Study on the Implementation of Quality Assurance Aspect on High-Temperature Gas Cooled Reactor (HTGR)

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Abstract – High-Temperature Gas Cooled Reactor (HTGR) Power Reactors have a layered safety system with the concept of a double barrier system. However, quality assurance is required to ensure the fulfillment of technological analysis weightings on power chamber materials, power ratings, fabrication components of High- Temperature Gas Cooled Reactor (HTGR) fuel elements, primary and secondary coolant pressures to meet customer requirements and be carried out continuously systematic and objective. This study analyzes the application of quality assurance, safety, security, the correctness of test/calibration results, increasing competitiveness, consumer protection and building trust (brand image) in the use of HTGR reactors to provide a reliable level of safety and security. The study method used is based on the literature review. The output of this study is the document of the HTGR reactor quality assurance systems to fulfill the IAEA-TECDOC-1645 requirements according to safety and standardization in frameworks design, material, fuel, and physical properties of the quality management systems. HTGR reactor has technical qualification, good performance of HTGR fuel, safety and accident analysis source term analysis, control of multi-modular HTGR and related human factor analysis, also optimizing radiation protection of HTGR

1. Introduction

Nuclear reactor technology is always evolving to improve the factors in question, namely Quality Assurance (QA) and safety, which will minimize the risks associated with accidents and avoid improvement in the event of an accident. The experience of turning commercial power reactors or nuclear power plants for six decades in 33 countries around the world has occurred 3 (three) major accidents namely the Three Mile Island reactor, United States (radioactive substances are still confined), the Chernobyl reactor, Ukraine and the Fukushima Dai-ichi reactor, Japan. In the last two reactor accidents the release of radioactive substances into the environment. The accident caused human death due to the Chernobyl reactor accident with a total casualty of 56 people [1]. This reflects that the nuclear power plant is a power generation system that has a higher level of security in nuclear reactors.

Based on the Power Reactor Information System (PRIS) provided by the International Atomic Energy Agency (IAEA), at the end of 2018 there were 454 PLTN commercial operations [2]. Of all the NPPs, around 97% are cooling water-based NPPs. The rests are 3 Fast Breeder Reactors (FBR) and 14 Gas Cooled Graphite Moderated Reactors (GCR). The NPP supplies around 298.65 GW of world energy demand [3]. Nuclear reactors are generally designed to have an operating life of around 30 years. Unfortunately, around 63% of them are more than 30 years old whose operations must be immediately extended following the aging management requirements or deactivated and replaced with new ones. But
in the end, there are also nuclear reactors in the world that are operated beyond the design life. This depends on the physical condition and function of each component, system, and reactor structure [4].

As a part of the old NPP replacement and the need of massive energy in some developing country especially in China and India, there are about 56 under construction commercial NPPs around the world that is dominated by water coolant-based reactors [1]. The interesting thing is one of the under-construction reactors are Generation IV nuclear reactor based on High Temperature Gas Cooled Reactor (HTGR) technology that is located in China [5]. HTGR is an advanced development of the Gas Cooled Reactor (GCR) technology. GCR uses carbon dioxide gas as its primary coolant. One disadvantage of carbon dioxide as a coolant is at a relatively high operating temperature. Oxidation of carbon dioxide against moderator graphite can be ruled out only at temperatures below 675°C [6]. At higher temperatures, carbon dioxide undergoes radiolitic oxidation which produces carbon monoxide and attacks graphite so that it has the potential to accelerate the degradation process. Therefore, to produce higher operating temperature around 900°C, HTGR adopts Helium as its coolant. As an inert gas, helium does not react to graphite and other reactor components which make it one of the determinants in their inherent safety concept.

Base on the Generation IV International Forum (GIF) system arrangements and memoranda of understanding as of January 2014, China, Europe Union, France, Japan, South Korea, Switzerland, and the USA are the active countries researching HTGR as the part of Generation IV reactor development [7]. GIF has also agreed on two types of HTGR designs, prismatic and pebble beds as the standard basis of Generation IV HTGR technology. Both HTGR types use Tri-structural-isotropic (TRISO) spherical fuel particle as the smallest part of its fuel component. Graphite is used as the neutron moderator of reflector also has the function as the core structure. Helium gas is chosen as the cooling system because of its inert characteristic that will able to minimize the degradation because of the chemical reaction between core components with the coolant. The aim, however, is to build future nuclear fuel cycles in concert with the aim of the Generation IV International Forum and includes nuclear reactor applications for process heat, hydrogen production, and electricity generation. Moreover, developmental work is ongoing and focuses on the burning of weapon-grade plutonium including civil plutonium and other transuranic elements using the deep-burn concept or inert matrix fuels, especially in HTGR systems in the form of coated particle fuels, which broadly covers several aspects of coated particle fuel technology, namely: manufacture of coated particles, compacts, and elements of quality assurance requirements [7].

