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COMPARISON OF HTGR FUEL DESIGN, MANUFACTURE AND QUALITY CONTROL METHODS BETWEEN JAPAN AND CHINA

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Comparison of HTGR Fuel Design, Manufacture and Quality Control Methods between Japan and China

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The first-loading fuel for the HTTR was started to fabricate at Nuclear Fuel Industries (NFI) in 1995 and the HTTR reached criticality in 1998. Meanwhile, 10MW high temperature reactor (HTR-10) was constructed in Institute of Nuclear Energy Technology (INET) of Tsinghua University, and the first-loading fuel was fabricated concurrently. The HTR-10 reached criticality in December 2000.

Though fuel type is different, i.e., pin-in-block type for the HTTR and pebble bed type for the HTR-10, the fabrication method of TRISO coated fuel particles is similar to each other.

This report describes comparison of fuel design, fabrication process and quality inspection between them.

Keywords: HTTR, HTR-10, Fuel Design, Fabrication, Quality Control, Coated Fuel Particle, HTGR, Fuel Element

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高温ガス炉燃料設計、製造方法、品質管理方法に関する日中の比較検討

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(2002 年 4 月 1 日受理)

日本の HTTR 用初装荷燃料は 1995 年より原子燃料工業㈱で製造を開始し、HTTR は 1998 年に臨界となった。一方、中国では清華大学の INET (Institute of Nuclear Energy Technology) にて 10MW の高温ガス炉 (HTR-10) 建設と並行して、燃料製造が進められた。この結果、HTR-10 は 2000 年 12 月に臨界に達した。

日本の HTTR と中国の HTR-10 では燃料型式がそれぞれピンインブロック型、ペブルベッド型と異なっているが、いずれも TRISO 粒子である被覆燃料粒子のように似通った部分もある。

本報は日本と中国における燃料設計の違い、製造方法の違い、品質保証方法の違いを比較検討し、まとめたものである。

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1 Introduction

High Temperature Gas-cooled Reactor (HTGR) is expected to be an advanced type of reactor with its inherent safety feature, fuel cycle flexibility, high fuel utilization, high efficient electricity generation and process heat application.

A 30MW high temperature engineering test reactor (HTTR) was constructed in Japan Atomic Energy Research Institute (JAERI), and attained its first criticality in November 1998. The fuel fabrication started at Nuclear Fuel Industries (NFI), 1995[1]. Meanwhile, the research work of high temperature reactor has been carried out in China and a 10 MW high temperature reactor (HTR-10) was constructed in Institute of Nuclear Energy Technology (INET) of Tsinghua University, Beijing[2]. HTR-10 achieved its criticality successfully at the December 2000.

Fuel element with graphite matrix is one of the main characteristics of HTGR. There are two kinds of fuel elements at present, one is the spherical fuel element adopted in Chinese HTR-10, and the other is the pin-in-block type fuel employed for Japanese HTTR. Fuel fabrication technology has been established through a lot of R&D activities both in China and in Japan for the long time [2-5].

The demand to retain all fission products in the fuel element will be satisfied by the coated fuel particles, which is the basic component in the fuel element. To form the coated fuel particle, UO_2 kernel preparation process and the continuous 4-layers coating process has been developed both in China and in Japan.

Although qualification test and irradiation examination showed that very high quality of fuel was achieved and satisfied the design requirement of HTR-10 and HTTR fuel, it should be noted that there are many differences between this two types of fuel element. Fuel safety design methods and criteria should be further comprehended, fabrication technology and quality inspection method could be improved to meet the design requirement. This report describes comparison of fuel design, fabrication process and quality inspection between HTTR and HTR-10.

2 Fuel Design

Spherical fuel elements are adopted for the HTR-10[2]. According to the nuclear design of HTR-10, over 27,000 fuel elements with outer diameter of 60mm will be loaded in the HTR-10 forming a pebble bed core. One fuel element comprises a spherical fuel zone, in which about 8,300 coated fuel particles are embedded in a matrix of graphite material, and a 5-mm-thick shell of pure graphite material free of fuel, which surrounds the spherical fuel zone.

On the other hand, pin-in-block type fuel is adopted for the HTTR[5]. One fuel compact consists of approximately 13,000 coated fuel particles. 14 fuel compacts are inserted in graphite sleeve and form a fuel rod. Then, 31 or 33 fuel rods are inserted in graphite block and form fuel assembly. In the HTTR reactor design, 150 fuel assemblies are loaded in the core. Fig.1 and Fig.2 show the structure of fuel element of the HTR-10 and fuel assembly of the HTTR, respectively.

As shown in Fig.1 and Fig.2, two different types of fuel element design are used, but same kind of coated fuel particles are inside the fuel element and the structure of the coated fuel particle is identical. The coated fuel particle is TRISO-type consisting of a low-density, porous pyrolytic carbon (PyC) layer adjacent to the spherical UO_2 kernel and followed by a high density isotropic PyC layer, a silicon carbide (SiC) layer and a high density outer PyC layer.

2.1 Fuel Safety Design

2.1.1 Safety Criteria for HTTR Fuel

The safety design criteria of HTTR fuel was settled for normal operation, anticipated transient and accident conditions [6].

(1) Normal Operation

- The initial, as-fabricated, failure fraction in the coating layers of the coated fuel particles

shall be less than design limit of 0.2%, which is determined from the viewpoint of limit of off-site exposure during normal operation.

- The coated fuel particles shall not fail systematically considering failure mechanisms such as Pd-SiC interaction, kernel migration and internal pressure. The additional failure fraction in the coating layers of the coated fuel particles shall be less than design limit through the full service period.
- The fuel compacts and the graphite sleeves shall not be broken or cracked considering thermal stress and irradiation-induced damage. The fuel compact and graphite sleeve shall not contact with each other to keep their mechanical integrity.

(2) Anticipated Transients

The phase transition is expected to occur from β-SiC (as-deposited) to α-SiC at temperature range of 1600～2200℃, therefore, the maximum fuel temperature shall not be exceeded 1600℃ at any anticipated transient to avoid fuel failure, i.e. To permit reutilization of the fuel after anticipated transients.

(3) Accidents

- The fuel shall be maintained in the graphite block or sleeve so that the fuel could be cooled by auxiliary cooling system and/or vessel cooling system.
- The structural integrity of the graphite support structures such as support posts shall be maintained.

2.1.2 Safety Criteria for HTR-10 Fuel

Development and qualification of the fuel elements for HTR-10 with pebble-bed cores have been determined, at all stages, by the general performance requirements as following[7]:

- Optimal fission product retention capability (fractional release of radiologically relevant nuclides from the fuel elements well below 10^{-4} under normal and design-basis accident

conditions);

- High mechanical strength of the integral fuel element (negligible release contribution by fuel elements damaged due to external forces exerted by in-core control rods or fuel loading system);
- High corrosion resistance with respect to oxidizing agents in the primary coolant (negligible reduction of retention capability and mechanical strength by corrosion effects);
- Sufficient dimensional stability (neutron induced shrinkage of outer diameter $\leqslant$2% to assure undisturbed handling during fuel element reloading);
- Efficient heat transfer characteristics (to be comparable with solid nuclear grade graphite).

2.1.3 Main Difference of Design Criteria

The basic design of the fuel element, which is determined by the demand of irradiation performance, is identical. The main difference is that the HTR-10 requires 10^{-4} of failure fraction even under accident conditions, with reference of the design criteria in Germany. Meanwhile, in Japanese design, failure is allowed to extent not to fail remarkably under accident conditions.

The different concept of fuel element caused some other differences of design criteria as mentioned above. In Chinese design, the fuel ball is considered and utilized as structural integrity, therefore, additional performances including mechanical strength and corrosion resistance to the primary coolant are emphasized in the design criteria in addition to the basic requirement of irradiation performance.

However, in Japanese design, the fuel compacts and graphite sleeves or blocks are separated each other, the mechanical strength and corrosion resistance are obtained from the graphite sleeves or blocks, which are not exhibited in the basic design criteria.

