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Radiation-Induced Damage to Concrete Biological Shielding Materials: A State-of-The-Art Review

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ABSTRACT

Concrete is the primary material for such shielding due to its mechanical and structural properties, suitable for neutron and gamma radiation protection. This review provides a comprehensive examination of the impact of nuclear irradiation on the structural integrity of concrete used in biological shielding within nuclear power plants (NPPs). This review highlights the critical role of the hydrogen content of concrete in attenuating neutron flux and its versatility in shape, density, and cost-effectiveness. The review was systematically collected and reviewed previous research papers on the topic, focusing on studies that address the degradation of mechanical properties in concrete exposed to gamma and neutron radiation. Our methodology involved an extensive literature search, critical analysis, and synthesis of findings from peer-reviewed journals, conference proceedings, and technical reports that specifically address the degradation of mechanical properties in concrete structures exposed to gamma and neutron radiation. Gamma radiation induces radiolysis in hydrated cement paste, while neutron radiation causes alterations in the crystalline structure of aggregates, leading to volumetric expansion and reduced mechanical strength. Additionally, this review highlights the combined effects of chemical attacks, moisture, and elevated temperatures on concrete degradation during reactor operation. The key findings underscore the need for further research into the degradation mechanisms of concrete biological shielding, emphasizing the influence of various types of nuclear radiation. This understanding is crucial for ensuring concrete's long-term durability and effectiveness in NPPs, thereby contributing to the safe and sustainable operation of nuclear energy facilities.

Keywords: Biological shielding concrete; nuclear power plants; Aggregate; Degradation neutron; Gamma rays; neutron radiation

INTRODUCTION

Enrico Fermi achieved a historic milestone in December 1942 by creating the inaugural nuclear reactor, Chicago Pile No. 1 (CP-1) (Allardice and Trapnell 1982). This groundbreaking reactor was constructed beneath the stands at Stagg Field, situated at Chicago University in the U.S. (Burchell 2001). Although the nuclear power plant (NPP) was commissioned in early 1960, construction had already commenced in the mid-1950s (Pierre, and J 2013). Since nuclear energy has a reputation for generating affordable, clean, and carbon-free energy, it has become one of the world's most prominent energy sources in the future. At present, NPPs are operational in 31 nations (Aumeier et al. 2011). The combined nuclear electricity production from China, South Korea, France, the United States, and Russia constitutes 70% of the global output (Ho et al. 2019). In highly industrialized nations such as China, nuclear power currently contributes approximately 2% of total electricity generation. Forecasts suggest that this proportion will expand to 8–10% by the end of 2030 (Jin et al. 2016). As of December 2021, there were approximately 437 functioning nuclear power plants globally, boasting a net capacity of 389,508 MW(e) and generating approximately 2,653.1 TW/h of electricity (IAEA 2022). Among the 56 reactors under construction at that time, a significant portion were concentrated in Asia, with China alone accounting for one-third of these projects (Ho et al. 2019; IAEA 2022). A review of the worldwide distribution of nuclear reactors, as illustrated in Fig. 1, reveals that pressurized water reactors (PWRs) dominate 66% of the total population. This was succeeded by boiling water reactors (BWRs), which constitute 16%, and pressurized heavy water reactors (PWHRs), which make up 11% of the total (Gospodarczyk 2022; Ho et al. 2019). The remaining reactors, comprising a smaller fraction, include sodium fast neutron reactors (FNR), water-cooled reactors (WCR), gas-cooled reactors (GCR), and graphite-moderated water-cooled reactors (GMWCR) (Gospodarczyk 2022; Ho et al. 2019; IAEA 2022).

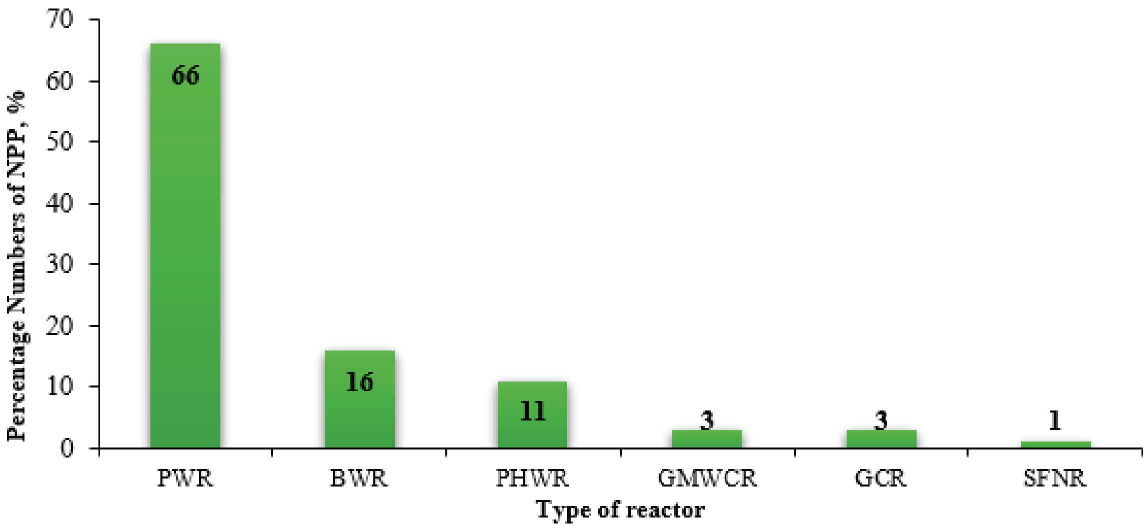

FIGURE 1. Percentage of NPP operated through December 2021
Source: adapted with improvements from Ho et al. (2019); Gospodarczyk (2022)

Nuclear energy originates from nuclear reactions that occur through fission, fusion, or nuclear decay (Arefin et al. 2021). The operation of this system involves the heat of the reactor converting water into steam, which then propels a turbine, leading to the production of electricity (Arefin et al. 2021). The goal of utilizing nuclear energy is to diminish dependence on fossil fuels and to act as a viable option for lowering greenhouse gas emissions (Adler, Jha, and Severnini 2020). Nuclear power, in conjunction with renewable sources, is regarded as a key player in worldwide economic decarbonization due to its ability to emit low levels of carbon (Adler, Jha, and Severnini 2020; Arefin et al. 2021). Nevertheless, while clean, nuclear energy does not guarantee safety for living organisms and may pose potential risks due to radiation, affecting surrounding habitats and nearby wildlife (Suman 2018; Adler, Jha, and Severnini 2020). Therefore, additional safety measures are necessary to protect the environment and nearby living organisms. Two types of shielding are essential for nuclear reactors: one to deflect neutrons back into the core, shielding the reactors from radiation damage, and the other to protect citizens and the environment from damaging radioactive radiation (Mortazavi and Raadpey 2010).

Shielding offers advantages, such as autonomous efficiency in secure working circumstances throughout time and space, which requires continual administrative control (Issard 2015). A good radiation shield should be capable of blocking, absorbing, or attenuating the majority of incident gamma and neutron radiation when possible (More et al. 2021). Thus, materials with a high hydrogen concentration, such as water, paraffin, polyethylene, and concrete, can be employed to shield against neutrons (Mortazavi et al. 2007; Mortazavi and Raadpey 2010; More et al. 2021). The most suitable materials for biological shielding in reactors are water and concrete as in Figure 2 (Bruck et al. 2019; Ouda and Abdelgader 2019). This is attributed to the presence of hydrogen in both materials, which makes them useful for shielding purposes, including as the foundation of reactor pressure vessels, for biological support, for containment buildings, and structural support in mechanical and electrical systems (Ouda 2015a; Khalaf et al. 2020; Ouda and Abdelgader 2019). Moreover, it is employed in the construction of various interior NPP structures, including spent fuel pools, hot cells, high-level waste dry casks, and water intake structures (Azreen et al. 2018). Biological shielding structures endure prolonged radiation exposure from the reactor, whereas containment units are engineered to withstand high-intensity and short-term hazards while operating for extended periods at elevated temperatures (Kurtis et al. 2017). Shielding materials for radiation serve diverse purposes. The purpose of thermal shielding is to safeguard components such as the pressure vessel, inner shield, and coolant loop from the extreme heat resulting from the absorption of nuclear radiation (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Rosseel 2014).

