Int. j. adv. multidisc. res. stud. 2026; 6(1):1345-1350

Received: 04-12-2025
Accepted: 14-01-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

A Comprehensive Review on the Safety of TRIGA Research Reactors

Md Altaf Hossen
Reactor Physics and Engineering Division, Institute of Nuclear Science and Technology, Bangladesh Atomic Energy Commission, Dhaka, Bangladesh

Corresponding Author: **Md Altaf Hossen**

Abstract
The TRIGA (Training, Research, Isotopes, General Atomics) type research reactor is a well-known design worldwide, widely recognized for its outstanding safety and operational capabilities. In this paper, the safety aspects of TRIGA reactor systems are reviewed in detail with respect to their design philosophy, fuel properties, thermal hydraulics and control systems. It also considers the regulatory environment, incident analysis, upgrading efforts and consequences of old infrastructures. One of the safety features is the UZrH fuel's strong negative temperature coefficient of reactivity, which allows for safe pulse operations and regulation of power. By consolidating global operational experience, safety evaluations and technological developments, this review highlights TRIGA's impressive safety history and continued relevance as a tool for nuclear research and training.

Keywords: TRIGA, Thermal Hydraulics, Safety

1. Introduction

Research reactors serve as central in advancing both scientific research and industrial application, and they support many fields such as neutron activation analysis, radioisotope production, materials testing, and nuclear engineering education [1]. Among them, the TRIGA (Training, Research, Isotopes, General Atomics) reactor has come to be well known as a world standard of versatility and safety and thereby is a favorite among national laboratories, universities, and developing nations [2]. Fig 1 shows three different versions of TRIGA reactors.

Fig 1: TRIGA Mark I, II and III reactor

Developed in the late 1950s by General Atomics, the TRIGA reactor introduced a revolution with its uranium-zirconium-hydride (U-ZrH) fuel. The fuel has an immediate negative temperature coefficient of reactivity, i.e., fuel temperature increases, the reactor power gets automatically suppressed. This self-limiting feature is one of the most important nuclear reactor safety advancements ever achieved, enabling TRIGA systems to achieve power pulses safely that would be dangerous in conventional reactors [3].

Safety of research nuclear reactors depends on the collective interaction among the impacts of physics, fuel material properties, engineered systems, operating practices, and regulatory arrangements [4]. TRIGA reactors integrate these factors in an effective manner with inherent safety characteristics, passive cooling, and redundancy that reduce dependence on operator intervention and mechanical complexity. Fig 2 illustrates different TRIGA reactor core cross-sections.

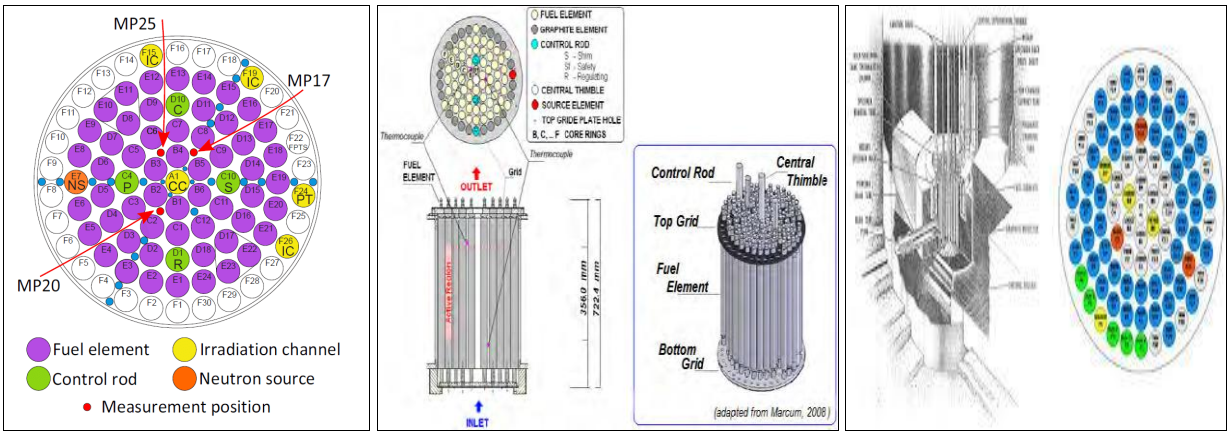

Fig 2: TRIGA core cross-section

Over years of operation, TRIGA reactors have demonstrated a flawless record of safety while having reached maturity through improvements such as computer instrumentation, enhanced monitoring, and revised safety standards. They remain today the focal point of isotope production, scientific research, and training and remain one of the most reliable and extensively used research reactor designs. This review examines the safety principles, operating performance, problems, and modernization of TRIGA reactors on the basis of decades of experimental experience and worldwide practice.

