Design and manufacture of the IMGA system for PIE of coated fuel particles of HTR fuel element in INET

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Abstract：The Post Irradiation Examination (PIE) lab of spherical fuel element used in High Temperature Gas-cooled Reactor (HTGR) has been designed and is being constructed now in INET, Tsinghua University, Beijing, China, aiming at the developing the PIE techniques of spherical fuel element and coated fuel particles. In this PIE lab, Irradiated Microsphere Gamma Analyzer (IMGA) system will be set up. The main body of IMGA system contains three functional parts: the particle singularizing part, the measuring part and the sorting-collecting part. In the particle singularizing part, per coated particle with diameter between 0.8 and 1.0mm is sucked out of the sample bottle one by one, using vacuum grip device connected to the mini vacuum pump. In the measuring part, The Ce144 and Cs137 are selected as the characteristic nuclide for examining if the particle is failure or not. The collimator is designed for measuring the irradiated coated particle specially. In the sorting-collecting part, the different kinds of particles will be collected by different criterions, and will be separated into 20 kinds, which will be used to do materials inspection in the next hot cell. The whole system is synchronized and controlled by the automatic computer system. The details of this IMGA system, such as measuring time and statistic analyses will also be discussed in the present paper.

Key words：Coated fuel particle; IMGA; HTR; PIE

1. Introduction

In China, HTR-PM (High Temperature gas-cooled Reactor-Pebble Module) was constructing now and HTR-600 will be developed in the near future[1]. The spherical fuel element made of TRISO (Tri-structural isotropic) coated particles and graphite matrix was used in current HTR design. TRISO coated particles is the first security assurance of the HTR. The Post Irradiation Examination (PIE) techniques of TRISO coated particle will be important for improving and modifying the design parameters and manufacture technology of the coated fuel particles, especially for the higher temperature and higher burn-up in the future[2]. Now the Post Irradiation Examination lab of HTR spherical fuel element has been designed and is being constructed in

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Institute of Nuclear and New Energy Technology (INET), Tsinghua University, Beijing, China, aiming at developing the PIE techniques of spherical fuel element and coated fuel particles and investigating properties of irradiated spherical fuel element[3].

In this PIE lab, hot cell-3# which was called Irradiated Microsphere Gamma Analyser (IMGA) system will be set up. The aim of this lab was to examine the coated fuel particles by the gamma-ray detector and find the failure particle one by one. The IMGA system is a fully automated device for examining individual HTGR microspheres using a high-resolution gamma-ray spectrometer. The IMGA system measures the absolute activities of the particles by means of special user programmed instructions, which is able to segregate particles based on the measured activities.

The IMGA system has been researched for many years in USA[4], Europe[5] and Russia [6], but it is the first time that the IMGA system was constructed in China. The details of the design principle and parameters of this IMGA system in INET will be presented in this paper. The paper is organized as follows: the design principle was summarized and given in Part 2. The system design details, including particle singularizing part, automatic part, measurement part and the process parameters are given in part 3. At last conclusions are drawn out in part 4.

2. IMGA design principle

The IMGA concept is based on the fact that immobile and mobile fission and activation products are created during irradiation. The terms immobile and mobile here mean that some fission products do not diffuse out of the coated particle, whether the particle is intact or not, whereas some fission products can be released upon failure of coating layers caused by irradiation, heating and/or production.

The primary function of the IMGA system is to measure accurately the immobile and mobile radioisotope in individual coated particles obtained from irradiated fuel elements, by detecting gamma radiation from individual coated particles. And then the ratio of the activity of the immobile and mobile radioisotope can be calculated, the irradiation coated fuel particle can be sorted by the ratio. Because the particle number is huge, so the whole system should be working quickly and controlled automatically by a computer. The design requests of the IMGA system can be given in following aspects:

1) Aim: Rapid detection of the activity of special radionuclide in the irradiated coated fuel particles one by one;

2) Automatic control function: The irradiated coated fuel particles are automatically picked up, automatic handling, automatic placement one by one with the utilization of computer and motion control systems.

3) Parameter setting function: Including motion parameters and measurement parameters, the user can manually set the movement speed, movement distance, the measurement time, coated fuel particles of radioactivity.

3. IMGA system design in INET

In general, the main body of IMGA system in INET contains three functional parts: the particle singularizing part, the measuring part and the sorting-collecting part. The total size is L=500, W=370, H=600 mm. The pressure measuring system will be used to detect if one particle is sucked out correctly. In the sorting-collecting part, different kinds of particles 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-cell 4#. The details of other parts will be given as follows.