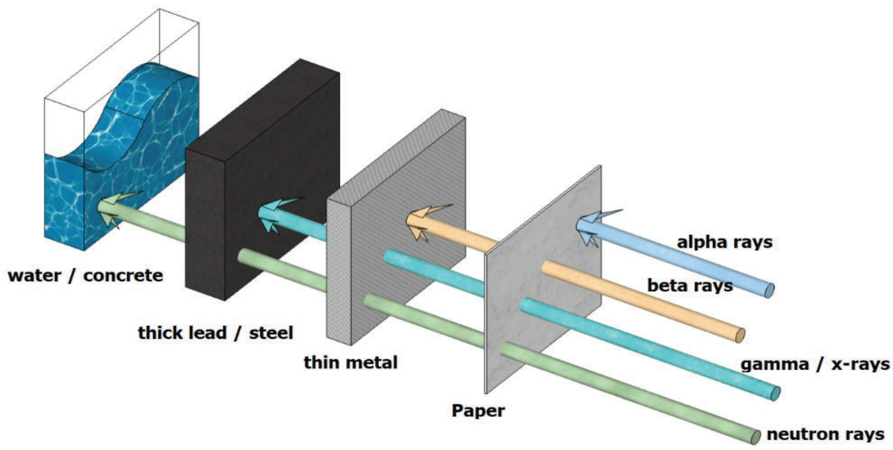

FIGURE 2. Different categories of radiation, their properties and penetration
Source: adopted from M. A. H. Abdullah et al. (2022); Tyagi et al. (2020)

The strength of a building structure relies on factors such as the material type, quantity, and ratio of ingredient combinations. External influences, such as the water-to-cement ratio, type of aggregate, and Portland cement, can affect the properties of concrete (Sims, Lay, and Ferrari 2019). It is frequently used for biological shielding materials because it has satisfactory mechanical and structural properties and is suitable for shielding from neutrons and protons compared to other materials (Ouda and Abdelgader 2019). Concrete has been chosen as a permanent shielding agent for nuclear irradiation due to its properties: concrete materials offer versatility in shape, density variation, cost-effectiveness, and robust structural integrity (Azreen et al. 2020; Ouda 2015b; Rasheed et al. 2022). Moreover, its impermeability to neutrons and photons renders it a suitable material for high-energy nuclear radiation shielding (Mortazavi et al. 2007). It contains a high hydrogen content and is capable of being a structural shield that can withstand heavy loads (Sariyer, Ku¨c¸er, and Ku¨c¸er 2015; Mortazavi and Raadpey 2010). It has also been reported that concrete containing at least 7 wt% water appears to be significant for attenuating neutrons (Mortazavi and Raadpey 2010). In addition, concrete boasts a high melting point, prolonged durability, excellent thermal conductivity, resilience against radiation damage, and thermal stress resistance (Matijević, Pevec, and Trontl 2015). Interestingly, concrete gains strength when compressed (Acevedo and Serrato 2010). It stands out as an efficient and extensively utilized material for neutron and gamma radiation shields and is often employed alongside graphite, water, lead, iron, polyethylene, and other materials in constructing nuclear radiation shields (Khalaf et al. 2020; Ouda 2015a). It stands out as an efficient and extensively utilized material for neutron and gamma radiation shields and is often employed alongside graphite, water, lead, iron, polyethylene, and other materials in constructing nuclear radiation shields (Khalaf et al. 2020; Ouda 2015a).

However, radiation could lead to deterioration in concrete and its structure. Gamma radiation leads to the radiolysis of hydrated cement paste (HCP), while neutron radiation triggers a transformation in the crystalline minerals within aggregates, resulting in volumetric expansion and a subsequent reduction in the material's mechanical properties (Yann Le Pape, Giorla, and Sanahuja 2016; Field, Remec, and Pape 2015). It is observed radiation-induced carbonation in the surface layer and center of samples due to an upward trend in calcite concentration in the HCP with increasing gamma irradiation dose (Vodák et al. 2011). Assessing damage in concrete structures is crucial for maintaining structural integrity and ensuring serviceability, significantly impacting these structures' security, energy sources, and economic viability. As concrete degrades, the frequency and extent of inspections and maintenance activities required to sustain operational standards inevitably increase. Understanding and mitigating concrete damage is essential for optimizing maintenance strategies, enhancing safety, and ensuring the long-term sustainability of infrastructure.

This review identified several critical factors contributing to the degradation of concrete biological shielding materials, warranting further investigation. Primarily, through a comprehensive review of the literature, this study aimed to investigate and correlate how numerous nuclear radiation types affect concrete biological shields. This highlights the effects of these types of radiation on the structural stability of reactor shielding, detailing mechanisms such as microstructural alterations or chemical reactions that elucidate how radiation modifies the physical and mechanical attributes of reactor concrete. Our methodology involved an extensive literature search, critical analysis, and synthesis of findings from peer-reviewed journals, conference proceedings, and technical reports that specifically address the degradation of mechanical and physical properties in concrete structures exposed to gamma and neutron radiation. This review is not constrained by a specific timeline, allowing for a comprehensive examination of the collected studies. Our selection criteria were based on relevance to the topic, the quality of the research, and the significance of the findings in advancing our understanding of radiation-induced damage in concrete used in nuclear power plants. This rigorous approach ensures that our review is comprehensive and includes the most pertinent and high-quality studies available.The gathered data has been synthesized and presented in new figures and charts, enhancing the understanding of the conditions within concrete structures and defining the scope of the research and the review.

RESEARCH GAPS

Long-Term Radiation Effects: While the short-term effects of radiation on concrete are relatively well understood, comprehensive data on long-term impacts is lacking. This review will provide an in-depth analysis of how prolonged exposure to low and high levels of radiation affects concrete over extended periods.

Combined Stressors: Concrete in NPPs is subjected to multiple simultaneous stressors, including radiation, thermal cycling, mechanical loads, and chemical attacks. Understanding the interactions and combined effects of these stressors is crucial. This review will explore how these combined factors contribute to the overall degradation of concrete, a topic currently underexplored in existing literature. By addressing these gaps, the review aims to enhance our understanding of concrete degradation in NPP's providing insights essential for improving material standards and ensuring nuclear power facilities' structural integrity and longevity.

SOURCES OF RADIATION IN NUCLEAR REACTOR

Nuclear energy is derived from fission, fusion, or nuclear decay reactions (Arefin et al. 2021). This form of energy generates heat, converting water into steam, which powers turbines to produce electricity (Arefin et al. 2021). Most nuclear reactors, including those in Japan (Luangdilok and Xu 2020), the Republic of South Korea (Yang 2018), China, the United States, France, Russia, Switzerland, and other regions using NPPs (Fernández-Arias, Vergara, and Orosa 2020), can be likened to high-tech kettles that efficiently boil water to generate electricity.

The reactors rely on the process of nuclear fission, in which one atom splits into two smaller atoms, producing heat and releasing neutrons into the air (IAEA 2015). One of those neutrons can be absorbed by another atom, prompting the atom to become unstable and undergo fission, releasing additional heat and neutrons (IAEA 2015). A steam generator recovers heat from pressurized water reactors (PWRs). When light water is pushed into a steam generator, it produces steam. Moreover, in pressure boiling water reactors (BWRs), light water boils in a pressure vessel, producing steam that directly drives a turbine (Arefin et al. 2021). The reaction process occurs when an incident neutron enters a heavy atom nucleus, splitting it into two distinct pieces and unleashing high-energy and new fast neutrons that set off an entirely new chain of fission events (Azevedo 2011). Systematically self-sustaining, the chain reaction creates a consistent supply of heat that boils water, powers steam turbines and ultimately generates electricity.

Most nuclear reactors utilize “enriched” uranium, characterized by higher concentrations of uranium-235 (^{235}U) isotopes, allowing easier splitting to generate energy (Dobozi 2016). While natural uranium ore contains only 0.7% ^{235}U, the fuel is typically enriched to 3-4% or even up to 5% for reactor use (Ricotti 2013; Upadhyaya et al. 2015; Dobozi 2016; IAEA 2015). In specific reactors such as TRIGA, uranium enrichment may reach 20% (Matsumoto and Hayakawa 2000). Notably, a kilogram of uranium (^{235}U) produces roughly three million times more power than a kilogram of conventionally burned coal (Azevedo 2011). Fuel rods, comprising sealed metal tubes housing ceramic pellets derived from enriched uranium, feature water channels for cooling (Steven J. Zinkle and Busby 2009). The uranium enrichment levels vary among different types of nuclear reactors, depending on their usage and power, as illustrated in Table 1. Top of Form

TABLE 1. The type of reactor and its fuel type with enrichment

Type of reactor	Moderator	Fuel type, enrichment	Refs.
AGCR	Graphite	UO_2, 2.3%	(Ricotti 2013)
MAGNOX	Graphite	U metallic, natural (0.7%)	
PWR	Light water	UO_2, 3.2%	(Arefin et al. 2021)
BWR	Light water	UO_2, 2.4%	
CANDU	Heavy water	UO_2, natural (0.7%)	(Bruck et al. 2019)
RBMK	Graphite available	UO_2, 1.8%	
HTGR	Graphite	UO_2/UC_2, 1.2%-93%	

Depending on the power level, a reactor core could be composed of several hundred fuel rod assemblies, with each fuel assembly usually consisting of more than 200 rods bundled together (El Bakkari et al. 2010). This core reactor produces ionizing radiation (IR), which is harmful to humans. IR, capable of causing atom ionization, interacts substantially more aggressively with biomolecules than non-IR (Reisz et al. 2014). The group of unstable radionuclides, known as radioisotopes, serves as the source of IR. These radioisotopes release high-energy particles that can displace atomic electrons, immediately initiating a chain reaction of electron ejection (Reisz et al. 2014). The four primary types of IR emitted by NPPs from nuclear sources are neutron, gamma, beta, and alpha radiation as Figure 2 in the introduction. Alpha particles and beta particles do not induce radioactivity in a substance or body; they can be effectively blocked by a piece of paper or a few mm of aluminum (Krishnan et al. 2018;. Abdullah et al. 2022). Alpha particles, constituting two protons and two neutrons, emanate from naturally occurring heavy elements such as uranium or radium. Conversely, beta particles, which can be electrons or positrons, are emitted by different radioactive elements (Reisz et al. 2014; Abdullah et al. 2022). In a nuclear reactor, the most common types of radiation are neutron beams and gamma rays due to their abundance of post-fission and high penetration ability, which can severely damage human biological cells, tissues, and organs (Reisz et al. 2014; Ouda and Abdelgader 2019). Only materials with high atomic numbers (Z) and high densities are effective at blocking both types of radiation. Gamma can be blocked by using lead, whereas neutrons can be blocked by using materials that contain hydrogen, such as concrete (Reisz et al. 2014;. Abdullah et al. 2022; Ouda and Abdelgader 2019; Ouda 2015a). Historically, the detrimental impact of nuclear radiation on concrete has been associated with the cumulative gamma-ray dose and neutron fluence (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Rosseel 2014). Generally, concrete deterioration is observed at approximately $2x10^{10}$ rad gamma-ray doses and $1x10^{20}$ n/cm^2 fast neutron fluence levels. These thresholds, however, significantly rely on the depth of radiation absorption within the concrete surface (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Kontani et al. 2013).