2. Key Safety Principles of TRIGA Reactors

The inherent safety of nuclear reactors has been a top consideration in their design and operation for decades, the TRIGA reactor being marked by an innovative approach to passive safety. Developed in the late 1950s, the TRIGA design incorporated uranium–zirconium–hydride (UZrH) fuel, the properties of which remain the basis of its safety design.

The distinctive feature of UZrH fuel is its very high prompt negative temperature coefficient of reactivity [5]. At low temperatures, hydrogen within the hydride lattice enhances neutron moderation, but as temperature rises, such moderation falls, significantly reducing reactivity. This feedback occurs in milliseconds, thereby allowing the reactor to react to power excursions and avoid prompt criticality with minimal reliance on active control systems. The result is a reactor that is self-controlling in its characteristics, something that made TRIGA different from the conventional reactor designs of the time.

This characteristic also allowed one of the reactor's most unusual features: safe pulsing, where TRIGA reactors are able to generate brief bursts of power up to hundreds of megawatts without jeopardizing the core or humans [6]. This ability, extensively utilized in experiments and isotope production, further enhanced their role as multi-purpose research tools [7]. The same feedback system assists steady-state operation by regulating power oscillations due to changes in fuel temperature or control rod movement, further reducing the task of operating the reactor.

The UZrH fuel was also made long-lasting. Composed of low-enriched uranium (up to 20%) homogeneously mixed with zirconium hydride and coated in stainless steel, the fuel contains fissile content and moderator within a single matrix [8]. The high hydrogen density in zirconium hydride ensures efficient neutron moderation, a key factor in the fuel's negative temperature coefficient—a safety feature that inherently stabilizes reactor performance [9]. This offers effective neutron economy, better thermal conductivity, and mechanical stability during irradiation and pulsed conditions. Post-irradiation testing has shown its dimensional integrity and toughness during thermal cycling, crucial factors for continued safe and reliable operation [10].

Finally, TRIGA fuel cores were made to accommodate these fuel properties. Typically configured as a close-packed lattice of fuel rods in a light water-pool [11], the design provided both coolant and moderator. Having reasonable power density, large thermal inertia in the water, and deliberate limits on excess reactivity, the design also provided increased safety margins. Even during times of high reactivity insertion rates, the highly negative temperature coefficient of the fuel ensured that power ramps were inherently limiting in themselves [12]. This reliance on passive safety qualities distinguished TRIGA from other reactors of its generation, which depended more heavily on engineered equipment to prevent criticality excursions.

3. Thermal-Hydraulic Safety Aspects

The TRIGA research reactor, designed in the late 1950s, was a significant innovation in reactor design in that it emphasized inherent safety and simplicity of operation [13]. In contrast to large commercial reactors, which use complex active systems, the TRIGA design used the path of passive systems—namely natural convection cooling—to enable safe and effective operation. This was a manifestation of a

broader design philosophy to reduce dependence on external power, operator interventions, and engineered barriers.

From its early days, the TRIGA reactor relied on natural convection as its primary method of cooling. When it is created in the core, surrounding water absorbs thermal energy, expands with reduced density and ascends, and is displaced by colder water descending to take its place. No pumps or mechanical devices are required to maintain this self-perpetuating circulation path, making it easier to operate and reducing the likelihood for mechanical breakdown [14]. Critically, the process continues even during power transients or loss-of-flow, with independent heat removal uninfluenced externally.

When operating requirements became more demanding, the pool itself was a key safety feature. Its large water inventory acts as a heat sink and radiological shield. Decay heat is withdrawn from the pool during shutdown, preventing overheating of the fuel and maintaining stable core conditions. Concurrently, the water mass provides significant radiation shielding, significantly minimizing exposure risks during normal operation and maintenance. These attributes facilitated the TRIGA strategy of complementing inherent material properties with simple, robust system design.

