New Hot Cell Laboratory and Post Irradiation Examination Research Project on HTR Spherical Fuel Element in INET

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Abstract: A new hot laboratory project is being carried out by Institute of Nuclear and New Energy Technology (INET), Tsinghua University, China. The project aims to establish an advanced platform with hot cell laboratory and ancillary facilities for HTR FE post irradiation examination (PIE). Hot laboratory facility specially designed for post irradiation examination of high temperature gas-cooled reactor (HTR) fuel elements and the construction will start by the end of 2016. The laboratory will cover functions of receiving, storage, inter-lab transport of both post irradiated spherical FE and TRISO coated fuel particles. The specimens will be characterised by 1) weighting; 2) burnup measurement; 3) heating test; 4) deconsolidation test; 5) failure fraction measurements; 6) sample preparation; 7) macrostructure and microstructure investigation. Analysis equipment including high purity Ge (HPGe) gamma spectrometer, accident simulation test apparatus (ASTA), FE deconsolidation system, irradiated micro-sphere gamma analyser (IMGA), integrated TRISO coated fuel particles sample preparation system, stereo microscopes and electron microscopes, etc. will be specially designed and modified for spherical elements and TRISO coated fuel particles and installed in the labs.

Key words: Hot Cell Laboratory; PIE technology; HTR Spherical Fuel Element

1. Introduction

The post irradiation examination is a crucial part of the research on high temperature gas-cooled reactor (HTR) fuel elements. INET has proposed a hot cell laboratory project for HTR post irradiated fuel element analysis. The systematic research carried along this project includes post irradiation examination, trying to find out the failure mechanisms of TRISO coated fuel particles and HTR spherical elements. Furthermore, the research works will support and provide theoretical basis for research and development (R&D) of new types of HTR fuel elements, and choosing appropriate operating condition of commercial HTR power plants in the future. The hot cell labs will be located in INET, Tsinghua University, Beijing, and

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the preliminary design is already completed. The facility mainly consists of five single hot cells, six shielded glove boxes, one conveyor line and a pneumatic sample transportation system, covering functions of receiving, storage, inter-lab transport and characterisation of post irradiated fuel element. This article will briefly introduce the layout of the INET HTR PIE hot lab and its characterisation facilities.

2. High Temperature Gas-Cooled Reactor and Fuel Element

HTR is graphite moderated, helium cooled thermal reactor. It is considered as one of the most promising candidates for the next generation of nuclear energy because of a series of features especially its significant safety. (Wu and Xiao, 1993) The China's HTR uses spherical fuel elements as shown in Figure 1. The spherical fuel element is 60 mm in diameter contains thousands of TRISO coated fuel particles. The TRISO coated fuel particles are UO_2 kernel of 0.5mm covered by four outer layers, namely buffer layer, inner pyrolytic carbon layer (IPyC), SiC carbide layer and outer pyrolytic carbon layer (OPyC). The coated layers play functions of small 'pressure vessel' and prevent release of fission products. (Nabielek et al., 1990; Tang et al., 2002) After a period of in core irradiation, fuel elements will have significant shape and properties change, and taken out from the core.