Therefore, the study in this paper has been conducted to harmonize the interest of quality assurance in carrying out of the characterization of TRISO coated particles in HTGR systems and comparative study of modular HTGR procedures being implemented in INET Tsinghua University, China and Japan Atomic Energy Agency (JAEA). For that purpose, on the rest of this paper. Section 2 describing the methodology used in this study. Section 3 discussing the study result. And finally, in Section 4 this paper will be closed by the conclusion.

2. Methodology
The methodology used in this paper based on literature review, includes collecting data and information from various libraries, journals and other publications related to the implementation of quality assurance aspects and analyzed using descriptive qualitative analysis methods.

The stages of the literature review are as follows [6]: (1) Organize; i.e., organizing the kinds of literature that will be reviewed. The literatures will be selected based on its relevance with the theme of the literature review. The stages in organizing kinds of literature are identifying the ideas, general purpose, and conclusion of the literature by reading the abstract, some of the introductory paragraph, and its conclusion, as well as grouping the kinds of literature based on certain categories; (2) Synthesize; i.e. combining the result of literature organization into an integrated summary by looking at the intertextuality between the literatures; (3) Identify; i.e. identifying the controversial issues of the literature. Controversial issues are issues that are deemed important to be analyzed to produce an interesting article to read; (4) Formulate; i.e., formulating the findings that require further research
For that purpose, we are doing some stage of study starting from literature study, applying current standards and guidance that usually used for quality assurance requirements, developing new methodology if needed, and finally establishing and proposing the appropriate graded approach for the real graded approach implementation. This paper is part of preliminary study and because of that, the methods used are adopted directly from current IAEA publications, JAEA, INET Tsinghua University as HTGR developers. IAEA has published some standards, guidance and technical report for graded approach purposes. One of that publication is IAEA TECDOC 1645 regarding graded approach for quality assurance requirements for High Temperature Gas Cooled Reactor Fuels and Materials. It would be useful to have a comparative study of QA procedures being implemented in HTGR developers.

3. Result and Discussion

HTGR safety is based on an inherent safety feature that does not have the potential to lead serious radiological hazard if the quality and integrity of inherent safety feature related components are well preserved [4]. The main features of HTGR are enhanced safety, high thermal efficiency, economic competitiveness, and proliferation resistance, and these make this technology a potential candidate for the nuclear power plant deployment. One of the driving forces behind the HTGR philosophy is its utilization in the production of process heat. Net thermal efficiencies greater than 45% are within the reach in some of the designs of HTGR. The foremost motivation for the development of HTGR technology is its enhanced safety features along with its high-temperature capabilities. The enhanced safety of the HTGR fuel is based on its coated fuel particle design consisting of uranium oxide/carbide particles coated with layers of pyrolytic carbon and silicon carbide. Coated particles are so designed that they can withstand high internal gas pressure without releasing any fission products to the environment.

The understanding gained through the quality assurance characterization of TRISO coated particles [8]. The analysis of the quality assurance process schematic for TRISO coating deposition is given in Fig. 1. The four coating layers are deposited on kernels in a heated furnace (see Fig. 2) by a process called chemical vapor deposition (CVD) [8].

![Figure 1. Analysis of quality assurance in coating process [8]](image-url)
As the part of inherent safety feature, TRISO fuel of HTGR consist of low enrichment uranium or plutonium. The fission material is coated by three-layer, high-density Pyrolytic Carbon (PyC), low-density PyC, and Silicon Carbide (SiC) with the size only about 0.9 mm. Low density with high porosity PyC layer able to capture almost all the fission products. The next layers consist of high-density PyC and SiC becomes the next deterrent against the release of fission products [9]. The use of large amounts of graphite material both in the TRISO fuel layer and as a moderator neutron, the reflector, and also the structure gives a negative reactivity coefficient, low power density, and high thermal conductivity characteristics. All of these characteristics cause the reactor temperature to never exceed the predetermined threshold even without inserting the control rod. Although has different core design, both of prismatic and pebble-bed HTGR using similar fuel, moderator, and cooling concepts [10].