NEUTRON AND GAMMA RAYS

Neutrons play a crucial role in various fundamental and applied physics fields (Luca, Camajola, and Casolaro 2019; Lunéville, Simeone, and Jouanne 2006). Neutrons are subatomic particles present in almost all nuclei except for hydrogen. The mass of neutrons is 1.67x10^{-27} kg, and they do not carry any charge (Murty and Charit 2013). Some neutrons are born post-fission, as either prompt or delayed neutrons are emitted during the radioactive decay of heavy elements (Luca, Camajola, and Casolaro 2019). Neutrons interact with atomic nuclei via diffusion or absorption as they travel through a material (Murty and Charit 2013). To provide criticality with a smaller fuel inventory and generate excess neutrons for various applications, including neutron-beam applications, the moderator or reflector in an NPP alters the energy spectrum of fast neutrons that escape the central core. This is achieved by redirecting a significant portion of these fast neutrons, once thermalized, back into the core region (Schoenborn and Knott 2006). Neutrons can be classified according to their energy, as tabulated in Table 2.

Neutrons produced within nuclear reactors engage in both elastic and inelastic collisions with stable nuclei, leading to the creation of metastable nuclei (Sublet et al. 2019). Inelastic scattering occurs when fast neutrons collide with heavier atomic nuclei, resulting in the transformation of a fast neutron into an intermediate neutron, emitting both gamma and neutron signals (Murty and Charit 2013). Once neutrons become thermal neutrons, their energy level becomes low and insufficient to free neutrons from the nuclei of atoms (Murty and Charit 2013). The neutron flux characterizes neutron penetration in shielding material in terms of its cross-sections (absorption, effective removal, scattering), neutron relaxation length and moderating ratio (Madbouly and A. El- Sawy 2018). The neutron cross section represents the likelihood of incident neutrons interacting with atomic nuclei within materials. This interaction is probabilistic and relies on both the neutron energy levels and the specific nuclei present within the substance (Murty and Charit 2013).

TABLE 2. Classification of neutrons and their range of energy

Types of neutrons	Ranges of neutron energy	Ref
Cold	<0.003 eV	
Slow (Thermal)	0.003-0.4 eV	(Murty and Charit 2013)
Slow (Epithermal)	0.4-100 eV	
Intermediate	100 eV-200 keV	(.Schoenborn and .Knott 2006)
Fast	200 keV-10 MeV	
High energy (relativistic)	>10 MeV	(Luca, Camajola, and Casolaro 2019)

Gamma rays are sources of radiation in NPPs and are generated alongside neutrons during fission. Gamma rays are high-energy photons that lack electric charge and mass but possess far greater penetrating power than beta and alpha particles (Murty and Charit 2013). Gamma radiation is a type of electromagnetic radiation that has a high frequency and high energy. When the energy of the photons exceeds 0.1 MeV, the photons are classified as gamma rays. (Mollah 2019). Approximately 5.9 ± 0.8 MeV of energy is emitted within the range of 0.3 MeV to 5.0 MeV during the time frame from 1 second to 10^8 seconds postfission (Roos 1959). In the photoelectric effect, photons are completely absorbed. At low photon energies, this interaction predominates for heavy metals such as lead and uranium (Mollah 2019). Conversely, the pair production process, where a photon is entirely absorbed, leading to the creation of a pair of positrons and electrons, prevails notably in heavy elements characterized by high photon energies. (Mollah 2019). Moreover, for all the elements, Compton scattering, which includes inelastic scattering of gamma rays and electrons and results in photon energy degradation, is dominant at intermediate photon energies. (Mollah 2019). Mostly, gamma radiation is found in spent nuclear fuel (Abdullah et al. 2022).

The damaging impacts of nuclear radiation on concrete historically pertain to the cumulative dose of gamma rays and the neutron fluence (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Rosseel 2014). Concrete deterioration is typically detected at a fast neutron exposure of 1x10^{20} n/ cm^2 and a gamma irradiation dose of 2x10^{10} rad. These principles are highly dependent on the depth of radiation attenuation within the concrete surface (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Kontani et al. 2013). A material's ideal tendency to interact with gamma rays is indicated by a high atomic number and mass attenuation coefficient, which helps minimize radiation exposure to a safe level (Kaundal 2017). Conversely, the primary parameters governing the photon–matter interaction include the following: the mean free path (λ), tenth-value thickness (TVT), linear attenuation coefficient (μ), half-value thickness (HVT), and mass attenuation coefficient (μ/ρ) (Akkaş 2016; Ouda 2015a; Ouda and Abdelgader 2019). The absorption and scattering of gamma rays correlate directly with the mass attenuation coefficient of materials. This coefficient quantifies the likelihood of incident photons interacting with matter, considering one unit of mass per unit area (Madbouly and A. El- Sawy 2018). It should also be noted that gamma-ray effect on concrete are relatively less significant than those of neutron beams, except near a large water gap where their DPAs are comparable (Kwon and Motta 2000). Furthermore, gamma damage can have a disproportionate impact on any radiation-enhanced phenomenon that relies on the size of long-range defects, such as radiation-induced voids, creep, irradiation, and segregation creep.

EVOLUTION OF CONCRETE SHIELDING

The principle of radiation protection, known as "as low as reasonably achievable" or ALARA, involves four primary factors: distance, time, activity and shielding (More et al. 2021). To decrease radiation exposure from a source, the strategy involves both reducing the duration of exposure and increasing the distance from the source. According to the reciprocal of the square law, doubling the distance from the source leads to the dose at the new location being one-fourth of the original dose (More et al. 2021). Nuclear safety has centered around the idea of "defense-in-depth" since the commencement of nuclear energy development. According to AIEA (2015), defense in depth in a nuclear reactor consists of five levels, emphasizing multiple layers of defense for safety and protection. The fourth line of defense involves physical barriers, such as concrete shielding or containment. concrete is frequently utilized to minimize radiation leakage from radioactive sources and to provide radiation shielding in nuclear reactors and radiotherapy facilities. Concrete with a density exceeding 2900 kg/m^3, achieved through the use of certain aggregates exceeding 3000 kg/cm^3, serves as an effective shielding agent against neutrons (Azreen et al. 2020; Rasheed et al. 2022). This type of concrete is commonly known as high-density concrete (HDC) or heavy weight concrete and typically has a density greater than 3.2-4.0 t/m^3 (Y. Abdullah et al. 2015;. Abdullah et al. 2022). HDC consists of high-weight aggregates with specific gravities greater than 3000 kg/m^3 (Azreen et al. 2018; Khalaf et al. 2020; Ouda 2015b). By utilizing heavy, fine, and coarse aggregates, each with densities spanning 3500 to 7500 kg/m^3, concrete densities ranging from 2800 kg/m^3 to 5600 kg/m^3 can be created. These variations in concrete density are instrumental in NPP structures to minimize the shielding thickness for effective radiation attenuation (Naus et al. 1996).

This concrete mixture may consist of many components, ranging from natural aggregates to a blend of metal and polymers, to produce safer protection (More et al. 2021). The aggregates used in concrete can consist of various natural, artificial, or even a mixture of both. The use of different minerals as aggregates will result in different concrete densities (Ouda and Abdelgader 2019; Azreen et al. 2020). It is anticipated that aggregates with varying mineralogies and sizes will exhibit different reactivities and fracture properties (Dunant and Scrivener 2012). The size of the aggregates significantly impacts the concrete properties and strength. Small aggregates have a maximum size of five millimeters (mm), while coarse aggregates typically range between five and 20 mm (Maruyama and Sugie 2014).

