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Reimagining Nuclear Reactor Safety: The Study toward Passive Safety

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Abstract

Nuclear power has been at a crossroads for decades. Acclaimed for its massive, decarbonized energy production, it has also been questioned because of the disastrous possibility of mishaps. Nuclear power remains a vital component of the global energy mix, offering a low-carbon, high-capacity solution to growing energy demands. However, its widespread adoption has historically been tempered by public safety concerns, amplified by incidents like Chernobyl and Fukushima. Traditional reactor designs primarily rely on active safety systems, which require external power, complex machinery, and human intervention during emergencies. These incidents made it clear that safety measures must be both strong and naturally resistant to outside disturbances, device malfunctions, and human mistakes. This paper explores a paradigm shift in nuclear reactor safety: the integration of passive safety systems. These innovative designs leverage natural forces like gravity, convection, and pressure differentials to ensure reactor stability and cooling without the need for external power or human action, significantly enhancing inherent safety, reducing accident probability, and fostering greater public confidence. This transition is not merely an incremental improvement but a fundamental re-imagining of nuclear safety, paving the way for a more robust and publicly acceptable nuclear future. The design of nuclear reactors is being revolutionized by passive safety systems, an inventive method that uses the fundamental rules of physics to reduce accidents frequently without the need for outside assistance or human action.

Keywords: Passive safety, safety, nuclear reactor, core cooling, containment cooling

INTRODUCTION

For decades, nuclear power has stood at a crossroads. Lauded for its immense decarbonized energy output, it has simultaneously faced skepticism due to the catastrophic potential of accidents. The incidents at Three Mile Island, Chernobyl, and Fukushima Daiichi, although vastly different in their causes and outcomes, collectively highlighted critical vulnerabilities in reactor design and operational procedures. These events underscored the need for safety systems that are not only robust but also inherently resilient to human error, equipment failure, and external disruptions [1].

Traditional, or "active," safety systems typically rely on a complex network of pumps, valves, sensors, and electrical power. In an emergency, these systems require a series of precise actions, whether automated or human-initiated, to maintain the reactor control and cooling. Although these systems are highly redundant and rigorously tested, their reliance on external power sources, moving parts, and operator intervention introduces potential points of failure, particularly under extreme or unforeseen circumstances.

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The public's image of nuclear power is heavily influenced by the legacies of Chernobyl and Fukushima Daiichi. These disastrous incidents highlighted the urgent need for a new paradigm in nuclear safety and were caused by a combination of human mistakes, design defects, and outside natural calamities.

For many years, "active" systems have been the mainstay of nuclear reactor safety. To inject cooling water, shut down the reactor, and control radiation in an emergency, these depend on an intricate system of pumps, valves, motors, and electricity. Major reliance on external power sources and the possibility of human mistakes or mechanical failure under severe pressure were major weaknesses, despite their great degree of redundancy and support from several tiers of defense-in-depth.

The concept of passive safety systems represents a profound evolution in nuclear reactor design, as illustrated in Figure 1. Instead of actively driving safety functions, these systems harness immutable laws of physics to perform critical tasks such as reactor shutdown, core cooling, and containment heat removal. This design philosophy dramatically simplifies safety mechanisms, reduces dependence on external factors, and fundamentally alters the risk profile of nuclear power plants [2].

