Exotic legacy Spent Nuclear Fuel: Challenges and Long-Term Management

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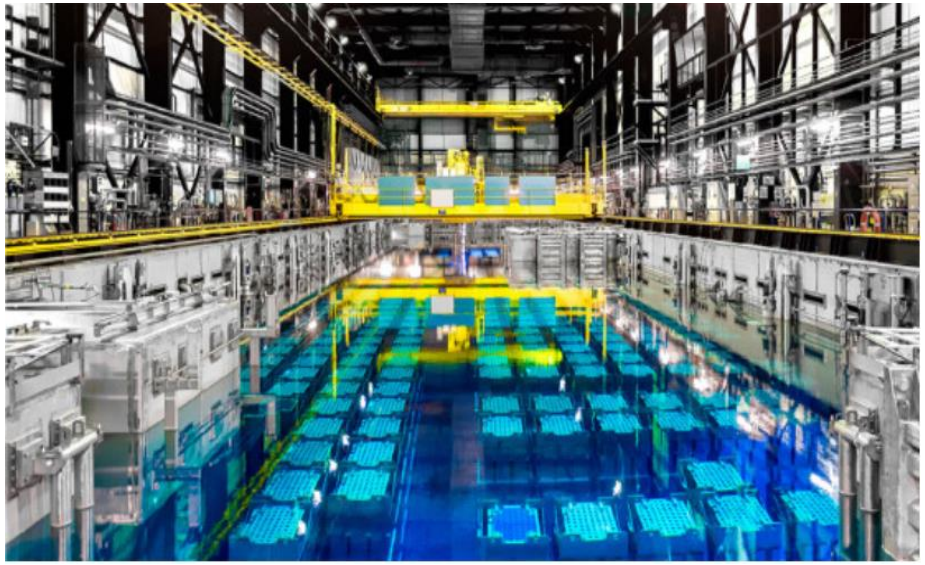

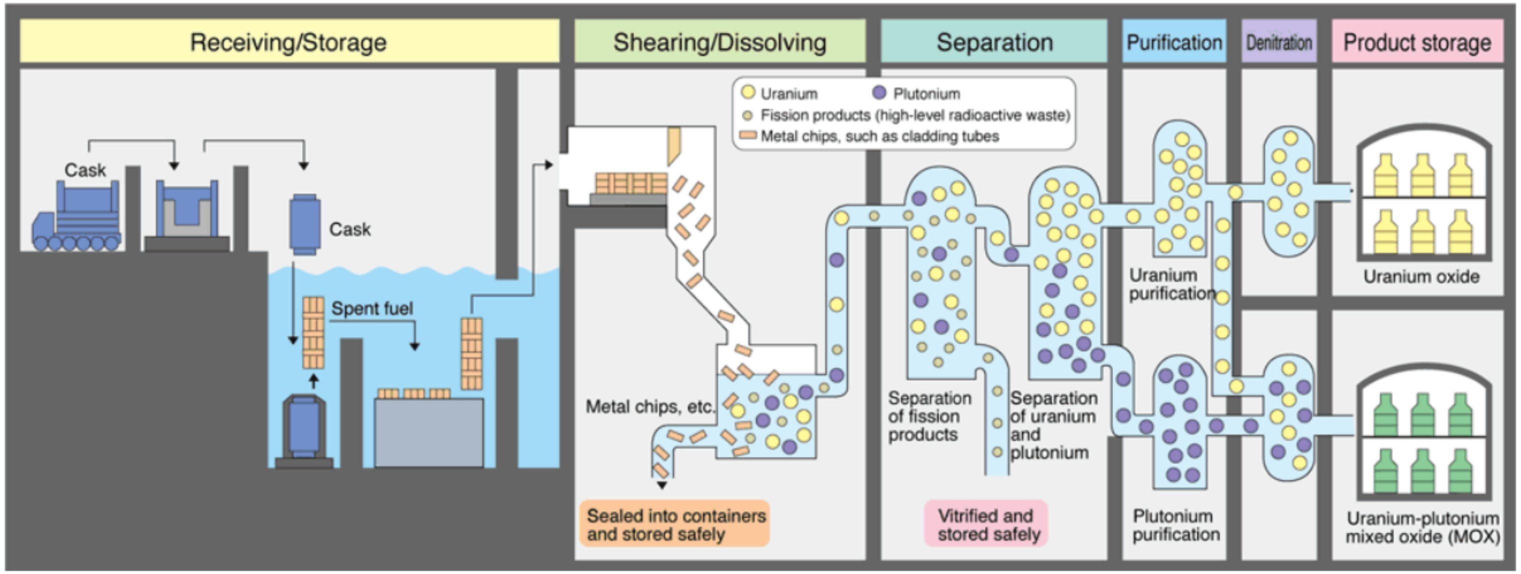

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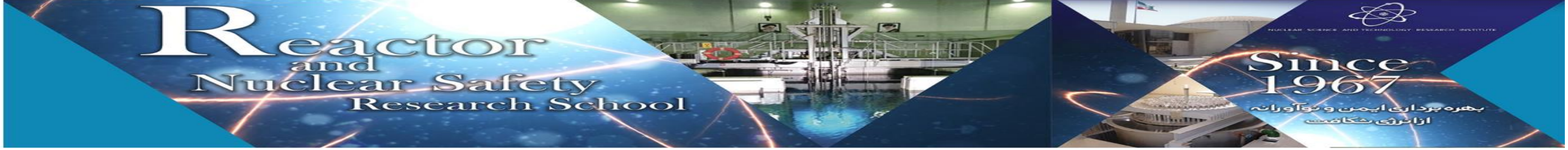


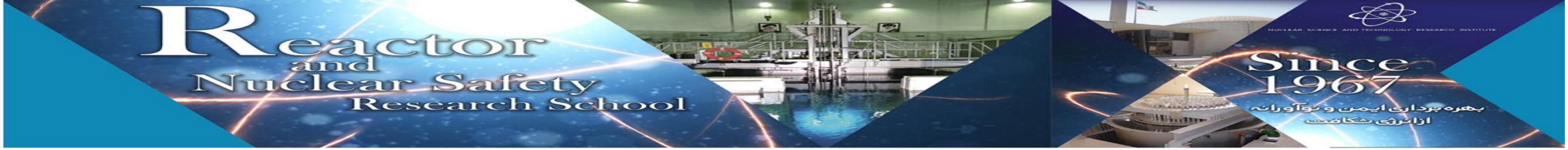
Introduction: The Legacy of Non-Standard Fuels

Early Years (1940s-1960s)

The first nuclear reactors were primarily experimental, leading to a variety of fuel types being tested. These early reactors often used unique fuel designs to optimize performance for specific research goals. Fuels such as U-Al alloy or U-ZrH, due to their high neutron flux capabilities, were common in early research reactors.