During pulsing operation, the power peaking effect causes fast temperature increase in the fuel. However, considering the intrinsic properties of the fuel and the extraordinary heat capacity of water, the risk of local overheating or fuel damage is effectively controlled [15]. The carefully elaborated reactor design allows the heat to quickly escape from the fuel to the overlying pool of water and thus transient temperature spikes are always restricted to predefined safe levels. Rigorous thermal-hydraulic modeling, complemented by empirical experimental data, substantiates that during pulsed operations, fuel temperatures invariably remain well below critical melting thresholds, thereby preserving the structural integrity of the fuel elements [16]. This capability is a cornerstone of the TRIGA reactor's distinctive pulsing functionality, enabling the safe execution of short-duration, high-power experiments.

Further analysis emphasized the pool's role as a transient thermal buffer. Its immense volume not only contains and distributes pulsing incident energy but also facilitates ongoing immersion of the core in the case of possible loss-of-coolant accidents (LOCA) [17]. The geometric design of the pool provides sufficient time for emergency action, as opposed to closely packed reactor designs with active emergency core cooling systems. By restricting the need for immediate operator response, TRIGA limits opportunities for human-error accident escalation.

In short, the TRIGA pool-type reactor is a chronological progression in safety-oriented design. From natural convection cooling and huge pool-type shielding to its proven record of reliability in steady-state performance and terminating in its safe pulsing capability and accident resistance capacity, the TRIGA reactor has a design approach that canters on intrinsic safety and economic operating principles. Its success has established it as one of the most reliable and versatile research reactors on the globe.

4. Reactor Monitoring and Safety Systems

Since their commissioning, TRIGA reactors have employed control rods composed of neutron-absorbing materials, most commonly boron carbide or cadmium alloys, which serve as the primary mechanism for regulating neutron flux and controlling reactivity [18]. These mechanisms were redundant and fail-safe designed for guaranteed insertion for regular shutdowns and emergency scram conditions, backed by independent and diverse scram systems for quick shutdown when safety limits were approached. The design and response of the rods were in line with the negative temperature coefficient of the reactor, constituting a hierarchical safety regime that was capable of responding to incremental operation changes and steep transients.

When reactors built in the 1960s and 1970s aged, they must be upgraded. Early analog instrumentation and control systems were progressively replaced by digital platforms yielding faster, more precise monitoring, advanced automated protection capabilities, and clearer operator interfaces [19]. These advancements reduced human mistakes, enhanced reliability, and allowed remote diagnostics, but had to face rigorous safety evaluations and regulatory approvals to ensure compliance with standards in place. Fig 3 shows a typical Reactor Monitoring and Safety Systems of TRIGA research reactors