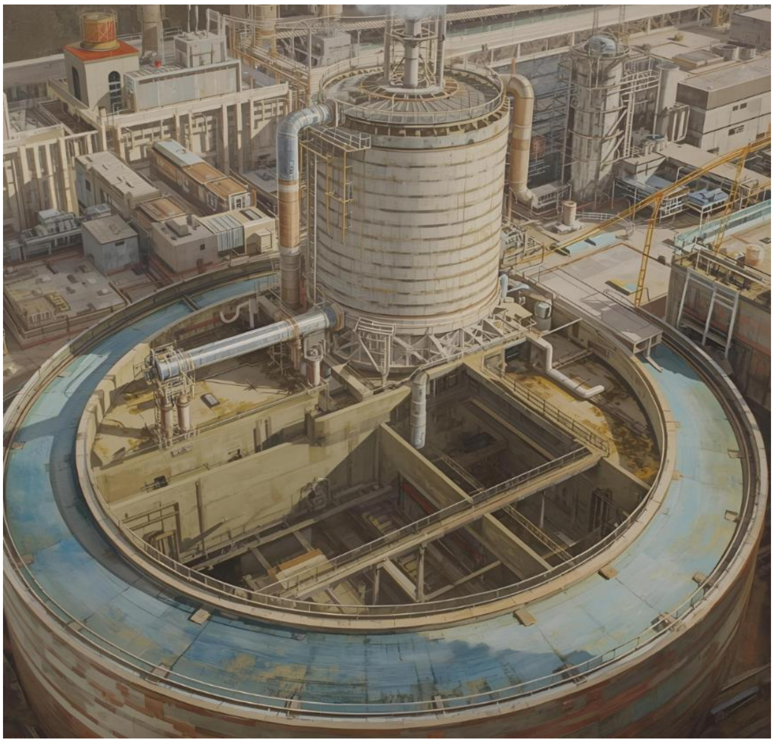

Figure 1. Passive safety in a nuclear reactor

How Passive Systems Work

Passive safety systems operate on principles such as:

1. *Gravity:* Water can be designed to flow into the core by gravity alone for emergency cooling, rather than by using pumps.
2. *Natural Circulation (Convection):* The heat generated in the reactor core can be dissipated through the natural circulation of fluids (such as water or air) as warmer fluids rise and cooler fluids fall, thereby creating a continuous flow without pumps.
3. *Pressure Differentials:* Differences in pressure can be utilized to drive fluids or gases; for instance, to inject borated water into the reactor to shut down the chain reaction.
4. *Stored Energy:* Energy stored in compressed gases or springs can be released to actuate valves or control rods, ensuring reactor shutdown.

5. *Heat Sinks:* Large volumes of water or air can absorb and dissipate residual heat from the reactor core or containment building over extended periods.

Examples in Modern Reactor Designs:

- *Westinghouse AP1000:* A prime example, AP1000, features a passive core cooling system (PXS) that uses gravity-driven flow and passive residual heat removal. Its passive containment cooling system (PCCS) utilizes the natural circulation of air and the evaporation of water from a large tank on top of the containment to provide long-term heat removal.
- *Small Modular Reactors (SMRs) like NuScale Power Module:* SMRs are at the forefront of passive safety integration. For instance, the NuScale design is self-contained within an existing water-filled pool. In an emergency, natural circulation drives the coolant through the core, and heat is passively transferred to the surrounding pool water, ensuring long-term cooling without the use of pumps or external power. These designs are often touted as "walk-away safe," meaning that they can maintain safety functions for extended periods without human intervention.
- *Advanced CANDU Reactor (ACR-1000):* This incorporates passive features for heat removal and shutdown, leveraging natural circulation.

The integration of passive safety systems offers a compelling suite of benefits:

1. *Enhanced Reliability:* By eliminating reliance on mechanical components, external power, and human intervention, passive systems are inherently more reliable. They are less susceptible to common-mode failures (where a single event disables multiple systems) and operator errors.
2. *Reduced Accident Probability:* The "fail-safe" nature of passive designs significantly lowers the probability of core damage and radioactive release, even under extreme accident scenarios.
3. *Simplified Design and Operation:* While initial design and validation can be complex, the operational simplicity of passive systems can reduce maintenance needs and streamline emergency procedures.
4. *Increased Public Confidence:* The concept of "inherent safety, " where a system naturally tends towards a safe state, resonates strongly with the public and aims to rebuild trust in nuclear technology.
5. *Enabling New Reactor Designs:* Passive safety is the cornerstone of many advanced reactor concepts, including SMRs, which promise greater flexibility, potentially lower capital costs, and suitability for smaller grids or remote locations. Their inherent safety makes them more palatable for deployment closer to population centers or industrial complexes.