2.2 Design Specifications

2.2.1 Design Specifications for UO_2 Kernel

U-content in one particle is determined by the requirement of nuclear reactor core design. Table 1 gives the main design specification of UO_2 kernel in both the HTR-10 and the HTTR, and most of the criteria are quite similar. In order to improve the stress distribution inside the following coating layer, which can seriously influence the failure fraction of coated fuel particles, non-spherical or odd-shaped particles are requested to be removed.

In China, fraction of odd-shaped particles is inspected in addition to sphericity inspection by using vibrating plate and certain specification ($\leq 5 \times 10^{-4}$ See Table.1) exists .

In Japan, all UO_2 kernels are sphericitically selected by vibrating plates after diameterically sieved. Odd-shaped particle is removed by vibrating plates in Japan. Therefore, there is no certain specification on the fraction of the odd-shaped particle in the HTTR.

2.2.2 Design Specifications for Coated Fuel Particles

Although there are many differences between the fuel being developed in pebble-bed reactor core for the HTR-10 and fuel in prismatic core designed for the HTTR, the similar TRISO coated fuel particles are employed in both reactors[8].

Design of coated fuel particles is essentially based on the nuclear design and requirements of irradiation performance. The buffer layer must be porous and low density to provide enough free volume for stable gas fission products and CO gas generated by fission and to attenuate fission recoils and migration stress. It also must have enough safety thickness for the migration distance of the UO_2 kernels during irradiation. The inner PyC layer retains fission gases, mitigates release of other fission products and protects adjacent SiC layer. The SiC layer provides mechanical strength for the particle that undergoes internal pressure induced by fission gases and CO gas from the kernel during irradiation and acts as the primary barrier to the diffusion of metallic fission products. The outer PyC layer protects the internal SiC layer from mechanical failure.

Table 2 lists the design specification of coated fuel particles. It is noteworthy that most of the coated fuel particle layers designed in China are thicker than those designed for the HTTR. This difference is resulted from design parameter of reactor operation conditions. The magnitude of gas fission products is mainly determined by fuel burnup. The average burnup will be ~7% FIMA and the maximum will be ~9% FIMA for the HTR-10 spherical fuel element. Compared with fuel burnup of ~3.6%FIMA in the HTTR, coated fuel particle layer must be thicker to provide more free volume and higher mechanical strength to retain more gas fission products inside the particle.

Both designs do not give exact specification of coating layer failure fraction. Since it is difficult to distribute the contribution to the final failure fraction of fuel element from coating process and from the following pressing process, it is better to regard failure fraction as an important reference inspection rather than a definite design specification during the coating process. The value is good evidence to evaluate feasibility of coating process and empirically should be limited one order below the failure fraction designed for either fuel the HTR-10 spherical fuel element or fuel compact in the HTTR [9].

2.2.3 Design Specifications for Fuel

Differences in the fuel design for the HTR-10 and the HTTR depend on the reactor core design, as known that pebble-bed reactor uses spherical fuel element and hexagonal fuel assembly is used for the prismatic core reactor.

Table 3 and 4 shows the main design specification of the HTR-10 fuel and the HTTR fuel, respectively. Table 3 and 4 show that there are graphite matrix ball specifications in the HTR-10, fuel rod test and fuel assembly specifications in the HTTR.

For the graphite matrix ball, it is served pure graphite ball free from coated fuel particle. As described in section 2.1.3, in the HTR-10 design, it is considered the fuel ball has to have the structural integrity. In the graphite matrix ball, graphite properties have to be assured.

For the defective coated fuel particle, Chinese design uses the specification of total free

uranium fraction to limit the amount of uranium outside an intact SiC coating. The specification of free uranium fraction is 3×10^{-4}, which comprises both the uranium in particles with defective SiC layer and the uranium contamination of the graphite matrix.

On the other hand, Japanese design has two kinds of specifications about defective coated fuel particle. One is the exposed uranium fraction and the other is the SiC-failure fraction, their specifications are $\leq 1.50\times10^{-4}$ and $\leq 1.50\times10^{-3}$, respectively. Exposed uranium fraction is the rate of through-coating failed particles of all the coated fuel particles in one fuel compact. SiC-failure fraction is the same with Chinese total free uranium fraction.

For the effects of the defective fuel particles, it is described in section 5.

3 Fabrication Process

Fabrication technology for fuel element has been established and developed both in China and in Japan, the discrepancy of the fuel concept led to the difference in the fabrication process. Fig.3 shows the fabrication process in China and in Japan and it indicates that separate routes appear after coated fuel particles are prepared. In the HTR-10, the fabrication includes (1) UO_2 preparation, (2) PyC and SiC coating and (3) spherical fuel element manufacture.

In Japan, the fabrication process can be divided into four steps: (1) UO_2 preparation, (2) PyC and SiC coating, (3) fuel compaction and (4) fuel rod making. At last, the fuel rods are inserted into a graphite block to form a fuel assembly before loaded into the reactor core.

The fabrication technology in the HTR-10 and in the HTTR is described below.

3.1 UO_2 Kernel preparation

Sol-gel technology is a promising way to prepare the ceramic UO_2 kernel because of its advantage of high quality of the products and easily controllable component. Sol-gel method is employed both in China and in Japan.

The process to prepare ceramic UO_2 kernel is mainly divided into two sections, which are wet chemical preparation and heat treatment after washing and drying the wet ADU particles. From this viewpoint, almost the same fabrication method is used to produce ceramic UO_2 kernel both in China and in Japan. The only exception is that reducing from UO_3 to UO_2 and sintering in high temperature are combined in Japan while the two steps are implemented separately in China as shown in Fig.4.

Both Chinese and Japanese researchers consider it an important standpoint that the mechanical strength of coated layers of the coated fuel particles strongly depends on uniformity of kernels diameter and sphericity of the kernels[2,4]. Therefore, it is essential to establish suitable fabrication technology in order to obtain kernels with more uniform

diameter and excellent sphericity.

Vibrating nozzles were adopted both in China and in Japan to disperse droplets into ammonia water and to form the wet ADU particles. This kind of wet ADU particle is the basis of UO_2 kernel produced in the following process. Most of the degradation of kernel sphericity is caused by the deformation at the stage of ADU particle formation. The stability of ADU particle formation depends on the physical properties of Sol preparation in the wet chemical process, among which Sol density and viscosity are two most important parameters.

There are two kinds of sol-gel method, internal gelation and external gelation. In Japan, external gelation process is adopted in UO_2 kernel formation process. Additives are used to adjust viscosity of the Sol. Gelation takes place from the surface of particles to the inside when droplets are dispersed into ammonia water and finishes after aging.

In China, the main process is mainly based on gel precipitation method which is well-known used in the production of UO_2 kernels in Germany and belongs to the external gelation method basically, but some modification has been implemented.

In Chinese modification, some additives like urea and HMTA are used. Due to the complex hydrolysis effect of urea and the internal gelation effect of HMTA, it is possible to increase the concentration of uranium, improve heat treatment performance of the xerogel and obtain good sphericity of the UO_2 kernels. So in China this preparation method is called total gelation process of uranium (TGU)[2].

Fig.5 describes Sol preparation step in the kernel fabrication process.

3.2 CVD Process for Coated Particles

The PyC and SiC coatings on the UO_2 kernels are deposited using chemical vapor deposition technology (CVD) in a fluidized bed type of coater by the pyrolytic decomposition of hydrocarbon and methyl-trichloro-silane (MTS) at temperature between 1250 and 1700℃.

At the stage of coating layers around the kernel, failure fraction of coating layers rather than the thickness and density is the most important to ensure the function to retain fission

products inside the particles. One of the reasons leading to the layer failure is mechanical impact against particles during loading and unloading of the particles. From this point, continuous process is an important and effective way to reduce the failure fraction of coated particles and it has been developed both in Japan and in China. Particles with multi-layer around the kernel can be produced, as required, by varying the coating parameters, such as depositing temperature, reactant concentration, gas flow rate and depositing time.

