# Assessment of the Safety Design Features of Small Modular Reactors with existing demonstration plants using Reactor Technology Assessment (RTA)

UNICO A. BAUTISTA

Department of Science and Technology-Philippine Nuclear Research Institute

Quezon City, Philippines

uabautista@pnri.dost.gov.ph

MARK GINO E. ALIPERIO

Department of Science and Technology-Philippine Nuclear Research Institute

Quezon City, Philippines

RINLEE BUTCH M. CERVERA

Energy Engineering Program, University of the Philippines-Diliman

Quezon City, Philippines

JULIUS FEDERICO M. JECONG

Department of Science and Technology-Philippine Nuclear Research Institute

Quezon City, Philippines

NEIL RAYMUND D. GUILLERMO

Department of Science and Technology-Philippine Nuclear Research Institute

Quezon City, Philippines

**Abstract**

Small Modular Reactors (SMRs) are a promising solution for nuclear power generation, offering compactness and flexibility with capacities ranging from 10 to 300 MWe. Building on previous technical analyses [1], which examined SMRs with operational demonstration plants, this study focuses on evaluating their safety design features to address the existing knowledge gap in SMR safety. A Reactor Technology Assessment (RTA) was conducted to analyze the active, passive, and inherent safety systems of SMR designs, as documented in various publications by the International Atomic Energy Agency (IAEA). The findings highlight the nuclear safety strengths of the KLT-40s and HTR-PM reactors. Specifically, the KLT-40s demonstrates robust active safety systems and hazard protection, whereas the HTR-PM is distinguished by its inherent safety features, including the use of TRISO fuel, which earned it the highest safety score. This study will provide valuable insights for decision-makers involved in the development of the Philippines' nuclear power program.

## INTRODUCTION

SMRs are increasingly becoming a focal point in the Philippines and are a subject of national discussion. Known for their scalability and inherent safety features, they present a potential energy source for the country. When considering nuclear power generation, SMRs are viewed as one of the potential options alongside the possible rehabilitation of the Bataan Nuclear Power Plant (BNPP) or the adoption of more established technologies like conventional large nuclear reactors [2]. However, the existing literature on evaluating and comparing the various aspects of SMR technologies, particularly in terms of nuclear safety, remains limited. This gap highlights the need for more research and analysis to inform policy decisions in this field.

Most SMR designs are first-of-a-kind (FOAK) technologies, posing challenges to decision-makers [3, 4]. Although SMRs are marketed as the safest nuclear power technology available today, those currently in operation have limited operational experience, complicating their adoption and regulation. Unlike traditional large reactors that rely on active mechanical components, the general safety features of SMRs often depend on passive systems that use natural phenomena to maintain safe operating conditions. Understanding these safety features is critically important for all stakeholders, particularly those involved in policy and decision-making.

The International Atomic Energy Agency (IAEA) has developed the Reactor Technology Assessment (RTA) to aid member states in planning and decision-making and in evaluating various reactor technologies [5] . The use of the RTA is flexible, as it can be applied at different stages of the IAEA's Milestones Approach [6]. It can also serve as a guide in the development and implementation of a nuclear power program to ensure that all relevant and critical aspects of a technology are thoroughly considered and addressed. The RTA is used in this research to select the most appropriate reactor technology in the Philippines as perceived by local nuclear energy experts, with a specific focus on the nuclear safety design of SMRs.

This paper concentrates on specific SMR designs that have achieved significant milestones in their construction and operation. It aims to provide a general overview of these designs, focusing particularly on the aspects of nuclear safety integrated within their design. The SMR technologies discussed here are limited to those for which information and intellectual property are publicly accessible.

## SELECTED SMR DESIGNS WITH OPERATING DEMONSTrATION PLANtS

The IAEA extensively documents various SMR designs across its publications, serving as a foundation for this research [3, 7, 8, 9]. However, due to rapid advancements in SMR technology, the IAEA's publications may not always provide the latest information. Therefore, it is advisable to consult government websites, vendor publications, and independent nuclear engineering news platforms for timely updates on SMR activities in various countries. This study specifically focuses on designs that have been proven records that are completed and are currently operational worldwide. Notably, China's HTR-PM, a high-temperature gas-cooled reactor, has recently commenced commercial operations. Additionally, Russia's KLT-40S, a floating nuclear power plant, has been successfully connected to the grid and is now in commercial operation. Table 1 show the selected parameters of the two SMRs.

