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Review

Current and future strategies for spent nuclear fuel management in Indonesia

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ABSTRACT

Currently, Indonesia has only three nuclear research reactors. However, Indonesia is the world's fourth most populous country. Owing to the enormous size and rapid growth of the population and the limited availability of fossil fuel and renewable energy resources, the construction of new nuclear power plants (NPPs) has been considered. Because of this, the management policies for long-term spent nuclear fuel in Indonesia have become crucial. This paper reviews the current handling and future management strategies for spent nuclear fuel in Indonesia. With a maximum capacity of 1448 spent fuel elements, Indonesia's interim wet storage of spent fuel (ISSF) is designed to store spent nuclear fuel arising from 25 years of reactor operation at maximum power. However, with the existing low-power reactor operation, the ISSF could be utilized for more than 75 years. The potential problem for long-term storage in the ISSF is system, structure, and component (SSC) aging. Continuous planning, operation, monitoring, and maintenance of the SSC in the ISSF have been conducted to ensure safe long-term utilization of the facility. In accordance with the possibility of NPP construction in the future, three possible scenarios may be considered for future nuclear spent fuel management strategies in Indonesia: 1) wet storage - dry storage - disposal; 2) wet storage -repatriation or sending to other countries; and 3) wet storage - moving to wet- or dry storage of NPP candidate - disposal.

1. Introduction

Indonesia is the world's fourth most populous country. According to the Intercensal Population Survey, the population of Indonesia was 264.2 million in 2015, and based on the projection data from Indonesia's Central Agency on Statistics, this figure is estimated to reach more than 319.0 million by 2045 [1], as shown in Fig. 1.

In 2019, Indonesia's government targeted an economic growth of 5.3% and assumed a range of 5.3–5.5% [2–5]. According to a collaborative study conducted by the National Development Planning Ministry and the Asian Development Bank, the potential economic growth in the next five years is 5.7% [6]. Given the economic growth and total population mentioned above, to meet the country's long-term energy needs, Presidential Decree No. 05 of 2006, which was revised and developed into Government Regulation No. 79 of 2014, set a target of generating 115 GWe of electrical energy in 2025. This means that it is necessary to build power plants generating a total power of 6.2 GWe/year [7,8].

The National Energy Policy in Presidential Decree No. 05 of 2006 stated that the share of oil in the primary energy mix in 2025 should be less than 20%. The total percentage of new and renewable energy planned should be more than 15%. The new and renewable energy consists of 2% hydro, 5% geothermal, and 8% other energy sources, which includes 2% nuclear energy [7].

Currently, fossil sources supply 85% of Indonesia's total energy needs. Oil production continues to decline, and Indonesia has been a crude oil importer since 2004. Coal production is only 3.1% of the total world production, and most of the produced coal is exported to increase the country's foreign exchange. If new reserves are not found, it is estimated that this energy source will be exhausted within a few decades [9]. With an annual population increase of 1.1% and an annual economic growth averaging 5%, alternative sources of base-load energy must be sought to support this change. On the other hand, according to the COP21 agreement, Indonesia has committed to achieving a 29% reduction in carbon emissions by 2030 [10]. Therefore, the only

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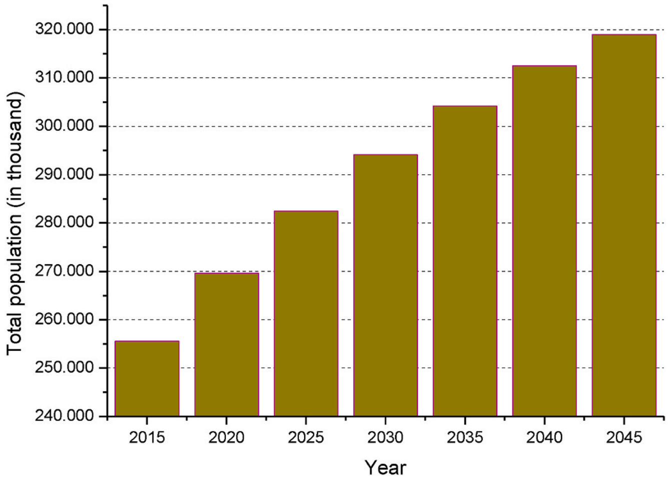

Fig. 1. Indonesia population projection.

Table 1
Current management options being considered for nuclear research reactor spent fuel in some countries.

Management policy	Countries[a]
Direct disposal	Netherland [57]
Reprocessing	UK [58]
Repatriation	Argentina [59], Australia [60], Brazil [59], Chile [59], Czech [61], Indonesia [62], Italy [63], Kazakhstan [64], and Ukraine [65]
Wait and see	Australia [60], Canada [66], Czech [61], Finland [67], Germany [68], Hungary [69], India [70], Indonesia [62], South Korea [71], Netherland [57], Norway [72], Poland] [73], Ukraine [65], US [74], and Uzbekistan [75]

[a] Some countries may follow more than one management policy.

Table 2
Summarized data of the nuclear research reactors in Indonesia.

Name of Reactor	Place/Site	Reactor Type	Start of Operation	Power
Reaktor Serba Guna G.A. Siwabessy (RSG-GAS)	Serpong	Multi-Purpose Reactor	1987	30 MW
TRIGA 2000	Bandung	TRIGA	1964	250 kW 1000 kW (1. Upgrade in 1972) 2000 kW (2. Upgrade in 2000)
Kartini	Yogyakarta	TRIGA	1979	100 kW

remaining option is to consider nuclear energy [11]. With the aforementioned considerations, along with the limited availability of fossil and renewable energy resources and policies regarding the reduction of carbon emissions [12–15], nuclear power plants (NPPs) are urgently needed in Indonesia. Currently, Indonesia does not have an NPP; however, there are three nuclear research reactors for radioisotope production and research purposes.

The results of a public opinion poll on the Indonesian NPP program in the 2015–2017 period indicated that more than 70% of the respondents supported the NPP program. However, the public expressed concern about accidents and the handling of the radioactive waste produced [16]. This paper presents a review of the policy, strategy, and current status of spent fuel management in Indonesia with an additional review on international approaches used for spent nuclear fuel management and practices. The discussion on spent fuel management in Indonesia applies not only to the existing spent fuel arising from nuclear research reactors but also from an NPP that currently does not exist in Indonesia but is planned. Some potential problems that may be encountered in spent nuclear fuel management and future strategies for spent nuclear management in Indonesia are also discussed.

2. International approaches for spent nuclear fuel management

Radioactive waste must be managed safely to ensure that it will not endanger human health and the environment. According to the International Atomic Energy Agency (IAEA) safety standards, radioactive waste must be stored in such a manner that it can be monitored, inspected, retrieved, and preserved in a condition suitable for subsequent management [17]. Several studies have been conducted on the management of radioactive sources or waste. The management process involves treatment, storage, and disposal [18–21].

One of the most dangerous radioactive wastes is spent nuclear fuel, which has a very high radioactivity and long half-life. Spent nuclear fuel is generated from the operation of NPPs and nuclear research reactors. After being discharged from the reactor, the spent nuclear fuel can be stored in wet or dry conditions. During wet storage, the spent fuel is kept in storage racks, which are placed in a water pool. The water in the pool serves as a cooling medium as well as radiation protection.

Generally, there are several options for spent nuclear fuel management [22–25]:

- Directly dispose of the spent fuel in a national geological repository (final disposal facility).
- Reprocess the spent fuel.
- Return the spent fuel to the origin country/supplier.
- Follow a “wait and see” policy; this means keeping the spent fuel in an interim wet or dry storage and waiting for the correct time to make a final decision.

The storage or management of spent fuel should meet the safety standards of the IAEA. The IAEA Safety Standard Series (SSG-15) provides guidance and recommendations on the safe design (containment, criticality, heat removal, radiation shielding, retrievability, and transportability) and safe operation (criticality, heat removal, radiation shielding, and handling) of spent fuel facilities. SSG-15 can be applied to spent fuel from NPPs and nuclear research reactors [17,26–28].