Continuously coating technology is successfully used in the fuel production of the HTR-10 and the HTTR. Generally, the process is almost the same, Fig.6 compares the coating process in China and in Japan and indicates that the main difference between Japanese and Chinese process is the precursor of preparing dense PyC layer.

In Japan, four layers around the kernel are continuously deposited by using mixing gas of acetylene (C_2H_2) and argon for the porous and low-density PyC layer, propylene (C_3H_6) and argon for the second and the fourth dense PyC layers, and mixture of MTS and hydrogen for the deposition of SiC layer, respectively.

In China, 3kg UO_2 kernels per coating batch are put into the graphite reaction tube with diameter of 150 mm. and four layers are deposited according to the process shown in Fig.6. Different from Japanese process, when inner and outer high-density PyC layer deposition is proceeding, the mixture of C_2H_2 and C_3H_6, as well as argon, flows into the fluidized bed coater. The purpose of using mixture of C_2H_2 and C_3H_6 is to maintain constant depositing temperature by counteracting the heat energy absorbed in the pyrolysis reaction of C_3H_6 with the heat energy generated in the pyrolysis reaction of C_2H_2.

Causes of coated layer failure are complicated, for example, random strong collisions between particles during coating introduce imperfections such as flaws into the layers, especially into the SiC layer[3]. To solve this problem, researchers have been focused on optimizing the fluidization conditions by using simulated fluidized bed. Ideal failure fraction level has been obtained after the optimum coating conditions were applied to the coating process of fuel particles loaded both in HTTR fuel assembly and in HTR-10 fuel element.

3.3 Manufacture of Fuel

The different concept of fuel design leads to the difference of manufacture of fuel. Spherical fuel elements were fabricated by the quasi-isostatic pressing technology in China and cylindrical fuel compacts were manufactured by using warm pressing method in Japan. Both fuel elements consist of coated fuel particles and graphite matrix.

Generally, the manufacture process of fuel element is divided into four steps which are (1) graphite powder preparation; (2) overcoating the particles; (3) pressing; and (4) heat treatment. The flow diagram of the process is shown in Fig.7.

Graphite matrix powder can be obtained from mixing natural graphite powder, artificial graphite powder and phenolic binder in the proportion of 64%, 16% and 20%. In China, after mixing the components, the raw materials are processed to resinated powder by means of kneading, drying and grinding. In Japan, fine grinding is used to ensure the quality of the powder. Particle size is an important factor in this powder preparation step.

In the second step, a portion of resinated powder is used to overcoat the coated fuel particles in an overcoating device. The function of this step is to prevent the coated particles from contacting each other so as to decrease the failure fraction during pressing. Due to the nuclear design, in order to ensure the U-content and packing fraction of fuel element, the thickness of overcoating layer should be limited. It is another dangerous case if one overcoated particle contains two or more coated particles. For this reason, overcoated particles must be sieved to proper dimension and odd shaped particles must be sorted by similar method used in kernel and coated fuel particles.

It is from the third step, pressing step, that different process route occurs. In China, quasi-isostatic pressing technology is used and the pressing line consists two parts, pre-press and high-pressure press. A portion of resinated powder is pre-molded together with the overcoated particles to form the spherical fuel zone of the fuel element with the diameter of 50 mm under 50MPa pressure. After formation of fuel zone, the rest of resinated powder is

used with the fuel zone for integral spherical fuel element under about 300MPa pressure.

On the other hand, warm-pressing technology is utilized in Japan to produce cylindrical fuel compact. Certain amount of the overcoated particles for a green compact are weighed by a set of automatic weighing instrument and pre-heated in a furnace to soften the graphite matrix. And then the particles are poured into dies of the warm-pressing machine that is a rotary hydraulic pressing machine with 8 sets of die and punch. After warm-pressing for about 15 minutes, green compacts are taken out to print a serial number and mark the U-235 enrichment. .

The pressing process is carried out automatically and handling robots are introduced to supply the certain amounts of the overcoated particles (and resinated powder in China) during the process both in China and in Japan. The Japanese fabrication flow diagram is shown in Fig.8[8].

It is notable to be pointed out that in order to reduce the pressing-caused failure fraction, the two kinds of pressing process have been adopted for their own advantageous technology. In Japan, warm-pressing and pre-heating the overcoated particles before pressing were used to soften the graphite matrix and decrease the pressing pressure. In Chinese process, silicon rubber stamps were utilized to maintain an isostatic pressure distribution during the pressing process. At mean time, relatively lower volume fraction of coated fuel particles in a fuel element led to possibility to mix resinated graphite powder with the overcoated particles, which efficiently protected the particles from contacting each other. An increased outer diameter of fuel element would reduce the volume fraction of coated particles in a fuel element, but on the other hand, the temperature difference between the surface and the center of the fuel element would increase. This could result in increase of the internal stresses in the fuel element, which is disadvantageous.

In the final step, the pressing products are heated for carbonization at 800℃ in argon atmosphere (in China) or in nitrogen atmosphere (in Japan), then sintered under vacuum in the high temperature furnace to remove the impurities. The sintering temperature is 1950℃ in China and 1800℃ in Japan, respectively.

4 Quality Control Method

In order to ensure that the quality of fuel element can satisfy the design requirement based on the nuclear design and certify irradiation performance during the reactor operation, it is necessary to determine the inspection items, establish the inspection methods and sampling methods. Table 5 and 6 summarize the inspection items, methods and sampling regulation of Japanese HTTR fuel and Chinese HTR-10 spherical fuel element respectively[6,10].

4.1 Inspection Methods

To assure the quality of fuel element, inspection items have been determined according to the demand for irradiation performance, the fuel design and some complementary quality control requirement. All the inspection methods have been established through a lot of research activities for the HTR-10 spherical fuel element and for the HTTR fuel. The quality control and assurance system has been successfully practiced in fuel fabrication for the HTR-10 and the HTTR.

In order to discuss and compare clearly, the following discussion categorizes the inspection items into three groups according to their main purpose of design, (1) compulsory or for demand of irradiation performance, (2) user's requirement or for nuclear design and reactor design requirement and (3) vender's quality control[6].

(1) Compulsory

The following items are selected mainly to certify irradiation performance of the fuel.

(a) Sphericity of the fuel kernel and coated fuel particles

This item is inspected to prevent locally stress on the coating layers during irradiation. Sphericity should be limited less than 1.2 in 95% confidences. In China, not only the sphericity is inspected, but a more rigorous item to limit the fraction of odd shape or non-spherical particles is selected and inspected during the fabrication of HTR-10 fuel.

(b) O/U ratio of fuel kernel

This item should be almost 2.0 to limit the gas release of CO during the irradiation process so as to assure irradiation performance. In Japan, O/U ratio is measured by oxidation and weighing method. In China, the thermo gravimetric method is utilized based on the same principle of oxidation and weighing.

(c) Coating layer density and thickness

Coating layer density and thickness are important to confirm integrity of coated fuel particle during irradiation.

X-ray project or radiograph and sink-float methods are used to inspect the thickness and density of the coating layer during fuel fabrication in both the HTR-10 and the HTTR. For the HTTR, solvent substitution method is also used in measuring density of coating layers.

(d) OPTAF in high density PyC layer

OPTAF in high-density PyC layer should be limited to prevent excessive deformation by fast neutron irradiation. In Japan, OPTAF of the PyC layers is measured by polarization photometer, and optical microscopy method is used in China.

(e) The failure fractions

SiC failure fraction and exposed uranium fraction, which are measured by burning/ acid leaching and deconsolidation/ acid leaching methods, respectively in the HTTR.

In China, a conception of total free uranium fraction is adopted in the fuel element design and applied in the acceptance criteria (pass/ fail) during the fuel element fabrication. However, coated particle failure fraction and matrix uranium contamination are measured separately to confirm validity of the fabrication process, while burning/ acid leaching and acid leaching methods are used, respectively[10].

(f) Graphite matrix density of fuel compact or spherical fuel element

According to the models describing fuel performance under irradiation, this parameter will influence the fractional release from matrix by diffusion, for this reason, the item of graphite matrix density is selected and inspected to assure irradiation performance.