Diversification and Experimentation (1970s-1980s)

As nuclear technology advanced, various non-standard fuels were developed for specialized applications. For example, some reactors used thorium-based fuels or mixed oxide (MOX) fuels. Moreover, due to innovation in reactor designs such as the High-Temperature Gas-cooled Reactor (HTGR) and the necessity to adapt with graphite moderators, unique fuel geometries were created.



Global Experience with Non-Standard Fuels

United States: The U.S. has a long history of experimental reactor programs, including those at national laboratories like Oak Ridge and Los Alamos, which have managed various non-standard fuels.

France: France has developed advanced reactor concepts like the Phenix fast breeder reactor, which used MOX (Mixed Oxide) fuel—a type considered non-standard compared to traditional uranium dioxide fuels.

Russia/USSR: The Soviet Union/Russia conducted extensive nuclear research with various reactor types, including those using thorium-based fuels or other exotic materials.

United Kingdom: The UK has operated several prototype reactors with specialized fuel designs, such as the Windscale Advanced Gas-cooled Reactor (WAGR) and the Dragon Reactor Experiment.

Canada: Canada's nuclear program includes research reactors like SLOWPOKE and MAPLE, which use different fuel forms than commercial power reactors.

Japan: Japan has also been involved in managing diverse spent fuels from its experimental reactors and prototype facilities.

Dragon Reactor

The Dragon Reactor Experiment was a pioneering high-temperature gas-cooled reactor (HTGR) project that operated from 1964 to 1975 at Winfrith in Dorset, United Kingdom. It was the first operational HTGR and served as a materials test facility for various HTR projects in Europe during the 1960s and 1970s.

Key features of the Dragon Reactor Experiment include:

1. Power output: 20 MWth (thermal power)
2. Coolant: Helium gas
3. Moderator: Graphite
4. Fuel: Coated particle fuel in the form of tiny spherical pellets mixed with graphite and pressed into block
5. These pellets were composed of Fissile material: Initially, highly enriched uranium (HEU) with about 93% uranium-235 was used. Later, lower enrichment fuel (about 20% U-235) was also utilized. Fertile material: Thorium was used as a fertile material, with a thorium to uranium ratio of about 10.
6. Reactor outlet temperature: 750°C

Windscale Advanced Gas-cooled Reactor (WAGR)

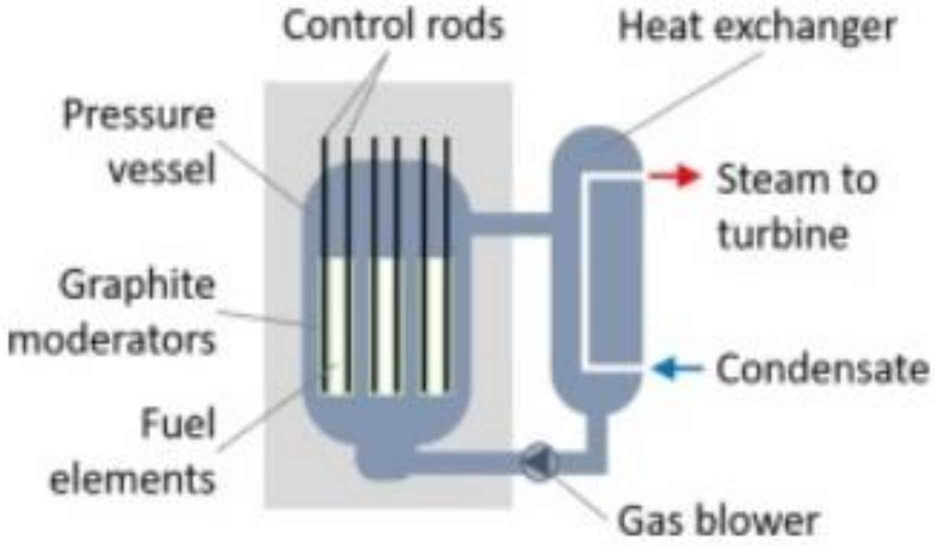
The Windscale Advanced Gas-cooled Reactor (WAGR), was a pioneering nuclear reactor that played a crucial role in the development of Britain's nuclear power program. WAGR was built in the early 1960s as a prototype for the UK's second generation of nuclear reactors, the Advanced Gas-cooled Reactors (AGRs).

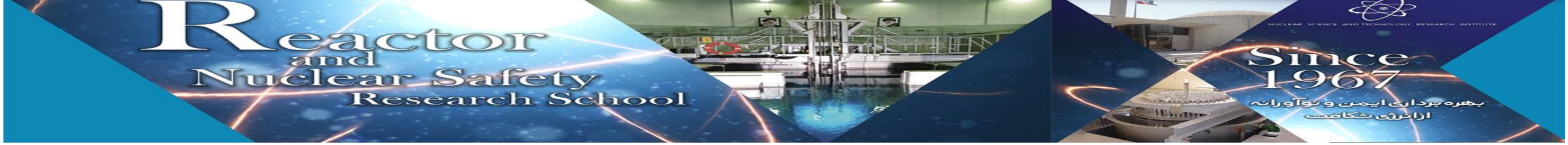
Its primary purpose was to test and validate the AGR technology, which used graphite as a neutron moderator and carbon dioxide as a coolant.

Key design features of WAGR included:

- Thermal power output: 100 MWt
- Electrical capacity: 32 MWe

- The WAGR fuel consisted of uranium dioxide (UO2) pellets with the enrichment of 2.5-3.5% uranium-235 in Stainless steel tubes.
- Decommissioning pioneer: WAGR became the first nuclear power reactor to be fully decommissioned in the UK.





SLOWPOKE Reactor

SLOWPOKE (Safe LOW-Power Kritical Experiment) is a family of low-energy, tank-in-pool type nuclear research reactors designed by Atomic Energy of Canada Limited (AECL) in the late 1960s. Key features include:

Power output: Typically 20 kW thermal

Fuel: Originally used 93% highly enriched uranium in the form of 28% uranium-aluminum alloy with aluminum cladding, later versions use low-enriched uranium (~19.9%) in the form of ceramic UO_2 fuel.