While offering significant advantages, passive safety systems are not without their considerations:

- *Longer Response Times:* Some passive systems may have longer response times than their active counterparts, although they are designed to compensate for this through sustained, long-term operation.
- *Larger Footprint:* Certain passive systems, particularly those relying on natural circulation or large water pools for heat sinks, require more physical space.
- *Validation and Licensing:* Demonstrating the effectiveness and reliability of passive systems, especially novel designs, requires rigorous testing, computational modeling, and a comprehensive regulatory framework. However, this is a time-consuming and expensive process.
- *Public Education:* While the concept of "inherent safety" is powerful, effective communication is vital to explain these complex systems and their benefits to a non-technical audience.

Passive safety systems are more than just engineering advancements; they represent a fundamental shift in the philosophical approach to nuclear power. They embody a commitment to making nuclear energy not just safe, but *unconditionally* safe, removing human fallibility and external vulnerabilities from the critical safety chain [3, 4].

As the world grapples with climate change and the urgent need for reliable, low-carbon energy sources, nuclear power, underpinned by passive safety, is poised for a renaissance. The development and deployment of passively safe SMRs, in particular, holds immense promise for expanding the nuclear energy reach, offering flexible deployment options that can meet diverse global energy needs.

THE POWER OF PASSIVE SAFETY SYSTEMS IN NUCLEAR REACTORS

Nuclear power has long been lauded for its ability to produce large amounts of clean, carbon-free energy. However, the shadows of past incidents, particularly Chernobyl and Fukushima, highlight the paramount importance of safety. While active safety systems relying on pumps, valves, electricity, and human intervention have been the backbone of reactor design for decades, a new generation of "passive safety systems" is taking center stage, promising an even greater degree of resilience and inherent safety.

At its core, a passive safety system operates without external power, human operators, or active mechanical components. Instead, these systems harness natural forces such as gravity, natural circulation (convection), density differences, and stored energy to perform their safety functions [5].

Contrast this with Active Safety Systems:

- *Active Systems:* Requires external power (electricity, diesel generators), moving parts (pumps, motor-driven valves), and often operator action (initiating or monitoring). While highly reliable when all conditions are met, they are vulnerable to events like "station blackout" (loss of all AC power) or human error.
- *Passive Systems:* These are designed to operate in the event of power loss and without operator intervention. Their simplicity often translates to higher reliability because there are fewer components to fail and no external dependencies.

The push towards passive safety stems from several critical advantages:

1. *Enhanced Reliability:* By relying on fundamental physical laws rather than complex machinery, passive systems intrinsically have fewer failure points. No pumps to seize, no pipes to burst under dynamic pressure from rapid flow, and no electrical circuits to short.
2. *Increased Resilience to Station Blackout (SBO):* Events such as Fukushima have highlighted the vulnerability of active systems to prolonged loss of off-site and on-site AC power. Passive systems are designed to function precisely under extreme conditions, providing crucial cooling and control when traditional systems fail.
3. *Reduced Human Error:* Because passive systems are activated automatically and function without operator input, the potential for human error during high-stress accident scenarios is significantly reduced.
4. *Simplicity in Operation (Not Necessarily Design):* Although the engineering behind passive systems can be complex, their operational principle is often straightforward. They "just work" when the conditions dictate.
5. *Longer Grace Periods:* Passive systems can often maintain reactor safety for extended periods (days, not just hours) without intervention, thus providing more time for recovery efforts or external assistance.
6. *Improved Public Perception:* The concept of an "inherently safe" or "walk-away safe" reactor, where fundamental physics ensures safety even in extreme scenarios, can help rebuild public trust in nuclear power.

Passive safety systems address the same critical safety functions as their active counterparts, that is, reactivity control, core cooling, and radionuclide containment.

1. *Passive Core Cooling/Decay Heat Removal*
   - *Natural Circulation:* Heat from the reactor core causes coolant (water) to expand and rise. As it rises, it transfers heat to a cooler region (e.g., a heat exchanger or a water pool), cools, becomes denser, and sinks back down to the core, creating a continuous, self-sustaining circulation loop. This is often used for decay-heat removal, which continues for days after reactor shutdown.