The density of graphite matrix of fuel compact of the HTTR and fuel element of the HTR-10 is measured by weighing and calculating. In the HTR-10 spherical fuel element, it is notable to be pointed out that most of the inspections for fuel element are carried out by measuring a reference graphite ball, which is produced in the same batch and use the fabrication process as the corresponding batch of fuel element.

(2) User's Requirement

The following items are determined mainly by user's requirements depending on the reactor design.

(a) ^{235}U enrichment of fuel kernel

^{235}U enrichment of fuel kernel is inspected to certify nuclear design. It is measured by using mass spectrum-analysis or γ-ray spectrum analysis method.

(b) Kernel diameter and density

Kernel diameter and density are inspected to certify nuclear design. Automatic optical particle size analysis and mercury substitution methods are used in Japan for measuring kernel diameter and density.

In China, kernel diameter is measured by X-ray radiograph and project system, in which a precise measurement projector displays the X-ray film of the kernel and the measured data are collected by a computer automatically. The density of kernel is measured by pycnometer method.

(c) Impurities

Impurities in the fuel kernel and in the fuel element /compact are inspected to certify the nuclear design. Some chemical elements in the kernel should be limited to prevent their reaction with coating layers during irradiation. Some chemical elements in the fuel element should be limited to prevent pollution of the primary coolant, which probably result in corrosion of some component of reactor.

The impurities are inspected mainly by chemical analysis.

(d) The diameter of the coated fuel particle

The diameter of the coated fuel particle is inspected to certify nuclear design. Similar with measurement of diameter of kernel, optical particle size analysis and X-ray radiograph and project methods are adopted in Japan and in China, respectively.

(e) Uranium content

Uranium content in a fuel element/compact is measured to certify nuclear design by calculation method and γ-ray spectrum analysis method in China and Japan, respectively.

(f) Dimension of fuel element

Fuel element/compact dimension is measured to certify thermal-hydraulic design. The inspection is carried out by routine method of micrometer.

(g) Corrosion rate of fuel element

This item of fuel element performance is designed and inspected to certify chemical safety of the HTR-10 spherical fuel element during the service period due to the possible impurities of the coolant gas which covers the fuel element. The corrosion furnace has been developed and used in the measurement of corrosion rate of HTR-10 fuel element.

(h) Mechanical strength of fuel element

The mechanical strength of the HTR-10 fuel element is designed to assure the mechanical safety when the fuel elements frictionize or collide with each other in the pebble-bed or drop into the reactor core again after checking.

A set of special erosion test equipment for the erosion rate measurement of HTR-10 fuel element has been developed. The erosion rate can be obtained after experiment in this equipment and weighing.

A mechanical and pneumatic test rig for the falling strength of HTR-10 fuel element has been developed. The falling strength can be measured and described by the number of drops from the 4-meter-high test rig.

(i) Thermal performance of fuel element

The thermal expansion coefficient of matrix graphite is determined by thermal

expansion gear analysis; the thermal conductivity is measured by laser pulse method.

(3) Vender's Quality Control

In addition to the inspection items determined according to the demand of irradiation performance and user's design requirement, the manufacturer established some inspection items to confirm the validity of manufacture process.

In Japan, appearance of coated fuel particles and fuel compacts are inspected to confirm irradiation performance. Cross section of coated fuel particles and fuel compact are inspected to examine the coating process and compacting process, for the same purpose, strength of coated fuel particle and fuel compact are also measured as reference criteria to assure the validity of coating and compacting process.

In China, free Si content, strength and Young's modulus were inspected by X-ray diffraction method and pressing SiC ring method during the research work of fuel element, but concrete criteria were not designed for acceptance standard (pass/ fail) during the fabrication of HTR-10 Fuel element.

In addition, some inspection items are proposed to examine properties of the raw materials including graphite powder and resinic binder.

4.2 Sampling Methods

Since there is enormous number of coated fuel particles or UO_2 kernels in a production batch, it is impossible to inspect all the particles. However, there are many inspection items aiming at the raw materials, intermediate and final products. Sampling methods must be established to ensure that the sample can make good representation to the production. Sampling includes taking suitable sample size and representative sample.

In Japan, the sampling rate is determined by considering the uniformity of inspection data. Three categories are basically classified as (1) small-scattering data; (2) medium-scattering data and (3) large-scattering data[6]. One sample from an inspection lot is measured for

small-scattering data. For the inspection lot with medium-scattering data, three samples are measured and all of them should satisfy the design requirement. For the case of large-scattering data, sample rate is derived from the point that measured data should meet the design criterion with statistically 95% confidence.

In China, acceptance standards of inspection items are calculated statistically based on the design specification. Some coefficients in the acceptance regulation seem to be different between Chinese design and Japanese design, which caused difference of sampling size, especially in the case of kernel and coated fuel particle with large-scattering inspected data.

Table 5 and Table 6 summarize the inspection items, methods and sampling rate mentioned above for the HTTR and the HTR-10, respectively.

5 Summaries

This paper briefly compared fuel design, fabrication process and quality inspection standards applied in the fuel fabrication of the HTR-10 and the HTTR. Chief differences between Japan and China are as follows.

(1) Pin-in-block type fuel and pebble bed type fuel is adopted for the HTTR and for the HTR-10, respectively.

(2) China requires 10^{-4} of failure fraction even under the accident condition. Meanwhile, in Japanese design, failure is allowed to some extent not to fail remarkably under the accident condition and fuel should be maintained in the graphite block or sleeve.

(3) In China, fraction of odd-shaped particles is inspected and certain specification is fixed. On the other hand, in Japan, there is no certain specification about it.

(4) Coated fuel particles layers except O-PyC designed in China are thicker than those designed for the HTTR. It is because that burnup of HTR-10 fuel will be higher than HTTR fuel.

(5) Pure graphite ball tests are conducted in the HTR-10 different from in the HTTR. It is because that it is considered the fuel ball has to have the structural integrity in HTR-10 design. To satisfy above demands, graphite matrix density, corrosion rate, erosion rate, mechanical strength and thermal conductivity test etc. are done in China.

(6) In the HTTR, UO_2 kernel is fabricated by using conventional external gelation process. Meanwhile, Chinese preparation method is called total gelation process of uranium (TGU). It is added urea and HMTA to dropping liquid in TGU.

(7) When I-PyC and O-PyC deposition is preceding the mixture of C_2H_2 and C_3H_6, as well as argon, flows into the fluidized bed coater in the HTR-10. In the HTTR, C_3H_6+Ar gas is used.

(8) In China, quasi-isostatic pressing technology is used and the pressing line consists two parts, pre-press and high-pressure press. Pre-press and high-pressure press is conducted

to form spherical fuel zone of fuel element and to pile up U-free zone, respectively. On the other hand, in Japan, warm-pressing technology is utilized to produce cylindrical fuel compact.

(9) SiC failure fraction and exposed uranium fraction, which are measured by burning/acid leaching and deconsolidation/acid leaching methods, respectively in the HTTR. Meanwhile in China, only SiC failure fraction is fixed as certain specification.