### KLT-40s

The KLT-40S reactor, developed by JSC “Afrikantov OKB Mechanical Engineering” (OKBM), is a compact pressurized water reactor (PWR) with a thermal capacity of 300 MWth and an electrical capacity of 70 MWe. Designed for use in floating nuclear power plants (FNPPs), the primary purpose of its development is to provide reliable and safe nuclear energy for remote regions and developing countries, including applications in district heating and seawater desalination. The KLT-40S builds on Russia's extensive experience with nuclear propulsion systems used in icebreakers and submarines, leveraging proven technologies to create a versatile and mobile energy solution [9].

The historical development of the KLT-40S reactor is rooted in the successful long-term operation of nuclear icebreakers and other marine vessels, which demonstrated the high performance and safety of OKBM's reactor designs. Key features of the KLT-40S include its modular layout, pressurized primary circuit, four-loop system with forced and natural coolant circulation, and passive safety systems. The safety design philosophy emphasizes inherent safety features, such as negative reactivity coefficients, high thermal conductivity of the fuel, and natural circulation flow, alongside a defence-in-depth strategy that includes both active and passive safety measures to prevent and mitigate accidents. The reactor's design ensures high reliability and a strong focus on minimizing environmental impact and enhancing proliferation resistance [9].

### Hight Temperature Gas-cooled Reactor Pebbled-bed Module (HTR-PM)

HTR-PM was developed by the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University in China. This modular reactor has a thermal capacity of 500 MWth and a gross electrical capacity of 211 MWe, derived from two reactor modules. Its main purpose of development is to serve as a demonstration power plant that showcases innovative small-sized reactor technology, aiming to enhance the efficiency, safety, and economic viability of nuclear power generation [8] .

The historical development of HTR-PM began in the 1970s with research on gas-cooled reactors in China, progressing through decades of R&D, international cooperation, and the establishment of the HTR-10 test reactor. Key features of HTR-PM include its use of helium coolant and graphite moderator, spherical low-enriched uranium fuel elements, and modular design for scalability. The safety design philosophy heavily emphasizes inherent safety features and passive safety systems, ensuring that maximum fuel temperatures remain within safe limits during accidents, thus preventing significant radioactive releases and eliminating the need for extensive emergency measures [8].

TABLE 1. SELECTED TECHNICAL PARAMETERS OF KLT-40S AND HTR-PM [7].

|  |  |  |
| --- | --- | --- |
| **Design Parameter** | **KLT-40S** | **HTR-PM** |
| Reactor Type | Pressurized Water Reactor (PWR) | Modular pebble bed HTGR |
| Fuel Type | Low-Enriched Uranium (LEU) | TRISO-coated particle fuel |
| Fuel Form | Fuel Assemblies | Spherical Pebbles |
| Coolant / Moderator | Light water / Light water | Helium Gas / Graphite |
| Thermal Power Output | 150 MWth | 2 × 250 MWth |
| Electric Power Output | 35 MWe | 210 MWe |
| Core inlet temperature | 280°C | 250°C |
| Core Outlet Temperature | 316°C | 750°C |
| Refueling cycle (months) | 30-36 | On-line Refueling |
| Seismic Design | 9 point on the MSK scale | 0.2 g |
| Deployment | Floating/Marine-Based | Land-based |

## NUCLEAR SAFETY AND DESIGN SAFETY FEATURES

Nuclear safety is an important aspect of nuclear power plants because it ensures the protection of workers, the public, and the environment. The design of SMRs incorporates multiple safety features based on the principle of 'defence in depth', which includes layers of physical barriers to prevent the release of radioactivity, and safety systems designed to maintain these barriers. The IAEA sets global safety standards that requires a comprehensive safety assessment and the application of proven engineering practices to achieve high safety margins [10]. These standards are refined over time, especially following significant nuclear events such as the Fukushima accident, to enhance safety and robustness of nuclear power plants.

