed and qualified to produce advanced VHTR fuels (such as the replacement of the SiC layer with ZrC-zirconium carbide), there is currently no activity on this subject within this project.

III.E. Waste Management

This domain covers two issues:

- Spent VHTR fuel management
- Irradiated graphite management

For the spent fuel, the research activity currently deals with long-term repository/direct disposal for SiC particles. It is believed that the SiC coated fuel particle acts as a miniature containment vessel to retain fission products during long-term repository or direct disposal. Confirmatory tests, which prove the long-term integrity of the coating layers, are needed. This work is underway in the frame of the EURATOM project RAPHAEL which will finish in April 2010. First reports have already been issued.

Another interesting route to investigate is the reprocessing of fuel which would contribute to a significant reduction of waste volumes and potential radio toxicity in comparison to the direct disposal. The main issue is there to access the particle kernels for dissolution and the work currently focuses on that. First results, obtained by EURATOM are encouraging. Contributions from JAEA and US/DOE in this field are also expected.

Regarding graphite management, besides the establishment of a detailed inventory of graphite waste produced by a VHTR, the work deals with technologies to separate the highly active fraction from low-activity and to evaluate the feasibility to reuse the graphite. Main contribution will come from the Euratom CARBOWASTE project which will last until April 2012.

III.F. Other Fuel Cycle Options

VHTR can also be used with Pu fuel and for Minor Actinide (MA) incineration or transmutation, due to the high burn-up capabilities of coated particle fuel. These features can also be used in symbiosis with other reactor types to reduce MA content and decay heat which are decisive parameters for repository design. The deep-burn potential of VHTR avoids multi-recycling of spent fuel as it is needed for alternate routes. It is especially attractive if it can be shown that ultra-high burn-up coated particles are still capable to maintain their barrier function under disposal conditions.

Currently, the activities in the domain are conducted in the frame of the EURATOM PUMA project, which will be concluded in summer 2009 and by the US/DOE with the "Deep-burn project".

The PUMA project deals with Pu/MA HTR burner reactor physics & optimization, transuranics bearing fuel design and manufacturing, assessment of the impact on fuel cycle and economics, and the qualification of analysis tools. Formal agreement from PUMA contributors is pending to allow the results to be incorporated in the FFC project.

The US "Deep burn" project has started in July 2008 under the leadership of INL. It covers two main areas of research:

- Fuel Cycle analysis (core design, fuel performance in reactor, repository issues, assessment of fuel cycle scenarios ...),
- Fuel Development (design of TRISO fuel, fabrication, recycle technologies ...).

No activity has yet started within the FFC project regarding the assessment of the VHTR thorium fuel cycle.

IV. CONCLUSION

After one year of collaborative work, the Fuel and Fuel Cycle project of the VHTR is producing its first results. Despite initial difficulties to protect intellectual property of the partners, all parties have succeeded to join their effort in an almost comprehensive program covering all aspects of fuel development and qualification and waste management issues.

References

1. *Coll.*, Fuel & Fuel Cycle Project Plan of the Very High Temperature Reactor system, OECD/NEA edition (2007).
2. *Coll.*, Project Arrangement on Fuel and Fuel Cycle For the International Research and Development of the VHTR, OECD/NEA edition (2007).

Glossary

AGR	Advanced Gas Reactor
ANTARES	AREVA New Technology based on Advanced gas-cooled Reactors for Energy Supply
FFC	Fuel and Fuel Cycle
GTHTR	Gas Turbine High Temperature Reactor
GT-MHR	Gas Turbine Modular High temperature Reactor
HFR	High Flux Reactor
HTR-PM	High Temperature Reactor-Pebble bed Modules

LWR	Light Water Reactor
NGNP	Next Generation Nuclear Plant
NHDD	Nuclear Hydrogen Development and Demonstration
PBMR	Pebble-Bed Modular Reactor
PIE	Post Irradiation Examinations
PMB	Project Management Board
PUMA	Plutonium and Minor Actinide management
PYCASSO	PYrocarbon irradiation for Creep And Shrinkage/Swelling of Objects
RAPHAEL	ReActor for Process heat, Hydrogen And ELectricity generation
SiC	Silicone Carbide
TRISO	TRIstructural ISOtropic
VHTR	Very High Temperature Reactor
ZrC	Zirconium Carbide