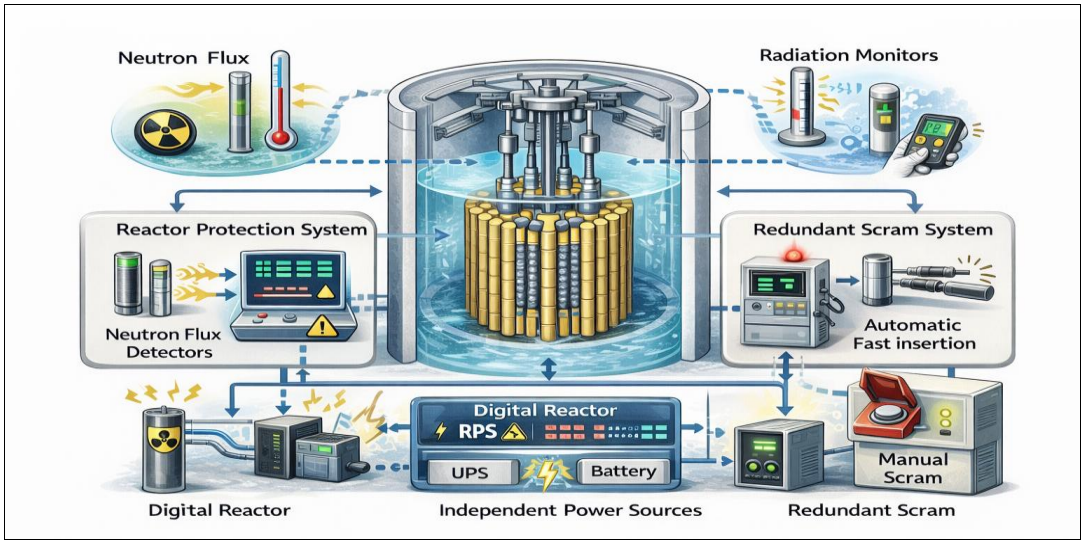

Fig 3: Reactor Monitoring and Safety Systems of TRIGA research reactor

In parallel, protection systems were strengthened. Automatic scram systems, initiated by excursions of power, fuel temperature, neutron flux, or radiation dose rate, now provide immediate shutdown [20]. Continuing radiation monitoring within the facility and effluent streams are employed to maintain regulation levels and readily detect anomalies. Safety interlocks are made redundant and diverse to avoid single points of failure, and manual override mechanisms and independent sources of power ensure that safety-critical systems continue on despite external power interruptions.

All together, these innovations—from original control rod design through digital upgrade and enhanced safety interlocks—show the steady improvement in TRIGA reactor safety architecture due to technology advancements and regulatory requirements.

5. Operational History and Safety Performance

More than sixty-five TRIGA reactors have been constructed and operated around the world, with numerous ones still in operation for over five decades [21]. Their worldwide operating experience is marked by an immensely low frequency of safety incidents and no serious accidents. TRIGA facilities have also shown through the years to be extremely versatile and reliable, accommodating activities ranging from education and training up to the generation of medical isotopes, neutron radiography, and material testing. The long-term performance data generated through these reactors continue to be priceless in demonstration of the hardness of the TRIGA fuel, effectiveness of its passive safety measure, and advantages of its modular design, which have made maintenance and system upscaling a walkover. Fig 4 shows the worldwide safety performances of TRIGA reactors.