3.1 Particle singularizing part

In the particle singularizing part, as shown in Fig. 1, per coated particle with diameter between 0.8 and 1.0mm is sucked out of the sample bottle one by one, using vacuum grip device connected to the mini vacuum pump. The pickup system of coated fuel particle consists of buffer spring, strut, vacuum suction cup, bracket, displacement sensor and other components. The vacuum suction cup is connected to a buffer spring and bracket mounted on the Z-axis elevating platform. The vacuum suction cup can be replaced based on the coated fuel particle size. The buffer spring can decrease the contact impact of coated fuel particles and increase the reliability. The vacuum suction cup can draw up coated fuel particles with a diameter of 0.8 to 1.2 mm by using different specifications of vacuum suction and appropriate accessories. The adsorption capacity of the vacuum cup device is about $0.035 \sim 0.9$ N which is enough for a coated fuel particle with a diameter of 0.8 to 1.2 mm when the vacuum degree is 70%.
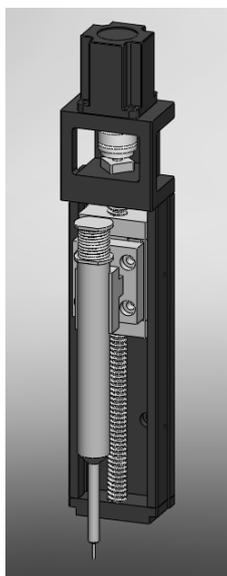
Fig.1 The particle singularizing part

3.2 Automatic motion design

The automatic motion part is designed as shown in Fig. 2. The X axis is mounted on the base, which is the horizontal axis, parallel to the upper three stations of the base. The base position can be adjusted so the distance between the irradiation coated particle and the r-ray detector can be changed according to the activity of radionuclide which was determined by the burn-up and cooling time of spherical fuel element. The Z axis, which is the vertically axis, is mounted on the X-axis, and perpendicular to the plane of the X-axis. The vacuum suction device is mounted on the Z-axis. Twenty small bottles and a sampling bottle are placed in parallel arrangement of the X-axis. In the analysis process, The coated fuel particle was draw out of the sampling bottle by vacuum cups with Z-axis movements. Then the coated particle is moved to the measuring position in front of the gamma detector by linear motion of X-axis. According to measurement results, the coated particle can be return to different kinds of small bottle by linear motion of X-axis, to

complete a coated fuel particle measurement. The whole apparatus is synchronised and controlled by a computer system.
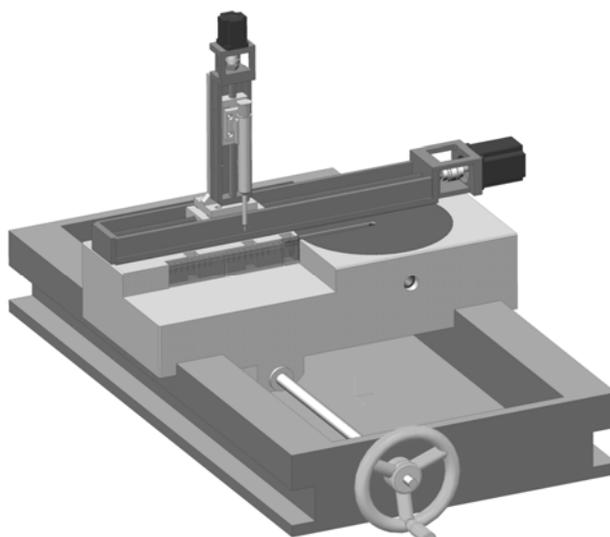
Fig.2 The automatic motion part of IMGA system

3.3 Measurement design

3.3.1 Radionuclide selection

Due to the fact that the activity ratio between a mobile and an immobile isotope will be unusually low if the mobile nuclide has diffused out of the failed coated particle, so the particle failure can be represented by the activity ratio between a mobile and an immobile isotope. There are many kinds of stable and volatile radionuclide in the irradiated coated particle. Special radionuclide should be selected for detecting at first. Generally, three isotopes, Zr95, Ce144 and Ru106, are considered as immobile isotopes. The mobile isotopes are normally represented by Cs137, Cs134, and Eu154 which have relatively long half-lives. In IMGA of Russian, Zr95 and 137Cs are selected. In IMGA of USA, Ce144 and 137 Cs are selected. In our IMGA system, the radionuclide Cs137 and Ce144 in the irradiation coated fuel particle are selected for detecting. Because the half-life of Zr95 is short, the activity is so low when the irradiated fuel element has been get out of the reactor and cooled for a long time, so the design of IMGA is based on the Cs137 and Ce144 radionuclide. The energy, half life, boiling point and maximum activity at final burn-up are given in Table 1.

