The development of HTGR-TRISO coated fuels in the globe: 
challenging of Indonesia to be an HTGR fuel producer

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Abstract. A first high quality coating TRISO high temperature gas-cooled reactor (HTGR) fuel has been developed since almost six decades ago. After Germany had invented the highly qualified HTR fuel in 2008, China contributed on the fabrication process of tri-structural isotropic (TRISO) UO2 coated fuel particle. Meanwhile, the University of South Carolina (USA) had also developed the design as well as fabrication of an advanced TRISO fuel with ZrC coating, the INET-China conveyed research on the over-coating process in the manufacture of spherical fuel elements for HTGR and invented the friendly-operated equipment to manufacture HTGR fuel mass in 2014. Since HTGR becomes a trend of nuclear technology in the globe, Indonesia is currently conniving a 10 MW experimental power reactor (RDE) which is HTGR type and the program of the RDE was firstly introduced to the Agency for National Development Planning (BAPPENAS) at the beginning of 2014 and the RDE is expected to be operable in 2022/2023. The RDE program is projected to have positive impacts on community prosperity, self-reliance and sovereignty of Indonesia. Since the country has a lot of small islands especially in the eastern part of the country, the small medium HTGR reactors with the power of 5 MWe to 50 MWe will be very suitable to be built in those areas. Among other GEN IV reactor types, HTGR is one of Gen-IV nuclear reactors to be mostly available by 2050 even till 2100. There are few advanced countries to deal with HTGR reactors, so that Indonesia has a very good opportunity to become one of the HTGR reactor producers and even further an HTGR fuel producer in the globe or in ASEAN countries. This paper pronounces the current status of R&Ds on HTGR fuels in the globe as well as that of nuclear technology perspectives till 2100 and policy implications for the global nuclear power industry. Moreover, the paper also showed some countries emerging their new NPPs by 2050. The country through BATAN has showed the long-term plan to treat all low-level radioactive waste resulted both from industries and from the future NPPs. The national capabilities supported by the strategic state-owned enterprises to support nuclear-energy-based industry are also explained. The participation of local industries to reinforce the nuclear-energy-based industry in the country proved more than 40%. Indeed, to become the HTGR fuel producer by 2030 seems much clearer for Indonesia taking into account the strong, legal sustenance from the government.

1. Introduction
The International Generation-IV Initiative was established in 2000 with the aim of fostering the R&D necessary to under the development of a new generation of nuclear energy systems (NES). The Generation-IV consortium seeks to develop a new generation of NES for commercial deployment by
2020–2030 [1]. These systems include both the reactors and their fuel-cycle facilities providing significant improvements in economics, safety, sustainability, and proliferation resistance. The systems selected for development are the very high-temperature gas-cooled reactor (VHTR), the sodium-cooled fast reactor (SFR), the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR) and the super-critical water-cooled reactor (SCWR). The science base for the VHTR and SFR systems is reasonably established although there are gaps and for the VHTR, these include the performance of graphite at high neutron doses, and the performance of the fuel [1].

![Very high temperature reactor (VHTR) (1).](image1)

Figure 1. Very high temperature reactor (VHTR) [1].

A high temperature gas-cooled reactor (HTGR), one of the candidate VHTR types, basically employs two types of fuel assemblies, namely, either prismatic or pebble fuel as presented in the Figure 2. The safety of the HTGR fuel is very significant, so that the fuel fabrication is one of the major concerns to be taken into account. At the beginning of its development, HTGR TRISO fuel was high enriched uranium (HEU) and it has been successfully tested in Material Testing Reactors (MTRs) and in Advanced Very High Temperature Reactor (AVR) under high temperatures condition in Germany [2].

![Schematic of coated fuel particle and fuel element for HTGR (3).](image2)

Figure 2. Schematic of coated fuel particle and fuel element for HTGR [3].

The coated particle, an evolution of HTGR fuel particle, was considered an ever important increasing role in the fission product confinement system to measure fuel properties and coated particle integrity to assure high fuel quality and Germany has successfully developed HTGR fuels, but,
the program of HTGR was discontinued in early 1990s. The technology was then transferred to China and the design of small HTGR called HTR-10 was ascertained [4, 5]. The development of spherical fuel elements for HTR designs was also done in Germany and special attention was given to the development, production and characterizations of kernel and coatings as well as to the post irradiation examination (PIE) of the different coated particle systems [2].

Germany and the United States have shown the irradiation performance of TRISO-coated fuel particle demonstrating gas release values during irradiation and hence concluding the failure mechanisms may be the cause of the poorer US irradiation performance. Republic of Korea (RoK) also successfully acquired the experiments on those in the HANARO research reactor as well as their respective characterizations and relevant quality control methods. This paper describes the results of the further investigation on the status of HTGR-coated fuel in few advanced countries in the globe Ref. [6] to Ref. [42].