The safety systems in a nuclear power plant can be categorized into active, passive, and inherent safety systems. Active safety systems depend on external power and control, using components like pumps, valves, and motors to execute safety functions. Examples include emergency core cooling systems (ECCS) that use pumps to inject coolant during accidents, reactor scram systems for rapid shutdowns, and backup power systems like diesel generators. In contrast, passive safety systems operate without external power, relying on natural forces such as gravity and natural circulation. These include gravity-driven coolant injection systems and passive heat removal systems that dissipate heat without active pumps. Inherent safety systems are built-in features that use physical laws like gravity and natural convection to ensure safety without active controls or human intervention, incorporating barriers for radioactive materials, redundant systems for critical functions, and passive safety features that automatically respond to specific conditions, thus enhancing the plant's overall safety and resilience. The design of SMRs may incorporate variations of these systems.

## SAFETY FEATURES OF KLT-40S AND HTR-PM

The KLT-40S reactor employs a comprehensive array of safety systems that include active, passive, and inherent mechanisms to ensure its safe operation. The active safety systems encompass reactor shutdown, emergency cooldown, emergency water supply, and filtration systems. Passive safety features include reactor shutdown, emergency cooldown, water supply, containment cooling, reactor vessel cooling, self-actuating devices, and containment. Inherent safety is ensured through negative reactivity coefficients, robust fuel composition, natural circulation, significant heat storage capacity, compact design, flow restrictors, the "leak before break" concept, and once-through steam generators. Together, these systems provide multiple layers of protection to maintain the reactor's stability and integrity under various operating conditions and potential accident scenarios.

The HTR-PM reactor integrates a blend of active, passive, and inherent safety systems to achieve high safety standards. Its active safety systems include a helium purification system, a reactor protection system, and the main helium blower. Passive safety features are engineered safety systems, heat removal systems, and a water discharge system. The inherent safety characteristics of HTR-PM focus on the retention of radioactive materials, efficient decay heat removal, and negative temperature reactivity feedback. These inherent safety features minimize the need for complex engineered safety systems, simplify safety management, and ensure that the reactor remains safe even under extreme conditions, thus significantly reducing the risk of significant radioactive releases. Table 2 summarises the safety features of KLT-40s and HTR-PM. The information was taken from the IAEA Advanced Reactor Information System (ARIS) [9, 8].

TABLE 2. SUMMARY OF SAFETY FEATURES OF KLT-40S AND HTR-PM.

|  |  |  |
| --- | --- | --- |
| **Type of safety systems** | **KLT-40s** | **HTR-PM** |
| Active | * Reactor Shutdown * Emergency Cooldown * Emergency Water Supply * Filtration System | * Helium Purification System * Reactor Protection System * Main Helium Blower |
| Passive | * Reactor Shutdown * Emergency Cooldown * Water Supply * Containment Cooling * Reactor Vessel Cooling * Self-Actuating Devices * Containment | * Engineered Safety Systems * Heat Removal * Water Discharge System |
| Inherent | * Negative Reactivity Coefficients * Fuel Composition * Natural Circulation * Heat Storage Capacity * Compact Design * Flow Restrictors * Leak Before Break Concept * Once-Through Steam Generators | * Retention of Radioactive Materials * Decay Heat Removal * Negative Temperature Reactivity Feedback |

## REACTOR TECHNOLOGY ASSESSMENT (RTA) METHOdoLOGY

The evaluation of the two SMR technologies was conducted using the Reactor Technology Assessment (RTA) methodology. RTA, developed by the IAEA, serves as a comprehensive guide for member states in identifying, evaluating, and selecting the most suitable nuclear technology options to meet their national energy requirements and nuclear policy objectives. The RTA framework includes ten Key Elements (KE), each defined by specific user and technical criteria, or Key Topics (KT). Each KE is defined by a varying number of KTs, and their importance is not uniformly distributed. The relative weights of each KE are determined by the specific priorities and needs of each country [5]. In this study, the rationale and weights were inputted by local nuclear engineers that have relatively strong background knowledge on nuclear power plants.