   - *Gravity-Driven Core Flooding/Injection:* Elevated tanks containing borated water were positioned above the reactor core. In an emergency (e.g., depressurization or loss of coolant), valves open automatically (e.g., by spring action or pressure differential), and gravity pushes the water into the core to keep it covered and cool. Examples include Core Makeup Tanks (CMTs) and accumulators.
2. *Passive Reactivity Control*
   - *Gravity-Driven Control Rod Insertion:* In the event of a reactor trip, control rods that absorb neutrons and shut down the fission chain reaction are designed to drop into the core by gravity when their electromagnets release them. This is a fundamental and highly reliable feature of passive safety.
3. *Passive Containment Cooling*
   - *Passive Containment Heat Removal (PCHR):* Some designs utilize large water tanks located above a containment building. In an accident, water from these tanks is released and flows by gravity down the outside of the steel containment vessel. Evaporative cooling from this water removes heat from the containment atmosphere, maintains pressure, and prevents structural damage. Westinghouse AP1000 is a prime example of such technology.
   - *Pressure Suppression Pools:* In boiling water reactors (BWRs), steam released during an accident is routed through vents into a large pool of water (the suppression pool). The steam condenses, reducing the pressure within the containment and limiting the release of radioactive materials.

Several advanced reactor designs are heavily reliant on passive safety features:

- *Westinghouse AP1000:* A Pressurized Water Reactor (PWR), which is a poster child for passive safety. It features passive core cooling (using gravity-driven tanks), passive containment cooling (external water spray), and passive residual-heat removal.
- *GE Hitachi ESBWR (Economic Simplified Boiling Water Reactor):* An advanced BWR design that uses passive systems for all emergency core cooling and decay heat removal. It relies on natural circulation for normal operation, further simplifying its design by eliminating the need for large recirculation pumps.
- *Korea's APR+ and China's CAP1400:* These next-generation designs also incorporate enhanced passive features, building on existing technologies.

Although passive systems offer significant advantages, their implementation is not without challenges. Validating their performance, especially for large-scale natural phenomena, can be complex and requires extensive testing and sophisticated modeling. Integrating them seamlessly with the existing active systems requires meticulous engineering.

Despite these challenges, the trend towards incorporating more passive safety features into nuclear reactor designs is clear and strong. Future reactors will likely be hybrid systems that combine the best aspects of both active and passive technologies to create layers of defense depth. These silent guardians, who harness the fundamental laws of physics, represent a crucial step forward in making nuclear power even safer, more resilient, and a more widely accepted solution for the world's energy needs [6].

THE SILENT GUARDIANS: DESIGNING PASSIVE SAFETY SYSTEMS FOR NUCLEAR REACTOR SAFETY

For decades, nuclear power has stood as a double-edged sword: a source of immense carbon-free energy, yet shadowed by the catastrophic potential of uncontrolled reactions. The industry's evolution has been a relentless pursuit of enhanced safety, moving beyond mere containment to inherent resilience against the unforeseen. At the forefront of this paradigm shift is the design of *passive safety systems*, a revolutionary approach that harnesses natural forces to protect nuclear reactors even in the event of extreme emergencies [7].

The safety of traditional nuclear reactors relies heavily on *active safety systems***.** These are typically electromechanical components, such as pumps, valves, diesel generators, and intricate control circuitry, designed to kick in during anomalies. Their effectiveness depends on the external power, human intervention, and precise operational choreography. While highly redundant and rigorously tested, events such as the Fukushima Daiichi accident, where the loss of off-site power and backup generators crippled active cooling systems, highlighted an inherent vulnerability: their dependence on external resources and complex sequences of operation.

Passive safety systems represent a profound philosophical departure. Instead of *forcing* a reactor into a safe state, they are designed to *default* to one using inherent physical phenomena. They require no external power, no operator action (beyond the initial arming in some cases), and are less susceptible to common-mode failures that can disable multiple active systems simultaneously. Their "fail-safe" nature means that if power is lost or a component malfunctions, the system naturally trends towards a safe configuration.