The objective of this research is to seek all possibilities for the country, if once time, interested in constructing an HTGR fuel plant. To begin with the assessment, R&Ds on HTGR fuels all over the advanced countries have been assessed, starting from some European countries, South Africa, USA, China, Japan and Korea. As previously mentioned, Indonesia through BATAN and its stakeholders are designing a 10 MW thermal experimental power reactor (RDE), one of the GEN-IV-type reactors. These kinds of varieties of small medium power will be very suitable if those are then operated in the Eastern part of the country. This paper also designates national stakeholders capabilities to participate in nuclear industry, such as, R&Ds implementation of HTGR fuels, uranium exploration programs and plans to treat low level wastes resulted from the future NPPs to be built in the country. Furthermore, to support and thus enhance the research objectives previously mentioned and to refer to the trend of the globe nuclear business in the future, a comprehensive review of the historical reactor technology developments in major nuclear states, namely, USA, Russia, France, Japan, South Korea, India and China is also discussed in this paper. A projection on the future potentials of advanced nuclear reactor technologies, with particular focus on pressurized water reactors (PWR), high temperature and gas cooled reactors (HTGR), and fast breeder reactors (FBR) by 2100 was also pronounced [6]. Finally, all results assessments proved BATAN and the national stakeholders are of course very possible to build the HTGR fuel plant in the country. Since there are currently only few advanced countries to deal with the HTGR reactors, Indonesia has then a very big opportunity to become the HTGR fuel producer in 2030s by taking into account the strong policy, support from the Indonesia government.

2. Methodology

As explained in section 1, the objective of this research paper is to assess the possibility of the country to build the RDE using HTGR fuels in the country. To achieve the previous mentioned objective, the following strategic methodologies are applied:

The first step is to scrutinize the R&Ds on HTGR fuels implemented by few advanced countries to do those research topics previously mentioned. The second step is to cover the national capabilities in the fields of research reactor fuel production, R&Ds on HTGR fuels, uranium and thorium exploration needed to support the operation of the new HTGR fuel plant construction in the future, the completion of Indonesia RDE basic design and the national global plan to treat low-level waste resulted from both industries and the future NPPs in the country.

To deal with the research topic of HTGR fuels, a lot of papers associated with HTGR TRISO-coated fuels were firstly reviewed and appraised in this paper from Ref. [1] to Ref. [42]. The papers are categorized based on the type of the HTGR TRISO-coated-fuel design and fabrication. The paper also investigates the capability of HTGR fuels in terms of R&D time and further improvement [8]. Actually, there is a lot of R&Ds on HTGR fuels instigated in Europe countries, such as, Germany, France, Russia and even the collaboration among some relevant countries to do a joint research collaboration. Firstly, R&Ds on HTGR fuels in the fields of coated particles, fission product, integrity, corrosion, coated layers etc. haven been implemented by the countries previously mentioned. Secondly, those on manufacturing and simulation have been achieved by some Europé countries,
Japan, China and South Africa. Lastly, the R&Ds on quality, transport mechanism of coated fuels, burn-up improvement and kernel characteristics have been performed by Japan and South Africa. All of these R&Ds results on HTGR fuels are explained in detail in section 3.1.

To enhance the plan to build the new HTGR fuel plant in the country, it is mandatory to assess the trend of NPP technology in the world now and the future, at least till year of 2100. This is needed, since there are some NPP technologies currently applied all over the globe, such as, pressurized water reactor (PWR), boiling water reactors (BWR), pressurized heavy water reactor (PHWR) and high temperature and gas cooled reactor (HTGR). In the year of 2030s and beyond, the specific NPP technologies may be applied, such as, fast breeder reactor (FBR), advanced PWR and very high temperature reactor (VHTR or advance HTGR) [1]. Nuclear technology perspectives till 2100 and policy implications for the global nuclear power industry are enlightened in section 3.2 in detail.

From other countries’ experiences, the construction of the first NPPs as well as that of the nuclear fuel plants should take into account not only technical matters, but also national political decision. It is, therefore, some countries, such as, United Kingdom, France, China, Malaysia, Turkey, Switzerland and India, have been taken into account and some of them are very feasible countries to build new and extended NPPs until 2050. This will, indeed, strengthen the plan of the country, not only to build the first NPP, but also to make the new HTGR fuel plant available in the country. The detail explanation of those previous mentioned countries to build NPPs by 2050 can be seen in section 3.2.2.

To build the new HTGR fuel plant in the country, a lot of money and human resources is required. Since the state-owned enterprises are mostly owned by the Indonesia government, their roles dealing with nuclear-energy-based industry are mandatory. It is noted that the detail design of RDE is in progress and to be completed in 2019, so that the RDE construction will then commence and RDE is expected to be operable in 2022/2023. It is also considered participation of local engineering companies achieved at least 40%. It is noted that BATAN and the national stakeholders supported by the foreign vendors had a lot of experiences to build the RSG-GAS nuclear reactor and its supporting laboratories in Serpong from 1982 till 2000. This experience will of course enhance the national stakeholders to build RDE and its HTGR fuel plant to support its RDE daily operation. The detail explanation on this matter is described in section 3.3.

In the following sections, results and discussions covering HTGR fuel R&Ds done by few advanced countries to do these research topics will be elaborated. The national capabilities in the fields of research reactor fuel production, R&Ds on HTGR fuels, the uranium and thorium exploration needed to support the operation of a new HTGR fuel plant construction in the future and other aspects will then be explained as well. The national policies of some countries to utilize nuclear energy by 2050 as well as the strategic state-owned enterprises dealing with nuclear-energy-based industry will also be enlightened. The conclusion can then be seen as the final of this paper.

3. Results and discussions

3.1. R&Ds on HTGR fuels implemented by advanced countries

3.1.1. Europe countries. The development of spherical fuel elements for HTR-designs in Germany had been tremendously amazing since 1960s and in 2002, development of HTGR fuel was also specifically given to the development, production and characterization including kernel and coatings as well as to the irradiation and PIE of the different coated particle systems [9]. In the framework of the French V/HTR fuel development and qualification program, the Commissariat L’Energie Atomique (CEA) and AREVA conducted R&D projects dealing with the mastering of UO$_2$ coated particle and fuel compact fabrication technology. Coated particles and a compacting line based on former CERCA compacting experience have been successfully designed, constructed and even have been in operation since early 2005 at CEA Cadarache and CERCA Romans, respectively [7].