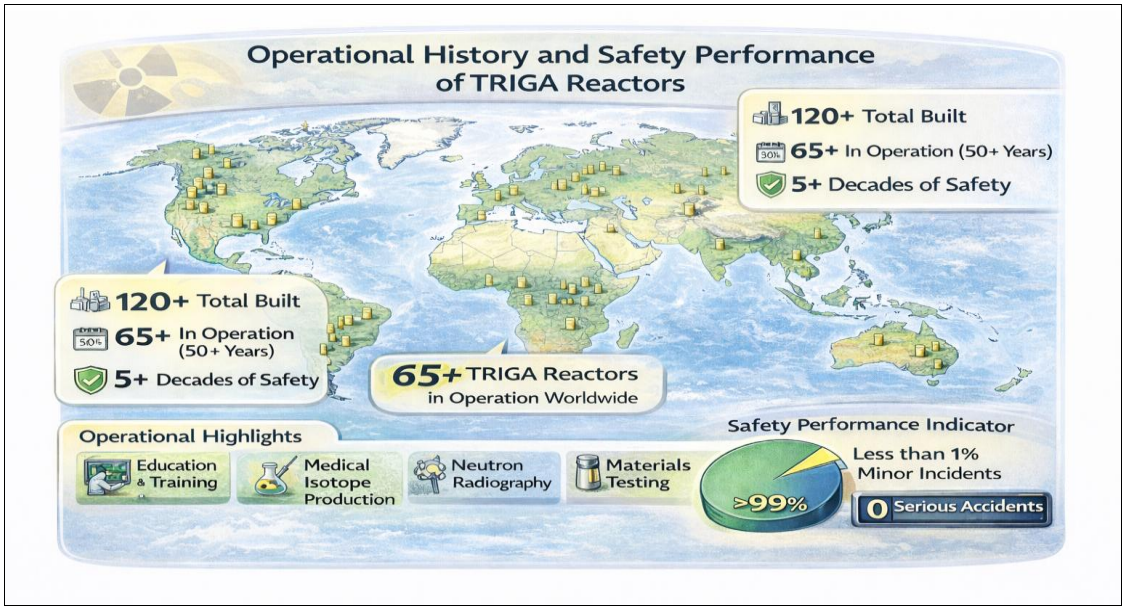

Fig 4: Impeccable Worldwide Safety Record

Although isolated instances of operator error, instrument malfunction, or maintenance shortfalls have on occasional occasions been reported, none have become major safety concerns, primarily due to the design's safety inherent qualities [22]. The TRIGA design possesses a high negative temperature coefficient for reactivity, which is also a self-limiting characteristic, such that power excursions cannot exceed safe levels. In addition, regular conduction of safety exercises, prolonged training programs for operators, and strict compliance with procedures also minimize the occurrence of human faults. All these are complemented by a safety culture further strengthened by regular regulatory oversight and required open reporting of incidents. The comparatively modest effects of the previous occurrences demonstrate the robustness of the operational and engineering design of TRIGA, with valuable lessons and examples that continue to influence improvements in research reactor safety worldwide.

6. Regulatory Structure and Licensing

TRIGA reactors operate under the control of the respective national nuclear regulatory bodies, in accordance with procedures compatible with the safety criteria established by the IAEA [23]. The licensing includes in general detailed safety studies in the fields of reactor physics, thermal-hydraulics, radiation protection and emergency capability. Operational authorization is granted on the condition that the licensee will operate in compliance with safety requirements, to be verified through periodic reviews and/or audits, the renewal of operating licences being subject to demonstrated compliance and acceptable safety performance. The regulations also have rigorous standards regarding nuclear fuel, radioactive waste handling, and physical protection. Challenges On the Digital Instrumentation and Control. In recent years, increasing attention has been directed toward the cybersecurity of digital instrumentation and control systems, as well as the enhancement of emergency preparedness planning to account for emerging and evolving threats.

7. Challenges and Advancements in Modernization

Today, many of the TRIGA reactors—most of which were built in the middle of the last century—suffer from the consequences of aging. Issues such as structural aging, aging instrumentation, and slow degradation in critical components could challenge the long-term reliability of safety systems and result in increasing maintenance requirements [24]. Therefore, modernization plans are

developed to extend the reactor operation lives and to safely operate the reactors in the future. These include making changes resulting from the degradation or aging of equipment, changes in control and monitoring systems, and the improvement of instrumentation so as to ensure that proven safety aims are maintained while preserving the inherent safety features of the original design.

One of the key features of such a process of modernization is the use of advanced non-destructive evaluation techniques. These methods of evaluation improve anticipatory aging management through the ability to identify early material degradation signs before it becomes harmful to safety margins. At the same time, international commitments regarding nuclear non-proliferation have driven the re-fuelling of TRIGA reactors from HEU to LEU fuel [25]. The transition is important to reducing proliferation threats at the expense of reactor performance and safety. The process typically requires extensive safety analyses and, in some cases, re-design of the reactor core to counter modifications in neutron behavior and fuel dynamics. Today, most TRIGA facilities have already converted or are converting, with LEU fuel designs carefully engineered to preserve the distinctive operating characteristics of TRIGA reactors, namely their large negative temperature coefficient and pulsing response. Fig 5 below shows a modern Instrumentation and Control (I&C) system, demonstrating its contribution to improving reactor safety.

Fig 5: Modern control room with upgraded digital instrumentation & control (I&C) systems

The recent past has also seen the gradual introduction of advanced technologies in TRIGA reactor operation [26]. Digital twin models, real-time diagnostic systems, and remote monitoring systems are increasingly becoming common to improve predictive maintenance, safety margins, and downtime. High-fidelity simulation platforms are also being introduced to improve operator training, safety analyses, and facilitate more extensive scenario testing. These steps together illustrate continued efforts toward reconfiguring TRIGA research reactors to satisfy evolving needs for safety, security, and technology while their role as versatile and reliable workhorses for research, training, and isotope production is maintained for future generations.

8. Conclusions

The TRIGA research reactor is an archetypal example of engineering process, the optimal mixture of passive-level safety features, dedicated design, uniqueness in the history of research reactor. The secret of its overall safety is in its fuel system, uranium zirconium hydride, which has a negative temperature coefficient -- the crucial characteristic that in the very nature of the system stabilizes the reactor operation: As temperature increases, power automatically falls off. These inherent safety functions are supplemented by passive thermal-hydraulic systems, and a comprehensive system of redundant safety systems that are coherently arranged for a robust protection of operational upsets. During decades of worldwide use, the TRIGA reactor has demonstrated an outstanding safety record and incident-after-study reports continually have emphasized the effectiveness of its design for minimizing the possibility of accidents and maintaining operating integrity.