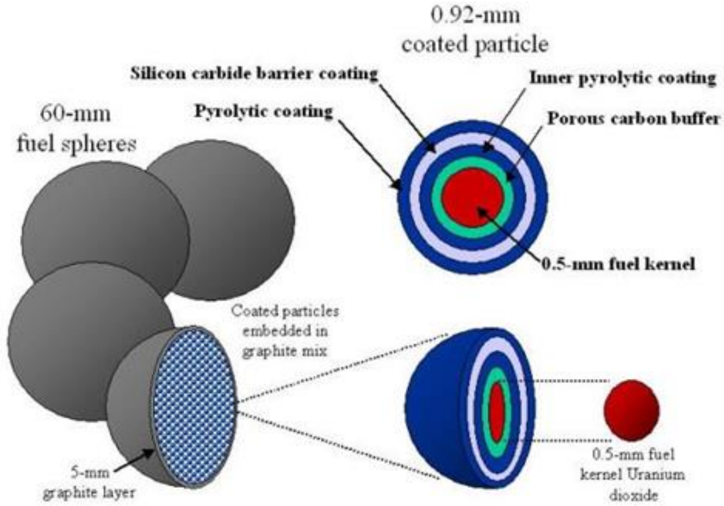

Figure 1 Structure of Spherical Fuel Element and TRISO Coated Fuel Particles

3. Laboratory Layout

The laboratory is built in order to realise spherical fuel element and TRISO coated particles deconsolidation and characterisation and minimise the radiation exposure and contamination to the stuff at the same time. Figure 2 is the virtual picture of hot cell laboratory.

Figure 2 The virtual picture of the INET Hot cell laboratory

3.1 Laboratory Zones

The whole hot lab building is divided into three control zones: ‘Red Zone’, ‘Orange Zone’, ‘Green Zone’ and one supervision zone: ‘White Zone’, based on radiation level variation. (IAEA, 1981) The floor plan (Figure 3) shows the four areas and their functions. The radiation level of each area is listed in Table 1.

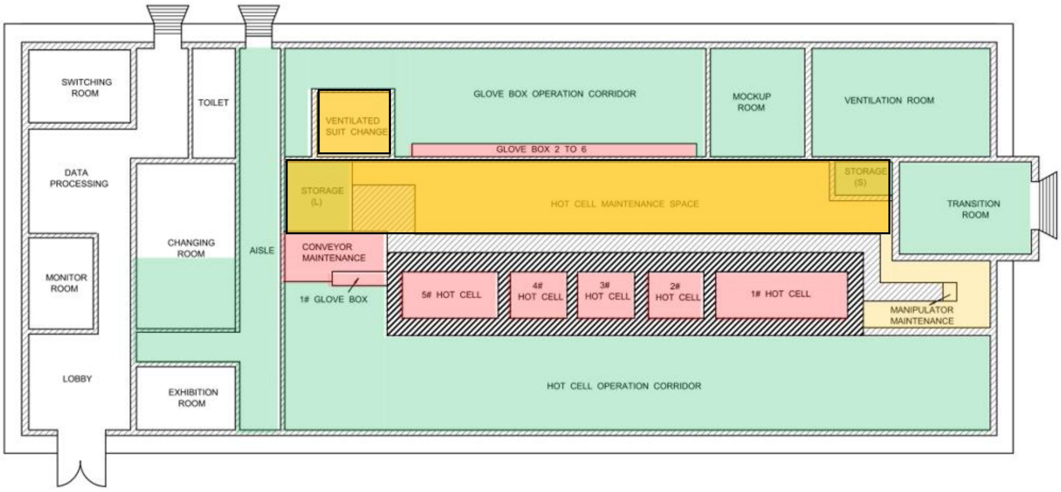

Figure 1 Floor Plan of the INET Hot Lab

The Red zone of the INET hot lab is where all experiment undertook and most of the post-irradiation examination facilities and apertures located. It includes all the interior space of hot cells and glove boxes. The red zone is all-time containment and has the highest radiation level among the entire lab. Personnel access to this area, i.e. into the hot cells, is only allowed for absolutely necessary maintenance, and requires complete protective clothing and respiratory protection. Orange zone, including the back space of hot cells and glove boxes, decontamination room and the ventilated suit change room. It is an intermediate area connecting high radiation level area and low radiation level area, which is, normally, containment free. However, it is recognised and accepted that contamination may be encountered in this zone during the maintenance of red zone. Green zone includes the operating corridor of hot cells and glove boxes, data processing room, non-irradiation procession room, storage area and the clean sides of the changing room for stuff. The green zone is recognised as a usually clean area, where stuff spend most of the time in building. In this area no radiation and contamination hazard would be expected. Protection requirement of personnel entrance to this area can minimise to change of clothing. White zone is a supervision area, including the lobby, antechamber, exhibition area. It is considered to be 'permanently clean' and no radiation or contamination hazard may exist.