2.1. *Management options for spent fuel from nuclear power plants in select countries*

The need for the management of spent fuel from NPPs is apparent, and the technology used for this purpose is more advanced. However, the absence of spent fuel disposal facilities compromises the credibility of the nuclear community and reduces public acceptance of current and future nuclear programs. Some people believe that it is unethical, irresponsible, and ultimately not sustainable to defer problems to future generations.

As stated above, there are several options for the management of spent nuclear fuel from NPPs. Different countries choose an appropriate option or options according to different circumstances. Currently, no deep geological repository or final disposal facility for spent fuel or high-level radioactive waste (HLW) is in operation, although research on this topic has been conducted using a range of underground laboratories for several decades [24]. Countries that have chosen a direct disposal policy include Belgium, Canada, Finland, Germany, Hungary, Japan, Lithuania, Slovakia, Slovenia, South Korea, Spain, Sweden, and the UK [24,29–38].

A reprocessing policy (reprocessing nuclear fuel and recycling the separated material) is followed by China, France, India, Japan, Russia,

Fig. 2. Locations of nuclear research reactors in Indonesia.

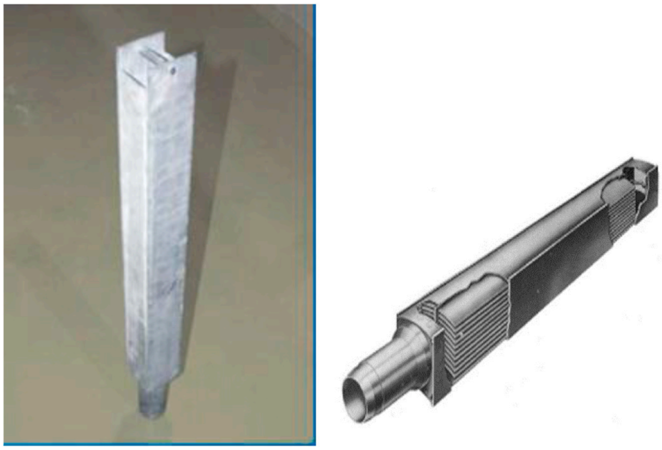

Fig. 3. MTR nuclear fuel from the RSG-GAS research reactor.

Table 3
Specifications of the RSG-GAS fuel element.

Specification	Value
Dimension (mm)	77.1 × 81 x 600
No. of plates per standard fuel element (FE)	21
No. of plates per control element (CE)	15
Clad material	$AlMg_2$
Clad thickness (mm)	0.38
Meat dimension (mm)	0.54 × 62.75 x 600
Meat material	U_3Si_2Al
^{235}U Enrichment (w/o)	19.75%
U_3Si_2Al density (g/cm^3)	2.96
^{235}U weight per FE (g)	250
^{235}U weight per CE (g)	178.6

the UK, and USA [12,24,29,38–48].

One policy on spent fuel management that is reasonably favorable for some countries is the repatriation of the spent fuel to its origin country. The countries that export their spent nuclear fuel are Belgium (export to France), Bulgaria (export to Russia), Italy (export to France), the Netherlands (export to France), and Ukraine (export to Russia) [29,49]. However, most contracts between reprocessing countries and countries that use the nuclear fuel require the waste to be returned to its original state. China, in their NPP promotion, may offer to finance, build, operate, supply fuel, and retrieve spent nuclear fuel from exported reactors [50].

The management option that is currently widely used is the placement of spent fuel in interim wet or dry storage while awaiting a further policy. This "wait and see" policy is practiced by Argentina, Armenia, Brazil, South Korea, South Africa, the USA, and all countries that have chosen the direct disposal option (as there are currently no operating disposal sites) [29,48,51–56].

2.2. *Management options for spent nuclear fuel from nuclear research reactors in some countries*

The spent nuclear fuel from research reactors usually has a smaller dimension than that of fuel from NPPs; however, as described above, the spent nuclear fuel management options for research reactors are similar to those for NPPs. Some countries, such as Indonesia, do not have NPPs but do have nuclear research reactors. In the same manner as for NPPs, it is possible to choose more than one option for management of spent nuclear fuel from research reactors. Although the amount of spent nuclear fuel is considerably less than that from NPPs, complex issues are also encountered during the handling of spent nuclear fuel from research reactors. Economic factors tend to cause the spent nuclear fuel from research reactors to be stored for the long term. Cooperative regional networks and frameworks for spent fuel storage and disposal may be a productive method of addressing this problem.

A summary of the current management options being considered by several countries for managing spent fuel from their nuclear research reactors is presented in Table 1. However, it should be noted that under certain circumstances, the management policies shown in Table 1 might change over time.

3. Current status of spent nuclear fuel management in Indonesia

3.1. *Research reactors in Indonesia*

As mentioned earlier, Indonesia has three nuclear research reactors but does not currently have an NPP. The research reactors are a 30-MW material testing reactor (MTR) at Serpong, a 2-MW training, research, isotopes, and general atomics (TRIGA)-type reactor at Bandung, and a 100-kW TRIGA-type reactor at Yogyakarta. The maximum fuel burnups of the Serpong reactor, Bandung research reactor, and Yogyakarta research reactor are 59%, 50%, and 10%, respectively.

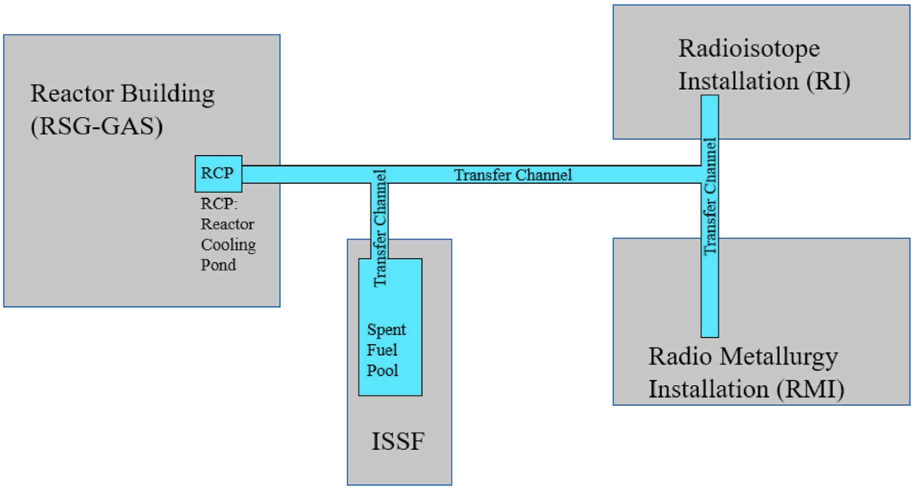

Fig. 4. Connections between the ISSF and Serpong research reactor, Radioisotopes Installation, and Radio Metallurgical Installation.

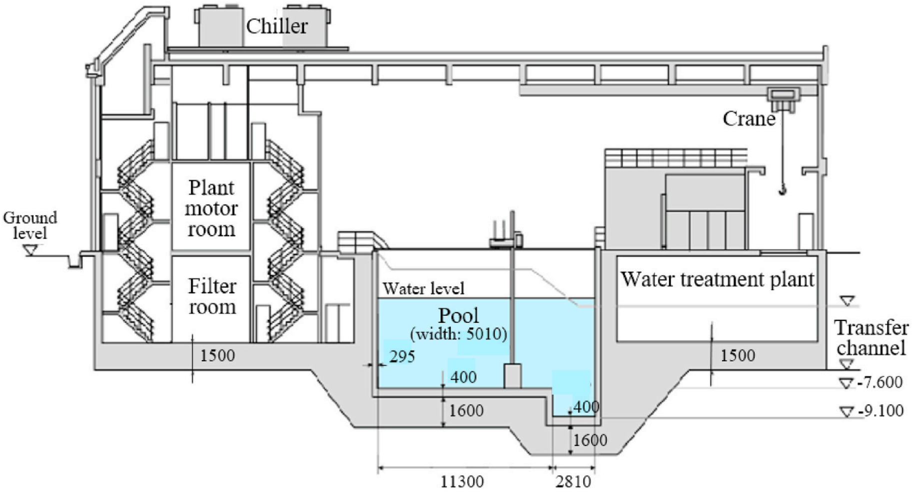

Fig. 5. Serpong ISSF layout.