MAPLE Reactor

MAPLE (Multipurpose Applied Physics Lattice Experiment) reactors were designed specifically for medical isotope production molybdenum-99. MAPLE reactors use a different fuel design:

1. Fuel material: Uranium silicide (U_3Si_2) particles dispersed in aluminum.
2. Enrichment: 19.7% by weight U-235.
3. Fuel form: Rods with finned aluminum cladding.

While SLOWPOKE reactors have been successfully operated for decades, the MAPLE project represents a significant setback in Canada's medical isotope production capabilities.

Phenix Reactor

Phénix was a fast breeder reactor located in France. It went critical for the first time in 1973. The reactor was designed with a net capacity of 233 MWe .

Phénix demonstrated several key achievements in nuclear technology:

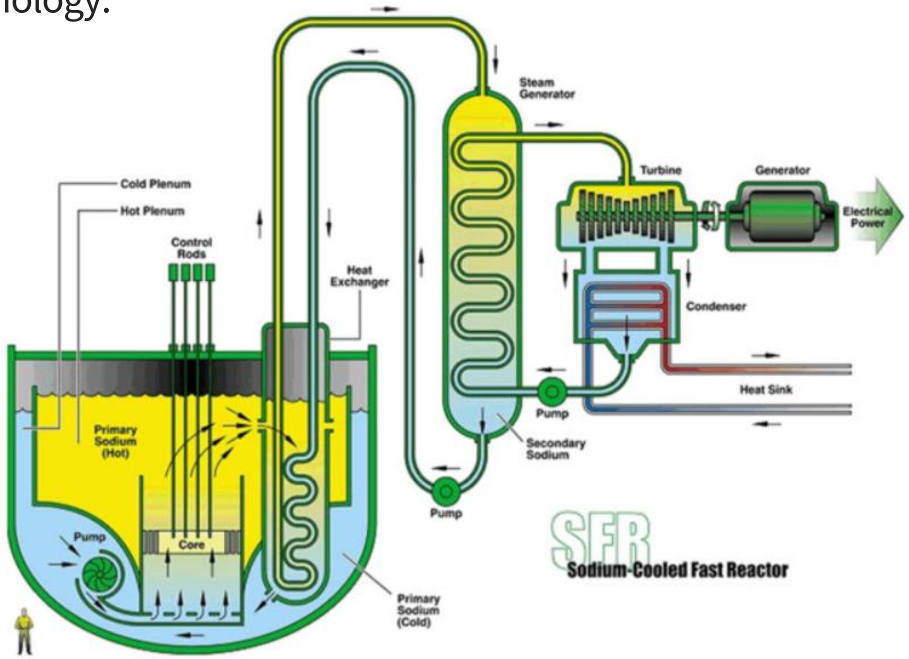
-It proved the viability of using sodium as a coolant for a 300 MWe-type reactor.

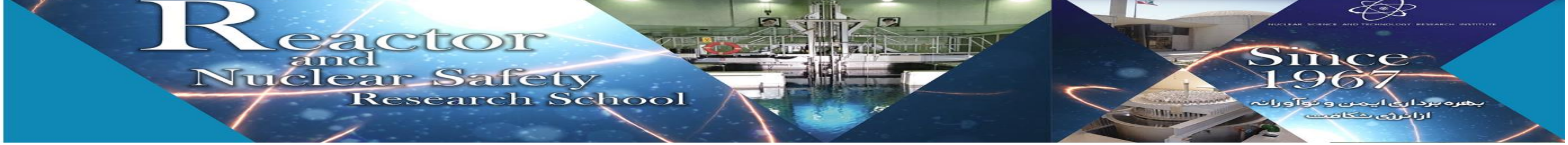
--It achieved a breeding ratio of 1.16, meaning it produced 16% more fuel than it consumed.

-The reactor used a plutonium-based fuel, consisting of a mixture of plutonium and uranium oxides.

Phénix operated successfully through the 1970s and 1980s. However, between 1989 and 1990, it experienced four power transients that triggered automatic shutdowns. In 1993, renovation and life extension works began, and the reactor was restarted in 2003 with a reduced power of 130 MWe.

The reactor was permanently shut down in 2010, after over 35 years of operation. Throughout its lifetime, Phénix served as a unique research reactor in Europe, contributing significantly to the development of fast reactor technology.





Advantages of Managing Non-Standard Fuels

Resource Recovery Potential

Non-standard or exotic legacy spent nuclear fuel (SNF) contains valuable materials that can be extracted and reused. SNF contains actinides (Uranium, Plutonium) and rare earth elements (Y, La, Ce, etc.) that can be recovered for energy generation and other applications. Moreover, isotopes produced during fission, such as noble metals and platinum group metals, can be utilized in various industries, enhancing the economic viability of nuclear waste management.

Economic, Social, and Environmental Benefits

Maximizing the recycling of SNF can improve the economics of the nuclear fuel cycle, potentially offsetting the high costs of reprocessing. Moreover, recycling the fissionable material from these non-standard or exotic legacy materials could be beneficial in compensating for the increasing demand in the uranium market by conservation of natural resources like uranium. Enhanced recovery methods may lead to better public perception of nuclear energy by demonstrating effective waste management and resource utilization. Recycling significantly decreases both the volume and radiotoxicity of high-level waste. This minimizes long-term storage needs and environmental impacts associated with disposal facilities.

Challenges of Managing Non-Standard Fuels

Characterization Techniques

Characterization techniques for non-standard or exotic legacy spent fuel involve a combination of nondestructive and destructive methods, each tailored to address the unique challenges posed by these materials. Recent advancements have enhanced the ability to assess various parameters critical for safe storage and disposal.

Regulatory Frameworks

The regulatory frameworks governing non-standard or exotic legacy nuclear fuels are complex and multifaceted, reflecting the need for safety, environmental protection, and non-proliferation. Existence regulations must adapt to the unique challenges posed by advanced nuclear technologies, such as Sodium Fast Reactors (SFRs), which introduce new proliferation risks due to their fuel cycles and special nuclear materials (SNMs) management.

Proliferation Concerns

The proliferation concerns of non-standard and exotic legacy spent fuels are multifaceted. While the Spent Fuel Standard (SFS) provides a baseline for proliferation resistance in plutonium disposition, advanced fuel cycles present new challenges. Partitioning and transmutation (P&T) processes, which separate spent fuel components, potentially increase proliferation risks by removing radiation barriers and complicating material accountancy.

Infrastructure Gaps

The infrastructure gaps related to non-standard fuel and exotic legacy spent nuclear fuel (SNF) primarily stem from inadequate storage, transport, and reprocessing capabilities.