Table 1 Radiation Level of the Control Area

Area name	Radiation level	Room
Supervision Area (White zone)	$<0.25\times10^{-2}$ mGy/h	Lobby Exhibition area
Control Area 1 (Green zone)	$<0.75\times10^{-2}$ mGy/h	Mock up room Corridor Data processing room
Control Area 2 (Orange zone)	$<2.5\times10^{-2}$ mGy/h	Maintenance space of hot cells Solid radioactive waste storage room Radioactive liquid waste storage room Decontamination room Ventilated suit room
Control Area 3 (Red zone)	$<50\times10^{-2}$ mGy/h	Hot cell 1-5 Glove Box 1-6

3.2 Ventilation

The ventilation system is designed to maintain certain pressure in the laboratory rooms. It leads air flow from low radiation level area to high radiation level area by provide a decrease air pressure. Within the hot cells, considering the different experiment events, the air flow is designed from hot cell 5 to hot cell 1. The waste air of the whole lab will be channelled by air ducts to a filtration plant and release to the atmosphere afterwards. The radiation level monitored to ensure is under permissible activity limit.

4. Post Irradiation Examination

The laboratory contains five hot cells and six glove boxes. Inter-lab sample transportation is carried out by one conveyor line and a pneumatic sample transportation system. The functions of facilities and apparatus in each one hot cell are listed in Table 2.

Table 2 Functions of Hot Cells

Hot Cell	Function	Facilities and Apparatus
1#	Element receiving and storage Macroscopic Observation	HPGe gamma spectrometer Storage facility Remote camera
2#	Accident simulation test	Accident Simulation Test Apparatus (ASTA)
3#	Irradiated micro-sphere analysis	Irradiated Micro-sphere Gamma Analyser (IMGA)
4#	Deconsolidation	FE deconsolidation system
5#	Sample preparation	Sample preparation system

All of them are remote controlled by master-slave manipulators from the hot lab operation area. After received, the post irradiated HTR fuel elements will be examined by steps shown in Figure 4. Hot cell-1 performing function of storage and shape observation and Hot cell-5 performing function of sample preparation will not be described in detail. This section mainly introduces three of the hot cells related to fuel element radiation test.