Acknowledgement

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Table1 Design specification of UO_2 kernel

ITEM	SPECIFICATION	
	HTR-10 in China	HTTR in Japan
Diameter	500±50 μm	600±55 μm (σ ≤25 μm)
Density	≥10.4 g/cm^3	10.63±0.26 g/cm^3
Sphericity	<1.2	<1.2 (for 95% of the total inspection particles)
O/U ratio	≤2.01	$2.00^{+0.01}_{-0.00}$
Fraction of odd-shaped particles	≤5×10^{-4}	

Table 2 Main design specification for coated fuel particles

ITEM		SPECIFICATION	
		HTR-10 in China	HTTR in Japan
Buffer layer	Thickness	95±45 μm	60±12 μm
	Density	≤1.10 g/cm^3	1.10±0.10 g/cm^3
I-PyC layer	Thickness	40±20 μm	30±6 μm
	Density	1.9±0.1 g/cm^3	$1.85^{+0.15}_{-0.10}$ g/cm^3
	OPTAF	≤1.03	≤1.03
SiC layer	Thickness	35±10 μm	25^{+12}_{-0} μm
	Density	≥3.18 g/cm^3	≥3.19 g/cm^3
O-PyC layer	Thickness	40±20 μm	45±6 μm
	Density	1.9±0.1 g/cm^3	$1.85^{+0.15}_{-0.10}$ g/cm^3
	OPTAF	≤1.03	≤1.03

Table 3 Main design specifications of HTR-10 in China

ITEM	SPECIFICATIONS
GRAPHITE MATRIX BALL	
Density	>1.70 g/cm^3
Total ash	≤300 ppm
Li content	≤0.3 ppm
Impurity	≤3.0 ppm
Thermal conductivity	≥0.25 w/cm·K
Corrosion rate	≤1.3 mg/cm^2·h
Erosion rate	≤6 mg/h·FE*
Number of drops	≥50
Breaking loading	18 kN
CTE anisotropy,$\alpha_\perp/\alpha_{/\!/}$	≤1.3
SPHERICAL FUEL ELEMENT	
Diameter	59.6-60.2 mm
Thickness of fuel-free shell	4.0-6.0 mm
U-loading	5.0±0.25 gU/Fuel Element
Free Uranium fraction	≤3×10^{-4}

*FE: Fuel Element

Table 4 Main design specification of HTTR in Japan

FUEL COMPACT	
Size	
Outer diameter	26.0±0.1mm
Inner diameter	10.0±0.1mm
Height	39.0±0.5mm
Matrix Density	1.70±0.05g/cm^3
Particle packing ratio	30±3vol%
O/U	$2.00^{+0.01}_{-0.00}$
Impurity	≤5 ppm
Exposed uranium fraction	≤1.50×10^{-4}
SiC-failure fraction	≤1.50×10^{-3}
Compression strength	≥4900N
FUEL ROD	
U content	188.58±5.66g-U/rod
Total length	577±0.5mm
Number of fuel compacts	14compacts/rod
Stack length	$546^{+5.0}_{-1.0}$mm
Surface contamination	≤0.04Bq/cm^2

Table 5 The inspection item, method and sampling rate in the fuel fabrication for HTTR in JAPAN

Inspection items	Inspection method	Sampling rate
Fuel kernel		
^{235}U enrichment	Mass spectro analysis & γ-ray spectro analysis	1 sample / enrichment
Diameter	Optical particle size analysis	1 sample (100 particles) / Fuel kernel lot
Sphericity	Optical particle size analysis	3 samples (100 particles / sample) / Fuel kernel lot
Density	Mercury substitution	3 samples / Fuel kernel lot
O/U ratio	Oxidation & weighing	1 sample / Fuel kernel lot
Impurities	Emission spectro analysis	1 sample / enrichment
Coated fuel particle		
Layer thickness	X-ray radiograph	1 sample (50 particles) / coating batch
Layer density	Solvent substitution or sink-float	3 samples / coated fuel particle lot
Optical Anisotropy Factor	Polarization photometer	1 sample (5 particles / sample) / enrichment
Diameter	Optical particle size analysis	1 sample (100 particles) / Coated fuel particle lot
Appearance	Visual observation	1 sample (2000 particles) / Coated fuel particle lot
Cross-section	Ceramography	1 sample (20 particles) / Coated fuel particle lot
Sphericity	Selection by vibration table	All coated fuel particles
Strength	Point crushing	30 particles / enrichment
Fuel compact		
^{235}U enrichment	Mass spectro analysis & γ-ray spectro analysis	1 sample / enrichment
U content	γ-ray spectro analysis	All fuel compacts
O/U ratio	Oxidation & weighing	1 sample / Fuel compact lot
Graphite powder	Density, impurities, grain size, water content	1 sample / graphite powder lot
Binder	Contents, ash, melting point, impurities	1 sample / binder lot
Exposed uranium fraction	Deconsolidation & acid leaching	2 samples / Fuel compact lot
SiC-failure fraction	Burn & acid leaching	3 samples / Fuel compact lot
Packing fraction	Weighing & calculation	3 samples / Fuel compact lot
Matrix density	Weighing & calculation	3 samples / Fuel compact lot
Dimensions	Micrometer	All fuel compacts
Appearance	Visual observation	All fuel compacts
Marking	Visual observation	All fuel compacts
Strength	Compression	3 samples / enrichment
Cross section	Ceramography	1 sample / Fuel compact lot
Impurities	Emission spectro analysis	1 sample / enrichment

Table 5 The inspection item, method and sampling rate in the fuel fabrication for HTTR in JAPAN (cont'd).

Inspection items	Method	Sampling rate
Fuel rod		
U content	Calculation	All fuel rods
Total length	Measurement	All fuel rods
Number of fuel compacts	Check of assembling record	All fuel rods
Stack length	Calculation	All fuel rods
Surface contamination	Smear	All fuel rods
Appearance	Visual observation	All fuel rods
^{235}U enrichment	Check of fuel compacts and graphite sleeve marking	All fuel rods
Components	Check of assembling record	All fuel rods
Marking	Check of graphite sleeve marking	All fuel rods
Weight	Weighing	Some fuel rods
Plug seal	Visual observation	All fuel rods
Fuel assembly		
^{235}U enrichment	Check of fuel rods and graphite block marking	All fuel assemblies
Components	Check of assembling record	All fuel assemblies
Appearance	Visual observation	All fuel assemblies
U content	Calculation	All fuel assemblies
Weight	Weighing	All fuel assemblies

Table 6 The inspection item, method and sampling rate in the fuel fabrication for HTR-10 in China

Inspection items	Inspection method	Sampling rate
Fuel kernel		
^{235}U enrichment	Mass spectrometer	3 sample / batch
Diameter	Radiograph and project	1 sample (200 particles) / batch
Sphericity	Image analyzer	1 samples (200 particles / sample) / batch
Density	Pycnometer	1 samples / batch
Fraction of odd shape particle	Vibrating on plate	1 sample(30,000 particles)/batch
O/U ratio	Thermogravimetric method	1 sample (0.2g)/ batch
Impurities	Chemical analysis	1 sample (0.5g)/ batch
Coated fuel particle		
Layer thickness	Radiograph and project	1 sample (200 particles) / batch
Layer density	Sink-float method	1 samples(200 particles) / batch
Optical Anisotropy Factor	Optical microscopy method	1 samples(10 particles) / batch
Diameter	Radiograph and project	1 sample (200 particles)/batch
Appearance	Visual observation	
Microstructure	Ceramography	1 sample (200 particles) / batch
Failure fraction	Burning/ acid leaching	1 sample (25g particles)/batch
Graphite matrix ball		
Density	Weighing and calculation	5 sample / batch
Total ash	Burning and chemical analysis	1 sample / batch
Li content	Burning and chemical analysis	1 sample / batch
Impurity	Burning and chemical analysis	1 sample / batch
Thermal conductivity	Laser pulse method	3 sample / batch
Corrosion rate	Corrosion furnace test/ weighing	3 samples / batch
Erosion rate	Erosion device/ weighing	20 samples / batch
Number of drops	Free dropping device	5 samples / batch
Breaking loading	Pressing device	10 samples / batch
CTE anisotropy,$\alpha_{\perp}/\alpha_{//}$	Thermal expansion analysis	6 sample / batch
Spherical fuel element		
Diameter	Visual observation	All fuel elements
Thickness of fuel-free shell	X-ray project	All fuel elements
U-loading	Calculation	5 sample / batch
U contamination	Acid leaching	2 samples/ batch
Free Uranium fraction	Burning/ acid leaching	2 sample / batch