Fig. 6. Spent fuel pool in the Serpong ISSF.

Table 4
Main systems of the ISSF in RSG-GAS.

System	Purpose
Water treatment system	To treat the pool and transfer channel water to maintain its chemistry, clarity, and radioactive content at acceptable levels.
Demineralized water unit	To replace water lost through evaporation under normal conditions. To wash the resin beds when they need replacing.
Pool cooling system	To remove heat arising in the pool from the spent fuel and maintain the water at 35 °C by chilled water.
Ventilation system	To provide a satisfactory working environment for the operators and to minimize the spread of any airborne contamination and, in particular, its release to the environment.
Fuel transfer system	To transfer spent fuel from the reactor to the ISSF and to handle the spent fuel at the ISSF building.
Make-up water system	To supply pool water as compensation for the water lost by evaporation or leakage.
Radiation monitoring system	To measure radiation dose rates and airborne radionuclides. Continuously operated with local alarm and unambiguous readouts. To detect contamination of workers.

The summarized data and the location of the research reactors are shown in Table 2 and Fig. 2.

The spent fuel or nuclear fuel that has been irradiated in these

Table 5
Operational limits of some important parameters in the Serpong ISSF.

Parameter	Value
pH	5.5–7.7
Conductivity	<15 μS/cm
Pool water level	6.5 m
Pool water temperature	<35 °C
Air contamination	<70 Bq/m^3
Room temperature	<30 °C
Dose rate in the pool	<0.025 mSv/h

research reactors must be handled, stored, and managed in a safe, responsible, and effective manner. Several studies have been conducted on Indonesia's spent fuel storage safety [76–80].

The policy on the management of spent nuclear fuel in Indonesia (through the National Nuclear Energy Agency (BATAN)) is to not recycle the spent nuclear fuel. Government Regulation No. 27/2002 on Radioactive Waste Management states that spent nuclear fuel is not allowed to be reprocessed. The spent nuclear fuel should be directly disposed or stored temporarily by waste producers/BATAN and then returned to the origin or supplier country [81].

A part of the spent nuclear fuel from the three Indonesian research reactors (Serpong, Bandung, and Yogyakarta) was sent to the supplier country. The first spent nuclear fuel repatriation to the US, which included 47 spent nuclear fuel elements from the Serpong research reactor, was performed in 1999, [85]. In 2004, 111 spent nuclear fuel elements from the Bandung research reactor, 71 elements from the Yogyakarta research reactor, and 111 elements from the Serpong research reactor were shipped to the US [84]. In 2009, 42 spent nuclear fuel elements from the research reactor in Serpong were sent to the Savannah River Site (SRS) in the US [82,83].

Since 2001, most of the uranium in the Serpong reactor has been obtained from France and Russia, with whom there is no contractual agreement for spent nuclear fuel repatriation [86].

3.2. Interim storage of spent fuel

A building for the interim storage of spent fuel (ISSF), which is located in Serpong, has been in operation since 1998. The ISSF was designed to store the spent nuclear fuel in a water pool (wet storage). Currently, the entirety of the spent fuel at the ISSF comes from the RSG-GAS in Serpong, while the spent fuel from the Yogyakarta and Bandung research reactors is still stored in a pond near each reactor.

The RSG-GAS fuel elements are of the low-enriched uranium-material testing reactor (LEU-MTR) type, as seen in Fig. 3. The detailed specifications of the RSG-GAS fuel elements are listed in Table 3 [62].

In the current practice, the fresh spent nuclear fuel, or spent fuel that has just been removed from the RSG-GAS research reactor, will be stored temporarily in a reactor cooling pond, which has a maximum capacity of 288 spent fuel elements, near the reactor core for 100 days or more [62]. Then, the spent nuclear fuel must be transferred to the ISSF through the transfer channels containing water and stored in a rack at the bottom of an ISSF pool.

The transfer channel is also used to transfer the irradiated targets from the reactors to the Radioisotope Installation (RI) facility and to transfer the spent fuel from the reactor to the Radio Metallurgy Installation (RMI) and from the RMI facility to the ISSF, as depicted in Fig. 4.

The ISSF pool has a 14-m length, 5-m width, and 7.6-m depth. It was designed by AEA Technology, UK, with a multi-barrier construction (SS-304 liner, walls, mild steel, and concrete). The ISSF layout and spent fuel pool inside the ISSF are shown in Figs. 5 and 6 [87,88].

The ISSF in Serpong has several main systems, as shown in Table 4.

The water treatment system, or water purification process, is operated continuously through an ion-exchange column to maintain the water quality (chemistry, clarity, and radioactive content) at acceptable levels, as shown in Table 5.

The demineralized ISSF pool water serves as a pool-cooling system and as radiation shielding for the spent fuel stored in the pool. The ISSF cooling system is designed to remove the decay heat generated by the spent fuel through water circulation to maintain the water temperature in the pool at less than 35 °C.

The ventilation and air-conditioning system maintains the facility

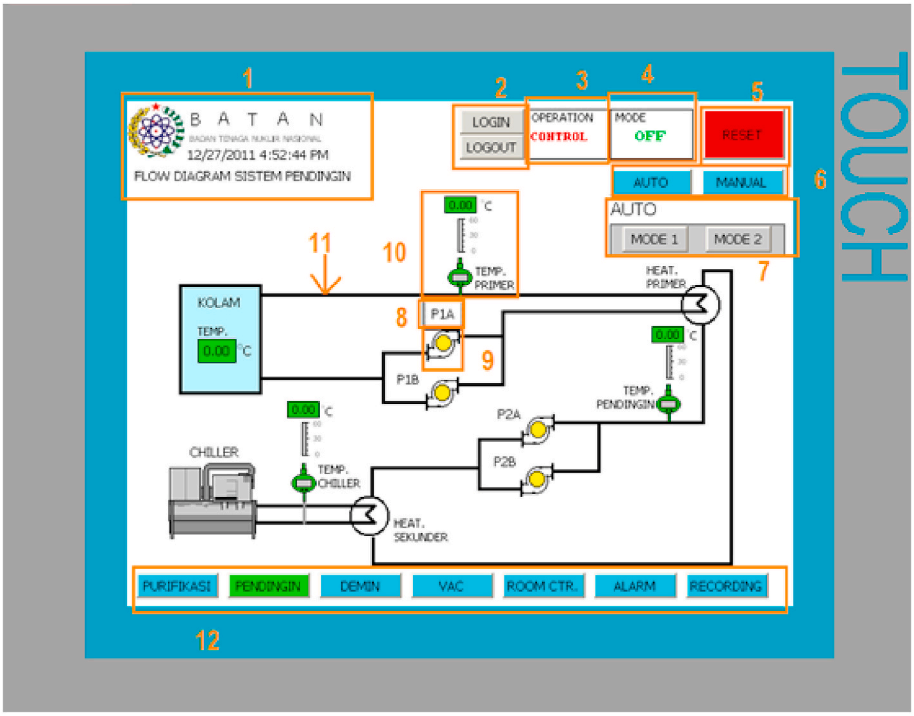

Fig. 7. HMI-screen for the cooling system for the pool in RSG-GAS.