Operational Experience with Non-Standard Fuels

1

United States

The U.S. has leveraged its experience with metal fuels, particularly U–10Zr, in sodium-cooled fast reactors, emphasizing the importance of design parameters and operational conditions for successful deployment. The development of evolutionary mixed-oxide (EMOX) fuels aims to enhance plutonium management in existing reactors, demonstrating effective plutonium conversion and destruction rates.

2

United Kingdom and France

Both countries have significant experience with high-burnup mixed-oxide fuels in sodium-cooled fast breeder reactors, focusing on overcoming challenges related to cladding materials and fuel behaviour which have been studied extensively since the 1960s. This research has led to industrial maturity in fuel performance and safety.

3

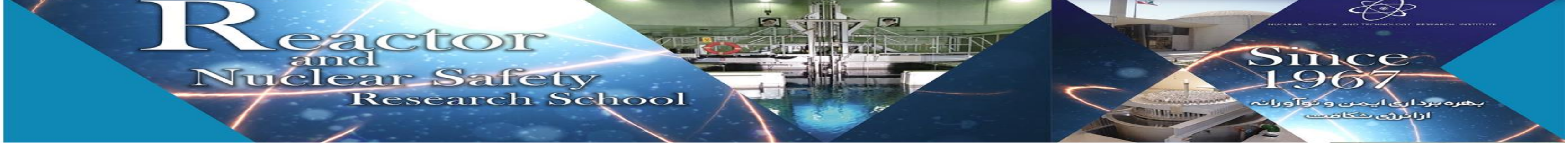
Russia

Russia's transition to uranium-erbium fuel in RBMK-1000 reactors has resulted in improved reactivity control, increased burnup, and reduced spent fuel volume, showcasing the benefits of innovative fuel compositions.

4

Canada

Canada has explored various non-traditional fuels, focusing on the potential of advanced fuel forms to enhance reactor efficiency and sustainability, although specific operational experiences are less documented compared to other nations. However, Canada has over 50 years of experience fabricating thorium-based fuels, including ThO2, (Th,U)O2, and (Th,Pu)O2, which could impact future nuclear energy development.



Lessons Learned: Adapting to New Technologies

Characterization

As mentioned above, the fuel composition, irradiation history, and radiological properties are paramount for the safe and efficient management of spent nuclear fuel, particularly when dealing with non-standard or legacy fuel types. This understanding is crucial not only for existing fuels but also for the design and deployment of future nuclear technologies. So, adapting the existing equipment to these innovative materials is inevitable.

Regulation

Existence regulations must adapt to the unique challenges posed by advanced nuclear technologies, such as Sodium Fast Reactors (SFRs), which introduce new proliferation risks due to their fuel cycles and special nuclear materials (SNMs) management. So the revision or expansion of the national regulations ensuring efficiency across all management activities, and considering long-term flexibility in packaging and disposal concepts is necessary.

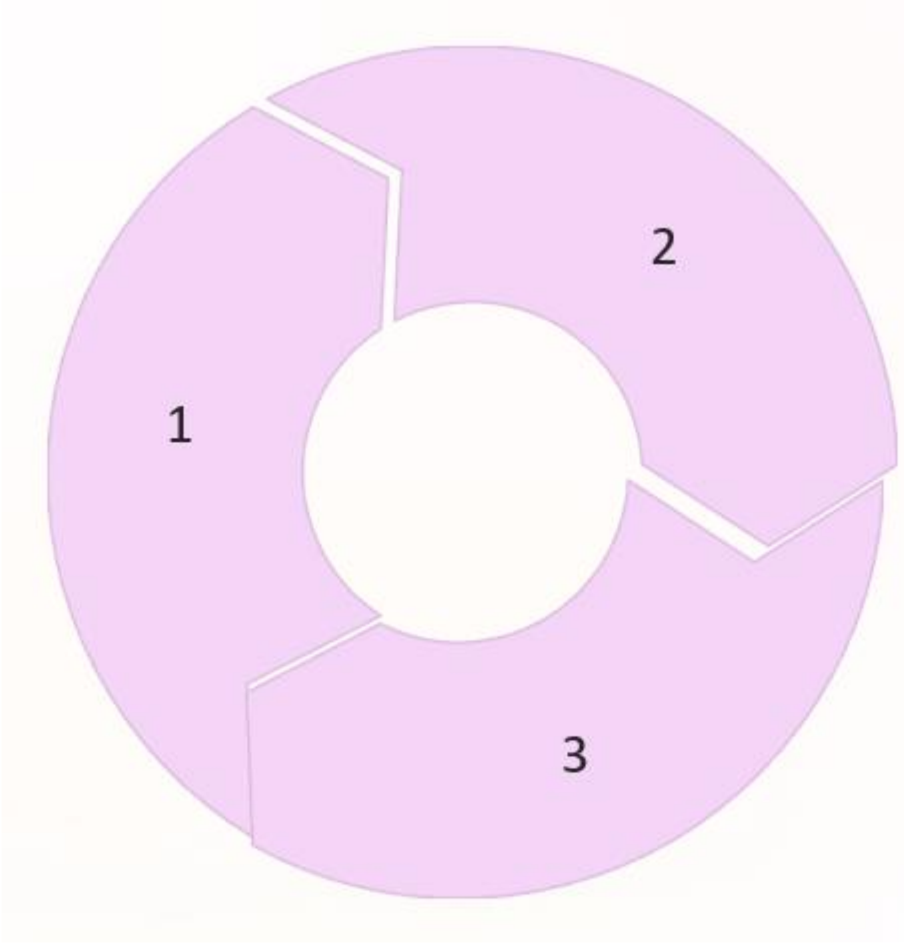
Proliferation

To address these concerns, innovative safeguards techniques and radiation signatures for mixed actinide fuels are explored. Another proposed solution involves developing proliferation-resistant fuel forms by increasing the 238Pu/239Pu ratio in spent fuel through the addition of 237Np or 241Am to low-enriched uranium oxide fuel or through the advanced reprocessing process such as GANEX. This approach aims to make the resulting plutonium less desirable for weapons production due to increased heat load.

Infrastructure

Development and modification of dry storage and transportation casks for non-standard fuel assemblies—varying in size, geometry, and materials—enhances long-term storage stability. For example, the Idaho National Laboratory has created customized dry cask designs for non-standard fuels. Additionally, enhancing pool storage capacity for interim storage of non-standard fuels is crucial. A study by the International Atomic Energy Agency (IAEA) indicated that advanced neutron absorbers in pool storage can increase both capacity and safety for legacy fuels.