This study employs the RTA on the nuclear safety only, which is the key element 3 (KE3). Nuclear safety, as determined by local experts, is a critical factor in SMR technology selection. It encompasses considerations of nuclear power plant (NPP) operating conditions, accident prevention, and the mitigation of accident consequences, ultimately protecting workers, the public, and the environment from undue radiation hazards. KE3 is defined and described by twelve (12) user/technical criteria or key topics. Complete details and description of these key topics are found in this reference [5].

To quantify the weight values and scores for each Key Topic, a comprehensive review of the status reports for KLT-40s and HTR-PM was conducted. Local nuclear energy experts discussed and provided input for the rationale behind the weight values and scores. The importance values of the 12 Key Topics within the Nuclear Safety Key Element (KE3) were assigned by these experts, with corresponding justifications or rationales developed simultaneously. The total importance values for all Key Topics in KE3 sum up to 100%.

Each reactor technology is then evaluated on a scale from 1 to 5, where 1 indicates that the design least meets the rationale for scoring, and 5 indicates the best fit. The reactor technology that achieves the highest scores after evaluating all Key Topics is considered the most suitable in terms of Nuclear Safety.

## RESULTS AND DISCUSSION

Table 3 presents the results of the RTA applied SMRs with a focus on nuclear safety. The table includes the weight percentages assigned to 12 key topics, the scores for each SMR technology, and the weight percentages provided by local experts. The implementation of the defence-in-depth (DiD) philosophy received the highest weight percentage (20%) among other key topics. Following this, the completeness of operational limits and conditions (OLCs), safety analysis report (SAR), probabilistic safety assessment (PSA), operating and emergency procedures (O&EPs), and severe accident management guidelines (SAMGs) received a weight of 15%. Protection against internal and external hazards, results of deterministic safety analysis, and results of probabilistic safety assessment each received 10%. Other key topics not mentioned here received only 5%.

TABLE 3. RTA WEIGHT PERCENTAGE SCORE, SMR DESIGN SCORE, AND WEIGHTED SCORES OF THE KLT-40S AND HTR-PM.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **NUCLEAR SAFETY** | | **%** | **Scores** | | **Weighted Score** | |
| **Key Topics** | | **KLT-40S** | **HTR-PM** | **KLT-40s** | **HTR-PM** |
| **1** | Implementation of defence-in-depth (DiD) philosophy | 20 | 4 | 5 | 0.8 | 1 |
| **2** | Safety design philosophy | 5 | 3 | 5 | 0.15 | 0.25 |
| **3** | Degree of diversity and redundancy | 5 | 5 | 5 | 0.25 | 0.25 |
| **4** | Protection against internal and external hazards | 10 | 4 | 5 | 0.4 | 0.5 |
| **5** | Response to off-site power loss | 5 | 5 | 3 | 0.25 | 0.15 |
| **6** | Completeness of OLCs (operational limits and conditions), SAR (safety analysis report), PSA (probabilistic safety assessment), O&Eps (operating and emergency procedures), SAMGs (severe accident management guidelines) | 15 | 2 | 3 | 0.3 | 0.45 |
| **7** | Results of deterministic safety analysis | 10 | 1 | 1 | 0.1 | 0.1 |
| **8** | Results of probabilistic safety assessment | 10 | 1 | 1 | 0.1 | 0.1 |
| **9** | Mitigation of severe accidents | 5 | 3 | 5 | 0.15 | 0.25 |
| **10** | Operational expectations affecting safety | 5 | 4 | 3 | 0.2 | 0.15 |
| **11** | Fuel storage facility safety | 5 | 5 | 3 | 0.25 | 0.15 |
| **12** | Management system | 5 | 4 | 3 | 0.2 | 0.15 |
| **TOTAL PERCENTAGE:** | | **100** | **TOTAL SCORE:** | | **3.15** | **3.5** |

The rationale for the DiD philosophy receiving the highest percentage is that local experts believe DiD is of paramount importance and must be emphasized in the safety design and safety-related activities of small modular reactors (SMRs). The topics weighted at 15% and 10% are critical in the licensing process and are typically required to license a technology. The items receiving 5% are generally incorporated into SMR designs, making them manageable.