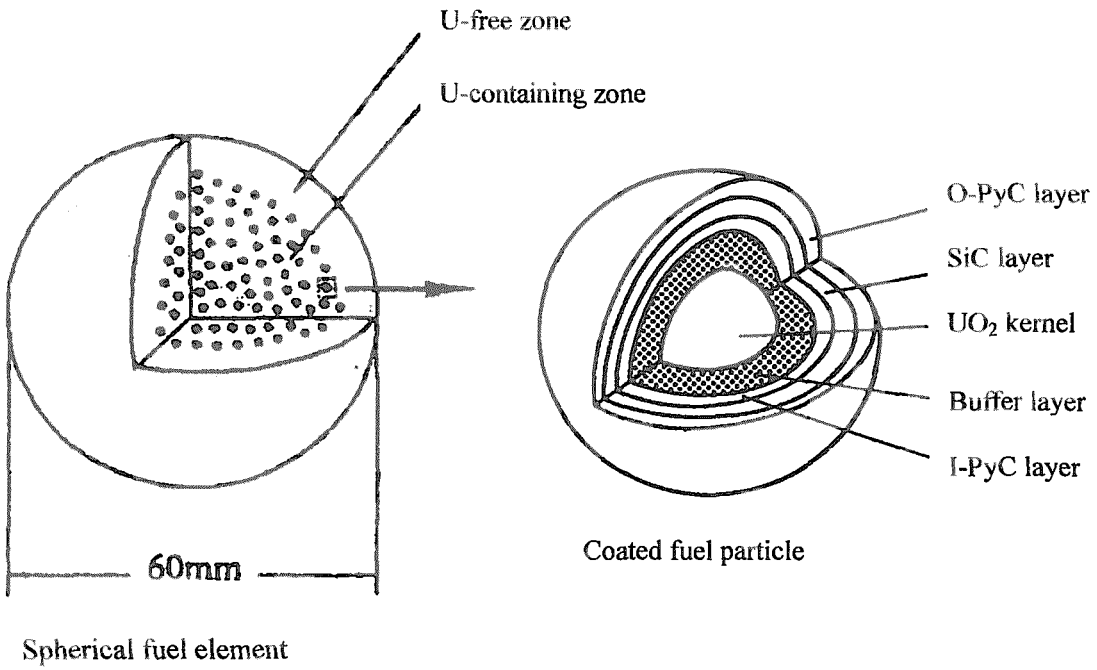

Fig.1 Structure of fuel element of HTR-10 in China

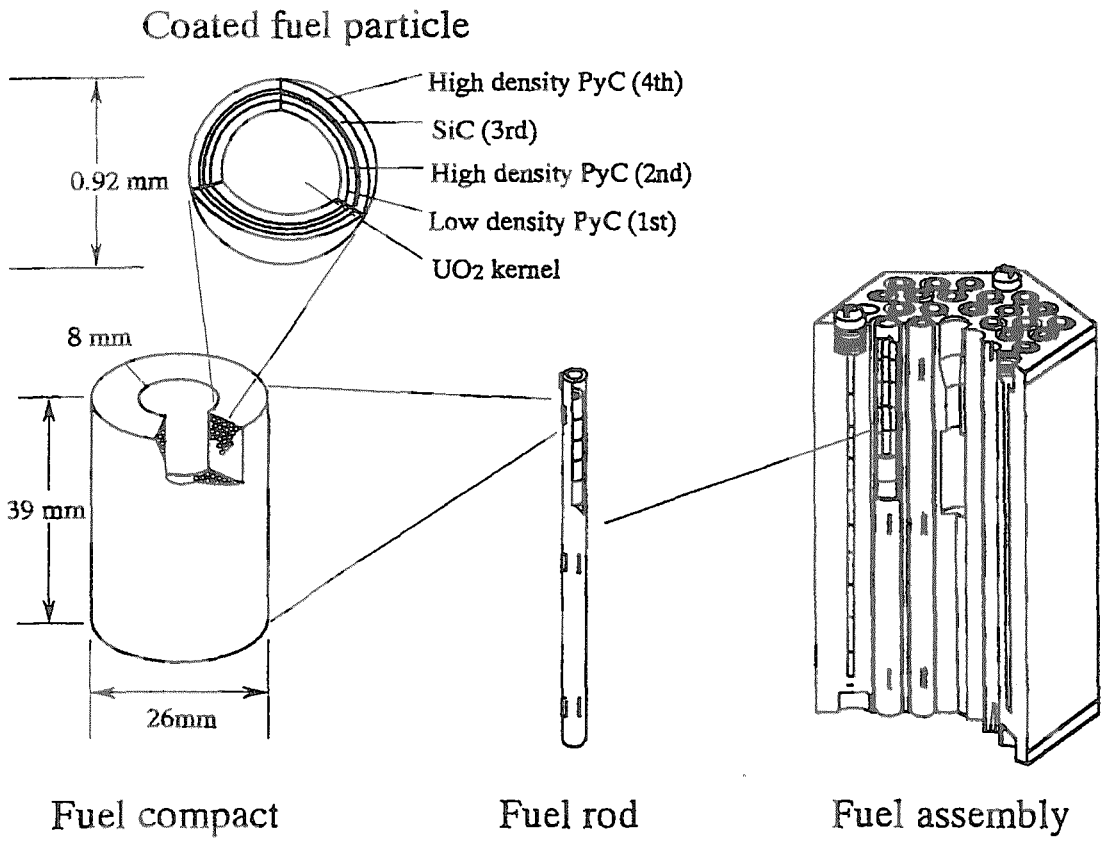

Fig.2 Structure of fuel assembly of HTTR in Japan

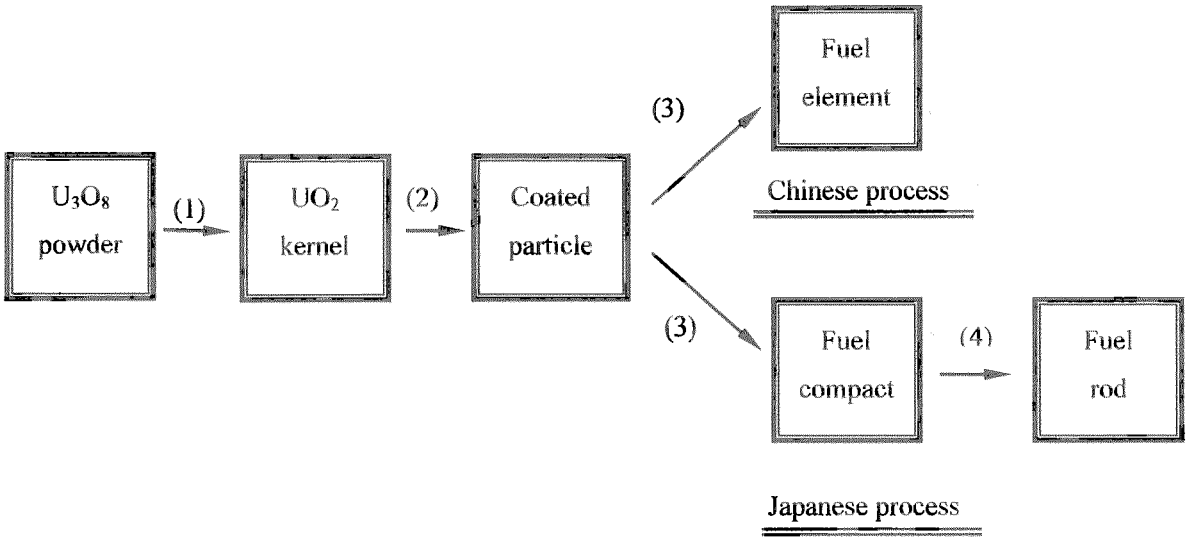

Fig.3 Fuel fabrication process

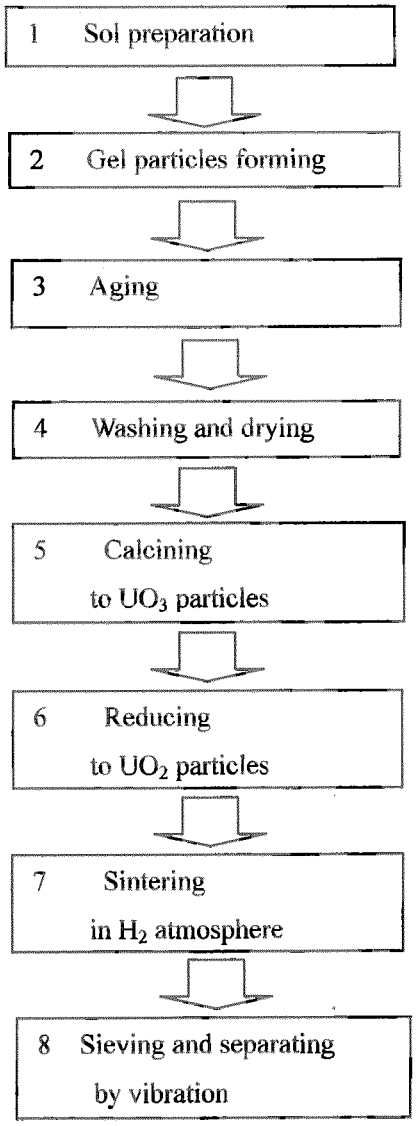