Several types of aggregates are used by researchers in concrete manufacturing, including the minerals barite, hematite, magnetite, limonite, and serpentine heavy minerals such as zircon, ilmenite, and fly ash; artificial aggregates such as iron waste (Ahmed et al. 2021; Kaplan 1989; Ouda 2015a; Ouda and Abdelgader 2019); tin tailing (Çullu and Ertaş 2016); bismuth oxide, galena, colemanite, bauxite, and hydrous iron ore (Khalaf et al. 2020; Mortazavi et al. 2007; Y. Elmahroug 2013); material that contains quartz (Krishnan et al. 2018); and recycled aggregates from abundant or used buildings (Shi et al. 2016). Utilizing a blend of dense aggregate materials such as barytes (Zagar and Ravnik 2000; Akkurt et al. 2012; Azreen et al. 2018), limonite (Northup 1965; Akkurt et al. 2012; Ouda 2015b), magnetite (Gallego, Lorente, and Vega-carrillo 2009; Józwiak-Niedzwiedzka, Glinicki, and Gibas 2016; Ouda 2015a), and ilmenites (Bashter 1997; Kansouh 2012) has the potential to diminish section thickness, meeting the attenuation prerequisites of biological shields. These shields may range from a few millimeters to several meters in thickness, depending on their structural design. Heavyweight concrete (HWC) has a high strength that reduces the thickness of concrete structures. HWC walls are approximately 40% thinner than ordinary concrete walls, yet they still have a comparable projected load-carrying capacity (Abdullah et al. 2022; Khalaf et al. 2020). The concrete used by researchers has been tabulated as in Table 3 composing the energies or sources of radiation and their effect on concrete depending on the type of concrete and aggregate used.

TABLE 3. Summary of the main findings of the analysis of the impact of radiation on concrete biological shielding, as reported by previous researchers worldwide.

Ref	Type of concrete	Aggregate	Density (g/cm^3)	Compression strength (MPa)	Energies/source of radiation	Linear attenuation coefficient (μ) (cm^{-1})	Mass attenuation coefficient (μ/p) (cm^2/g)	Half-value layer (HVL) (cm)	Tenth value layer (TVL) (cm)
(Bashter 1997)	-Ordinary -High density	NI	2.3	NI	1.5 to 6 MeV	1.64-0.078	0.079-0.034	NI	NI
		Hematite-serpatine (HS)	2.5			0.124-0.082	0.049-0.033		
		Ilminet-limonat (II)	2.5			0.146-0.082	0.058-0.033		
		Basalt-magnetite (BM)	3.05			0.155-0.089	0.051-0.029		
		Ilminet	3.5			0.1757-0.1036	0.05-0.029		
		Steel scrap	4.0			0.208-0.126	0.052-0.032		
		Steel -magnetite (SM)	5.11			0.252-0.157	0.049-0.0307		
(Mortazavi et al. 2007)	High-density concrete Ordinary concrete	Galena (pbs)	4.89	500	Cobalt 60	NI	NI	2.65	NI
		Barite	3.5	140-359				3.6-4.0	
		limestone	2.5	300				5.25-6.2	
(Mortazavi and Raadpey 2010)	High-density concrete	Colominite -galena (CoGa)	4.1-4.65	398-464	Cobalt 60	NI	NI	2.49	NI
(Kansouh 2012)	Ordinary concrete	Gravel	2.3	NI	2-11 MeV	0.106	0.046	6.5349	21.7469
	High-density concrete	Serpentine	2.4			0.098	0.041	7.0355	23.3807
		Ilmenite-limonite	2.9			0.128	0.044	6.3057	20.9554
		Hematite-serpentine	2.5			0.102	0.041	6.8141	22.6450

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(Y. Elmahroug 2013)	Shielding material (polyethylene-based)	Pure	0.92	NI	1KeV-1GeV	NI	1.89E+03-1.63E-02	NI	NI
		Lithium	1.06				1.72E+03-1.56E-02		
		Borated	1.19				2.51E+03-1.71E-02		
		Bismuthloaded	2.92				4.54E+03-9.20E-02		
		Borated-lead	3.8 g				4.68E+03-9.46E-02		
(Ouda 2015a)	Shielding concrete	Magnetite	2.64-3.02	NI	Cesium 137 Magnetite mix only	0.04-0.2009	NI	17.32-3.44	57.50-11.44
		Barite	2.91-3.51			0.041-0.205		16.90-3.38	56.15-11.23
		Geotite	2.65-2.84		Cobalt 60 Magnetite mix only	0.039-0.1954		17.77-3.55	59.02-11.78
		Serpentine	2.52-2.43			0,0395-0.1975		17.54-3.51	58.28-11.65
(Kavaz 2019)	Glass Gamma ray shielding	Dolomite	2.21-2.44	NI	Barium 133	NI	0.1734-0.0957	1.7081-2.6517	NI
		Hematite	2.34-2.73		Cesium 137		0.1734-0.0957	1.7081-2.6517	
		Goethite	2.45-3.32		Cobalt 60		0.1871-0.0954	1.5118-2.1875	
(Azreen et al. 2020)	Ultra-high performance	Amang (A)	3.03	157	Barium 133	0.155	0.065	2.56	4.17
					Cesium 137	0.060	0.060	2.40	4.01
		Silica sand (SS)	2.4	165	Cobalt 60	0.071	0.071	2.44	4.05
					Barium 133	0.096	0.040	3.04	4.65
		Lead glass (LG)	2.47	170	Cesium 137	0.112	0.037	2.89	4.50
					Cobalt 60	0.106	0.043	2.94	4.55
(Akkurt et al. 2012)	High-density concrete	Siderite	2.95	NI	1173 KeV	0.12	NI	NI	NI
					1332 KeV	0.13			
		Barite	3.41		1173 KeV	0.15			
					1332 KeV	0.15			
		Limonite	2.60		1173 KeV	0.14			
					1332 KeV	0.16			

continue ...

... cont.

(Akkurt, Günoglu, Basyigit, and Akkas 2013)	lightweight concrete (LC)	NI	0.6-1.5	Cobalt 60 (1173 KeV and 1332 KeV)	NI	NI	6.86	22.79
							7.70	25.58
	semi lightweight concrete (SLC)		1.4-2.0				6.03	20.02
							6.36	21.12
	ordinary concrete (OC)		2.0-2.5				3.98	13.23
							4.20	13.95
	semi heavyweight concrete (SHC)		2.5-3.0				3.96	13.15
							4.15	13.78
	heavyweight concrete (HC),		3.0-4.0				3.85	12.79
							4.08	13.54
(Al-Humaiqani, Shuraim, and Hussain 2013)	Heavy performance concrete (HPC)	Limestone	2.407	0.663MeV	0.1672	0.0695		
		Quartz	2.454		0.1698	0.0692		
		Meta sediment	2.472		0.1788	0.0723		
		Barite	3.376		0.2519	0.0746		
		Hematite	3.697		0.2661	0.0720		

*NI-not indicate

IMPACT OF NUCLEAR RADIATION IN NPP SHIELDING

Radiation fields that can have a direct effect on shielding materials are typically characterized by gamma-ray dose and neutron fluence also the number of loops in the reactors as in (Fig. 3) (Remec et al. 2017a). According to (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978), the strength and modulus of elasticity of concrete could be adversely affected by neutron fluence surpassing $1.0x10^{19}$ n/cm² or 10^{10} rads. Moreover, experimental findings demonstrating the diminished significance of neutron shielding evaluations up to neutron fluences of approximately 10^{19} n/cm² highlight the potential adverse effects of higher fluences on the modulus of elasticity, tensile strength, and compressive strength of concrete. This underscores the importance of further investigations in this domain (Zalegowski et al. 2020; Kaplan 1989). When certain materials are exposed to irradiation above a certain threshold, their mechanical qualities decrease (Rasheed et al. 2022). However, complexity arises from the amalgamation of nuclear radiation with mechanical, thermal, and moisture loads, variables that are contingent on reactor design (Field, Remec, and Pape 2015). The impact of radiation on concrete properties within nuclear structures becomes intricate due to multiple radiation exposure components, encompassing ionization, nuclear transmutation and atomic displacement or their combined effects.

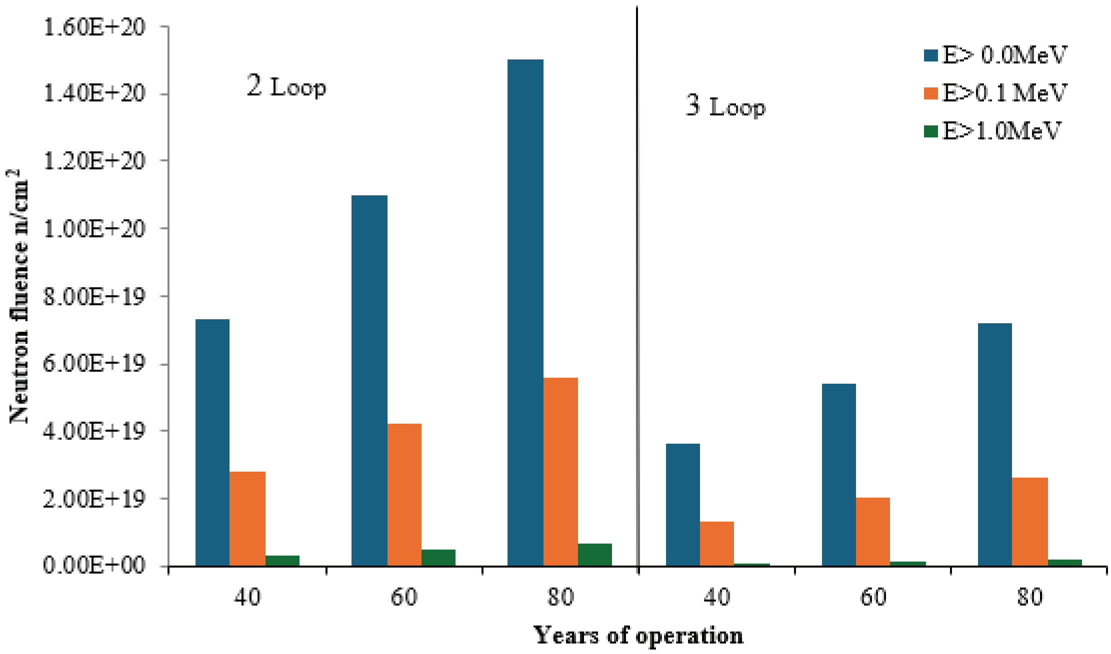

FIGURE 3. Comparison of the neutron fluence in two-loop and three-loop PWRs after 80 years of operation
Source: adapted and modified from Remec et al. (2017b)