Conclusion: Towards a Sustainable Future



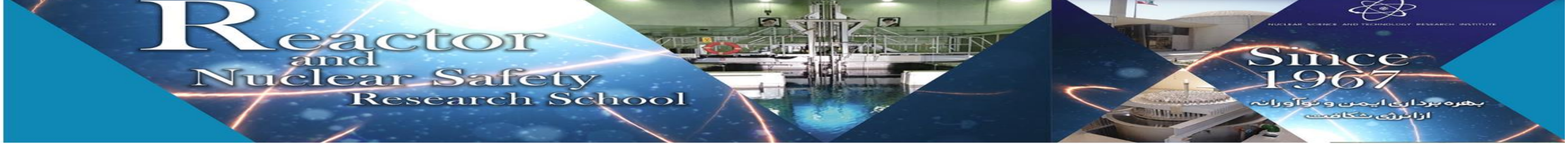
Addressing these challenges requires tailored solutions, including infrastructure development, regulatory adjustments, and a comprehensive understanding of long-term storage and disposal options.

Lessons Learned

The lessons learned from managing legacy SNF are invaluable for informing the development of spent fuel management strategies for emerging nuclear technologies like SMRs.

Sustainable Growth

By applying these insights, the nuclear industry can ensure the safe, responsible, and sustainable growth of nuclear energy.



Next Steps: Collaboration and Innovation

Moving forward, international collaboration and continued innovation are essential to address the challenges of managing non-standard legacy spent nuclear fuel. By sharing knowledge, resources, and best practices, the global nuclear community can work together to develop safe, efficient, and sustainable solutions for the long-term management of these materials.

Case Study: Tehran Research Reactor (TRR)

1

Fuel Options

Research on TRR fuels has explored various options, including U-Al alloy, UZrH, and UO2 rod fuels, and a wide range of theoretical studies were conducted on the simulation of these fuel materials' behaviour during the reactor operation.

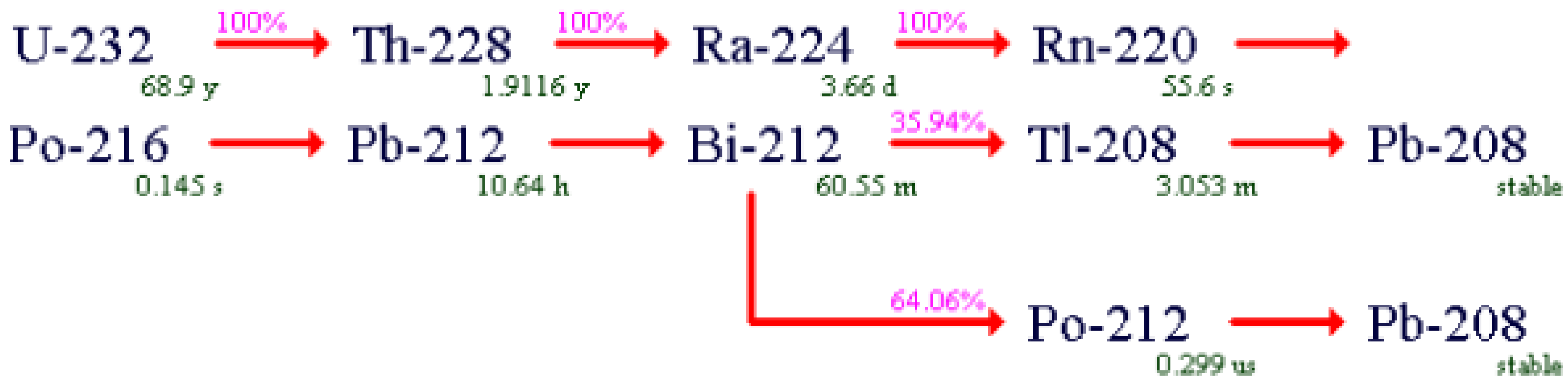
2

Thorium Fuel Transport

In this work, the radiological safety and the amount of shielding required for the transport of irradiated thorium fuel in the Tehran Research Reactor are investigated. The ORIGEN and MCNPX codes were used for calculations of the gamma spectrum of the irradiated fuel and the dose rate of the fuel placed inside the cask.

Increasing cooling time in Thorium spent fuel

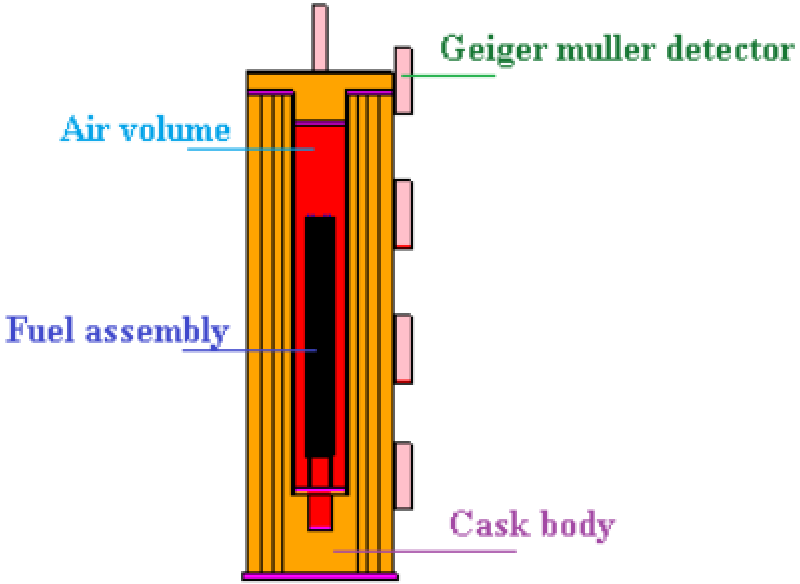
In the ^{233}U decay chain, it is well observed that the accumulation of ^{208} Tl and^{212} Po increases with the spent thorium fuel. spent thorium fuel. This causes the doses of spent thorium fuel assemblies to decrease more slowly with the cooling time with the cooling time compared to spent uranium fuel ones.