Furthermore, ongoing improvements via upgrading programs and fuel conversion programs confirm a firm commitment to the safety and technological evolve. Accordingly, TRIGA reactors continue to serve as a valuable resource for scientific research, educational instruction and isotope production and will continue to provide a safe, reliable and state of the art facility for many years to come. Their long-lasting performance is testament to the vision and confidence of their design, establishing them as a benchmark for secure technology across the globe.

9. References

1. International Atomic Energy Agency. Research reactor utilization, safety, and management. IAEA Technical Reports Series No. 487, 2016.
2. General Atomics. (n.d.). TRIGA reactors: Overview and safety features. Retrieved from https://www.ga.com/triga
3. Kastenberg WE, Stanciu S. Safety analysis of TRIGA reactors. Nuclear Technology. 1980; 49(1):1-12.
4. U.S. Nuclear Regulatory Commission. Research reactor safety requirements. NUREG-1537 Rev. 1, 2019.
5. Lanning DD, Massie HL. Principles of nuclear reactor physics. CRC Press, 2014.
6. Holmes JT, Schultheisz DJ. Thermal feedback in uranium-zirconium hydride fuel. Annals of Nuclear Energy. 1986; 13(6):295-310.
7. Nejati H, Hashemian HM. Pulsed power analysis of TRIGA Mark II reactor. Annals of Nuclear Energy. 2017; 101:146-154.
8. Scott J. TRIGA fuel manufacturing and behavior. Nuclear Engineering International. 2005; 50(612):12-14.
9. Ravnik M, Glumac B. Fuel performance in operational TRIGA reactors. Annals of Nuclear Energy. 2012; 42:62-70.
10. Vujic J, Bergmann R, Pevec D. Transient fuel behavior testing in TRIGA reactors. Nuclear Engineering and Design. 2007; 237(3):363-370.
11. Persic A, Ravnik M, Glumac B. Thermal-hydraulic analysis of TRIGA reactors. Nuclear Technology & Radiation Protection. 2005; 20(1):36-43.
12. Thomas T, Shaver J. Digital control upgrades in TRIGA reactors. Proceedings of the American Nuclear Society Winter Meeting, 2017.
13. Irani M, Fatemi S, Tavakoli-Anbaran H. Heat removal in TRIGA pulsing. Journal of Nuclear Science and Technology. 2019; 56(4):418-425.
14. De Corte F. Pulsing behavior and safety of TRIGA reactors. Journal of Radioanalytical and Nuclear Chemistry. 2012; 291(1):1-10.
15. U.S. Department of Energy. Research reactor fuel conversion guidelines, 2021.

16. Jalilian AR, Siahpoush V. Loss of coolant scenarios in TRIGA reactors. Nuclear Safety. 2018; 59(2):145-154.
17. International Atomic Energy Agency. Research reactor control and safety systems. IAEA Nuclear Energy Series No. NP-T-3.1, 2019.
18. Scott J. Digital instrumentation modernization in research reactors. Nuclear Engineering International. 2014; 59(721):14-18.
19. U.S. Nuclear Regulatory Commission. Reactor protection systems. Regulatory Guide 1.33, 2018.
20. IAEA Research Reactor Database. Operational data summary, 2020. Retrieved from https://www.iaea.org/resources/databases/research-reactor-database
21. Vujic J, *et al*. Incident reporting and safety culture in TRIGA operations. Nuclear Safety. 2015; 56(3):245-255.
22. International Atomic Energy Agency. Safety standards for research reactors. IAEA Safety Standards Series No. SSR-3, 2018.
23. Ravnik M, *et al*. Aging management in TRIGA research reactors. Annals of Nuclear Energy. 2016; 87:54-62.
24. U.S. Department of Energy. Fuel conversion technical support document, 2019.
25. Zdravkovic S, Skoda R. Digital twin applications for research reactors. Nuclear Engineering and Technology. 2020; 52(6):1121-1129.
26. Zdravkovic S, Skoda R. Digital twin applications for research reactors. Nuclear Engineering and Technology. 2020; 52(6):1121-1129.