DISPLACEMENT PER ATOM

Radiation can affect materials by transferring energy to electrons or nuclei via several kinds of mechanisms, including ionization, electron, or nuclear activation, depending on the radiation type (B. Wang et al. 2015). The DPA is a frequently used measure for assessing the impact of displacement damage within a material (Li 2010; Qadr and Mamand 2022). Material transformations triggered by irradiation are quantified in terms of DPA (Qadr and Mamand 2022), a unit used to gauge irradiation exposure (S. Chen et al. 2019). For instance, radiation-induced swelling peaked at 0.16% after exposure to 5 DPA and increased to 0.66% after 25 DPA. This tenfold increase over the acceptable swelling for reactor core materials serves as an indicator (Voyevodin et al. 2021). However, DPA is not equivalent to damage (S. Chen, Bernard, and Blaise 2020). DPA is the outcome of energetic neutrons generated by fission and fusion processes, which have enough kinetic energy to dislodge numerous atoms from their lattice positions within structural materials, leading to the creation of vacancies (Steven J. Zinkle and Busby 2009; S. Chen et al. 2019). The damage begins when energetic irradiation particles collide with a target nucleus, displacing atoms from their original lattice sites (Steven J. Zinkle, Tanigawa, and Wirth 2019; S. Chen et al. 2019). The primary knock-on atom (PKA) occurs when an energetic particle imparts recoil energy to a lattice atom, displacing neighboring atoms and culminating in an atomic displacement cascade (Mascitti and Madariaga 2011; S. Chen, Bernard, and Blaise 2020; Qadr and Mamand 2022), as illustrated in Fig. 4

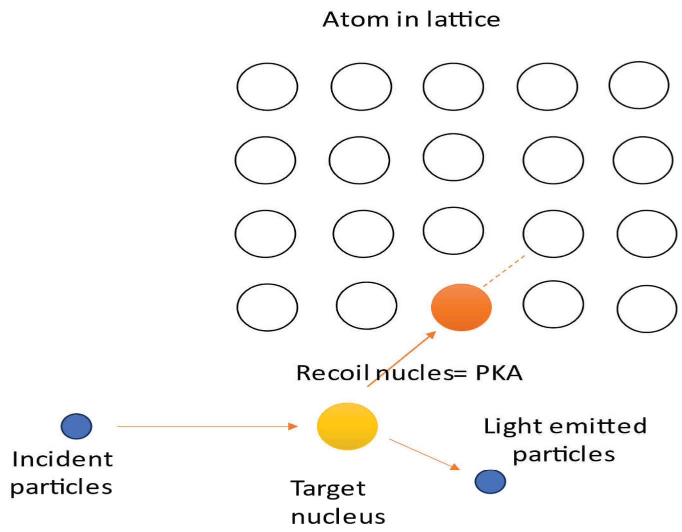

FIGURE 4. Schematic design of atomic displacement caused by an incident
Source: adapted from S. Chen et al. (2020)

Determining DPA values involves considering factors such as the type of irradiation particles, their energy spectrum, the duration of irradiation, and other relevant aspects (Kwon and Motta 2000; Li 2010). The consequence of this collision is known as a Frenkel pair, where an atom is displaced from its initial position, leaving behind a void (Mascitti and Madariaga 2011; S. Chen et al. 2019). The displaced atom becomes interstitial once it settles in one of the lattice sites. The fundamental idea behind the irradiation effect and the primary source of damage to the microscopic structure of materials is this vacancy–interstitial pair, commonly referred to as the Frenkel pair (Nordlund et al. 2018; Mascitti and Madariaga 2011). As a result of irradiation exposure, minerals may change their atomic structures, consequently altering their physical and chemical properties (S. Chen, Bernard, and Blaise 2020; Li 2010). Diffusion processes occur over time, leading to the recombination or clustering of irradiation-induced defects, generating more stable damage structures, including dislocation networks, loops, voids, helium bubbles, residues, and so on (Li 2010). A material's physical and mechanical properties are significantly altered when its microstructure is destroyed (Mascitti and Madariaga 2011).

Various parameters are utilized to assess specific attributes and segments within the neutron energy spectrum that could account for the observed changes. Among these parameters are the total neutron fluence, thermal fluence (energy less than approximately 0.5 eV), and fast fluence (energy greater than a predefined threshold) (Stoller et al. 2013). A neutron fluence exceeding 1.0 MeV is frequently employed as a primary indicator of dimensional and mechanical property alterations in metals and alloys, attributing the damage to atomic displacements caused by neutrons within this energy range (Stoller et al. 2013; Chang et al. 2014). A comparison between the SRIM and other simulation codes, such as PHITS, MCNPX, MARS15, and FLUKA, for DPA calculations based on Meier's experimental data (Iwamoto et al. 2010) was presented by Qadr and Mamand 2022 for 1000 MeV photon interactions with 3 mm thick iron benchmarking data (Fig. 5). In addition, it has been reported that when excited at 113 MeV or 256 MeV, protons interact with thick cylindrical targets of Be, C, Al, and Fe. The study showed that the usage of the study mode did not significantly differ, except for MCNPX, which did not provide readings for Be or W. In addition, the Fe concentration was the highest among all the modes.

Previously, Qadr and Hamad (2020) utilized SRIM to compute atomic displacement and total vacancy numbers in accordance with the NRT model for various proton energies irradiating Fe and Cu targets and revealed an increase in the number of target vacancies with rising ion energy. Consequently, the forecasts for Cu at 0.5, 1.0, and 9.0 MeV indicated a higher total vacancy count per ion than that for Fe. Numerous significant findings regarding shielding computations were discovered by Oh et al. (2011) at comparable thicknesses in the proton range. The neutron yields demonstrated a proportional relationship with the atomic number of the target material (Oh et al. 2011; Mokhtari Oranj et al. 2020). Higher differential yields were discovered at high Z targets, with an increase of less than a factor of two or three at higher neutron energies above 10 MeV (Trinh et al. 2017; Oh et al. 2011). Fortunately, at 10 MeV, the discrepancy in yield between the low-Z and high-Z target strains increased significantly. Specifically, the yields from Pb targets exceeded those from Al targets by tenfold.

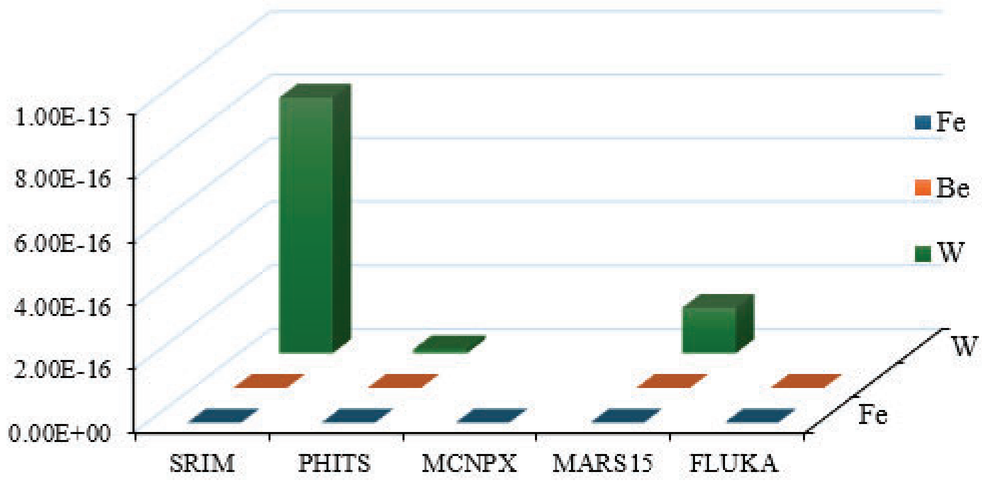

FIGURE 5. Comparison of DPAs for different elements calculated using various types of Monte Carlo codes
Source: adapted from Qadr and Mamand (2022)