The Cold Finger Apparatus (Kühl/KüFA Finger-Apparatur) in operation at JRC-ITU is designed to experimentally examine the effects of Depressurization and LOss of Forced Circulation (DLOFC) accident scenarios on irradiated HTR fuel pebbles. In inert helium atmosphere, an HTR fuel pebble is
subjected to heating schedules up to 1800 °C for several hundred hours. The analysis of the substances deposited on the plates by means of gamma spectroscopy provided information on the fission product release as a function of time and temperature [10]. NUKEM also implemented the experiments on SiC layers of coating particle to improve the mechanical strengths of this barrier and considerably increase the retention the high quality German LEU TRISO spherical fuel and it has demonstrated the best fission product release rate, particular at high temperatures [11].

In 2013, the German High Temperature Reactor Fuel Development Program successfully developed, licensed and manufactured many thousands of spherical fuel elements that were used to power the experimental AVR reactor and the commercial THTR reactor. The German fuel development program met and exceeded the challenges on manufacturing and qualifying the low-enriched UO₂ TRISO-fuel system for HTR systems with steam generation, gas-turbine systems and very high temperature process heat applications [12].

Various countries engaged in the development and fabrication of modern HTGR and within the European irradiation testing program for HTGR fuel and as part of the former EU RAPHAEL project, the HFR-EU1 irradiation experiment explores the potential for high performance of the presently existing German and newly produced Chinese (HTR-PM) fuel spheres under defined conditions up to high burn-ups. For comparison, a single defective or failed particle of R/B (⁸⁵Kr) of 5.4 × 10⁻³ at 1000 °C (INET fuel) and 8.4 × 10⁻³ at 1100 °C (AVR fuel). For particle failure, those are one particle failure of 2×8,500 INET particles and 3×9,500 AVR particles respectively.

In addition, the European HTR R&D project Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D (ARCHER) builds on a solid HTR technology foundation in Europe, established through former national UK and German HTR programs. In line with the R&D and deployment strategy of the European Sustainable Nuclear Energy Technology Platform (SNETP), ARCHER contributes to maintaining, strengthening and expanding the HTR knowledge base in Europe to lay the foundations for demonstration of nuclear cogeneration with HTR systems [13].

3.1.2. South Africa. The PBMR (pebble bed modular reactor), as seen in Figure 3, is a particular design of pebble bed modular reactor under development by South African company PBMR (Pty) Ltd since 1994 [14]. Firstly, the PBMR is characterized by inherent safety features, and the heat from the PBMR can be used for a variety of industrial process applications, including process steam for cogeneration applications, in-situ oil sands recovery, ethanol applications, refinery and petrochemical application [15]. Secondly, based on Ref. [16], the influence of deposition temperature, methyl trichlorosilane (MTS) concentration, hydrogen carrier-gas flow rate and gas inlet design on the strength of silicon carbide coated TRISO particles was investigated using whole particle crushing strength. Crush strength was measured using soft aluminum anvils and for comparison, a selection of particles was also measured with hard anvils. It proved that the strength of the underlying pyro-carbon coated particles had a significant influence on the crush strength of the silicon carbide coated particles. Deposition temperature and gas inlet design are indeed the only process parameters that influenced the coated particle crush strength.
Lastly, in Ref. [18], transport of $^{110m}$Ag in the intact SiC layer of TRISO coated particles has been studied for approximately 30 years without arriving at a satisfactory explanation of the transport mechanism. The possible mechanisms postulated in previous experimental studies, both in-reactor and out-of-reactor research environment studies are critically reviewed and of particular interest are relevance to very high temperature gas reactor (VHTR) operating and accident conditions. It is proved that among the factors thought to influence Ag transport are grain boundary stoichiometry, SiC grain size and shape, the presence of free silicon, nano-cracks, thermal decomposition, palladium attack, transmutation products, layer thinning and coated particle shape.

From all information earned and explained previously, the PBMR has been prevented by the Government of South Africa due to national budget short cut, so that the PBMR experts all over in the country may not be then involved in further implementing the HTGR fuel research activities as many as the other countries do. However, their expertise on HTGR fuel research be utilized through a state-to-state joint research collaboration.

3.1.3. People’s Republic of China, Japan and Republic of Korea. As previously mentioned, a Very High Temperature Reactor (VHTR) has been evaluated highly worldwide since 2010s, and is a principal candidate for the Generation IV reactor systems. In Japan, HTGR fuel fabrication technologies have been developed through the HTTR project in JAEA since 1960’s. The total of 2 tons of uranium of the HTTR fuel has been fabricated successfully and performed excellent through the long-term high temperature operation. Furthermore, SiC TRISO fuel has also been successfully developed for burn-up extension targeted VHTR and ZrC-TRISO coated fuel is as an advanced fuel design [19].

The TRISO-coated fuel particle mixed with graphite for the high temperature gas-cooled reactor (HTGR) is composed of a nuclear fuel kernel and outer coating layers. The weight of fuel kernels contained in the element is one of the important items for evaluating the characteristics of fuel element. The three-dimensional (3D) density information is acquired by the X-ray CT for a simulated compact including simulated TRISO-coated particles with ZrO$_2$ kernels. The weight of kernels and the average of it in the simulated compact was amazingly calculated from the volume of kernels and the average density of kernels [20].