calculations

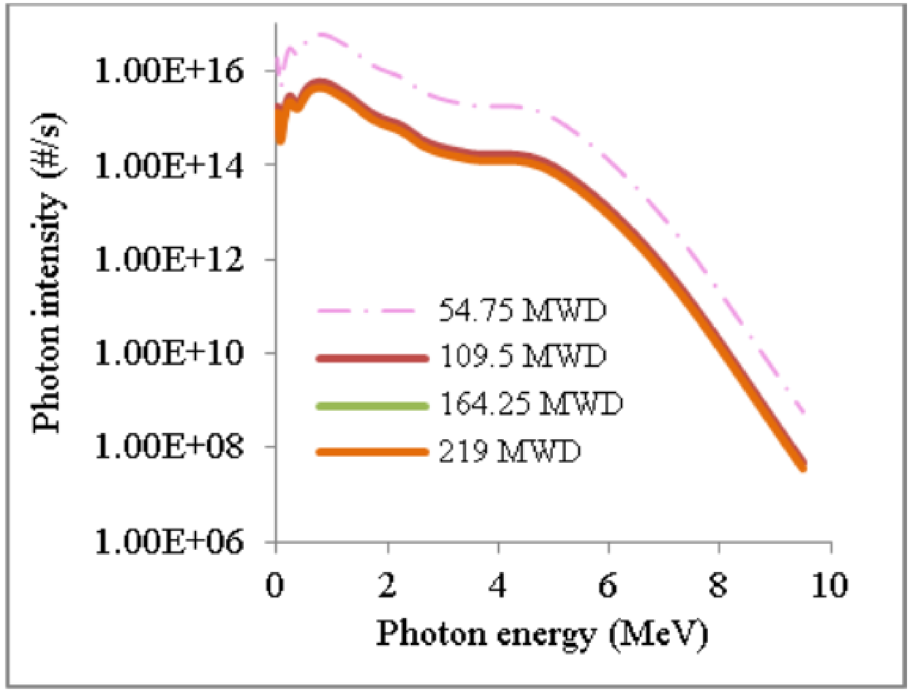
Initially, the consumption of thorium oxide fuel assemblies at different times and average power 4 MW was calculated using the ORIGEN code. The photon spectrum of the spent fuel assemblies was extracted according to different burn up (different MWD) and different cooling times.

Using the photon spectrum extracted from the ORIGEN code, which is defined as a source in the input of the MCNPX code, the dose of thorium fuel assemblies on the surface of the lead cask modeled by the MCNPX code were calculated and compared with each other at different cooling times and different fuel burnups. Also, different thicknesses of the lead cask for transporting the irradiated thorium fuel assemblies were discussed and investigated. This figure shows the simulated of transportation cask with

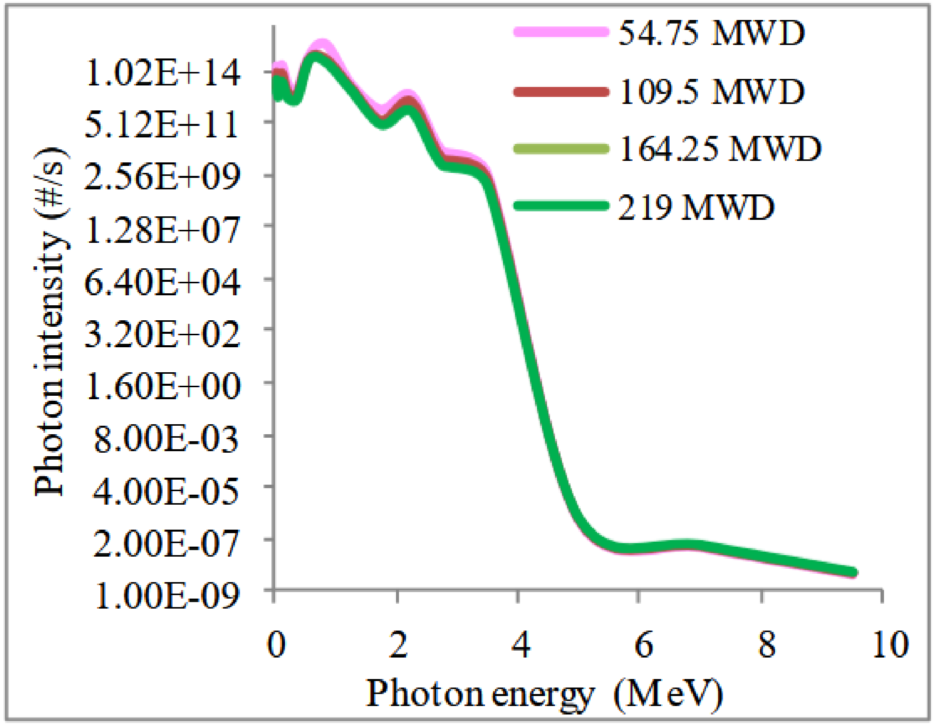


photon spectrum

These figures shows the photon spectrum of a thorium oxide fuel assembly at different MWDs immediately and after 6 months of cooling at the end of the cycle (end of irradiation).



Immediately after the end of fuel cycle

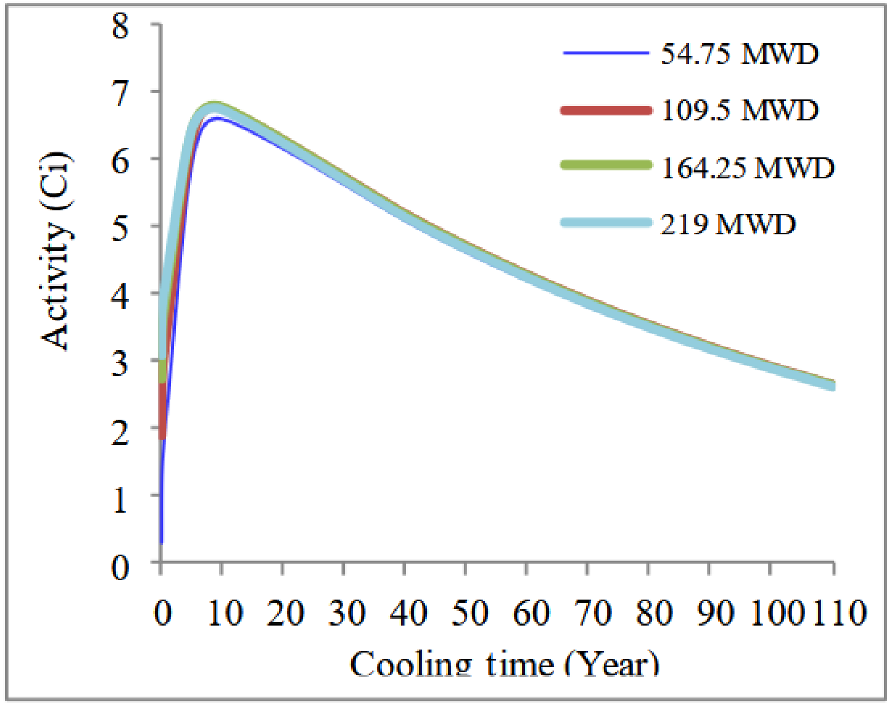


6 months later

for fuel assemblies immediately are removed after the irradiation, the photon spectra are not significantly different from each other. However, at different cooling times, due to the change in the concentration of gamma-emitting radioisotopes, the difference in the spectra of fuel assemblies with different burn ups will be more noticeable.