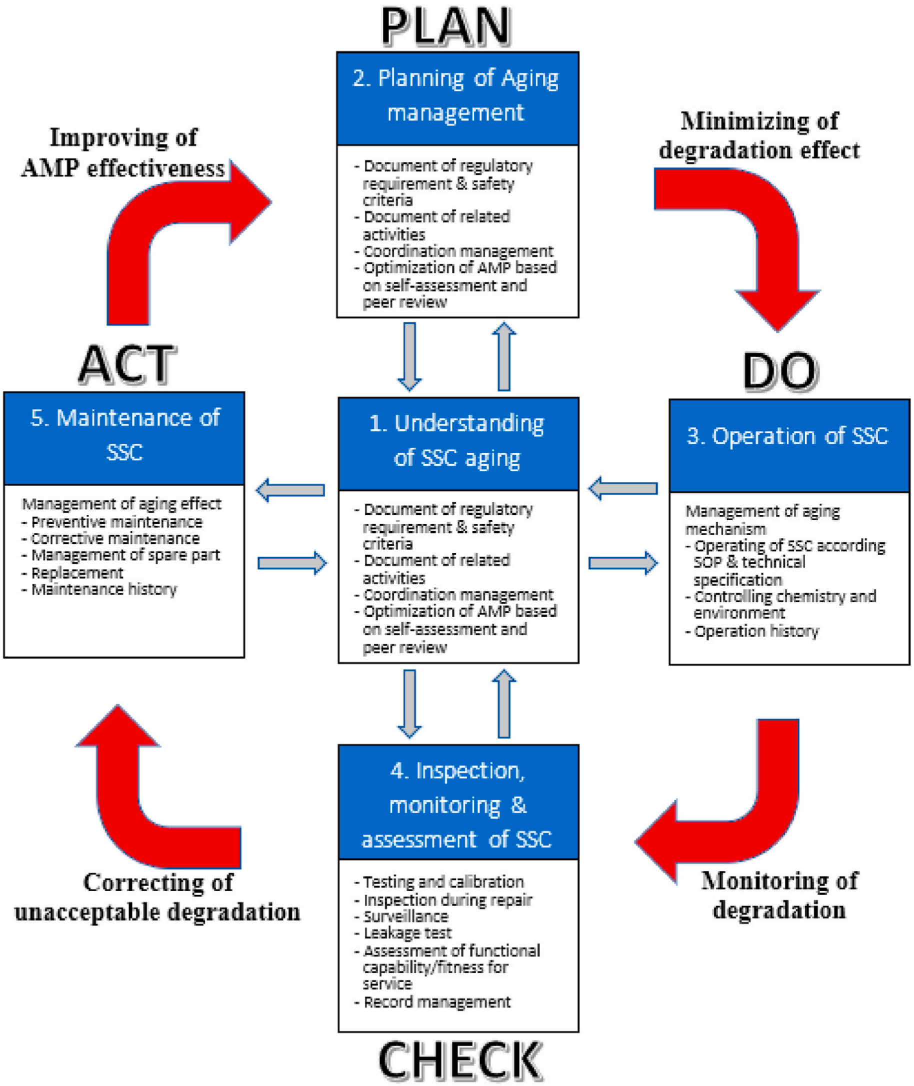

Fig. 8. PDCA cycle of aging management program in the ISSF.

building temperature of 20–25 °C, relative humidity of 40–60%, room negative pressure of 100 ± 25 Pa, and radiation exposure of 0.02–0.05 mSv/h, through air renewals five times per hour [89–91].

The ISSF in RSG-GAS uses a control system in its operation. The RSG-GAS system control serves some systems via a remote I/O programmable logic controller (PLC) and human machine interface (HMI). The controllable systems in RSG-GAS are the purification system, demineralization system, ventilation and air conditioning (VAC) system, cooling system, and room-monitoring system. From the HMI screen, the systems in RSG-GAS can be monitored and controlled remotely. The HMI screen is shown in Fig. 7.

3.3. *Current spent fuel management*

The ISSF facility in Serpong is designed to accommodate spent nuclear fuel arising from 25 years of reactor operation at maximum power. By a maximum RSG-GAS reactor operation design of 30 MW, the nuclear fuel elements are replaced seven times per year (seven replacement cycles). In each cycle, eight nuclear fuel elements are replaced. For 25 years of reactor operation, the total number of spent fuel elements will be 1400. The storage capacity of the ISSF is 1448 spent nuclear elements, including the spent element control rod. However, in the current practice, the RSG-GAS reactor has not been operating at maximum power. There are only six nuclear fuel element replacements per cycle and only three cycles per year. Under these conditions, with a maximum capacity of 1448 spent nuclear fuel elements, the ISSF could be utilized for 80 years of RSG-GAS operation.

From when the RSG-GAS reactor first began operating, in 1987, to 2020, the number of spent nuclear fuel elements that are stored in the ISSF pool was only 287, including 244 spent fuel elements and 43 control rod elements. As mentioned above, in accordance with the policy that all spent nuclear fuel from the US must be sent back to its home country, 198 spent nuclear fuel elements have been sent back to their country of origin.

4. Potential problems in spent nuclear fuel management in Indonesia

When the research reactors were established in Serpong, Bandung, and Yogyakarta a few decades ago, these locations were far from densely populated settlements. However, in the last ten years, community housing has developed at sites around the nuclear facilities. Thus, there are fears of public safety risks, and there is increasing pressure to find various options for handling radioactive waste and spent nuclear fuel [92].

Another potential problem that may be encountered during long-term storage in the ISSF is system, structure, and component (SSC) aging. Aging is a gradual process that is a function of time or utilization,

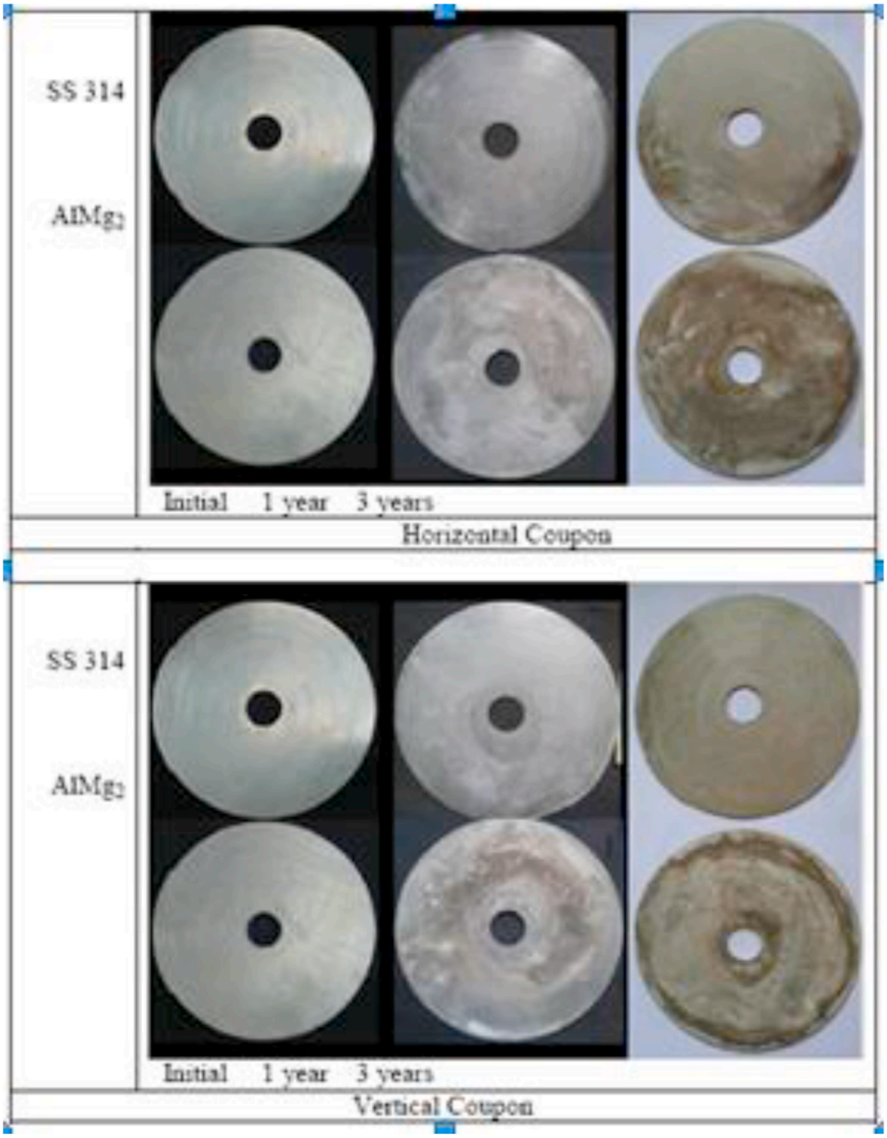

Fig. 9. Galvanic corrosion between SS and $AlMg_2$ at various exposure times up to 3 years.

in which the characteristics or properties of the SSC degrade. Because aging can affect the general safety conditions of the ISSF facility, an aging management program (AMP) is needed to overcome this issue. The AMP activities include planning, operation, monitoring, and maintenance to control and maintain the effects of aging on the SSC within acceptable limits. Fig. 8 presents the plan-do-check-act (PDCA) cycle of the AMP implemented at the ISSF.