Table 1 The properties of radionuclide

Isotope	γ photon Energy (KeV)	Half-Life	Maximum activity(Bq)	Boling point(℃)
Cs-137	661.6	30.1y	5.61E+06	671
Ce-144	133	285d	3.69E+07	3443

3.3.2 Collimator design

Collimators are needed in many hot-cell applications due to the fact that gamma detectors are generally limited in the count rates that they can handle. The collimator is also the important part in the IMGA system design. Here we chose a simple design because of the radioactive of each coated particle is very small. The diameter and length of the collimator is 180mm and 350mm

respectively, with the collimation hole is 25 mm. The distance between the coated particle and Gamma spectrum detector is 1050 mm initially which can be adjusted accordingly. The collected efficiency is enough according to the calculation results of the spectrum detector. The total length of the collimator is subdivided into segments. This design facilitates the manufacturing of the collimator since Tungsten alloys are mechanically difficult to work. The steel nesting is embedded into the cement wall of hot-cell. The collimator, detector, sealing flange are installed in the steel nesting, as shown in Fig 3-b.
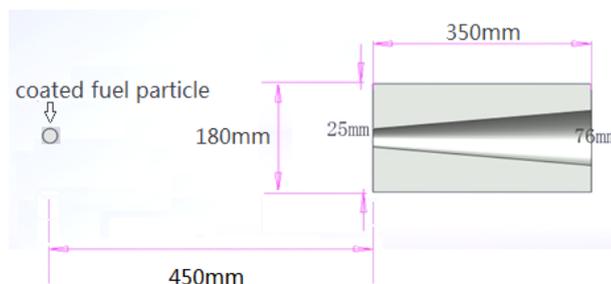
(a)
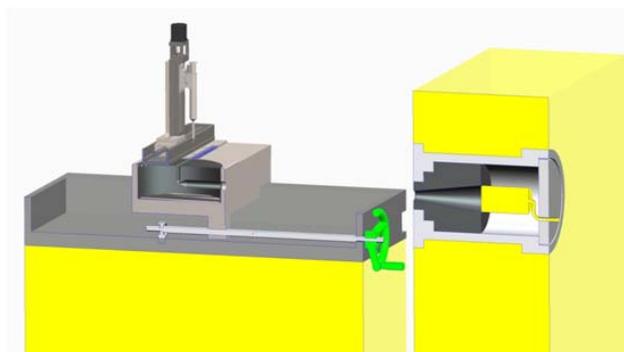
(b)

Fig.3 The collimator design (a) and installations design (b)

3.3.3 Detector efficiency calculation and selection

Detectors for a specific application are frequently selected on the basis of their efficiency, energy resolution, and peak to Compton ratio. It is required to identify isotopes presenting in the coated fuel particle. HPGe detectors with their superior energy resolution are clearly the most suitable detectors for this application although an additional inconvenience of Ge detectors is the fact that they have to be cooled during use.

The radionuclide to be measured are Cs-137, Ce-144 as metioned above. The characteristic energy of Cs-137 and Ce-144 are 661.6KeV and 133KeV respectively. The characteristic energy belongs to the range of 50KeV-10MeV, so the ORTEC P-type HPGe detector is chosen here. High purity germanium detector GEM30P4-76 and DSPec Jr2.0 spectrometer with electrical refrigeration X-Cooler-III can be selected to achieve the detection of the radiated coated fuel particle. The detecting efficiency curve based on the selected detector and collimater is shown in Fig. 4. The detection efficiency of energy 661.6Kev is about 5*10E-5. The Cs-137 activity in coated particle is about 5*10E6 Bq, as shown in Table 1, so the energy spectrum count number is 250CPS. The measurement time should be larger than 40s (the count number>10000) to reach statistical error requirements.
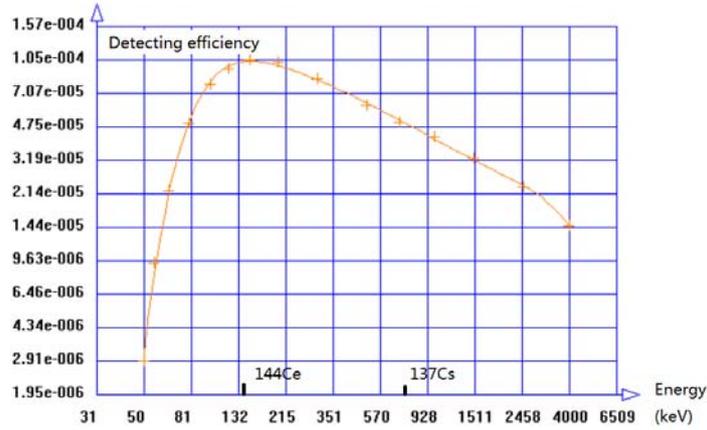
Fig. 4 The detecting efficiency curve