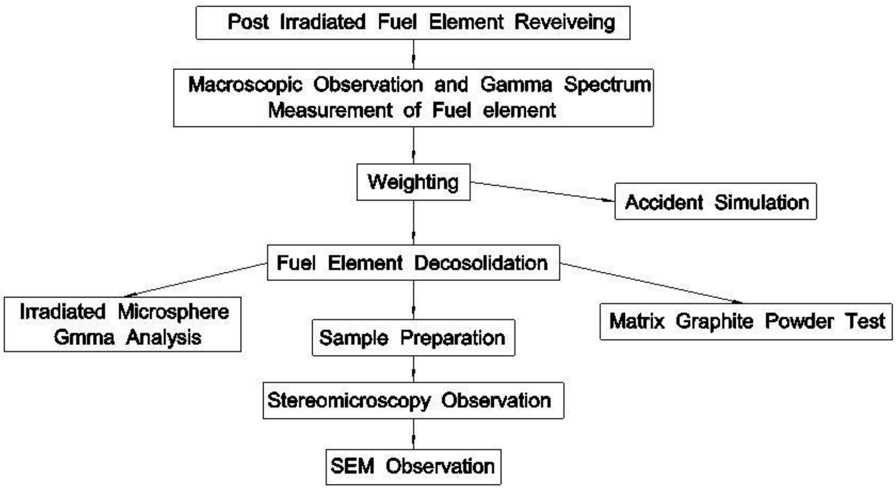

Figure 2 Post Irradiation Examination Route

4.1 Accident Simulation Test Aperture

The accident simulation test aperture (ASTA) (Figure 5) is a specialised test device which is capable of handling an entire spherical fuel element and simulated a 'De-Pressurised Loss of Forced Circulation' (DLOFC) condition. A fuel element is held in the ASTA aperture and then heated to the expected temperature of DLOFC accident condition. Possible fission product release will be measured as a function of test time. The release of gaseous fission products, ^{85}Kr and ^{133}Xe, illustrates the time to failure and the number of particles that fail in a given time at certain temperature. The two radioactive nuclides are measured by means of gamma spectrometry, and can be measured continuously. However, release of the solid fission products can only be measured from time to time after every period of accident simulation test. When testing, a cold finger protrudes into the heat tube. A condensation plate is attached at the end of the cold finger. The temperature of which is well below 100 ℃, so that the fission products can condense on it. Afterwards, the condensate plate can be replaced with a fresh one before re-insertion into the furnace. Subsequently, the condensation plate will be sent to Glove Box-1 to measure the amount of released solid radioactive isotopes by gamma spectrometry.

Figure 3 Accident Simulation Test Aperture in the INET Hot Lab

4.2 Fuel element deconsolidation

Deconsolidation is a sample preparation method to grab loose coated particles after the irradiation test in ASTA, in order to do further study on the failure mechanisms on the coated fuel particles. The electro-chemical deconsolidation method is used in Hot Lab-4. This method is based on the mechanism that insertion of a fuel element as the anode in an electrical circuit (Figure 6). HNO_3 is used as the electrolyte. The deconsolidation is divided in two stages. In the first stage, the fuel element sphere is partially deconsolidated into a cylinder. And the cylinder will continuous deconsolidated in the second step. The two steps yield a sample of electrolyte solution, graphite matrix, and associated coated particles. However, the OPyC layer will be deconsolidated at the same time. As a result, individual TRISO coated particles without the OPyC layer are extracted and collected.

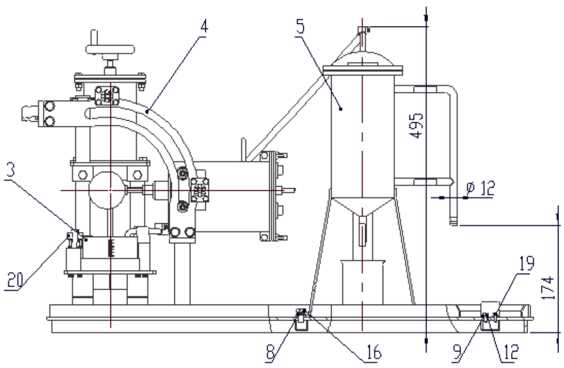

Figure 4 Fuel Element Deconsolidation Aperture

4.3 Irradiated microsphere gamma analyser

Collected by deconsolidation, the coated fuel particles are sent to Hot Lab-3, where an irradiated microsphere gamma analyser (IMGA) located, aiming to examine the TRISO coated particles by gamma-ray detector and find the failure particles. (Baldwin, et al., 1990). For the hot cell project in INET, a novel IMGA device is being designed. (Figure 7) In general, the main body of IMGA system contains three functional parts: the single particle part, the measuring part and the sorting-collecting part. The single particle part is where TRISO coated particle is sucked out of the sample bottle by vacuum grip device. A pressure measuring system is used to detect if the one particle is sucked out correctly. In the measuring part, Zr-95 and Cs-137 are selected as the characteristic nuclide to decide if the particle is failure or not. If the particle is broken, Cs-137 will be released from the coated particle when Zr-95 will be retained. As a result, the ratio of the Gamma spectral intensity of Zr-95 and Cs-137 will be changed. A collimator is used collect an enough efficiency for the Gamma spectrum detector in 1050 mm away. After detected, different particle will be collected by different criterions, and will be separated into 20 kinds, which can be used to do materials inspection in the next hot lab. The IMGA system is fully automatic for examine the coated fuel particles, contains automatic sorting particles, automatic picking particles, automatic handling particles and automatic placing particles. The rapid detection of radionuclide activity can be achieved. The measuring time is 45s and it needs 1 min to examine one coated particle.