The type of degradation of the material, structure, or system at the ISSF that needs to be monitored continuously is corrosion. One of the most critical components of the ISSF in terms of the corrosion risk is the liner. The liner is 304 stainless steel and lines the entire wall and bottom surface of the spent fuel pool. This liner serves to prevent pool leakage and also acts as a neutron absorbent; hence, it can provide more security in terms of criticality safety. Criticality is a nuclear chain reaction that can continue by itself which refers to the balance of neutrons in the system. Whereas, criticality safety refers to the prevention of accidents resulting from self-sustained nuclear chain reactions and the minimization of the consequences of such accidents if they do occur [93].

There have been several assessments and studies related to safety parameters such as material, component, and system aging; criticality safety; pool water chemistry surveillance; and corrosion management at the ISSF [86,94–96]. In the ISSF, several corrosion test coupons were prepared and positioned in the service pool. The test coupons for the fuel cladding were fabricated using an aluminum alloy (same as the material used for the fuel cladding) and stainless steel (same as the material used for the liner and the spent fuel storage rack). The analysis result of the test coupons indicated the following [86,94]:

- The water quality in the spent fuel pool meets the relevant standard: the pH values were between 5.5 and 7.7, the conductivity was between 1.33 and 1.50 μS/cm (much smaller than maximum allowable value of 15 μS/cm).
- The corrosion rate of the 304 stainless steel liner was $5.08.\ 10^{-5}$ mm per year. This means that the liner can be utilized for more than 40 years.
- The corrosion of the stainless steel and aluminum alloy of the test coupons mainly involved galvanic and crevice effects, as can be seen in Figs. 9 and 10. In addition, based on the microscope observation, there was no pitting, and no biofilm was present either. Changes in the physical appearance of the coupon surface after one and three years are due to the scaling process derived from the pool water.

Controlling the quantity of aggressive ions, such as chloride, is also necessary to maximize the margin of the safety material and to avoid

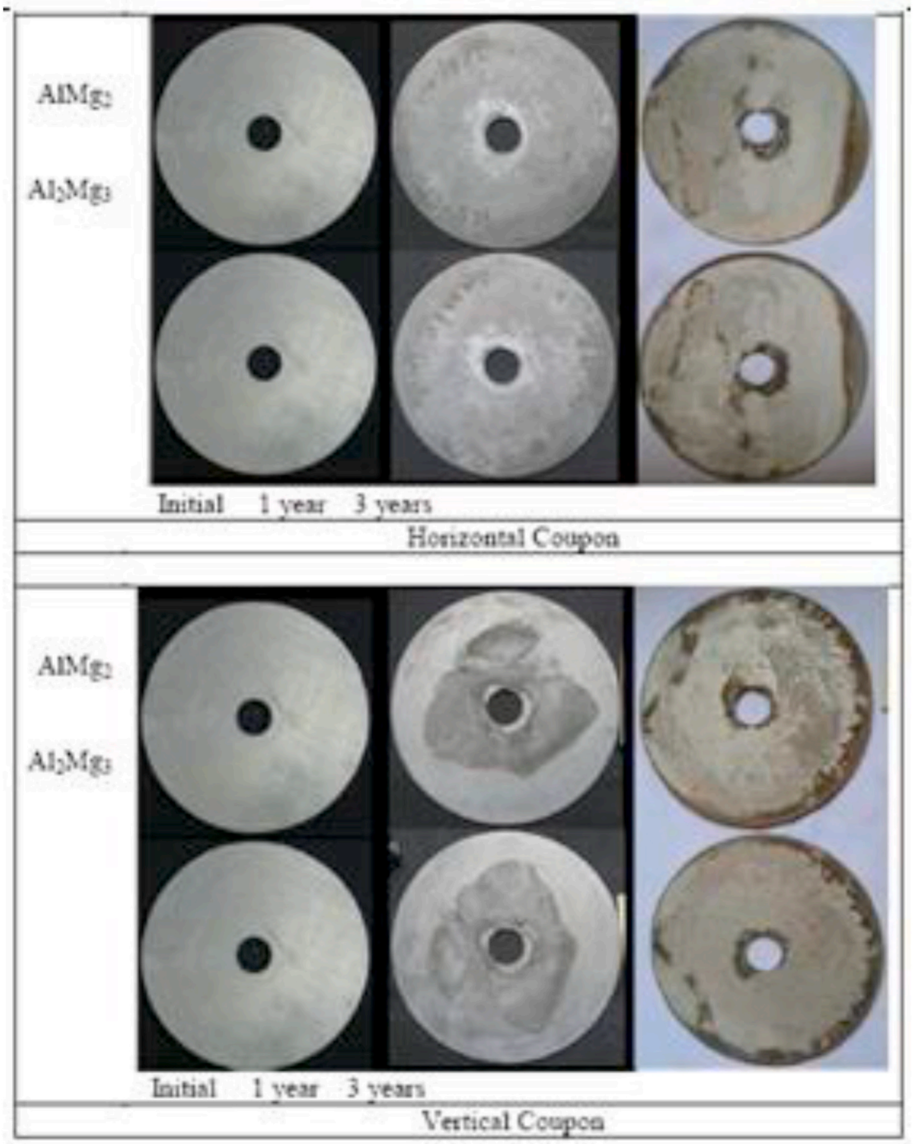

Fig. 10. Crevice corrosion between AlMg$_2$ and AlMg$_2$ at various exposure times up to 3 years.

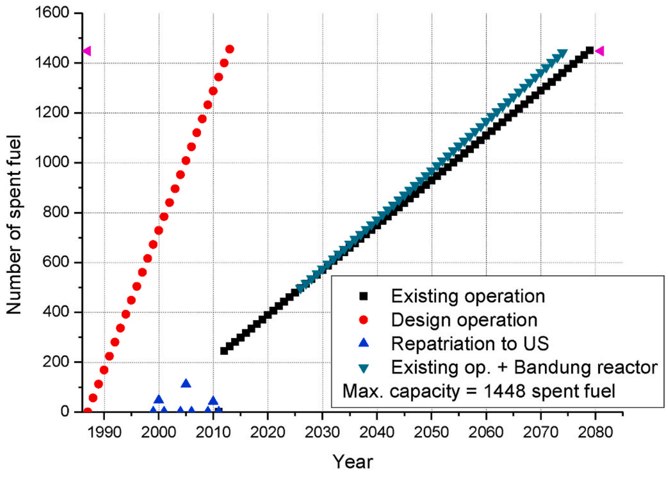

Fig. 11. ISSF utilization prediction.

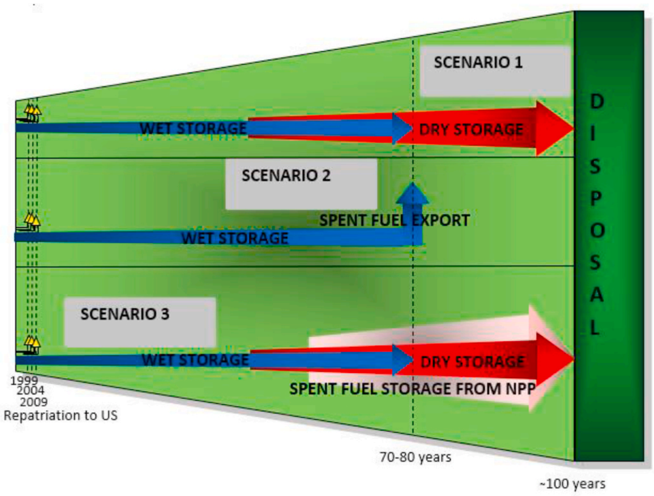

Fig. 12. Scenarios for spent fuel management in Indonesia.