It is noted that China obtained the pressure signals in the coating furnace experimentally from the TRISO UO$_2$ coated fuel particle fabrication process and during the coating process, those are analyzed and a simplified relationship about the pressure drop change due to the coated layer was proposed based on the spouted bed hydrodynamics. It was proved the pressure signals analysis was an effective method in the coating process at high temperature up to 1600$^\circ$C [21]. The coating system of coated fuel particles kept intact below 1600 $^\circ$C and under normal operation temperature, thermal decomposition is not an important contributor to the fuel failure.
The spherical fuel elements were successfully manufactured in the period of China HTR-10 and the optimized fuel elements manufacturing process met the requirements of design specifications of spherical fuel elements for HTR-PM of 200 MW by developing the new over-coater system and its corresponding parameters exhibited good stability and high efficiency in the preparation of over-coated particles. The system not only reduced the carbonization time from more than 70 h to 20 h, but also improved the manufacturing efficiency [7]. Spherical fuel elements technology is a main innovation of HTGRs, which effectively improves the safety of the reactors for higher stability at high temperature, and their quality is crucial for the safety and reliability of high temperature digital radiographies (HTDRs) [22]. For fast and accurate detection of escaped coated fuel particles, X-ray DR (digital radiography) imaging with a step-by-step circular scanning trajectory was adopted for Chinese 10 MW HTGRs. A dynamic calibration method for accurate tracking the projection of the fuel-free zone, instead of using a fuel-free zone mask of fixed size and position, was successfully adopted to recognize escaped coated fuel particles, and some practical inspection results [23].

High temperature oxidation behavior of SiC coatings in TRISO coated particles is crucial to the in-pile safety of fuel particles for an HTGR. Oxidation tests of SiC coatings, by assuming the postulated accident condition of air ingress, were carried out in the ranges of temperature between 800 and 1600°C and time between 1 and 48 h in air atmosphere. Carbon was detected by Raman [24]. Due to the commercial HTGR development, higher requirements for mass production of over-coated particles for fuel elements were taken into account. The experiments using optimized parameters showed that the yield is high and stable and the average yield reached 93.94% and the over-coating equipment satisfying the mass production is also easy to operation and control [25].

TRISO particle has been successful in HTGR, but an improved design is required for future development. The coating layers are reconsidered, and an improved design of TRISO particle with porous SiC inner layer is proposed. Three methods of preparing the porous SiC layer, called high methyltrichlorosilane (MTS) concentration method, high Ar concentration method and hexamethyldisilane (HMDS) method, are experimentally implemented. The porous SiC layer was successfully prepared and the density of SiC layer had been adjusted by tuning the preparation parameters. By using SEM, XRD, Raman scattering and EDX (energy X-ray analysis), the improved TRISO coated particle with porous SiC layer can be mass successfully produced [26].

To face a commercially HTGR in the future, after the first concrete was poured on December 9, 2012 at the Shidao Bay site in Rongcheng, Shandong Province, China, the construction of the reactor building for the world’s first HTR-PM demonstration power plant was completed in June, 2015. Installation of the main equipment then began, and the power plant is currently progressing well toward connecting to the grid at the end of 2017 and it is expected that the connecting to the grid will be considered at the end of 2018. Due to China’s industrial capability, great difficulties, manufacture first-of-a-kind equipment, and series of major technological innovations have been successfully overcome. The successful results in many aspects, including planning and implementing R&D, establishing an industrial partnership, manufacturing equipment, fuel production, licensing, site preparation, and balancing safety and economics have been achieved and hence these obtained experiences may also be referenced by the global nuclear community [27].

To investigate the potential HTGRs for transmutation of long-lived fission products (LLFPs), numerical simulation of four types of HTGRs was carried out. In addition to the gas-turbine high temperature reactor system “GTHTR300”, which is the subject of the previous research, a small modular HTGR plant “HTR50S” and two types of plutonium burner HTGRs “Clean Burn with MA” and “Clean Burn without MA” were taken into account. The results showed that an early realization of LLFP transmutation using a compact HTGR is possible since the HTR50S can transmute fair amount of LLFPs for its thermal output. The Clean Burn with MA can transmute a limited amount of LLFPs, but, an efficient LLFP transmutation using the Clean Burn without MA seems to be convincing, since it is able to achieve very high burn-ups and to produce LLFP transmutation more than GTHTR300 [28].
The thermal conductivity of SiC ceramics and fully ceramic microencapsulated (FCM) fuel composites, consisting of a SiC matrix and TRISO coated particles, was measured and analyzed. SiC ceramics and FCM pellets were fabricated by hot press sintering with Al₂O₃ and Y₂O₃ sintering additives. Several factors that influence thermal conductivity, specifically the content of sintering additives for SiC ceramics and the volume fraction of TRISO particles and the matrix thermal conductivity of FCM pellets, were investigated. The thermal conductivity of FCM pellets in various sintering conditions was in close agreement to that predicted by the Maxwell-Eucken equation with the fitted thermal conductivity value of TRISO particles [29].

In ref [30], it was investigated the dispersibility of carbon in carbon contained ammonium diuranate (C-ADU) gel particles and the characteristics of C-ADU gel liquid droplets produced by the vibrating nozzle and integrated aging-washing-drying equipment. The those two are needed to be easily for HTGR fuel fabrication. Furthermore, the excellent stability of carbon dispersion was only observed in the C-ADU gel particle that contained carbon black named CB 10. ADU gel liquid droplets containing carbon particles with the excellent sphericity of approximately 1,950 mm were then obtained using an 80-100 Hz vibrating nozzle system.