The brilliance of passive safety lies in its elegant simplicity, which leverages the fundamental laws of physics:

1. *Natural Circulation (Convection):* Hot fluids are less dense and rise, while cooler and denser fluids sink. This principle was harnessed to remove decay heat from the reactor core. As the coolant heats up by passing through the core, it naturally rises, flows through a heat exchanger (e.g., a pool of water or reactor vessel walls), cools down, and then sinks back to the core. This creates a continuous, self-sustaining circulation loop without pumps.
2. *Gravity:* The most straightforward force, gravity, was used to deliver cooling water or boron-rich solutions to the reactor core. Elevated tanks of water, such as the In-containment Refueling Water Storage Tank (IRWST) in advanced PWRs, can passively flood the core when required by simply opening a valve.
3. *Differential Pressure:* Pressure differences can drive fluids from a high-pressure zone to a low-pressure zone. This can be used to inject coolant or open/close certain valves automatically as the system pressure changes.
4. *Heat Sinks:* Large volumes of water or the ambient environment can act as passive heat sinks. The heat generated by the reactor core, even after shutdown, can be transferred to these sinks through natural convection or conduction, thereby preventing overheating.
5. *Inherent Material Properties:* Some reactor designs leverage the intrinsic properties of the materials. For instance, negative temperature coefficients of reactivity mean that, as a reactor core heats up, its power naturally decreases, providing an inherent, self-regulating safety mechanism.

Modern reactor designs, particularly advanced light-water reactors (LWRs) and small modular reactors (SMRs), integrate passive safety features extensively.

- *Passive Core Cooling System (PCCS):* utilizes elevated water tanks (like the AP1000s IRWST) to gravity-feed water into the core during a Loss-of-Coolant Accident (LOCA).
- *Passive Residual Heat Removal (PRHR) System:* In reactors such as the AP1000, heat exchangers submerged in large water pools (the IRWST) remove decay heat from the primary coolant system through natural circulation, condensing steam, and returning water to the reactor.
- *Passive Containment Cooling System (PCCS):* In some designs (e.g., AP1000, ESBWR), water is passively directed to cool the exterior of the containment vessel, condense steam within, and ensure the integrity of the containment. Water can be held in tanks above the containment and sprayed over its surface, with the resulting steam vented to the atmosphere and the cooled water recirculated.
- *Isolation Condensers (ICs):* In boiling water reactors (BWRs), these systems condense steam from the reactor vessel by transferring heat to a surrounding pool of water, returning the condensed water to the reactor via gravity, thus removing decay heat without pumps.

- *Gravity-Driven Core Cooling System (GDCS):* Another BWR innovation in which water from elevated pools is directly injected into the reactor vessel via gravity following a depressurization event.

Beyond LWRs, Generation IV reactor concepts and SMRs often consider passive safety to an even higher level, aiming for "walk-away safe" designs. High-Temperature Gas-cooled Reactors (HTGRs), for example, rely on large thermal masses and robust fuel forms to inherently manage heat, even without active cooling for extended periods. NuScale's SMR design features an integrated primary system that sits within a large pool of water, leveraging natural circulation for decay heat removal and inherent safety [8–10].

The benefits of passive safety systems are compelling:

- *Enhanced Reliability:* Fewer moving parts, less reliance on external power or human action, and simpler mechanics lead to higher intrinsic reliability.
- *Reduced Accident Progression:* Slower response times are often offset by the system's ability to operate autonomously for extended periods (e.g., 72 h for the AP1000), buying critical time for intervention or recovery.
- *Improved Public Confidence:* The inherent safety features offer a strong narrative of resilience, addressing public concerns about nuclear risk.
- *Lower Operational Costs:* Simple systems can lead to reduced maintenance, operational staffing, and training requirements.
- *Defense-in-Depth Enhancement:* They add an entirely new layer of protection, complement active systems, and significantly reduce the core damage frequency.

However, designing passive systems is not without its challenges:

- *Slower Response:* By nature, systems driven by natural forces can react more slowly than high-capacity active pumps. This requires a careful initial design to ensure that transient events can be managed.
- *Limited Capacity:* Compared to active systems, passive systems may have a lower absolute heat removal or water injection capacity, necessitating careful sizing and often meaning that they are designed for post-shutdown decay heat rather than full-power operation.
- *Complex Analysis:* Proving the efficacy and performance of passive systems often requires sophisticated computational fluid dynamics (CFD) and thermal-hydraulic analyses, as natural phenomena can be difficult to model precisely.
- *Regulatory Acceptance:* As a newer paradigm, gaining regulatory approval can sometimes take longer, as regulators adapt their frameworks to evaluate these innovative designs.