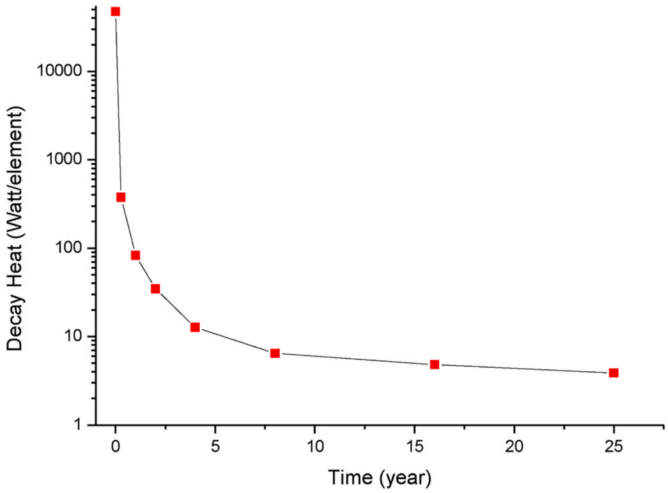

Fig. 13. Spent fuel decay heat as a function of time.

premature damage to the material. In general, well-organized management of water temperature, activity level, water chemistry, and corrosion products is necessary to ensure safety in long-term storage.

Another potential problem is the spent fuel storage capacity in the future. However, in RSG-GAS, with the large pool capacity and the low existing discharge rate of spent fuel, the spent fuel pool can be operated for the next 60 years, as discussed in Section 5.

5. Future prediction and strategies for spent nuclear fuel management in Indonesia

As of 2020, due to repatriation and the low power of the RSG-GAS operation, the number of spent nuclear fuel elements in the ISSF pool was only 287. As explained earlier, at the maximum RSG-GAS power of 30 MW, the number of nuclear fuel elements replaced is eight per cycle, and seven replacement cycles are performed per year. However, in practice, there have been only six fuel element substitutions with three cycles per year. Fig. 11 shows that if the maximum RSG-GAS design had been used, the ISSF pool would have reached its maximum capacity in 2013 (25 years after the first operation in 1987). However, with the existing operation, the ISSF pool could be utilized until 2079, more than 80 years after RSG-GAS first started operating. Fig. 11 also shows the spent fuel repatriations to the US in 1999, 2004, and 2009.

Several studies have proposed that the Bandung TRIGA reactor's nuclear fuel should be converted from the TRIGA cylindrical fuel element to the MTR plate fuel element [97,98]. Because of the limited amount of existing nuclear fuel and the fact that the TRIGA fuel is currently no longer being produced, in 2026, the fuel in the Bandung reactor will be replaced. With 2 MW of thermal power, after the conversion, Bandung's reactor will produce four spent fuel elements and one spent control rod every 2.34 years. This additional spent fuel from Bandung, which will be sent to and stored at ISSF Serpong, will reduce the time required until the ISSF reaches its maximum capacity. The maximum capacity of the ISSF will be reached in 2074 (5 years earlier than 2079), as shown in Fig. 11.

To ensure that the ISSF installation operates properly over a long period, the potential degradation of materials caused by factors such as corrosion and water chemistry needs to be monitored and conditioned to ensure that the spent fuel wet storage remains in a safe condition. Controlling the quantity of aggressive ions, such as chloride, is also necessary to maximize the margin of safety and to avoid premature damage to the material. In general, well-organized management of water temperature, activity level, water chemistry, and corrosion products is necessary to ensure safe long-term storage.

Generally, for long-term spent-fuel management in Indonesia, several scenarios or strategies can be implemented, as presented in Fig. 12. The yellow arrows indicate the repatriation policy of spent fuel to the origin country that has previously been followed (1999, 2004, and 2009).

The management strategy currently used in Indonesia is to store the spent fuel for a specified period in wet storage, while the next management policy is being formulated (wait-and-see policy). When the final spent fuel policy to be followed is implemented, it can be assumed that the waiting time until a disposal site is ready for use would be decades, as no HLW disposal site currently exists, and considering the high cost and complexity of disposal procurement. However, considering the existing operations of the RSG-GAS and future Bandung reactor, the maximum capacity of the ISSF pool will not be reached until 2074 (more than 75 years after RSG-GAS began operation); thus, the spent fuel can be moved from the wet storage to a dry storage system before 2074. BATAN has planned to build a dry storage system for Indonesia's spent fuel. Several studies have been conducted on important parameters of spent fuel dry storage systems, such as spent fuel characterization, criticality, radiation protection, and natural airflow caused by temperature differences for spent fuel decay heat removal [76,79,99]. From the decay heat data of the RSG-GAS spent fuel (MTR with 300 g of U-235 per fuel element and 72% burn-up), it can be seen in Fig. 13 (semi--logarithmic graph) that the decay heat declines exponentially. In spent fuel, if the decay heat declines, the radiation exposure also decreases. After approximately four years, the decay heat declines by 3.7×10^3 times, and the curve starts sloping. At this time, the spent fuel can be moved from wet storage to dry storage.

Other possibilities include the repatriation policy or sending spent fuel to other countries. However, this second scenario or strategy could be high-cost or not even possible, as Indonesia's existing and "future" spent fuel is low-enriched-uranium spent fuel. Since 2001, Indonesia has had no contractual agreement for spent nuclear fuel repatriation. In 2014, PT INUKI, a nuclear fuel fabrication company in Indonesia, faced a technical problem. Therefore, BATAN had discussed with Russia the possibility of purchasing fuel for the Serpong reactor. Among the matters discussed was the repatriation of the spent nuclear fuel. This option is available, with the consequence of significant additional costs. However, the discussion did not continue because PT INUKI resumed operation.

A third scenario that can also be considered is the possibility of an NPP or experimental NPP construction in Indonesia. In 2014, BATAN launched a plan to build an experimental NPP, named Reaktor Daya Eksperimental (RDE)/Non Komersial (RDNK) [78,100,101]. This experimental NPP is planned to be a research-and-development facility as well as the first NPP in Indonesia, with an aim to gain public acceptance. The spent nuclear fuel from the research reactors can be relocated collectively with the spent fuel from the NPP to the spent nuclear fuel storage of the NPP.

6. Conclusions

With a growing population and increasing industrialization, energy demands are continually increasing. However, limited fossil-source energy reserves and commitments to reduce carbon emissions are requiring Indonesia to consider the use of nuclear energy. The management of radioactive waste and spent fuel is a significant factor controlling public acceptance. The success of the current management of radioactive waste and spent nuclear fuel, as well as the preparation for the future, is one of the keys to the success of Indonesia's future NPP program.

Although the ISSF could be utilized theoretically for more than 75 years with the existing reactor operations, the construction of a spare interim storage site might be necessary for emergency conditions or if the operation of the existing ISSF needs to be halted to repair any possible damage. The continuous maintenance, assessment, and surveillance of the material, structure, and system aging, which have been conducted to ensure the long-term utilization safety of the facility, must be maintained and improved. Moreover, a plan to build a dry storage system that can serve as another spare storage site should also be finalized as soon as possible, to ensure that the spent fuel elements that have been stored for more than four years can be moved to dry storage. After four years, the natural decline in the decay heat and radiation exposure of the spent fuel will be at an acceptable level for the spent fuel to be moved to dry storage.