From all enlightened earlier, the TRISO particle, the standard US LEU UCO particle with the SiC layer substituted by a ZrC layer, was used to further investigate and hence becoming advanced candidate of HTGR coated fuel particle in the future. All R&D activities on the previous matter are very spread out all over the countries, such as, People’s Republic of China, Japan and Republic of Korea, since they are the members of GIF (Gen IV Industrial Forum) which are, for the time being, developing the future nuclear power system to support not only the world’s energy need, but also heat application for industry. The success of producing commercial HTGR fuels as well as that of the R&Ds on HTGR fuel should be further developed. The collaboration among China, Japan, Korea and the other related countries will totally inspire to establish such an advanced HTGR coated fuel in the near future.

3.1.4. Unites States of America. The additional ZrC layer acts as an oxygen getter to prevent typical TRISO failure mechanisms including over pressurization of the particle and kernel migration of the kernel within the particle, also known as the amoeba effect, and the ZrC layer was confirmed through X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS) [31]. The extent and nature of the chemical interaction between the outermost coating layer of coated fuel particles embedded in zirconium metal during fabrication of metal matrix microencapsulated fuels indeed took place. ZrC–Zr interaction was the least substantial, while the PyC–Zr reaction can be exploited to produce a ZrC layer at the interface in an in situ manner. The thickness of the ZrC layer in the latter case can be controlled by adjusting the time and temperature during processing. The kinetics of ZrC layer growth is significantly faster from what is predicted using literature carbon diffusivity data in ZrC [32].

Three TRISO fuel composites from the AGR-1 irradiation experiment were subjected to safety tests at 1600 and 1800 °C for approximately 300 h to evaluate the fission product retention characteristics. Measurable release of silver from intact particles appears to become apparent only after around 60 h at 1800 °C. The release rate for europium and strontium was nearly constant for 300 h at 1600 °C (reaching maximum values of approximately 2x10⁻³and 8x10⁻⁴ respectively), and at this temperature the release may be mostly limited to inventory in the compact matrix and OPyC prior to the safety test. Indeed, the krypton and cesium release fractions remained less than approximately 10⁻³ after 277 h at 1800 °C [33].

High-temperature oxidation behavior of SiC coating layer of TRISO fuel particles in 1500–1700 °C steam at 1 atm has been examined inside a zirconia furnace. The SiC coating layers experienced a thickness loss of less than 2.5 μm under these conditions up to 24 h. The thickness of the oxide layer formed under these conditions was consistent with prior steam oxidation tests on high-purity bulk SiC. Upon reducing the presence volatile impurities from the test environment (particularly Al) by conducting the tests inside a zirconia furnace, melting of the silica layer at 1700 °C was avoided [34]. Referred to [35], TRISO-coated particle fuel has been fabricated and tested around the world and a
review of the fuel performance database indicated that high-quality low-defect TRISO fuel, the heart of the high-temperature gas-cooled reactor, is achievable.

Generally, there are changes in coating morphology dominated by the behavior of the buffer and inner pyrolytic carbon (IPyC), and infrequently observed SiC layer damage was usually related to cracks in the IPyC. Palladium attack of the SiC layer was relatively minor, except for the particles that released cesium during irradiation, where SiC corrosion was found adjacent to IPyC cracks [36]. TRISO coated particle fuel is a promising fuel form for advanced reactor concepts such as HTGR and is being developed domestically under the US Department of Energy’s Nuclear Reactor Technologies Initiative in support of Advanced Reactor Technologies. The fuel development and qualification plan includes a series of fuel irradiations to demonstrate fuel performance from the laboratory to commercial scale [37].

Recent post-irradiation-examination from the German AVR and Advanced Gas Reactor Fuel Development and Qualification Project have shown that $^{110m}$Ag is released from intact TRISO fuel. It is the fact that Ag was first identified in the SiC layer of a neutron-irradiated TRISO fuel particle. The existence of Pd- and Ag-rich grain boundary precipitates, triple junction precipitates, and Pdnano-sized intragranular precipitates in neutron-irradiated TRISO particle coatings was investigated using Scanning Transmission Electron Microscopy and Energy Dispersive Spectroscopy (STEM-EDS) analysis to obtain more information on the chemical composition of the fission product precipitates. Preliminary semi-quantitative analysis indicated the micron-sized precipitates to be Pd$_2$Si$_2$U with carbon existing inside these precipitates and nano-sized precipitates may be influenced by the SiC matrix [38].

From all enlightenments previously mentioned, it is summarized that the advanced HTGR coated-fuel is to be implemented in the near future. However, due to challenging of time consuming and a lot of aspects to be investigated, the HTGR coated-fuel researchers in the global region are still requested to develop a joint research collaboration among the related countries and the Agency.

3.2. Future nuclear energy technology and policies to utilize NPPs
3.2.1. Future nuclear technology. There have been two completed phases of developments in nuclear reactor technologies. The first phase is the demonstration of exploratory Generation I reactors. The second phase is the rapid scale-up of Generation II reactors in North America and Western Europe followed by East Asia. We are in the third phase, which is the construction of evolutionary Generation III/III+ reactors. Driven by the need for safer and more affordable nuclear reactors post-Fukushima, the nuclear industry has, in parallel, entered the fourth phase, which is the development of innovative Generation IV reactors [6]. The reactor types of Generation IV has been clearly described in Ref. [1].