The design of passive safety systems is no longer a theoretical exercise; rather, it is a fundamental pillar of modern nuclear reactor development. As the world seeks to decarbonize its energy supply, nuclear power offers a viable path, and passive safety systems are instrumental in building public trust and regulatory confidence required for its expansion. They represent a commitment to inherent safety, moving nuclear energy closer to a future where reactors are not just powerful, but also, in the words of engineers, "gracefully safe." These silent guardians are indeed the future of nuclear safety, ensuring that the power of the atom can be harnessed responsibly for future generations.

DISCUSSION

The shadow of Chernobyl and Fukushima Daiichi looms large in the public perception of nuclear power. These catastrophic events, driven by a confluence of design flaws, human errors, and external natural disasters, underscored the critical need for a new paradigm in nuclear safety. Enter *passive safety systems* – An innovative approach that leverages the fundamental laws of physics to mitigate accidents, often without human intervention or external power, transforming the architecture of nuclear reactor design.

Moving Beyond Active Reliance: The Evolution of Safety

For decades, nuclear reactor safety was primarily built upon "active" systems. These rely on a complex network of pumps, valves, motors, and electrical power to inject cooling water, shut down the reactor, and contain radioactivity during emergencies. While highly redundant and backed by multiple layers of defense-in-depth, their Achilles' heel lies in their dependence on external power sources and the potential for human error or mechanical failure under extreme duress.

In particular, the Fukushima incident highlighted this vulnerability. The earthquake and tsunami crippled the power supply of active cooling systems, leading to core meltdowns. It was a stark reminder that even robust active systems could fail if the infrastructure supporting them was compromised.

This realization spurred a global push towards inherently safer designs, where safety is not just an add-on, but an intrinsic characteristic of the reactor's fundamental operation.

At its core, a passive safety system relies on *natural phenomena* such as:

- *Gravity:* Water reservoirs positioned above the reactor core can passively drain to provide cooling.
- *Natural Convection/Circulation:* Heat naturally rises, creating convection currents that can cool the components or circulate fluids without pumps.
- *Pressure Differentials:* Differences in pressure can drive fluid flow or actuate safety valves.
- *Stored Energy:* Compressed gases or springs can release stored energy to activate mechanisms.

Crucially, these systems require *no external power, no active pumps or valves, and no immediate human intervention* to initiate their safety function. They are self-activating and rely on predictable behavior in the physical world.

Several advanced reactor designs, particularly the "Generation III+" reactors and emerging Small Modular Reactors (SMRs), have extensively integrated passive safety features.

1. *Passive Core Cooling:* Instead of relying on pumps to inject emergency cooling water, designs such as Westinghouse's AP1000 feature large water tanks (e.g., the in-containment refueling water storage tank (IRWST) located high above the reactor vessel). In an accident scenario, gravity automatically feeds this water into the core, cooling the fuel and preventing a meltdown without any active pumping.
2. *Passive Containment Cooling:* The AP1000 utilizes a passive system to cool its robust steel containment vessel. In an emergency, water from a rooftop tank flows by gravity down the outside of the containment shell, where it evaporates, dissipates heat, and maintains the containment integrity. Air circulation around the containment further aids this natural cooling process.
3. *Passive Heat Removal from Spent Fuel Pools:* Similar principles can be applied for spent fuel storage. Natural circulation loops or heat pipes can continuously remove decay heat from spent fuel, preventing overheating, even in a station blackout.
4. *Automatic Depressurization Systems (ADS):* These systems automatically vent steam from the reactor vessel if pressure builds up, allowing gravity-fed water from low-pressure sources to enter the core more easily.

The integration of passive systems offers a multitude of benefits:

- *Inherent Safety:* By relying on fundamental physics, these systems are designed to prevent core damage or large radioactive releases by default, responding to off-normal conditions automatically.
- *Reduced Complexity:* Fewer mechanical parts, less piping, and simpler control logic result in fewer potential points of failure and reduced maintenance requirements.
- *Lower Operational Costs:* Less reliance on active components translates to lower energy consumption and reduced staffing requirements for operation and maintenance.