Each of the three strategies for future nuclear spent fuel management in Indonesia has advantages and disadvantages. Hence, these strategies need to be compared with consideration of current and future conditions, and the strategy that has the fewest disadvantages should be selected.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Indonesian Ministry of National Development Planning (Bappenas) and Indonesia Statistics Bureau (BPS), Indonesian Population Projection 2015-2045, 2018.
[2] ADB, Economic Indicators for Indonesia, 2019.
[3] L. Silaen, Indonesia Eyes 5.5% Economic Growth in 2020, 2019.
[4] D.R. Institute, "What about Indonesia's GDP Growth in 2019 and beyond, 2018.
[5] T.J. Post, Bank Indonesia Revises Down GDP Growth Projection in 2019, 2018.
[6] V. Lingga, Reinvigorate Manufacturing or Remain Trapped in 5 Percent Growth, 2019.
[7] President of Republic Indonesia, *the Presidential Decree no. 05 of 2006 on National Energy Policy*, 2006.
[8] P. of R. Indonesia, Government Regulation No. 79/2014 on National Energy Policy, 2014.
[9] Ministry of Energy & Mineral Resources of the Republic of Indonesia, Indonesian Nuclear Energy White Book, 2015. Jakarta.
[10] Republic of Indonesia, Act on Climate Change, 2016. Indonesia.
[11] National Development Planning Board, National Medium Term Development Plan 2020 - 2024, 2019.
[12] S.W. Yudha, B. Tjahjono, Stakeholder mapping and analysis of the renewable energy industry in Indonesia, Energies 12 (4) (2019).
[13] M. Maulidia, P. Dargusch, P. Ashworth, F. Ardiansyah, Rethinking renewable energy targets and electricity sector reform in Indonesia: a private sector perspective, Renew. Sustain. Energy Rev. (2019) 231–247.
[14] S.P. Hadi, B. Prabawani, H. Purnaweni, Environmental and social issues on energy policy in Indonesia, in: E3S Web of Conferences, vol. 73, 2018.
[15] D. Pappas, K.J. Chalvatzis, D. Guan, X. Li, Industrial relocation and CO 2 emission intensity: focus on the potential cross-country shift from China to India and SE Asia, Energy Procedia 142 (2017) 2898–2904.
[16] D.S. Wisnubroto, Ruslan, D. Irawan, T. Erni, Public opinion survey on nuclear energy in Indonesia: understanding public perception on nuclear power plant program, in: AIP Conference Proceedings, 2019.
[17] G. Jones, IAEA safety standard SSG-15-storage of spent fuel, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.
[18] S.A. McMaster, R. Ram, N. Faris, M.I. Pownceby, Radionuclide disposal using the pyrochlore supergroup of minerals as a host matrix—a review, J. Hazard. Mater. 360 (2018) 257–269.
[19] R. Ram, J. Vaughan, B. Etschmann, J. Brugger, The aqueous chemistry of polonium (Po) in environmental and anthropogenic processes, J. Hazard. Mater. 380 (2019) 120725.
[20] M. Kojo, P. Richardson, The use of community benefits approaches in the siting of nuclear waste management facilities, Energy Strateg. Rev. 4 (2014) 34–42.
[21] M.M. Gouda, Y.H. Dawood, A.A. Zaki, H.A. Salam Ibrahim, M.R. El-Naggar, A. Gad, Adsorption characteristic of Cs+ and Co2+ ions from aqueous solutions onto geological sediments of radioactive waste disposal site, J. Geochem. Explor. 206 (2019) 106366.
[22] K. Fukuda, W. Danker, J.S. Lee, A. Bonne, M.J. Crijns, IAEA Overview of global spent fuel storage,, in: Proceedings of an International Conference on Storage of Spent Fuel from Power Reactors, IAEA in cooperation with OECD/NEA, Vienna, 2003, pp. 2–6.
[23] IAEA, Management and Storage of Research Reactor Spent Nuclear Fuel, 2009.
[24] IAEA, Status and Trends in Spent Fuel and Radioactive Waste Management, 2018.
[25] IAEA, Options for Management of Spent Nuclear Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes, 2018.
[26] IAEA, Storing Spent Fuel until Transport to Reprocessing or Disposal, 2019.
[27] IAEA, International Safeguards in the Design of Facilities for Long Term Spent Fuel Management, 2018.
[28] IAEA, Behaviour of Spent Power Reactor Fuel During Storage, 2019.
[29] P. Högselius, Spent nuclear fuel policies in historical perspective: an international comparison, Energy Pol. 37 (1) (2009) 254–263.
[30] E. Amaral, K. Brockman, H.G. Forsström, International perspectives on spent fuel management, in: International Conference Management of Spent Fuel from Nuclear Power Reactors, 2006, pp. 17–29. Vienna.
[31] W. Goll, K. Nissen, G.L. Garner, D. Hoffmann, P. Dyck, Trends in dry spent fuel storage and transport in Germany and the United States of America, Management of Spent Fuel from Nuclear Power Reactors, Proc. Int. Conf. (2007).
[32] P.A. Brown, Canada's national policy on the long term management of nuclear fuel waste, Storage Spent Fuel Power React. 92 (2003).
[33] H.-W. Seo, W. Sohn, K.-H. Jo, Proposal for the spent nuclear fuel management plan from the decommissioning of Kori site NPPs, Ann. Nucl. Energy 120 (2018) 749–762.
[34] B.C. McLellan, Q. Zhang, N.A. Utama, H. Farzaneh, K.N. Ishihara, Analysis of Japan's post-Fukushima energy strategy, Energy Strateg. Rev. 2 (2) (2013) 190–198.
[35] B.H. Park, Assessment of spent nuclear fuel amounts to be managed based on disposal option in Republic of Korea, Ann. Nucl. Energy 109 (2017) 199–207.
[36] J. Václav, Power reactors spent fuel storage in Slovakia, Storage Spent Fuel Power React. (2003) 61.
[37] J.E. Martínez, J.A. Gago, An update on spent fuel and HLW management in Spain,, Storage Spent Fuel Power React. 64 (2003).
[38] M.M. Sediqi, A.M. Ibrahimi, M.S. Shah Danish, T. Senjyu, S. Chakraborty, P. Mandal, An optimization analysis of cross-border electricity trading between Afghanistan and its neighbor countries, IFAC-PapersOnLine 51 (28) (Jan. 2018) 25–30.
[39] F. Fiori, Z. Zhou, Sustainability of the Chinese nuclear expansion: natural uranium resources availability, Pu cycle, fuel utilization efficiency and spent fuel management, Ann. Nucl. Energy 83 (2015) 246–257.
[40] Y. Zhou, "China's spent nuclear fuel management: current practices and future strategies, Energy Pol. 39 (7) (2011) 4360–4369.
[41] J. Zhang, Z. Liu, L. Wang, Uranium demand and economic analysis of different nuclear fuel cycles in China, Energy Strateg. Rev. 9 (2016) 50–61.
[42] F. Fouquet, "Back End of the Nuclear Fuel Cycle: the French Choices," *IAEA Saf. Relat. Publ.*, p. 73.
[43] H.B. Kulkarni, R.S. Soni, K. Agarwal, Spent fuel storage in India, Storage Spent Fuel Power React. (2003) 30–36.
[44] P. Liu, P. Chu, J. Hou, Accommodation issue of nuclear power in China: status quo, barriers and solutions, Energy Strateg. Rev. 22 (2018) 166–178.
[45] R.B. Grover, Green growth and role of nuclear power: a perspective from India, Energy Strateg. Rev. 1 (4) (2013) 255–260.
[46] Y. Ikoma, Spent Fuel Management Strategy in Japan, 2003.
[47] V.M. Korotkevich, E.G. Kudryavtsev, Some aspects of the Russian nuclear fuel cycle development, Storage Spent Fuel Power React. 99 (2003).
[48] K. Yancey, P. V Tsvetkov, Quantification of U.S. spent fuel inventories in nuclear waste management, Ann. Nucl. Energy 72 (2014) 277–285.
[49] A.A.A.N. Steinberg, National policy in the area of spent fuel management in Ukraine: current status and trends, in: Storage of Spent Fuel from Power Reactors, 2003.
[50] China's Nuclear Export Strategy Clarifies and Concerns - Partnership for Global Security." .
[51] M. Auderoa, J. Sidelnikb, R. Versacia, A. Bevilacquaa, Management of spent fuel from power reactors in Argentina, Storage Spent Fuel Power React. 19 (2003).
[52] G. Buday, S. Szabo, M. Oerdoegh, F. Takats, Spent Fuel Dry Storage in Hungary, 1999.
[53] I. Krivova, P. Banisterb, New interim spent fuel storage facility at INPP, Storage Spent Fuel Power React. 111 (111.20) (2003) 37.
[54] B. Pellaud, "Multinational Approaches Relevant to Spent Fuel Management," *IAEA Saf. Relat. Publ.*, p. 41.
[55] T. Saegusa, K. Nagano, Spent fuel management: present and future, in: Management of Spent Fuel from Nuclear Power Reactors. Proceedings of an IAEA International Conference in Vienna, 2007, pp. 19–22. June 2006.
[56] M. Songa, C.-L. Kim, D.S. Kessel, Consideration of spent fuel pool island as an interim management option of spent nuclear fuel for Kori unit 3 & 4 during decommissioning of Kori site, Energy Strateg. Rev. 21 (2018) 163–171.
[57] J. Kastelein, Research reactor spent nuclear fuel, national practice for interim storage in The Netherlands, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.
[58] P.N. Standring, A.H.C. Callaghan, The storage of power development and research reactor fuel at sellafield, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.
[59] R. Mourao, Dual purpose cask for dry storage of research reactor spent fuel in Latin America, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[60] L. Dimitrovski, M. Anderson, Forty-Nine years of safe storage of research reactor spent fuel at Ansto, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[61] J. Rychecky, Management programme for research reactor spent nuclear fuel storage and interim storage facilities at Nuclear Research Institute Řež plc, Czech Republic, in: Management and Storage of Research Reactor Spent Nuclear Fuel, 2009.