The combination of TRISO fuel, graphite moderator, and helium, create an inherent safety design that is the main requirement of the Generation IV nuclear reactor. The similarity and differences between those design furthermore can be seen in Fig.3 [4]. Both prismatic and pebble-bed HTGR use B4C material as their control rod that can be inserted on the hole beside the reflector. In the case of loss
of cooling accident, the core reactor power and temperature will become transient below the safety limit [12]. As the backup, the control rod is possibly needed to return the reactor to normal conditions faster and avoid component degradation due to excessive temperatures exposure. The backup reactivity control of prismatic HTGR is designed based on B4C pellets that can be inserted into the channels bored in the control rod blocks. The pebble bed HTGR be equipped with B4C pebbles that can be inserted as the reactivity control backup system [11].

Quality Assurance, Quality Control, and Testing go hand in hand to ensure the quality of the product and client satisfaction. Quality Assurance is the process by which development and/or production is ‘guided’ to ensure the system will attain the objectives set for it and ensure the quality of the product and client satisfaction. Quality Control is in essence a set of procedures laid down to evaluate a work product. Products are evaluated by testing against stringent specifications whether they are raw materials, intermediate products, or final products. However, The Nuclear industry is far more rigid and stringent in defining its requirements, standards, and specifications as the client always involves the safety of the greater public [8].

Coated fuel particles for development and testing purposes must be manufactured and controlled following a documented QA program that has been established following an appropriate standard, for example, IAEA TECDOC1645, ASME NQA-1 (American Society of Mechanical Engineers - Quality Assurance Requirements for Nuclear Facility Applications) provide for: (a) Product and material specifications to prescribe the technical and quality requirements that must be met; (b) Appropriate sampling procedures and acceptance criteria for determining that the specified values have been met; (c) Performance of work following written manufacturing and test instructions; (d) Calibration and control of measuring and test equipment; (e) Identification and control of materials and product, and (f) Generation of reports following established formats and maintenance of appropriate QA records [8]. Figure 4 contains a list of typical QA-QC tests and the preferred techniques used to diagnose TRISO coated particles. Some of them are (1) TRISO particle size and shape analysis (PSA); (2) Optical anisotropy; (3) Kernel, buffer and layer density determination; (4) Layer thickness determination: Micro-radiography; (5) SiC layer integrity: Burn-leach testing; (6) Thermal conductivity; (7) Elasticity modulus.

Figure 4. List of typical QA-QC tests and the preferred techniques used to diagnose TRISO coated particles
The first type, TRISO particle size and shape analysis (PSA) have the benchmark apparatus for measuring particle diameters (and their associated volumes) for spherical particles in the size range applicable to kernels and coated particles is an automated optical particle analyzer with pneumatic particle transport, custom developed by Seibersdorf for NUKEM. It is a reliable, accurate, and precise method that relies on the intensity dip observed by a detector when a particle passes through a light beam. For spherical particles, it is possible to achieve a linear response between an appropriately defined function of the intensity dip and the particle diameter. Accurate calibration of the system is achieved through standard steel balls. Particles are pneumatically transported, separated, and passed through the light beam where they are counted and measured. Although a maximum rate of about 50 particles per second is achievable, the feed rate is chosen to match the desired accuracy and precision of the application [12], [15].

Table 1. Properties and preferred test of TRISO particle size and shape analysis (PSA) [13], [14], [15]

| Properties                              | Test                                                                 |
|-----------------------------------------|----------------------------------------------------------------------|
| Uranium enrichment                      | Mass spectrometric analysis using thermal ion                        |
| Equivalent boron content (impurities)   | Spectroscopic analysis using plasma source mass spectrometry or emission spectrometry |
| Stoichiometry (O:U ratio)               | Thermo-gravimetric analysis                                          |
| Diameter and sphericity                 | Particle Size Analyzer (PSA) Shadow-scope techniques using an optical microscope and image analysis system |
| Density                                 | Geometrical determination by means of PSA Mass by helium pycnometry or mercury porosimetry |
| Density of buffer layer 95 µm;         | Geometrical determination by means of PSA                           |
| Density of other layers                 | Gradient column (sink- float method)                                |
| Microstructure                          | Microscopy on ceramographic sections                                 |
| Layer thickness and symmetry            | Micro-radiography Ceramography using image analysis techniques       |
| PyC layers                              | Advanced Two-Modulator Generalized Ellipsometry Microscope (2-MGEM) |
| PyC layer: 40 µm; must be impermeable; have an isotropic texture | Burn-leach testing Micro-radiography                               |
| SiC layer integrity β-SiC with a cubic structure; equiaxed microstructure with fine grains and as few flaws as possible |