Since KLT-40S and HTR-PM are two different technologies, the scores they received are heavily based on the identified safety systems presented in Table 2 and the availability of publicly disclosed information. The strongest safety features of KLT-40S are its comprehensive implementation of defense-in-depth (DiD) philosophy and its robust design against internal and external hazards. Scoring 0.8 in DiD implementation and 0.4 in hazard protection, KLT-40S demonstrates significant capability in ensuring layered safety measures and resilience against potential threats. The reactor also performs well in terms of diversity and redundancy, with a score of 0.25, which indicates a strong presence of multiple, independent safety mechanisms to handle emergencies. Additionally, KLT-40S scores highly in response to off-site power loss (0.25), showing its ability to maintain essential safety functions during power outages. The reactor's fuel storage facility safety score of 0.25 reflects robust measures in place for managing spent fuel, further contributing to its safety profile. The overall management system score of 0.2 underscores a solid organizational framework supporting its safety operations.

Conversely, HTR-PM's most notable safety features include its high inherent safety design and emphasis on passive safety systems. It scores the highest in the implementation of the defense-in-depth (DiD) philosophy (1.0) and protection against internal and external hazards (0.5), showcasing its advanced safety architecture. The inherent safety features, such as effective decay heat removal and negative temperature reactivity feedback, are pivotal in maintaining safe conditions without relying heavily on active systems. HTR-PM also excels in the completeness of operational limits and conditions (OLCs), safety analysis report (SAR), probabilistic safety assessment (PSA), operating and emergency procedures (O&Eps), and severe accident management guidelines (SAMGs) with a score of 0.45, indicating thorough preparation and robust safety documentation. While it scores lower in fuel storage facility safety (0.15) and management system (0.15), its overall safety design philosophy and mitigation of severe accidents (0.25) reflect a well-rounded and resilient safety framework.

Both reactors have strengths in nuclear safety, but the KLT-40S excels in active safety systems and hazard protection, while the HTR-PM shines in inherent safety features and detailed safety documentation. The HTR-PM scores slightly higher overall, with 3.5 compared to the KLT-40S's 3.15. This result may be expected because the HTR-PM's design incorporates lesser number of passive safety features that operate without operator intervention, which can be crucial in preventing accidents before they escalate, as well as TRISO-fuel that is inherently safe.

However, the recent exclusion of non-water-cooled reactors, like the HTR-PM, from the list of proposed approved technologies in the Philippines poses a significant challenge. Despite its higher safety score, the HTR-PM cannot be deployed under the current proposed law [11]. This decision requires further review and should be supplemented with comprehensive data analysis to ensure that the opportunities offered by advanced SMR technologies are not overlooked.

## CONCLUSIONS

In this study, the nuclear safety systems of Small Modular Reactors (SMRs) with operating demonstration plants, specifically the KLT-40S and HTR-PM, were assessed. A literature review of the safety systems of these SMRs was conducted using the IAEA Advanced Reactor Information System. Local experts with extensive backgrounds and experience in nuclear engineering processed the information to formulate rationales and provide scores for the two SMR technologies as part of the Reactor Technology Assessment (RTA).

Both SMR technologies demonstrate notable strengths in nuclear safety. The KLT-40S excels in its comprehensive implementation of the defense-in-depth (DiD) philosophy and its robust design to withstand internal and external hazards. In contrast, the HTR-PM stands out for its high inherent safety design and extensive use of passive safety systems. Among the two, the HTR-PM received the highest score of 3.5, primarily due to its more advanced passive safety features that function without operator intervention, which is crucial for preventing accidents from escalating, as well as its strong inherent safety characteristics. While both SMRs exhibit substantial safety performance based on their reactor designs, another crucial aspect of nuclear safety, namely technology maturity, must also be considered. However, the maturity levels of these SMRs cannot be adequately evaluated due to the limited availability of publicly accessible information on this aspect, and this limitation will influence the final score.

The findings from this study, though derived from a limited pool of local experts and public sources, offer a preliminary basis for further discussion on evaluating SMR safety. It is also important to note that the RTA includes nine other key elements that need to be assessed, which may affect the overall evaluation and assessment process.

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