Through a comprehensive review of the historical reactor technology developments in major nuclear states, namely, USA, Russia, France, Japan, South Korea, and China, based on [6], a projection on the future potentials of advanced reactor technologies, with particular focus on pressurized water reactors, high temperature reactors, and fast reactors by 2100 is presented. Cumulative reactor power (in red) in the countries previously mentioned can be seen in Figure 4 and the trends increase. The projected potentials provide alternative scenarios to develop insights that complement the established technology roadmaps. Findings suggest that there is no clear winner among these technologies, but fast reactors could demonstrate a new and important decision factor for emerging markets. Findings also suggest small modular reactors, especially those belonging to Generation IV, as a transitional technology for developing domestic market and indigenous technology competence for emerging nuclear states. With reference to the East Asian experience in developing nuclear competence, participation with international cooperation in the research and development of Generation IV and nuclear fusion reactor systems could demonstrate strategic entry points for countries with a long-term plan to derive indigenous nuclear reactor technologies.

Referring to [39] and to maximize the use of new and renewable (NRE) energies, Indonesia predicted nuclear power plant (NPP) to be constructed in the country till 2050. For the first time, the country will have a couple of NPPs in 2027 with the powers of 2,000 MW or 2 x 1,000 MW in Java.
Madura Bali (JAMALI) electricity grid and it is understood since most of industries are available in Java. Furthermore, by 2031, a couple of NPPs (2 x 1000 MW) will be operable in Sumatera, the second biggest island in the country. At the same time, Kalimantan, the biggest island in the country, will have a small medium NPP with the power of 100 MW due to the growth of industry in Kalimantan not as fast as that in Java. For islands other than previously mentioned, NPPs with the power of less than 40 MW would be available in those areas. The HTGRs which have the power between 20 MW to 50 MW are to be suitable in those areas. The detail prediction of NPPs all over the country can be clearly seen in Ref. [39].

![Figure 4](image)

**Figure 4.** Cumulative reactor power in Russia (RU), United Kingdom (GB), USA (US), France (FR), Canada (CA), Germany (DE), Japan (JP), India (IN), South Korea (KR), and China (CN) and the resulting cumulative number of reactors added by these countries [6].

As previously mentioned, Figure 4 shows the cumulative reactor powers in Europe countries (Russia, United Kingdom, France, Germany), USA, Canada and Asian countries (China, India, Japan and South Korea). From the Figure, it is definitely clear that the trend of NPPs construction is continuously increased due to contribution of China to construct NPPs till 2050 [40] although they just started to construct NPPs around 1985, the latest country compared to the others.
Now, it is very apparent that the development of HTGR in the globe was not as fast as PWRs and BWRs and as Figure 5 shown, the era of HTGR actually started from the very beginning in the Republic of Germany in 1950s [2] and ended in 1980s. Since the Germany did not continue the HTGR type reactor at that time, the HTGR technology was then transferred to China and they were succesfull to develop and construct HTR-10 in 2001. Again, they were finally successfully to start the construction of a couple of HTR-PM (HTR-pebble bed module) 200 MW in 2012. Actually, they plan to connect the HTR-PM to the China electricity grid in 2018 [27]. Once they are to succeed the operation of HTR-PM 200 MW in 2018, they are currently planning to build the other six HTR-PM reactors with the power of each 200 MW and those will be built in the eastern part of China.

3.2.2. Policies of countries to utilize nuclear energy. China focuses on the use of new and renewable energies and based on [41], China is the world's largest emitter of greenhouse gases and consumes the world's largest quantity of energy with 67% of the primary energy consumption and 73% of electricity generation from coal. China has been actively developing renewable energy since the year 2000 and has made rapid progress (with an average annual growth rate of 62.5% over the past decade). China plans to achieve 16% renewables by 2030 and aggressive studies reveal that China should be able to reach 26% and 60% renewable energy by 2030 and 2050 respectively, and hence achieving 86% renewable electricity by 2050.

Referring to [42], the UK electricity sector is undergoing a transition driven by domestic and regional climate change and environmental policies. Aging electricity generating infrastructure is set to affect capacity margins after 2015. The future development of the UK electricity generation sector has motivated a study which aims to develop a policy-informed optimal electricity generation scenario to assess the sector's transition to 2050. The study analyses the level of deployment of electricity generating technologies in line with the 80% by 2050 emission target. The study focused on the least-cost electricity generation portfolio, emission intensity, and total investment required. A carbon neutral electricity sector is feasible if low-carbon technologies are deployed on a large scale.

Based on [43], Turkey studied for the first time a life cycle environmental, economic and social sustainability assessment of future electricity scenarios for Turkey up to 2050. Fourteen scenarios have been developed and assessed for 19 sustainability indicators, using multi-criteria decision analysis (MCDA) to help identify the most sustainable scenarios including the global warming potential (GWP) which increases up to four times on today's impact. MCDA shows that renewable and nuclear intensive scenarios outperform those dominated by fossil fuels, except for the very high preference for
the economic criteria. The renewable–nuclear intensive scenarios are the most sustainable options with respect to most of the environmental, economic and social impacts considered.

Referring to [44], it was evaluated the feasibility of future electricity scenarios drawn in the Swiss Energy Strategy 2050. These scenarios are characterized by a nuclear phase-out and high shares of renewables. It was used Calliope, a linear programming model, special to model transition to renewables. Results show that it will be impossible to cover future demand only with domestic production, even if Switzerland reduces the consumption as envisaged. The daily profile of solar and limited capacity of wind lead to scenarios with maximum generation during peak hours. Moreover, it was found a need to rearrange generation by flexible technologies to cover future demand.