The second type, Optical anisotropy. Recently, advanced ellipsometry techniques have been applied to the measurement of pyrocarbon anisotropy in TRISO fuels. A system developed by Oak Ridge National Laboratory (ORNL) called the Two-Modulator Generalized Ellipsometry Microscope (2MGEM) was designed to completely determine the polarization effect on light reflected off of a polished pyrocarbon cross-section [16], [17]. This ellipsometer provides a very accurate determination of the pyrocarbon anisotropy with a selectable spatial resolution down to a few micrometers. It is a reliable, accurate, and precise method that relies on the intensity dip observed by a detector when a particle passes through a light beam. For spherical particles, it is possible to achieve a linear response between an appropriately defined function of the intensity dip and the particle diameter.

The third type, Kernel, buffer, and layer density determination Silicon carbide and pyrocarbon (PyC) densities are measured through suitable density gradient columns [18]. A density gradient column is
created by filling a glass column with two liquids of different density, where the ratio of the two liquids is varied during filling to create a linear density gradient as a function of the column height. This linear density gradient is determined by measuring the zero-buoyancy position of calibrated floats. Samples of the Inner-PyC (IPyC), SiC, and outer-PyC (OPyC) layers are obtained by fracturing the coatings of individual TRISO particles.

The fourth type, Layer thickness determination: Micro-radiography Although PSA analysis can be used to derive layer thickness, the method becomes increasingly imprecise for outer layers due to error propagation. To achieve good statistics of intrinsic layer variation over a large number of particles (100 – 200), X-ray microradiography can be utilized [19], [20]. A single layer of particles is positioned directly on the emulsion of a high-resolution photographic film (about 1 µm resolution) and illuminated with an X-ray source approximately 300 mm away.

The fifth type, SiC layer integrity: Burn-leach testing A very important test for SiC layer integrity is the burn-leach test. A representative sample of coated particles of statistically significant size is selected. Under clean laboratory conditions, these are burned down to the SiC layers and the remaining particles and ash are leached under reflux for an extended period in a nitric acid solution. A sample of the liquid is then preconcentrated in a rotary evaporator and analyzed for uranium with an extremely sensitive analytical technique such as fluorimetry, mass spectrometry methods, or delayed neutron counting (after activation in a reactor). When there is no defective SiC coatings, the analytical result reflects the unconfined uranium content. The number of broken particles or defective SiC layers can be calculated after the division of the total concentration by the expected contribution per particle [8].

The sixth type, Thermal conductivity, the most important property for predicting the in-reactor fuel temperature is the thermal conductivity. For the graphite element (compact or sphere) this property can easily be obtained by the conventional laser flash method. The thermal properties of coated particles must also be evaluated to improve the prediction of in-reactor behavior [8]. Thermal characterization applied to dense PyC layers Thermoreflectance microscopy has been applied to characterize dense pyrolytic carbon layers of TRISO particles. Measurements have been performed at room temperature [21], and tests at temperatures of up to 1500°C are currently in progress. Thermal characterization applied to the buffer layer thermal property measurements can be performed at room temperature. The diffusivity obtained for the dense parts of the buffer layer is 5.2 ± 0.5 mm².s⁻¹ [21].

The seventh type, Elasticity modulus Elastic modulus measurements were performed with a Nano indenter NT 600 (Micro Materials Limited) that allows indentation displacement of 50 µm. The penetration of the nondeformable diamond indenter is measured by a capacitive sensor with about 0.01 nm accuracy.