[62] G.R. Sunaryo, D.S. Wisnubroto, Wet interim storage of research reactor spent fuel in Indonesia, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[63] M. Palomba, R. Rosa, The management of TRIGA spent fuel at ENEA RC-1 research reactor, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[64] P. V Chakrov, D.A. Nakipov, "Shipment of spent nuclear fuel from WWR-K research reactor, Kazakhstan, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[65] O. Diakov, KINR experience on storage of WWR-M research reactor spent fuel, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[66] J.W. Lian, R.W. Chapman, Dry storage of spent fuel discharged from research reactors in Canada, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[67] I.A.S.E.J. Salmenhaara, Spent fuel management and storage at the Finnish FiR TRIGA Reactor, in: Management and Storage of Research Reactor Spent Nuclear Fuel, 2009.

[68] M. Roder, Good practice of interim storage of RRSNF 1 inside Castor MTR-2 Flasks in Ahaus, Germany, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[69] S. Tozser, Wet and semi-dry storage of spent nuclear fuel at the Budapest research reactor, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[70] N. Ramesh, Experience on spent nuclear fuel handling and storage at research reactors of Trombay, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[71] C.S. Lee, I.C. Lim, M. Lee, Storage and management of spent fuel in Hanaro research reactor, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[72] B.C. Oberlander, P.I. Wethe, P. Bennett, Storage of research reactor spent fuel in Norway, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[73] A. Golab, Management and storage of research reactor Maria spent fuel, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[74] R.L.S.D.W. Vinson, N.C. Iyer, R.W. Deible, M.D. Shaffer, US Practice for Interim Wet Storage of Research Reactor Spent Nuclear Fuel, 2009.

[75] S.A. Baytelesov, F.R. Kungurov, A. Boltabaev, S. Alikulov, Study of tightness of spent fuel assemblies in storage of WWR-SM research reactor, in: Management and Storage of Research Reactor Spent Nuclear Fuel. Proceedings of a Technical Meeting, 2009.

[76] R. Ratiko, et al., Optimization of dry storage for spent fuel from G.A. Siwabessy nuclear research reactor, Int. J. Technol. (2018).

[77] R. Ratiko, N. Nasruddin, W. Wulandari, A. Rosidi, E. Marzuki, Multi-objective optimization of ventilation and air conditioning system at interim storage for spent nuclear fuel, in: 3rd International Conference on Power Generation Systems and Renewable Energy Technologies, 2018-Janua, PGSRET 2017, 2018, pp. 73–78.

[78] P.H. Liem, T.M. Sembiring, B. Arbie, I. Subki, Analysis of the optimal fuel composition for the Indonesian experimental power reactor, Kerntechnik 82 (1) (2017) 78–86.

[79] K. Artiani, P. A, R. Ratiko, Y. Purwanto, Heriyanto, Effect of radiation potection on dry storage of spent nuclear fuel for experimental power reactor, J. Pengemb. Energi Nukl. (2019).

[80] Nasruddin, M.I. Alhamid, Budihardjo, Ratiko, Contaminant dispersion analysis in interim storage for spent nuclear fuel building, in: The 14th International Conference on QIR (Quality in Research), 2015, pp. 450–456.

[81] P. Indonesia, Peraturan Pemerintah No. 27/2002 Tentang Pengelolaan Limbah Radioaktif, Jakarta, 2002.

[82] D.S. Wisnubroto, Policy and Strategy of Radioactive Waste Management of Indonesia, 2010.

[83] D. Sulistyani and A. Budiyanti, "Pemindahan Bahan Bakar Nuklir Bekas Dari Kolam Reaktor Ke Cask Transnuclear Material Testing Reactor.".

[84] K. Iman, T. Taryo, H. Hastowo, RRSNF shipment operation of Indonesia research reactors, in: IAEA-TECDOC-1593, Return of Research Reactor Spent Fuel to the Country, of Origin: Requirements for Technical and Administrative Preparations and National Experiences, 2006. Vienna.

[85] D.S. Wisnubroto, Strategy on the spent nuclear fuel management in Indonesia, J. Teknol. Pengelolaan Limbah 16 (2) (2013).

[86] S.G.R. Sunaryo, Spent fuel storage corrosion management, in: International Conference on Research Reactors: Safe Management and Effective Utilization, Rabat Morocco, 2011.

[87] P.T.L.R. BATAN, Laporan analisis Keselamatan KH-IPSB3, in: Pus. Teknol. Limbah RadioaktifRadioaktif, 2009.

[88] Sumarbagiono, Spent Fuel Storage Management in Indonesia, IAEA, Vienna, 2013.

[89] BATAN, AEA Engineering Contract, Transfer Channel and ISSF for BATAN, Preliminary Desgn Package, 1992.

[90] Z. Salimin, Transfer Panas Bahan Bakar Bekas Dalam sistem Penyimpanan sementara Tipe Basah PPTA Serpong, in: Seminar III Teknologi Dan Keselamatan PLTN Serta Fasilitas Nuklir, Serpong, Indonesia, 1995.

[91] Z. Salimin, Heat transfer analysis on the storage of spent fuel of Indonesia multi-purpose reactor-30 MW, in: International Topical Meeting on Nuclear Reactor Thermal Hydraulics Operations and Safety, Nara, Japan, 2004.

[92] D.S. Wisnusubroto, H. Zamroni, R. Sumarbagiono, G. Nurliati, Challenges of implementing the policy and strategy for management of radioactive waste and nuclear spent fuel in Indonesia, Nucl. Energy Technol. submitted (2020).

[93] IAEA, Criticality Safety in the Handling of Fissile Material, 2014.

[94] Budiyono, Titik Sundari, Parjono, Study on aging of transfer cannel –interim storage for spent fuel installation, Bul. Limbah 13 (1) (2016).

[95] Pungky Ayu Artiani, Mirawaty, Kuat Heriyanto, Sub-criticality analysis of spent fuel racks at TC-ISSF using aluminum, Urania 23 (2) (2017), 69–13.

[96] G.R. Sunaryo, D.E. Lestari, Water Chemistry Surveillance for Multipurpose Reactor 30MW GA Siwabessy, 2007. Indonesia.

[97] A.I. Ramadhan, A. Suwono, E. Umar, N.P. Tandian, Preliminary study for design core of nuclear research reactor of TRIGA Bandung using fuel element plate MTR, Eng. J. 21 (3) (2017) 173–181.

[98] P. Basuki, P.I. Yazid, Z. Suud, Desain Neutronik Konversi elemen Bakar Tipe Pelat pada Teras TRIGA 2000 Bandung (neutronic design of plate type fuel CONVERSION for Bandung TRIGA2000 reactor), J. Sains dan Teknol. Nukl. Indones. 15 (2) (2014) 69–79.

[99] J. Moriizumi Ratiko, H. Yamazawa, Nasruddin, Quantification of the impact of temperature difference between two connected indoor spaces on 222Rn concentration, Build. Environ. 149 (Feb. 2019) 322–329.

[100] P.H. Liem, T.M. Sembiring, H.-N. Tran, Evaluation on fuel cycle and loading scheme of the Indonesian experimental power reactor (RDE) design, Nucl. Eng. Des. 340 (2018) 245–259.

[101] P.H. Liem, H.-N. Tran, T.M. Sembiring, B. Arbie, I. Subki, Alternative fueling scheme for the Indonesian experimental power reactor (10 MWth Pebble-Bed HTGR), Energy Procedia 131 (2017) 69–76.