India gives a summary of the developments carried out for over four and a half decade in the field of nuclear fuel fabrication for power reactors in India [45]. The facility at Nuclear Fuel Complex (NFC) is unique in the world with fully integrated manufacturing of fuel and core structural for the Pressurized Heavy Water Reactors (PHWRs), Boiling Water Reactor (BWR) and Fast Breeder Reactors (FBRs) operating in India. The integrated processing starts with the ore which is processed through several intermediate products to the finished fuel assemblies and several core structures. It showed automation and advanced quality control methods used in the production line for capacity building to meet the enhanced fuel requirement as well as the future expansion program for fuel fabrication for enhancing the installed capacity of nuclear energy in India.

Based on [46], the Malaysian Government has been introducing fuel diversification policies over the past decade by considering other sources of fuel such as alternative and renewables into the electricity mix as a measure to lengthen the oil and gas reserves against premature depletion. An analysis of district heating networks are commonly addressed in the literature as one of the most effective solutions for decreasing the long-term power generation options for Malaysia by deploying the integrated MARKAL-EFOM system (TIMES) model. The results indicated that Malaysia has sufficient renewable prolonging the investment return period of energy resources to meet the projected electricity demand by 2050 and fossil fuels can be fully replaced with electricity sourced. By sustainable policy, nuclear power would then not be an ideal option as uranium fuel relies on continuous imports.

Based on [47], it is said that nuclear power is an important technology in the global electricity mix, comprising a share of 11% of global power generation. Its contribution to electricity generation is currently substantially higher in OECD countries (18% versus 4% in non-OECD countries), where nuclear power has been widely deployed since the 1960s in an effort to reduce the import dependency on fossil fuels, diversify the power mix and reduce power system costs. Despite its potential to contribute to the de-carbonization of the power sector, nuclear power is a politically sensitive topic in many countries due to the inherent risk of nuclear accidents and subsequent environmental catastrophes as well as the uncertainties about costs of dismantling and waste disposal. Nuclear power is an important pillar in electricity generation in France. However, the analysis showed that additional system costs in France of a nuclear phase-out amount up to 76 billion Euro. Additional costs are mostly borne by the French power system. Surprisingly, the analysis found that the costs of uncertainty are rather limited. Indeed, a commitment regarding nuclear policy reform is only mildly beneficial in terms of system cost savings.

China has a very ambitious plan for nuclear development existed and the study of scenarios with prospect of 150 GWe to 400 GWe in 2050 is carried out using the COSI6 simulation software, and aims at analyzing the evolution of nuclear energy currently planned in China [40]. Results rely on natural uranium supplies, fuel fabrication, spent fuel reprocessing, quantities of proliferating materials and the opportunity of a rapid deployment of fast reactors (FBR). Fast Breeder Reactor (FBR) may represent at the most around 30% of the total nuclear capacity in the country by 2050. The deployment of FBR only can indeed start from 2035 to 2040. Finally, the pace of FBR development should be controlled carefully by the proportion of FBR and PWR with respect to the reprocessing capacity.
3.3. National stakeholders to participate in nuclear industry

3.3.1. Capabilities of nuclear facilities. Indonesia through BATAN has carried out uranium exploration as well as the plan of radioactive waste treatment in detail, respectively and the two detail information can be seen in References [48] and [49]. Nuclear power plants are to be first established in 2027 [39] and the waste treatment for a following century to support nuclear industry has been planned as well [49]. Indonesia has a lot of thorium and uranium and thorium is mainly found in monazite sand. Geologically, the prospect of monazite in Indonesia is controlled by granite of tin lane stretching from Thailand-Malaysia-Bangka Belitung-West Kalimantan. Thorium exploration in Indonesia is still in general investigation and was carried out in Bangka Belitung and Ketapang Regency, West Kalimantan in 2009–2014. The results of some surveys and studies indicate that thorium distribution is also found in West Sulawesi (Mamuju), which currently becomes the focus of exploration, Sumatera, Central Kalimantan, Central Sulawesi, and West Papua. The largest thorium reserve in Indonesia is 130,974 tones consisting of 4,729 tones thorium estimated in Bangka Belitung and the rest is a speculative reserve.

Exploitation of uranium and thorium ores in Indonesia has not been performed recently since there is no demand yet. The uranium potential related to activities carried out in Indonesia through exploration has been carried out by BATAN. BATAN’s exploration activities take place in Kalan, West Kalimantan Province. This exploration activity identifies that uranium reserve is located in metamorphic sedimentation in Kalan basin, and monazite placer sedimentation in Ketapang. In addition to uranium reserve, monazite also contains sufficiently significant concentration. In addition to West Kalimantan, exploration is also conducted in other areas, such as, Mentawa, Central Kalimantan, Mahakam Hulu, East Kalimantan, Mamuju, West Sulawesi, Biak Numfor, Papua, and Bangka Belitung.

BATAN has also implemented R&D in nuclear fuel cycle and one phase of R&Ds carried out was UO₂ production from uranium yellow cake. This R&D consists of several activities, such as, UO₂ powder production in sub-micron size that meets quality requirement, optimization of UO₂ powder compaction process, and sintering at low temperature in annular UO₂ pellet production. In addition, the R&D activities also include the manufacture of structural material of power reactor fuel elements. This structural material together with UO₂ nuclear fuel can be developed to produce nuclear fuel assembly which is ready to use in a nuclear reactor. Engineering activities related to this R&D of material structural manufacture include the design of the melting furnace to make zirconium alloys and the design of conversion equipment of rod/plate products from Zircalloy ingots. The processes that have been undertaken are the manufacture of ZrC, coating of ZrY cladding with ZrC with micron-order thickness, characterization of mechanical properties and microstructure of ZrC layer, and manufacture of SiC alloys and composites.