Low-energy recoils, such as electron irradiation, are more effective at creating point defects, while high-energy recoils, such as heavy ion or neutron irradiation, induce cascade damage and defect clusters (Li 2010). Dose rates resulting from high-energy proton irradiation may be 2-3 orders of magnitude greater than those resulting from neutron irradiation (Qadr and Mamand 2022). The dosage rate in a normal thermal (or mixed spectrum) neutron reactor is approximately 10^{-7} dpa/s, but the rate of dose in a rapid fission reactor is approximately 10^{-6} dpa/s (Nordlund et al. 2018; Li 2010). It was previously observed that the DPA cross-sections for all materials are similar below 100 eV and increase with increasing neutron energy (Luu et al. 2020). One of the common effects of nuclear radiation on concrete is DPA in aggregates (Luu et al. 2020). Remec et al. (Remec et al. 2017a) reported that approximately 90% of DPAs stem from neutrons that occur between 0.1 MeV and 2 MeV in energy, with approximately 20-25% attributed to neutrons surpassing 1 MeV (Fig. 10). Oak Ridge National Laboratory suggested that, in simple crystalline materials, more than 95% of DPAs are generated by fast neutrons surpassing 0.1 MeV, based on initial theoretical analyses (Remec et al. 2016). Fig. 6 shows radiation-induced atomic displacements in concrete aggregates where three loops of the reactor have a lower DPA rate than two loops of the reactor. Albite, silicon, and quartz are the most common elements affected by DPA in reactors. All these aggregates contain silica as one of their main elements; approximately 90% of the atomic displacements were caused by neutrons with 0.1~2 MeV energies. >1 MeV neutrons caused 20~25% of the total atomic displacements, with 95% due to < 0.1 MeV neutrons (Remec et al. 2017a). As such, >0.1 MeV neutrons were more important than >1 MeV neutrons in terms of displacing atoms in the aggregates. It should also be noted that the DPA rates for all the aggregates were within ~10% of each other (Remec et al. 2016; 2017a).

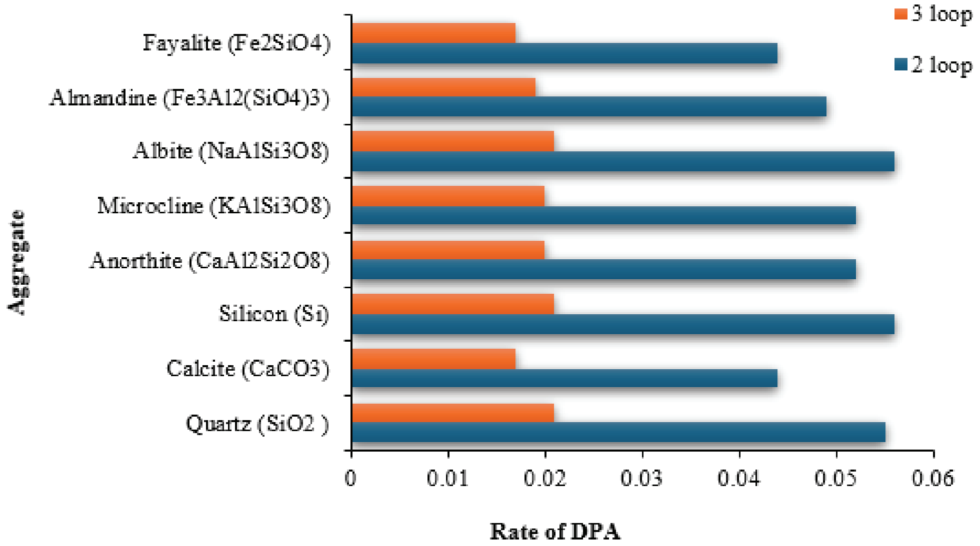

FIGURE 6.DPA rate of aggregates in concrete
Source: adapted from Remec et al. (2017b)

Understanding the DPA rate during the operation of NPP provides valuable insights into the changes occurring within materials, particularly at the crystallite structural level, after irradiation. This knowledge has critical practical implications for the nuclear power industry for prolonged service life. By identifying materials that better withstand radiation and environmental stressors, the operational lifespan of nuclear power plants can be extended. This ensures that facilities can safely function for longer periods, thereby enhancing the return on investment and reducing the frequency of costly overhauls and replacements. Moreover, by considering the DPA effects, would help for future-proofing. As the nuclear industry advances, having a detailed understanding of material performance under various stressors ensures that existing facilities can adapt to new safety protocols and technologies. This future-proofing is essential for nuclear power plants' sustainable and safe operation.

RADIATION INDUCE VOLUMETRIC EXPANSION (RIVE)

Radiation attenuation within concrete is chiefly influenced by aggregate type, elemental composition, moisture content and W/C, all of which are contributing factors aside from the density of concrete (Yann Le Pape, Giorla, and Sanahuja 2016). The concrete was made up of 70% aggregate. High-energy ballistic collisions produced by recoil radiation from alpha particles, ions, or neutrons cause damage cascades in the crystalline structures of rock-forming minerals, resulting in a shift in the coordination of silicate tetrahedrons (Torrence et al. 2021; Yann Le Pape, Giorla, and Sanahuja 2016). As a result, atomic bonds strain and eventually break. Ultimately, the aggregate material may expand volumetrically, leading to swelling and thereby affecting its mechanical and physical properties (Yann Le Pape, Giorla, and Sanahuja 2016). Radiation induces alterations in the physical aspects of both the cement paste and aggregates in two distinct ways: first, it releases gas and increases shrinkage at high temperatures by radiolyzing the water in the high-temperature cement HCP; second, it amorphized the crystalline minerals in the aggregates through the emission of neutron radiation. and cause radiation-induced volumetric expansion (RIVE) (Y. Le Pape, Field, and Remec 2015; Y. Le Pape, Sanahuja, and Alsaid 2020). This RIVE became the main factor for the loss of mechanical properties (Y. Le Pape 2015a; H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Yann Le Pape, Giorla, and Sanahuja 2016). RIVE fundamentally influences the degradation of irradiated reactor concrete as RIVE can lead to notable dimensional alterations, demonstrating similarities in impact to or even surpassing those induced by the alkaline silica reaction (ASR) (Jóźwiak-Niedźwiedzka and Lessing 2019; Ouda and Abdelgader 2019). Research has substantiated the relevance of RIVE as a potential degradation process in concrete, particularly with silica-bearing aggregates under neutron irradiation.

Most related research agrees that aggregates are most affected by RIVE under nuclear irradiation since concrete is composed of 70% aggregates (Rosseel et al. 2016; Alain, Le Pape, and Huang 2016; Field, Remec, and Pape 2015; Y. Le Pape, Field, and Remec 2015). The composition of aggregates within concrete directly influences the structural strength, density, and compressive qualities of the material in various applications. As a result, when a neutron collides with a crystal lattice aggregate, its lattice constant may increase, potentially leading to the formation of lattice defects (Petrounias et al. 2018). Exposure to high doses of fast neutrons with a fluence >~10^{19} n/cm^{-2} and kinetic energy surpassing 0.1 MeV degrades the constituent minerals responsible for forming aggregates in concrete (Y. Le Pape, Sanahuja, and Alsaid 2020). Y. Le Pape, Sanahuja, and Alsaid (2020) also proposed that silicate-bearing minerals, carbonated minerals, and metal-bearing oxides, along with initial pristine crystalline structures, undergo RIVE. This process often leads to a decrease in density following irradiation (Mirhosseini, Polak, and Pandey 2014). In addition, it has been reported that when concrete containing natural aggregates is exposed to gamma irradiation above 10^{10} Gy, the compressive and tensile strengths decrease (Kontani et al. 2013; Jóźwiak-Niedźwiedzka and Lessing 2019). In comparison to gamma irradiation, fast neutron irradiation induces more substantial degradation in the mechanical properties of concrete. This difference arises because neutrons exhibit stronger interactions with solids than with liquids. Considering that aggregates are more well-crystallized and denser than cement pastes, they tend to be more susceptible to the effects of neutron interactions (Kontani et al. 2013). Table 4 presents a compilation of research findings from previous studies, providing a comparative analysis of the RIVE encountered by various types of aggregates.

The suggested threshold for concrete deterioration is 2.0×10^{10} rad for gamma rays and 1.0×10^{20} n/cm² for fast neutrons. However, the exact fluence levels and the limit of neutron fluence before concrete deterioration are subjects of ongoing debate (Y. Le Pape 2015a; Field, Remec, and Pape 2015; H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978). However, RIVE in concrete aggregates occurs when concrete is exposed to high energy, which is more than 0.1 MeV, and has a fast neutron fluence of 10^{19} n/cm^2, as suggested and discussed by researchers when assessing the issue of irradiation against concrete (Y. Le Pape 2015a; Field, Remec, and Pape 2015; Y. Le Pape, Field, and Remec 2015). The model simulations by Bruck et al. (2019) predict that damage to concrete shielding will mostly come from radiation impacts and will infiltrate due to the accumulated fluence. Despite the radiation, the estimated values for stress are minimal (below 1 MPa) (Bruck et al. 2019). The most significant observed damage, estimated to occur after 50 years of operation, aligns with the concrete radiation damage threshold (0.5). This notably manifests at the surface of the CBS or where the highest fluence peaks (Bruck et al. 2019).

