

NUCLEAR ENERGY SAFETY: MODERN TRENDS AND TECHNOLOGICAL APPROACHES

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ANNOTATION

The study focuses on contemporary trends and technological solutions aimed at enhancing nuclear energy safety. It reviews recent advancements in reactor engineering, digital protection systems, and risk assessment techniques designed to prevent accidents and reduce environmental risks. Particular emphasis is placed on passive safety mechanisms, next-generation small modular reactors (SMRs), and the use of artificial intelligence for predictive maintenance and rapid emergency response. Additionally, the research underscores the significance of international safety standards and regulatory frameworks in guiding the development of the nuclear sector. Ultimately, the work highlights how technological progress and global collaboration are essential for building a safe and sustainable nuclear energy future.

Keywords: Nuclear energy safety, modern trends, technological approaches, passive safety systems, small modular reactors, risk assessment, artificial intelligence, emergency response, international standards, sustainable energy.

БЕЗОПАСНОСТЬ ЯДЕРНОЙ ЭНЕРГЕТИКИ: СОВРЕМЕННЫЕ ТЕНДЕНЦИИ И ТЕХНОЛОГИЧЕСКИЕ ПОДХОДЫ

АННОТАЦИЯ

В исследовании рассматриваются современные тенденции и технологические решения, направленные на повышение безопасности ядерной энергетики. В нем рассматриваются последние достижения в области реакторостроения, цифровых систем защиты и методов оценки рисков, направленных на предотвращение аварий и снижение экологических рисков. Особое внимание уделяется пассивным механизмам безопасности, малым модульным реакторам (ММР) нового поколения и использованию искусственного интеллекта для предиктивного обслуживания и быстрого реагирования на аварийные ситуации. Кроме того, в исследовании подчеркивается важность международных стандартов безопасности и нормативно-правовой базы для руководства развитием атомной отрасли. В конечном счете, в работе подчеркивается, насколько технологический прогресс и глобальное сотрудничество необходимы для построения безопасного и устойчивого будущего ядерной энергетики.

Ключевые слова: Безопасность ядерной энергетики, современные тенденции, технологические подходы, пассивные системы безопасности, малые модульные реакторы, оценка рисков, искусственный интеллект, реагирование на аварийные ситуации, международные стандарты, устойчивая энергетика.

INTRODUCTION

Nuclear energy remains essential in addressing the world's increasing need for clean, reliable electricity while contributing to the reduction of greenhouse gas emissions. Nevertheless, its use has consistently raised safety concerns due to potential hazards such as radiation exposure, reactor accidents, and long-term waste disposal challenges. Historical events like Chernobyl and Fukushima have highlighted the necessity for ongoing advancements in nuclear safety technologies and regulatory practices.

In recent years, major strides have been made toward enhancing the safety of nuclear power plants. Key developments include advanced reactor designs equipped with inherent and passive safety features, the integration of digital monitoring and control systems, and the application of artificial intelligence for predictive risk assessment and early fault detection. Additionally, the emergence of small modular reactors (SMRs) and the reinforcement of international safety regulations are driving a new era in nuclear energy focused on minimizing hazards while improving efficiency and sustainability.

This study explores current trends and technological innovations in nuclear energy safety, emphasizing the role of modern technology, regulatory oversight, and global collaboration in building a safer and more resilient nuclear power sector.

DISCUSSION AND RESULTS

Over the past twenty years, nuclear energy safety has experienced substantial changes driven by technological innovation, evolving regulations, and insights gained from past nuclear accidents. A key development has been the move toward passive safety systems, which utilize natural physical processes—such as gravity and convection—to maintain reactor cooling in emergencies, reducing reliance on active mechanical systems or human intervention.

Another major advancement is the rise of Small Modular Reactors (SMRs), offering improved safety through smaller reactor cores, standardized factory production, and simplified configurations that lower the risk of accidents. Their modular design allows phased capacity expansion and provides deployment flexibility while upholding rigorous safety standards.

Moreover, digitalization and automation have become integral to modern nuclear facilities, enabling real-time system monitoring, rapid detection of irregularities, and data-driven decision-making during critical events.

The review of these technological trends reveals several important outcomes. The adoption of passive safety mechanisms marks a fundamental shift in reactor safety philosophy, enhancing reliability under extreme conditions while reducing emergency response complexity and cost. Similarly, the deployment of SMRs and other advanced reactor technologies, such as Molten Salt Reactors and Fast Neutron Reactors, shows great potential for both safety improvements and cost-effectiveness. Their innovative design features—such as low operating pressure, compact reactor cores, and simplified cooling systems—significantly decrease the risk of core damage or radioactive release. Pilot projects and feasibility assessments suggest these systems could see large-scale implementation within the next two decades.

In addition, integrating artificial intelligence (AI) and digital twin technologies into nuclear energy systems has enhanced predictive maintenance, risk forecasting, and operational monitoring. Evidence from real-world nuclear facilities indicates that predictive analytics can identify potential system failures before they occur, cutting unplanned outages and operational risks by as much as 30%.

On a global scale, organizations such as the International Atomic Energy Agency (IAEA) have played a crucial role in advancing safety by promoting standardized regulations, peer reviews, and international knowledge exchange. Reports from the World Nuclear Association show a measurable decrease in significant safety incidents, coinciding with the adoption of modern safety technologies and strengthened global oversight.

Finally, research on public opinion demonstrates that combining technological innovation with transparent risk communication fosters greater societal trust in nuclear energy. This factor is essential for expanding nuclear power's role in achieving long-term global decarbonization objectives.

CONCLUSION

The analysis of current trends and technological strategies in nuclear energy safety shows that considerable progress has been made toward developing a safer and more sustainable nuclear power sector. The adoption of passive safety systems, advanced reactor designs, and digital technologies has lowered the risk of severe accidents while enhancing operational efficiency and reliability. Innovations such as Small Modular Reactors (SMRs), digital twins, and AI-based predictive maintenance are driving a new generation of nuclear facilities that are both safer and more flexible in meeting evolving energy demands.

Equally crucial is the influence of international collaboration and regulatory frameworks, which promote the standardization of safety practices and facilitate the global exchange of best practices. These efforts help build public confidence in nuclear energy as a credible and sustainable option for achieving global decarbonization goals. In summary, the findings suggest that combining technological advancement with robust governance and transparent communication can effectively address long-standing safety concerns in nuclear power. With continued innovation and cooperation, nuclear energy is positioned to play a central role in a secure, low-carbon, and sustainable energy future.

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