- *Faster Response:* Because they do not require human decision-making or power-up sequences, passive systems can begin their safety function almost instantaneously.
- *Enhanced Public Confidence:* The "inherent safety" aspect directly addresses public concerns about catastrophic accidents, offering a more robust and intuitive safety argument.
- *Resilience to External Events:* Their independence from external power grids makes them highly resilient to extreme natural disasters or cyberattacks, which could cripple active systems.

Although passive safety represents a significant leap forward, its implementation is not without challenges. The initial design and engineering of these systems can be more complex, requiring sophisticated modeling and validation to ensure their efficacy under all potential accident scenarios. Proving the reliability of systems that do not involve traditional "on-off" controls can also be a unique regulatory hurdle.

However, the future of nuclear power is becoming increasingly intertwined with passive safety. Small Modular Reactors (SMRs), with their compact size and standardized designs, are particularly well suited for passive safety integration, offering a path to scaled deployment and further cost reduction. Fourth-generation reactor designs are also being developed with inherent passive safety as the foundational principle, pushing the boundaries of what is possible.

In an era that demands reliable, carbon-free energy, nuclear power is a vital solution. By embracing the elegance and robustness of passive safety systems, the industry is not just building safer reactors; it is also rebuilding trust and laying the groundwork for a more secure and sustainable energy future. Silent guardians of passive safety are poised to be the bedrock upon which the next generation of nuclear energy will thrive.

CONCLUSION

The evolution of nuclear reactor safety, marked by the increasing adoption of passive safety systems, represents a transformative leap forward in the industry. By leveraging the fundamental laws of nature, these innovative designs create reactors that are inherently more reliable, resilient, and virtually immune to external failures and human errors that have plagued earlier generations. This paradigm shift addresses the root causes of public apprehension by dramatically reducing the probability and potential consequences of severe accidents, making nuclear power fundamentally "walk-away safe." In an era demanding clean, continuous power, passive safety systems are not merely enhancements; they are the bedrock upon which a safer, more sustainable, and publicly acceptable nuclear future can be built. Their continued development and widespread integration are crucial for unlocking the potential of nuclear energy as a cornerstone of global decarbonization efforts, ultimately fostering renewed confidence in this indispensable energy source.

REFERENCES

1. Mulani K, Shaikh HT, Liyakat KKS. Nuclear power generation using UO_2 materials. J Adv Electr Eng Devices. 2025;3(2):27–40.
2. Mulla NR, Liyakat KKS. Nuclear energy: Powering the future or a risky relic. Int J Sustain Energy Thermoelectr Gener. 2025;1(1):52–63.
3. Kazi DK, Gaikwad A, Chendke A, Mulani N, Sarika M. Submersible pump theft indicator. IEJRD Int Multidiscip J [Internet]. 2020 May 14 [cited 2025 Dec 11];5(4):1-5. Available from: https://iejrd.com/index.php/iejrd/article/view/627
4. Raut MA, Mali MM, K Kutubuddin. Bagasse level monitoring system. Int J Trend Sci Res Dev. 2018;2:1657–1659. doi:10.31142/ijtsrd11469.
5. Hotkar PR, Kulkarni V, et al. Implementation of low power and area efficient carry select adder. Int J Res Eng Sci Manag. 2019;2(4):183–184.
6. Kazi KS. Detection of malicious nodes in IoT networks based on throughput and ML. J Electr Power Syst Eng. 2023;9(1):22–29.

7. Karale N, Jadhav S, et al. Design of vehicle system using CAN protocol. Int J Res Appl Sci Eng Technol. 2020;8(5):1978–1983.
8. Kazi K. Lassar methodology for network intrusion detection. Sch Res J Humanit Sci Engl Lang. 2017;4(24):6853–6861.
9. Verma A, Djokić D. Reimagining nuclear engineering. Issues Sci Technol. 2021;37(3):64–69.
10. Aswal DK, Chandra A. Reimagining exclusion zones for enabling SMR deployment in India's nuclear future. J Radiol Prot. 2025;45(3):034001. doi:10.1088/1361-6498/adf972. PubMed: 40780221.