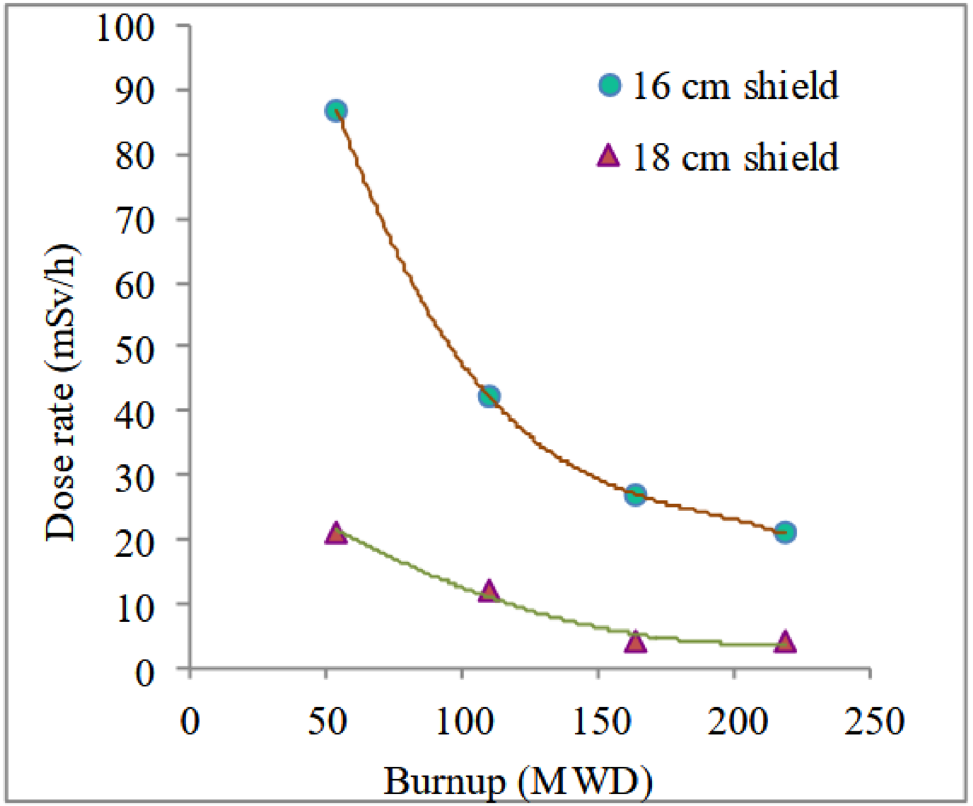
Cooling time

As mentioned, one of the important radioisotopes that makes the cooling time and dose of thorium fuel different from that of irradiated uranium fuel is ^{208}Tl, whose accumulation in irradiated thorium fuel and its production rate greatly affect the photon spectrum of the spent fuel and also the dose of the spent fuel assemblies. As this Figure shows, the concentration of the ^{208}Tl radioisotope produced is slightly higher in the more fuel burnups, but in all of them, after the cooling time, the accumulation of ^{208}Tl in the fuel is increasing due to the decay of other radioisotopes to it, and after 10 years of cooling, this concentration of the radioisotope shows a decreasing trend. This suggests that the dose of spent thorium fuel in terms of cooling time decreases at a slower rate than that of the spent uranium fuel.



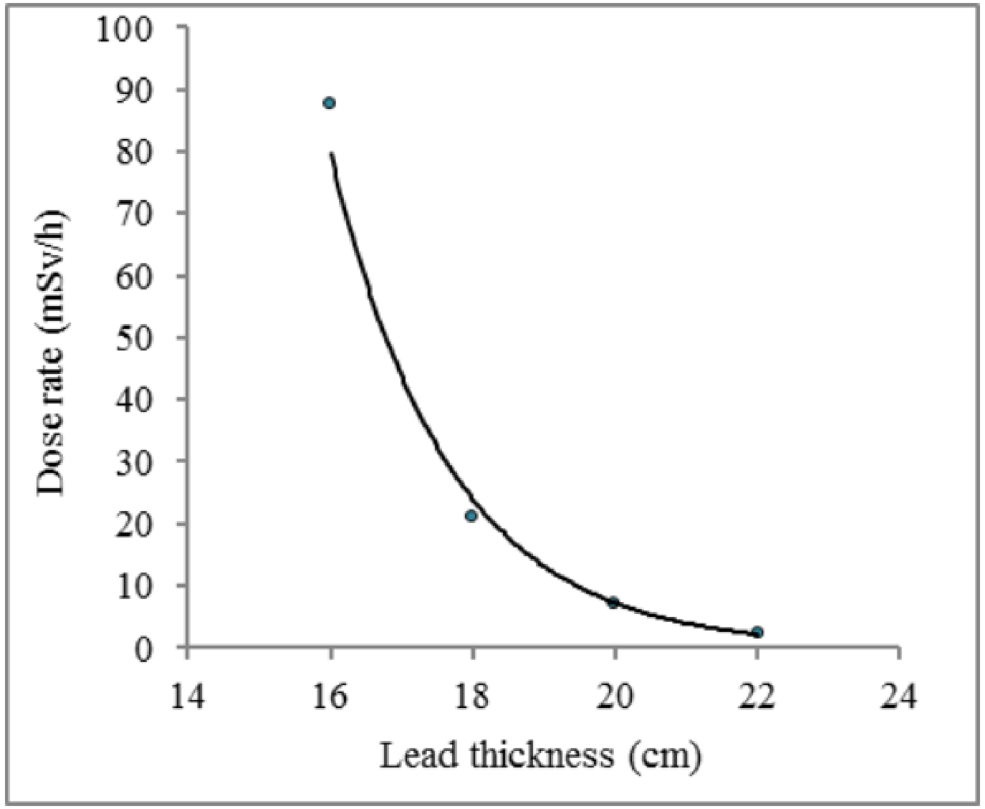
center of the spent fuel assemblies after 6 months of cooling, in terms of the wall thickness of the lead cask. According to this figure, the thickness of 16 cm is not suitable for transporting any of the fuel assemblies with different burnups, but the thickness of 18 cm can be used for transporting spent fuel assemblies with burnup of MWD 164.25 and MWD 219.