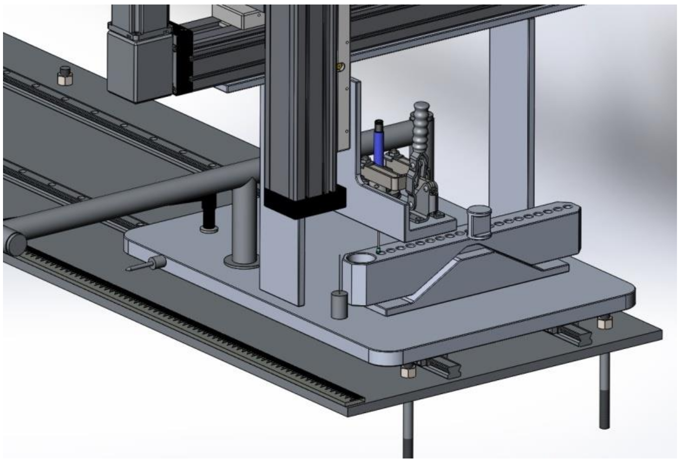

Figure 5　Modified IMGA in the INET Hot Lab

4.4 Glove boxes

Compared to hot cell, precisely experiment can be undertaken in glove boxes by manual operation without master-slave manipulators. The function of and apparatus and facilities in each glove box are listed in Table 4. In glove box-1, a gamma spectrometry is modified to measure the radiation of the condensation plates from ASTA, the graphite powder and acid liquid from FE deconsolidation. In glove box-2, a stereomicroscopy and a metallography microscopy are modified as remote controlled to observe the microstructure of prepared TRISO coated particles specimens. Afterwards, the specimens are sent to glove box 3 for detailed observation and having element analysis by Scanning Electron Microscopy. In glove box 4, a remote controlled precise balance is equipped. The balance undertakes all pre-weight measurement work for analysis in glove boxes, especially for glove box 1 radioactivity measurement. The other two glove boxes are used to research thermal conductivity and thermal expansion coefficient of graphite materials.

Table 3 Functions of Glove Boxes

Glove Box	Function	Facilities and Apertures
1#	Radioactive measurement	HPGe gamma spectrometer
2#	Microstructure characterisation	Metallography microscopy Stereo-microscopy
3#	Microstructure characterisation	Scanning Electron Microscopy
4#	Weighting	Precision balance
5#	Thermal conductivity	Laser Thermal Conductivity
6#	Thermal expansion coefficient	Dilatometer

5. Conclusions

The post irradiation examination of HTR spherical fuel element is always crucial for the fuel element research. The construction of hot cell laboratory specially designed for HTR spent fuel elements in INET will start by the end of 2016. It is believed that this new hot cell lab will meet the requirements and fulfil all the expectations for finding out failure mechanisms of both HTR spherical elements and TRISO coated fuel particles, moreover, providing support and theoretical basis for R&D of high quality fuel elements, and choosing appropriate operating condition of future commercial HTRs.

6. References

1) Baldwin, C A and Kania, M J. 1990. IMGA examination of set #4 fuel. ORNL/TM-11455, 1990.
2) E.H. Toscano, W. Klopper and J.H. Venter, The Guidebook on Post-Irradiation Examination of High Temperature Reactor Fuel Elements, 2010.
3) Makihara, Y. 2006. Development of a safety report on accident analysis for nuclear power plants with modular high-temperature gas-cooled reactors. Johannesburg, RSA: Proceedings of the HTR-2006 Conference, Paper 0218, 2006.
4) Manual on Safety aspects of the Design and Equipment of Hot Laboratories, Safety Series No. 30, IAEA1981.
5) Nabielek, H., Kuehnlein, W., Schenk, W., Heit, W., Christ, A., Ragoss, H., 1990. Development of advanced HTR fuel elements. Nuclear Engineering and Design, 121, 199.
6) Tang, C., Tang, Y., Zhu, J., Zou, Y., Li, J., Ni, X., 2002. Design and manufacture of the fuel elements for the 10 MW high temperature gas-cooled rector. Nuclear Engineering and Design, 218, 91.
7) Wu, Z., Xiao, H., 1993. The safety features of the modular HTGR. Chinese Journal of Nuclear Science and Engineering, 13 (1), 22 (Special Issue of HTGR).