As previously mentioned in this paper, Indonesia is predicted to have the first NPP with the power of 2x 1,000 MW in 2027 [39] and the total of power for all NPPs would be around 20 GW in 2050. Come along with this national plan, the assessment of waste treatment from Indonesia’s NPP has also been planned [49] till a following century. The government so far has authorized BATAN to treat all national low level wastes coming from industries and hospitals. Instead of BATAN, it is very open opportunity for state-owned enterprises to treat the all low level wastes in the country in the future. For this, it is indeed BATAN and other relevant stakeholders should firstly develop a new government decree regarding the national nuclear waste treatment in the country.

3.3.2. National strategic-state-owned enterprises to support nuclear-energy-based industry. BATAN carried out the assessment of local participation to support nuclear-energy-based industry [50]. Data on raw material requirements for NPP Gen III and Gen III + are not so far fully disclosed by the vendors, but raw material requirements have been established. Based on these requirements, the need for raw materials can be estimated, especially in new NPP construction projects. The raw material requirements for the sophisticated Gen IV nuclear power plant are not known yet because of the absence of a Gen IV NPP in operation. Other raw material requirements from NPP development are
land area and water volume. This is a separate consideration if there is a need for comparisons between different types of NPPs, in order to analyze the feasibility of NPPs.

In the framework of Increasing the Use of Domestic Products (P3DN) as mandated by Article 85 Act No. 3 year 2014 on Industry and Presidential Instruction Number 2 Year 2009 on the Use of Domestic Products in the Procurement of Government Goods/Services, the Ministry of Industry has compiled a list of inventories of manufactured local content levels (TKDN) Year 2011-2016.

Industrial groups that support the construction and operation of nuclear power plants are civil heavy equipment, civil building materials, civil EPC & engineering services, machinery & equipment, electronic equipment, electrical equipment, computers and office equipment. To map the potential of these industries is essential to support the NPP construction in the country. As a mission to become newly developed industrialized country, Indonesia’s industrial sector must be able to meet several basic criteria, such as, high role and contribution to the national economy; small & medium industry abilities with large Industries; strong industrial structure (complete Industrial structure); advanced technology to lead market development and creation; strong industrial services to support the international competitiveness of the industry and to have strong competitiveness with global companies.

Based on Ref. [51], during the RDE construction, there will be a lot of knowledges dealing with project management organization and all aspects, such as, nuclear and safety, mechanical, electrical, process, instrumentation and control (I&C) and civil. It is noted that in the first quarter of 1980s, Indonesia, specifically BATAN in Puspiptek area Serpong, had ever experiences on the construction of Multi Purpose Reactor, called RSG-GAS reactor, and its supporting laboratories, such as, centers of radioisotope, radiopharmaceutical, and nuclear research reactor fuel element production, and both are now belonged to the state-owned company Indonesia Nuclear Industry (INUKI). In addition, the others are also fuel element, nuclear safety and technology and radioactive waste treatment centers as well as nuclear facility engineering center and most of these facilities have safely operated since 1987.

It is highlighted that all civil construction and non-nuclear-safety related devices supervised by the reactor vendor were executed by Indonesia state-owned engineering companies. From the latest assessment carried out, it is estimated that all RDE construction will be at least 40% supported by the local engineering companies.

BATAN has also planned to have an HTGR fuel plant to support RDE daily operation and there are two developed scenarios. Prior to discuss that matter, BATAN has significant experiences on R&Ds of HTGR fuel kernels, fabrication of NPP fuel pin and PHWR fuel bundles and others [52]. It is therefore no doubt in the future, BATAN and its stakeholders should have a courage to build the HTGR fuel plant. The first strategy is that for the first three year of RDE operation from 2022-2025, the HTGR fuel need should be included in the RDE EPC contract. The second strategy which is very possible is that BATAN and the national stakeholders will have a big opportunity to construct the HTGR fuel plant to support RDE daily operation. However, at that time, BATAN should still collaborate with advanced fuel producers, such as, USA, Russia, Japan and China to enhance the experiences on the construction of the new HTGR fuel plant. Since HTGR is one of the Gen IV reactors to be demanded by all developed countries in the near future and there are currently only few countries to develop HTGR reactor, Indonesia has a very high possibility not only to be able to develop and construct HTGR plant, but also to become an HTGR fuel producer by 2030s by taking into account the strong policy, support from the Indonesia government.

4. Conclusion

Regarding the advanced HTGR coated fuels, two advanced particle designs consisting of the conventional German and the US particle designs may be adopted in the future. Europe countries (Russia, Germany and France) has still developed R&Ds on HTGR fuels to support current HTGR and Gen IV VTR in the future and China, Japan and South of Korea are of course to do the same things as well. Regarding the future prospect of NPPs, few advanced countries, not only in Asia but also in Europe, planned to develop and construct NPPs till 2050, and even HTGR advance technology would
be one of the NPP technologies to be available till 2100.

As planned, RDE will be operated in 2022/2023 and to support the RDE daily operation, BATAN and stakeholders are of course very possible to build an HTGR fuel plant in the country. Since there are currently only few advanced countries to deal with the HTGR reactors, Indonesia has a very big opportunity to become an HTGR fuel producer by 2030s by taking into account the strong policy, support from the Indonesia government.

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