Fig.4 UO_2 kernel preparing process

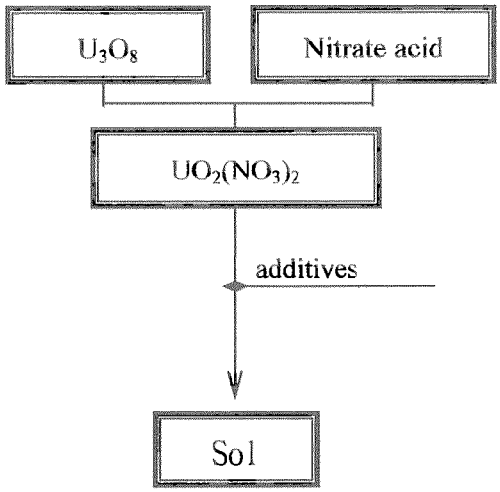

Fig.5 Sol preparation step

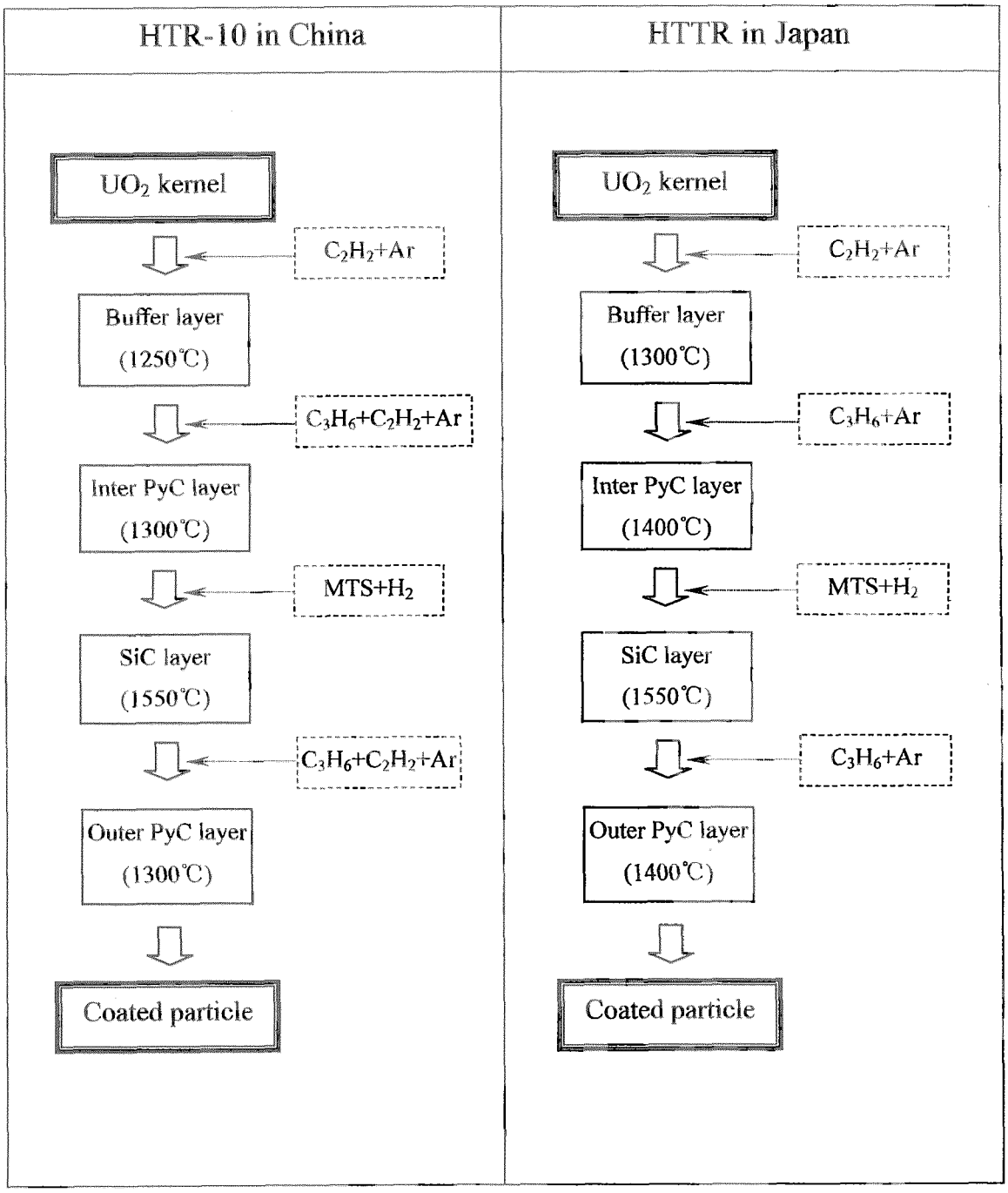

Fig.6 CVD coating process in fuel fabrication

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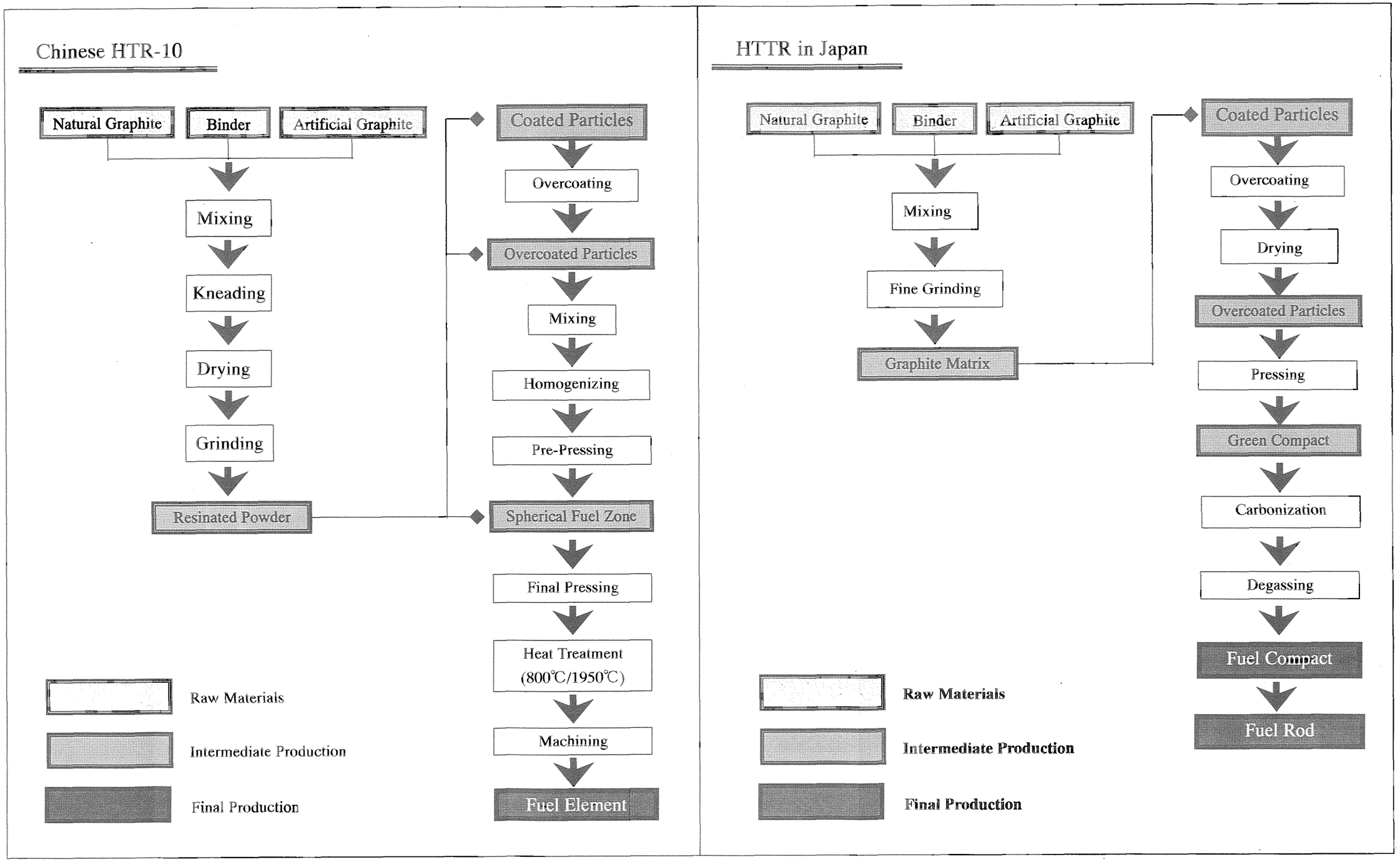