It has been reported that quartz possesses the highest potential for RIVE compared to other aggregates (Yann Le Pape, Alsaid, and Giorla 2018; A. Giorla et al. 2015; Yann Le Pape, Giorla, and Sanahuja 2016; Field, Remec, and Pape 2015). Quartz, normally composed of SiO_2, is commonly used in ordinary concrete aggregates, such as silica sand or other silicate glass (X. Wang et al. 2018). Previous studies have been conducted to investigate the damage inflicted on quartz by various forms of radiation, including neutrons and other ions (B. Wang et al. 2015; Petrounias et al. 2019; Yann Le Pape, Giorla, and Sanahuja 2016). Khmurovska et al. (Yuliia Khmurovska and Štemberk 2021) concluded that aggregates commonly used in ordinary concrete are not suitable for application in irradiated concrete because of their high potential for RIVE (Table 4). Wang et al. (B. Wang et al. 2015) utilized extensive molecular dynamic (md) simulations to investigate damage in quartz after irradiation and observed that conjointly synchronized Si and O species constitute the primary types of point defects leading to the conclusion of the cascade, the prevalence of which significantly relies on the incident energy. Structural damage also entails significant alterations to the Si-O structure, resulting in tiny silicon-oxygen rings and silicon tetrahedra sharing edges (Czakoj et al. 2020; B. Wang et al. 2015). Radiation-induced amorphization may have played a role in these changes. The average displacement of the threshold energy for Si and O yields values of 70.5 eV and 28.9 eV, respectively. These numerical findings facilitate a more accurate assessment of radiation-induced damage in quartz (Primak 1958; B. Wang et al. 2015; Luu et al. 2020). RIVE has emerged as a key factor causing cracks in the cement paste of PWRs (Pomaro 2016). When subjected to irradiation, water molecules undergo radiolysis, resulting in the formation of both relatively stable primary products and unstable free radicals (Maruyama and Sugie 2014). Radiolysis of water in hardened cement paste releases hydrogen and oxygen gases (Kontani et al. 2013), possibly enhancing the shrinkage of cement paste and increasing shrinkage at high temperatures (Yann Le Pape, Giorla, and Sanahuja 2016).

TABLE 4. RIVE values of selected aggregates under >0.1 MeV and >10^{19} n/cm^2 neutron fluence

Ref	Concrete aggregates	RIVE values (% expansion)			
		Length	Mass	Volume	Maximum RIVE
(Y. Le Pape, Sanahuja, and Alsaid 2020)	Quartz (90%)	+ 18	2.6	-	-
(Soo and Milian 2001)	Quartz (50%)	-6.6	1.8		
(Krishnan et al. 2018)	Limestone		1		
	Flint		1		
	Serpentine		0.1		
(Yann Le Pape, Giorla, and Sanahuja 2016)	α-quartz			4.5	
(Maruyama and Muto 2016)	Feldspars			18	
(Alsaid 2017)	Limestone			0.80	
	Granite			0.57	
	Aphanatic liparite				
(Y. Le Pape, Sanahuja, and Alsaid 2020)	Feldspar.			7-8	
	Amorphized quartz	+17.8			
	Carbonate			<1	
	amorphization				
	Metal oxide			<5	
	Silicate bearing			18	
	Quartz with siderite matrix			0.55-0.7	
(Yuliia Khmurovska and Štemberk 2021)	Quartz				17.90
	Potassium Feldspar				7.70
	Albite				9.70
	Anorthite				2.50
	Biotite				15
	Enstatite				2.75
	Diopside				2.75
	Hornblende				1.70
	Olivine				0.75
(Y. Khmurovska and Štemberk 2019)	Mica				5
	double-chain silicates				2.8
	single- chain silicates				1.5
	olivine				0.9
(A. V. Denisov 2020)	Olivine			0.3	
	Diopside			0.15	
	Enstatite			0.15	
	Hornblende			0.12	
	Serpentine			0.055	
	Calcite			0.055	
	Dolomite			0.055	
	Microline minerals			0.03	
	Oligoclase			0.018	
	Hematite			0.020	
	Magnetite			0.007	
	Quartz			0.065	
	Labrador			0.018-0.02	
	Quartz glass			-0.03	

Specifically, irradiated aggregates generally expand, while irradiated cement paste usually shrinks (Maruyama and Sugie 2014). As a result, the HCP undergoes shrinkage and subsequent cracking due to the volume disparity between the aggregates and the HCP (Maruyama et al. 2018). This is because the HCP, characterized by a coefficient of thermal expansion α, can be described as a viscoelastic material exhibiting thermal expansion tendencies and isotropic linear damage. Therefore, the complex interactions between irradiated cement pastes and aggregates cause concrete to degrade under the influence of fast neutrons rather than solely owing to the deterioration of aggregates and cement paste and aggregates (Y. Khmurovska and Štemberk 2019). Kambayashi et al. 2020 set parameters for compression analyses over 15, 30, and 60 years, predicting the neutron fluence and the percentage of volumetric aggregate expansion at the surface after irradiation (Fig. 7). The volumetric aggregate growth increases with increasing neutron fluence during the operational period of the reactor. After nearly 60 years of operation, the neutron fluence in the reactor increases, and the expansion of the aggregate reaches 10%. It has also been reported that post-irradiation X-ray diffraction studies have revealed the degradation of crystalline phases such as ettringite, the anhydrous clinker phase, and portlandite, indicating their decomposition into metastable peroxide followed by carbonation into calcite (Vodák et al. 2011; Maruyama and Sugie 2014). Consequently, this alteration causes a shift in pore size distribution, favoring larger pores and reducing the overall average pore diameter (APD) (Vodák et al. 2011). The displacement of pores by calcium crystals larger than portlandite crystals was measured by the APD, which quantifies the changes in the pore structure. For example, at the surface layer, the APD decreased from 30.7 nm to 24.7 nm and from 41.9 nm to 36.4 nm when the irradiation dose was increased from 0 to 1 MGy (Vodák et al. 2011).

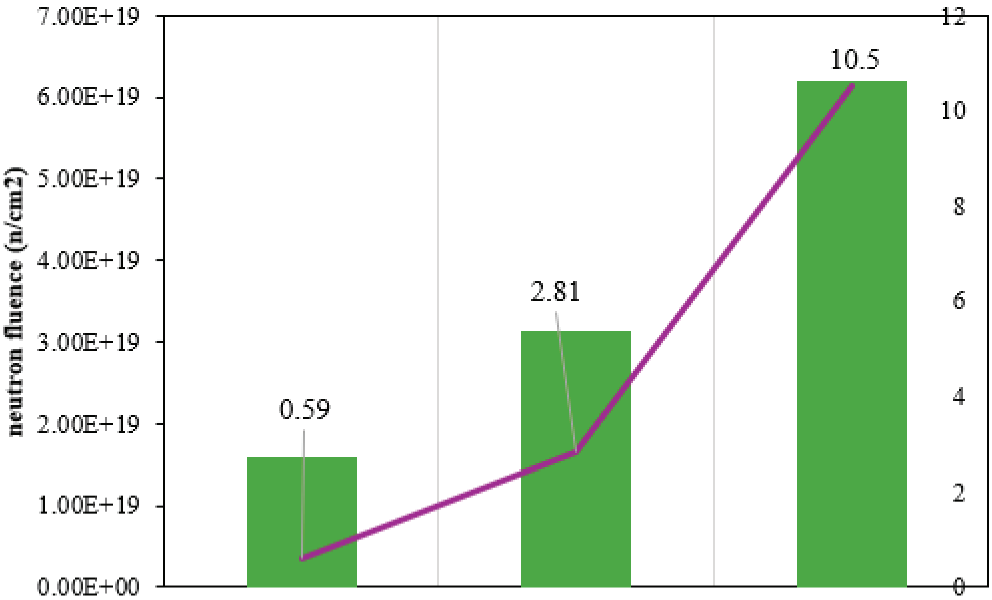

FIGURE 7. The impact of reactor operation time on the neutron fluence and the expansion of aggregates
Source: adopted from Kambayashi et al. (2020)

Understanding RIVE offers significant benefits for the nuclear power industry. Enhanced safety measures, improved regulatory compliance, better environmental protection, and increased economic efficiency are key outcomes of this knowledge. In term of enhanced safety measures, comprehending the mechanisms of concrete degradation under radiation and combined stressors is crucial for the nuclear power industry. By understanding RIVE, the industry can develop more robust safety protocols that enhance material selection and maintenance strategies. Enhanced material durability reduces the environmental impact associated with frequent repairs and replacements. Robust materials can prevent leaks and structural failures, minimizing the risk of radioactive contamination. By ensuring the long-term integrity of concrete in nuclear facilities, the industry can better protect the environment. This proactive approach can prevent structural failures, significantly reducing the risk of catastrophic events. Moreover, in terms of economics, implementing materials with higher resistance to radiation and environmental stressors can lead to lower maintenance costs. By reducing the need for frequent repairs and replacements, nuclear power plants can operate more economically. This efficiency ultimately lowers the cost of nuclear energy production, making it a more viable and sustainable energy source. An in-depth understanding of RIVE and its implications can inform updates to regulatory standards and guidelines for materials used in nuclear facilities. Ensuring that materials meet stringent safety and durability criteria will help maintain compliance with international nuclear safety standards. This alignment with regulatory requirements ensures the safe and efficient operation of nuclear power plants.