- However, the maximum acceptable dose rate at the surface of the cask (less than 2 mSv/h) is achieved in uranium assemblies with a burnup of 100 MWD (54%) after about 3 months cooling by using a lead cask with a thickness of 16 cm.



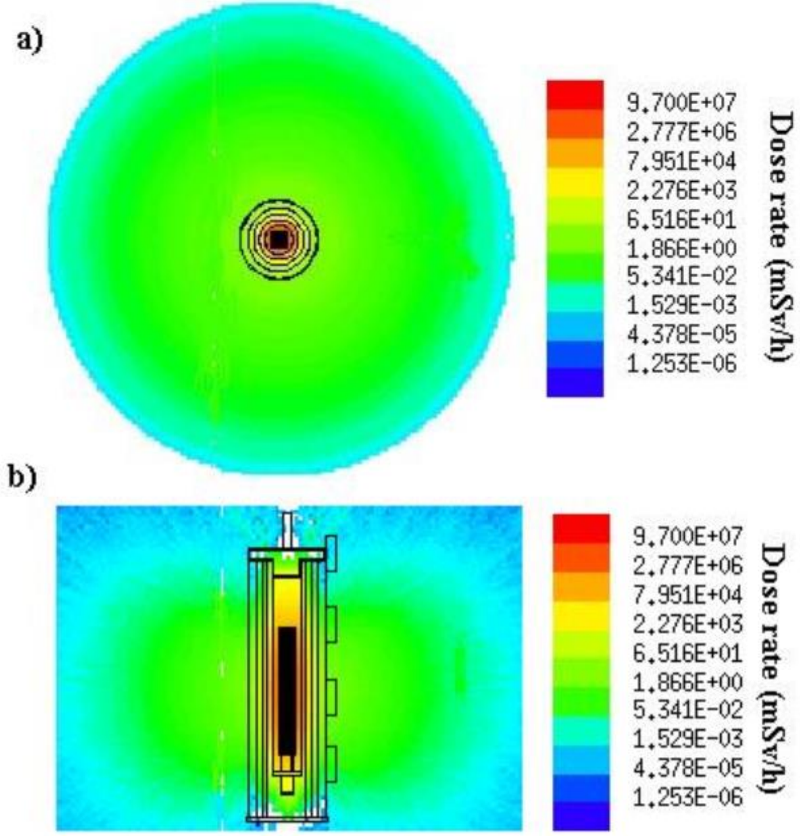
Lead thickness(continued)

This figure shows that for lower fuel burnup assemblies (54.75 MWD) , where the gamma-emitting radioisotopes have not been lost by other equilibrium reactions such as absorption, the thickness of the transfer cask body needs to increase by about 20 cm during 6 months cooling period. This increases the cask weight from 2.47 to 3.22 tons.



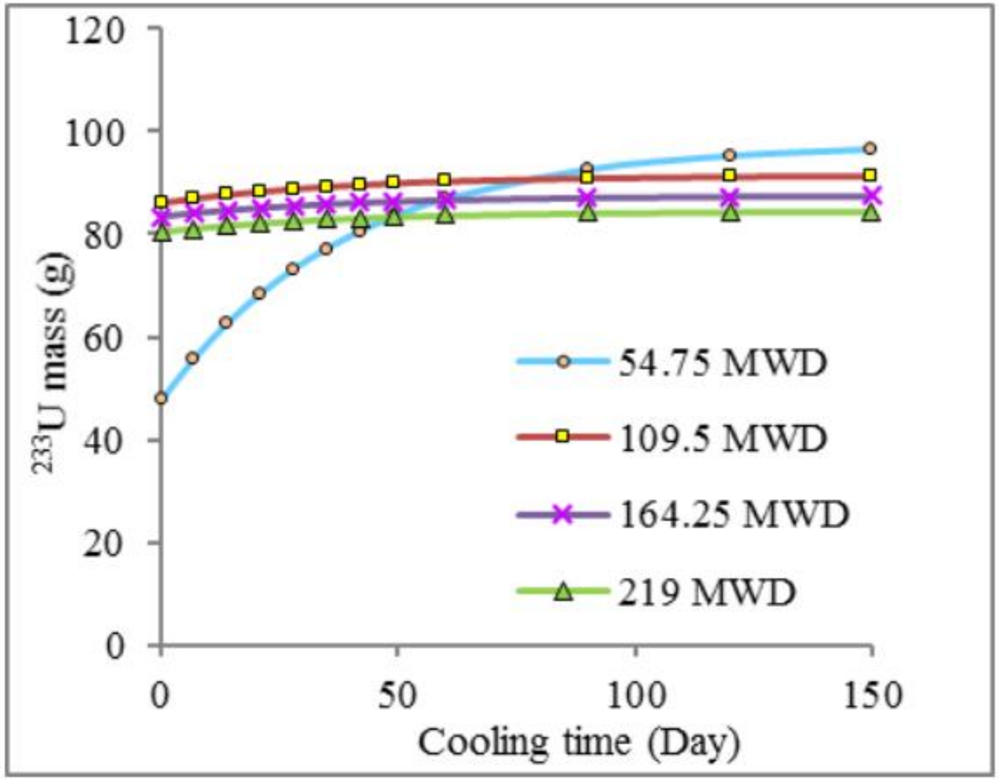
Dose distribution

This figure shows the dose distribution up to a distance of 1 m from the surface of a lead cask with a thickness of 16 cm for a spent thorium fuel assembly with a burn up of 54.75 MWD 54.75. Results show that the dose decreases on average to less than 2 µSv/h, while in the body of the cask it is on average about 65 mSv/h.



accumulation of uranium-233

This figure shows the accumulation of uranium-233 after cooling time in the thorium oxide fuel assembly with different burnups. Calculations show that due to the decay of protactinium-233 to uranium-233, the amount of this fissile radioisotope in the fuel irradiated for 1 years in the Tehran Research Reactor (54.75 MWD) is increasing rapidly, so that after 150 days of cooling of the fuel assembly, its amount reaches about 96 grams. therefore, such fuel assemblies should not be transferred to dry storage casks before 3 months after cooling, as this could create a risk of increasing the Multiplication Factor (Keff) of the cask to more than 95%.



conclusion

- compared to the uranium fuels used in the Tehran Research Reactor, the spent thorium fuel requires longer cooling times before being transported by a lead cask.
- the thickness of the cask required for the transfer of irradiated thorium fuel is greater than that of uranium fuel (about 6 cm) wchich increases the weight of the cask into 2 times.
- the fuel transfer delay time for adequate cooling is at least 2 times the spent uranium fuel at maximum burnup of Tehran Research Reactor (54%).

Thank you