3.4 Process parameter design

The rapid detection of radionuclide activity can be achieved. The measuring time is 20s and it needs about 1 min to examine per coated particle one time. Although it is possible to analyze all particles, sampling measurement is always considered as a possible means for saving time and cost. When the examination is finished, the maximum failure rate can be calculated by the statistical equation:

$$C = 1 - \sum_{i=0}^{n} \binom{N+1}{i} Z_{max}^{i} (1 - Z_{max})^{N+1-i}$$

(1)

In which, N is the sampling coated fuel particles number which have been examined, n is the failure coated particles, C is the confidence coefficient. Z_{max} is the maximum failure rate. The relationship of particle number and the failure rate was given in Table 2.

Table 2 The maximum failure rate($\times$10-4), C=0.95

n \ N	5988	5989	9000	12000
0	5.00080674	4.99997209	3.32766782	2.495924
1			5.26927903	3.95227450
2				5.24511867
3				6.45956255

Base on the above table, assuming that zero or one failure particle is found and the maximum failure rate should be smaller than 5e-4, 5989 or 9475 particles should be detected if the confidence coefficient is 0.95. Based on the novel designed IMGA system, it needs about 4.16 or 6.58 days to finish the whole process. If more failure particle is found and the maximum failure rate should be smaller than 5e-4, the measuring time should be increased significantly.

4. Conclusions

The IMGA principle and design parameters in INET, Tsinghua university, Beijing, China are discussed in details. The IMGA system is fully automatic for examining the coated fuel particles, containing picking particles automatically, handling particles automatically, sorting particles and

placing particles automatically. Some conclusions can be drawn out as follows.

1) The design principle of the IMGA was given and used to set up the first China IMGA system in INET.

2) The details of the IMGA design in INET are presented, including the particle singularizing part, the measuring part and the sorting-collecting part. The design parameters are given in details. The stability and generality of the new IMGA design will be increased significantly.

3) The measuring time of IMGA can be as quick as 40s. It will need 1min at maximum for detecting per particle. The statistical analyses of detecting process is also given.

4) The novel IMGA system will be set up in hot-cell 3# in the PIE lab in INET, and will be completed in 2017 in the plan.

Acknowledgements

Notations

L Length, mm

W Width, mm

H Height, mm

N the sampling coated fuel particles number, -

C confidence coefficient, -

n the failure coated particles number, -

Z_{max} maximum failure rate, -

Reference

[1]H. T. Wang, et al., Future Development of Modular HTGR in China after HTR-PM, 2014, HTR meeting proceedings, Weihai, Shandong, China.

[2]T. X. Liang, H. S. Zhao, C. H. Tang, K. Verfondern, Irradiation performance and modeling of HTR-10 coated fuel particles, 2006, Nuclear Engineering and Design 236:1922-1927.

[3]H. S. Zhao, et al., The report on post irradiation examination of spherical fuel element used in high temperature gas-cooled reactor, 2014, National S&T Major Project of China, Grant No. ZX06901-015.

[4]M. J. Kania, K. H. Valentine, The Irradiated-Microsphere Gamma Analyzer (IMGA) – An Integrated System for HTGR Coated Particle Fuel Performance Assessment, 1980, ORNL-5606.

[5]X. Corino, D. Bottomley, D. Freis, A. Kellerbauer, V. Rondinella, P. Van Uffelen, Assessment of Coated-Particle Failure with the IMGA Device, 2010, HTR meeting proceedings, Prague, Czech Republic.

[6]E.H. Toscano, W. Klopper, J.H. Venter, The Guidebook on Post-Irradiation Examination of High Temperature Reactor Fuel Elements, 2010.