Fig. 7 Manufacture process of fuel

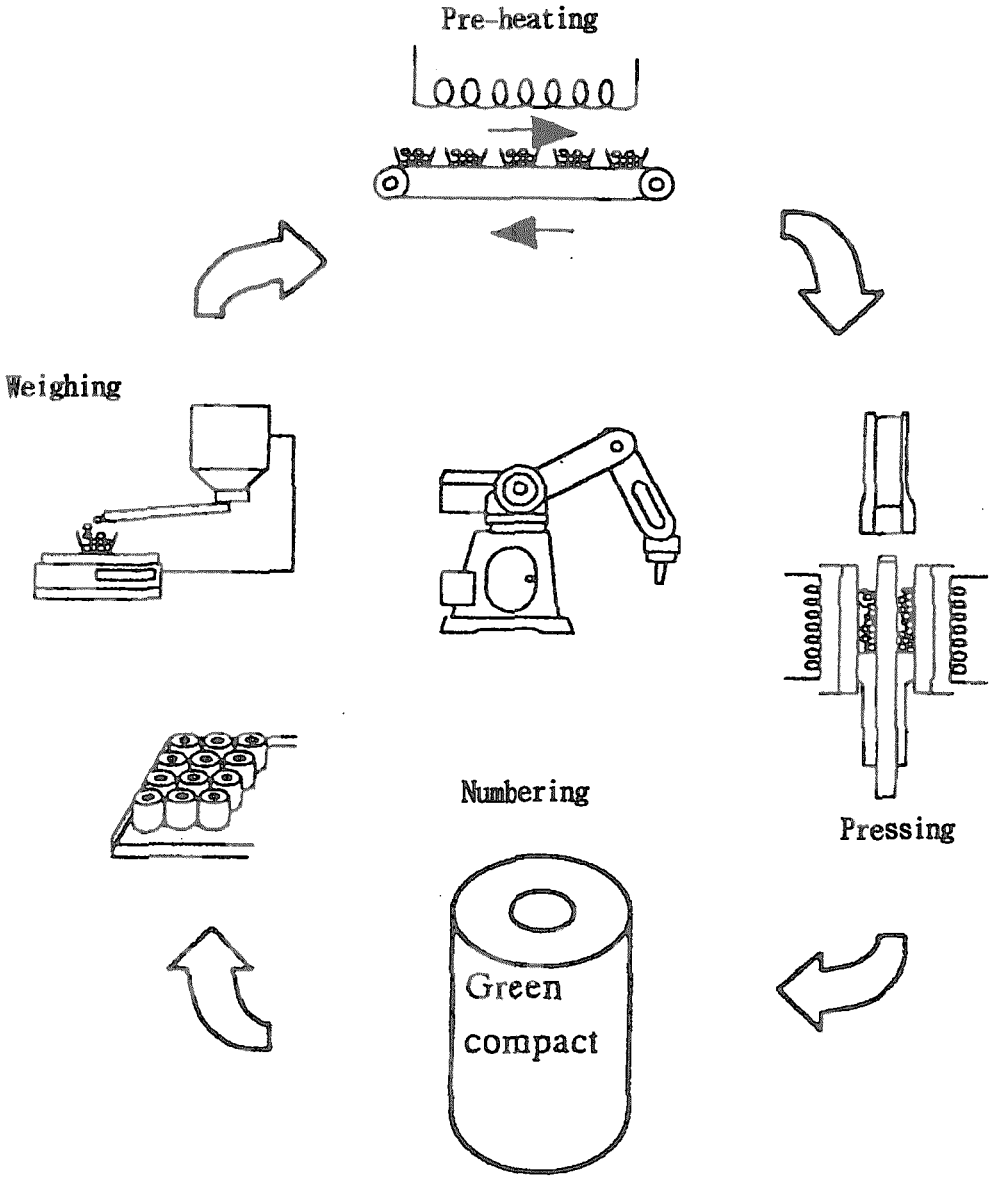

Fig.8 Flow diagram of fuel compacting in Japan

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国際単位系 (SI) と換算表

表1　SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2　SIと併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218 × 10^{-19} J

1 u = 1.66054 × 10^{-27} kg

表3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	m·kg/s^2
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å = 0.1 nm = 10^{-10} m

1 b = 100 fm^2 = 10^{-28} m^2

1 bar = 0.1 MPa = 10^5 Pa

1 Gal = 1 cm/s^2 = 10^{-2} m/s^2

1 Ci = 3.7 × 10^{10} Bq

1 R = 2.58 × 10^{-4} C/kg

1 rad = 1 cGy = 10^{-2} Gy

1 rem = 1 cSv = 10^{-2} Sv

表5　SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5 dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　1 Pa·s(N·s/m^2) = 10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s = 10^4 St(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062 × 10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322 × 10^{-4}	1.35951 × 10^{-3}	1.31579 × 10^{-3}	1	1.93368 × 10^{-2}
	6.89476 × 10^{-3}	7.03070 × 10^{-2}	6.80460 × 10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778 × 10^{-7}	0.238889	9.47813 × 10^{-4}	0.737562	6.24150 × 10^{18}
	9.80665	1	2.72407 × 10^{-6}	2.34270	9.29487 × 10^{-3}	7.23301	6.12082 × 10^{19}
	3.6 × 10^6	3.67098 × 10^5	1	8.59999 × 10^5	3412.13	2.65522 × 10^6	2.24694 × 10^{25}
	4.18605	0.426858	1.16279 × 10^{-6}	1	3.96759 × 10^{-3}	3.08747	2.61272 × 10^{19}
	1055.06	107.586	2.93072 × 10^{-4}	252.042	1	778.172	6.58515 × 10^{21}
	1.35582	0.138255	3.76616 × 10^{-7}	0.323890	1.28506 × 10^{-3}	1	8.46233 × 10^{18}
	1.60218 × 10^{-19}	1.63377 × 10^{-20}	4.45050 × 10^{-26}	3.82743 × 10^{-20}	1.51857 × 10^{-22}	1.18171 × 10^{-19}	1

1 cal = 4.18605 J (計量法)

= 4.184 J (熱化学)

= 4.1855 J (15 °C)

= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)

= 75 kgf·m/s

= 735.499 W

放射能	Bq	Ci
	1	2.70270 × 10^{-11}
	3.7 × 10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58 × 10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

Comparison of HTGR Fuel Design, Manufacture and Quality Control Methods between Japan and China