Quality assurance analysis for program Fuel Fabrication Process Improvements: (a) Reduced human interactions in the process: Eliminated tabling with 3D sieving of coated particles, Improved matrix production (dry mixing and jet milling), Improved overcoating with automated fluidized bed overcoater, Multi cavity compacting press with automatic fill; (b) Kernel fabrication: Internal gelation to improve sphericity, Method of carbon addition modified to improve distribution of oxide and carbide phases; (c) Improved chemical vapor deposition process control: Argon dilution during Si-coating, Coater chalice and multiport nozzle to improve process yields (>95%), Mass flow controllers to control gas flows during deposition of each coating layer, improved MTS vaporizer (Si-C layer deposition); (d) Specifications on source materials, production processes and process limits; (e) Specifications on kernel, coating, and compact properties; (f) Specifications on defect populations that may impact performance [22]. Therefore, current Industrial Interest in TRISO-fueled power. HTGR reactor has a technical qualification, good performance of HTGR fuel, safety and accident analysis source term analysis, control of multi-modular HTGR, and related human factor analysis, also optimizing radiation protection of HTGR. The quality control and assurance system have been successfully practiced in fuel fabrication for the HTGR.

In addition, China's long-term development plan of nuclear power, the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University developed and designed a Modular HTGR demonstration plant, named high-temperature gas-cooled reactor pebble bed module (HTR-PM). The
HTR-PM came into the construction phase at the end of 2012. The HTR-PM aims to demonstrate safety, economic potential and modularization technologies towards future commercial applications. Based on experiences obtained from the HTR-PM project with respect to design, manufacture, construction, licensing and project management, a further step aiming to promote commercialization and market applications of the MHTGR is expected. To this purpose, INET is developing a commercialized MHTGR named HTR-PM600 and a conceptual design is under way accordingly. HTR-PM600 is a pebble-bed MHTGR power generation unit with a sixpack of 250MWth reactor modules. The objective is to cogenerate electricity and process heat flexibly and economically in order to meet a variety of market needs. The design of HTR-PM600 closely follows HTR-PM with respect to safety features, system configuration and plant layout. HTR-PM600 will have the six modules feeding one steam turbine to generate electricity with capacity to extract high temperature steam from various interfaces of the turbine for further process heat applications. A standard plant will consist of two HTR-PM600 units. Base on the economic information of HTRPM, a preliminary study is carried out on the economic prospect of HTR-PM600 [23].

The modular high temperature gas-cooled reactor (MHTGR) is an inherently safe nuclear energy technology for efficient electricity generation and process heat applications. The MHTGR is promising in China as it may replace fossil fuels in broader energy markets.

Meanwhile, Progresses in Hydrogen Production and Application for Establishment of Low-carbon Society in Japan. Hydrogen (H2) is expected to be a new energy carrier for independent from dependency on fossil fuels. Hydrogen system driven by high temperature gas cooled reactor (HTGR) of inherent safety reactor is one of practical technologies for establishment of low-carbon society post Fukushima. The high temperature engineering test reactor (HTTR) in Japan Atomic Energy Agency (JAEA) has demonstrated heat output at 950°C which is relatively higher-quality energy than one from other type reactors. For efficient utilization of the high thermal energy, it is useful thermodynamically to be used as a heat source of endothermic chemical reaction. Then, thermochemical hydrogen (H2) production from water by using heat from HTGR is rational way. A thermo-chemical Iodine-Sulfur (IS) process is a process which can produce H2 at less than 900°C in liquid-gas flowing type reactor. The IS process in HTTR demonstrated continuous H2 production of 30 NL/h for a week the world's first in 2004. Establishment of H2 consumption and supply systems is needed for practical H2 energy system. A new energy system of Active Carbon Recycle Energy System (ACRES) driven by HTGR has been proposed as low-carbon energy system. A smart iron making system based on ACRES (iACRES) has been discussed in Iron and Steel Institute of Japan. H2 is important energy material for reduction of carbon dioxide into useful carbon materials in iACRES. Progresses in hydrogen production and application are been expecting for establishment of low-carbon society [23].

4. Conclusions
Quality Assurance, Quality Control, and Testing go hand in hand to ensure the quality of the product and client satisfaction. Specified criteria on both process conditions and fuel properties The main features of HTGR are enhanced safety, high thermal efficiency, economic competitiveness, and proliferation resistance, and these make this technology a potential candidate for the nuclear power plant deployment. Thus, HTGR for quality assurance program cover: (1) Acceptance stages for kernel batches, kernel composites, particle batches, particle composites, and compacts; (2) Specified mean values and/or critical limits on the dispersion for variable properties, such as diameter, stoichiometry, layer thickness, layer density, micro-structure; (3) Specified maximum defect fractions for attribute properties, such as SiC defects, PyC defects, exposed kernel defects.

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