SHORT- AND LONG-TERM PROPERTIES

SHORT-TERM PROPERTIES

The evaluation of concrete performance depends on various mechanical factors that impact short-term properties, such as compressive strength, tensile strength, flexural strength and creep strength (Table 5) (Ghebrab and Soroushian 2011; Ahmed et al. 2021). Neutron irradiation impacts the mechanical properties of concrete, particularly the Young's modulus and compressive strength. Sensitivity analyses delve into scenarios involving mortar expansion due to sand, limited expansion of isolated mortar and aggregate mineral expansion, leading to aggregate mortar cracks and creep (Sasano et al. 2020). Understanding the impacts of IR on the properties of nuclear constructions is complex, given the amalgamation of thermal, mechanical, and moisture stresses, all of which are contingent upon reactor design (Santoro 2000; National et al. 2006). During the structure's construction and early operation, initial settlement and shrinkage occur, which are considered short-term issues. However, significant settlement and shrinkage are curbed through design protocols and stringent quality control during construction (Shah and Hookham 1998).

Along with the RIVE, compression and tensile strength are the most discussed parameters for concrete irradiation (Park et al. 2016; Horszczaruk, Sikora, and Zaporowski 2015; Y. Le Pape 2015a). For quality control, concrete acceptance, structural strength evaluation, and assessing the effectiveness of protection and curing, at least two strength specimens constructed from the same concrete and tested at the same age (after 28 days of curing) were averaged to obtain a strength test result. The compressive strength ensures that the provided concrete mixture meets the strength requirements outlined in specific construction specifications (national ready mixed concrete association 2003). Radiation not only impacts the compressive strength of concrete but also, the carbonation process accompanying irradiation becomes a significant factor in its decrease (Maruyama et al. 2018). Although the tensile strength of ordinary concrete is significantly lower than its compressive strength, constituting approximately 10% of the latter, this

TABLE 5. Reduction in strength for short-term properties

Ref	Neutron flux (n/cm^2s)	Time (years)	Neutron fluence (n/cm^2)	Compression strength reduction (%)	Tensile strength reduction (%)
(Mirhosseini, Polak, and Pandey 2014)	$1.58x10^{10}$	40	$2.0x10^{19}$	95	80
	$1.58x10^{11}$	40	$2.0x10^{20}$	72	50
	$1.58x10^{12}$	40	$2.0x10^{21}$	40	20
(Flanagan 1959)	$5.0x10^{15}$	12	$1.0x10^{12}$	60	
			$1.0x10^{19}$	50	
(A. Giorla et al. 2015)	-		1.0×10^{19}		25
(Y. Le Pape 2015a)	-	50	$9.20x10^{19}$		15
			$4.58x10^{19}$	56	
(Field, Remec, and Pape 2015)	-		1.5×10^{19}		
(Sasano et al. 2020)	-	3 weeks	4.52×10^{19}.	56	
(Kelly et al. 1969)	-	-	2×10^{19}	-	30-40

technique is justified by the fact that the axial tensile strength of the material is essentially unaffected by stress–strain circumstances, such as tension at bending, tension at continuous beam middle supports, torsion, splitting, major tensile stresses, and transverse tension (Iskhakov and Ribakov 2021). Since the concrete tensile strength is directly linked to the performance of structural components under shear loads, it may be more significant than the concrete compressive strength (Field, Remec, and Pape 2015; Alsaid 2017). Notably, neutron radiation affects the tensile strength of concrete more than its compressive strength. At an identical neutron fluence ($2.0x10^{19}$ n/cm²), the reduction in the initial tensile strength was 25%, which is lower than the 50% decrease observed in compressive strength (Field, Remec, and Pape 2015). It has been observed that neutron irradiation influences the properties of concrete, while gamma irradiation has no effect on the properties of concrete (Yuliia Khmurovska et al. 2019; H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978). Fig. 12 shows the reduction in compression and tensile strength and the time required for the process to occur. Concrete exhibits resilience against gamma rays up to a radiation level of 10^{10} Gy and remains unaffected by fast neutrons up to approximately 10^{19} n/cm^2 (Ichikawa and Koizumi 2002; H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Y. Le Pape 2015a).

The mechanical properties of cement paste are minimally altered by neutron radiation, primarily because the minerals in the aggregate possess limited long-range order (Field, Remec, and Pape 2015). Nevertheless, this type of radiation can indirectly influence the mechanical traits of cement paste. This is achieved through the initiation of cracks stemming from damage induced in the aggregateTop of Form (Field, Remec, and Pape 2015). Irradiation not only influences concrete compression and tensile strength but also elevates the temperature in the reactor and surrounding areas. Increasing the temperature had several negative effects on the constituent parts of the concrete, such as decreasing the compressive strength, microcracking the microstructure, changing the color correlated with decreasing strength, increasing the pore structure, and increasing the degree of spalling (Nazri et al. 2017). When concrete is exposed to high temperatures, its strength decreases (Anupama Krishna, Priyadarsini, and Narayanan 2019; Nazri et al. 2017), with a potential 50% loss at 600°C (Sancak, Dursun Sari, and Simsek 2008). The strength loss in hydrates can reach 80% above 800°C due to the release of bound water, leading to structural collapse (Sancak, Dursun Sari, and Simsek 2008). Radiation, along with temperature, influences the percentages of changes, either increase or decrease, in the volume and strength of aggregates, as shown in Fig.8 for the 30°C treatment and Fig. 9 for the 100°C treatment. Denisov (A. V. Denisov 2020) described the effects of irradiation on different elements at different temperatures and described the most significant radiation-induced changes caused by gamma rays. Among the rocks primarily composed of silicate-class minerals, the observed range of absorbed doses indicates a notable increase in volume expansion and a decrease in strength when subjected to gamma radiation.

The compressive strength of concrete structures is a critical mechanical parameter that is indicative of the overall performance based on the concrete quality. Previous studies (Liu et al. 2022; Aleksandr Denisov 2018; 2020; A. V. Denisov 2020; Horszczaruk, Sikora, and Zaporowski 2015) reveal that mineral admixtures initially reduce the early strength of concrete. However, this reduction rate significantly diminishes with prolonged curing periods. These studies agreed that the use of different types of aggregates results in different compressive and tensile strengths of concrete and may even increase the compressive strength. It is worth noting that different aggregates have diverse impacts on radiation and temperature. The attenuation of gamma rays is enhanced by the compressive strength of heavy concrete, with gamma-ray attenuation increasing proportionally with strength (Brandt and Jóźwiak-Niedźwiedzka 2013). The relationship between attenuation and compressive strength is approximately linear. Significant alterations in concrete aggregates and their minerals are observed only at doses exceeding 10^9 Gy under gamma radiation (A. V. Denisov 2020).

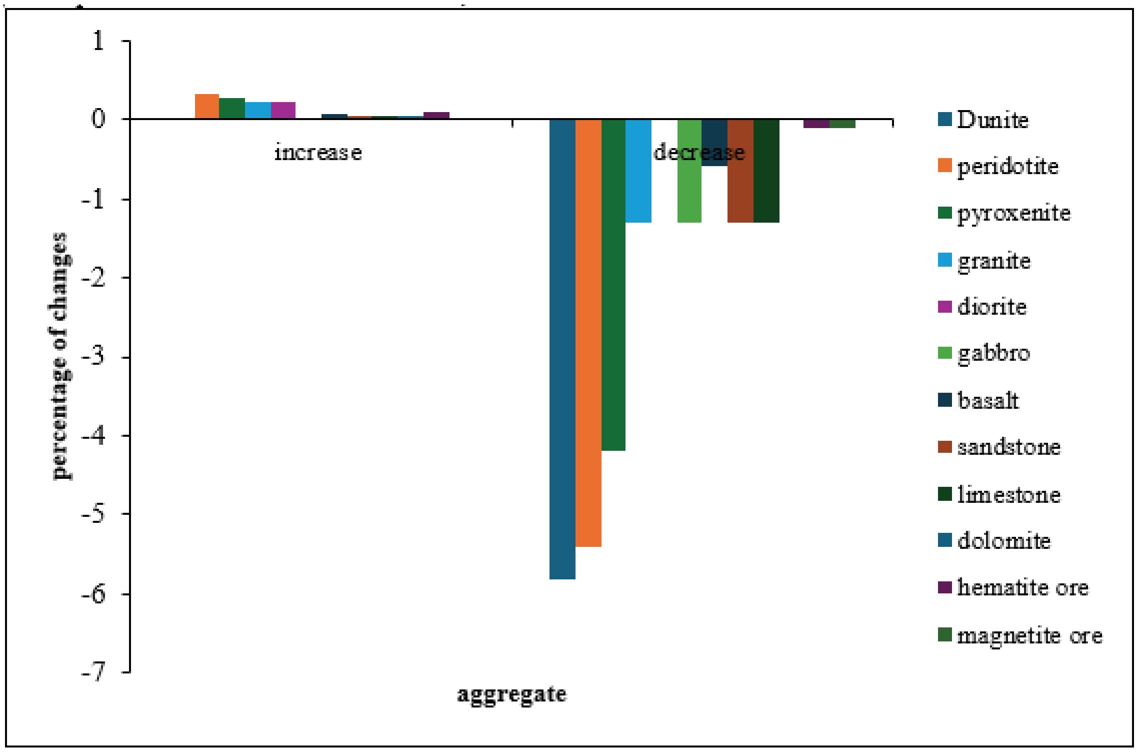

FIGURE 8. Percentage changes in aggregate properties after irradiation at a temperature of 30°C (adapted with improvement from (A. V. Denisov 2020)

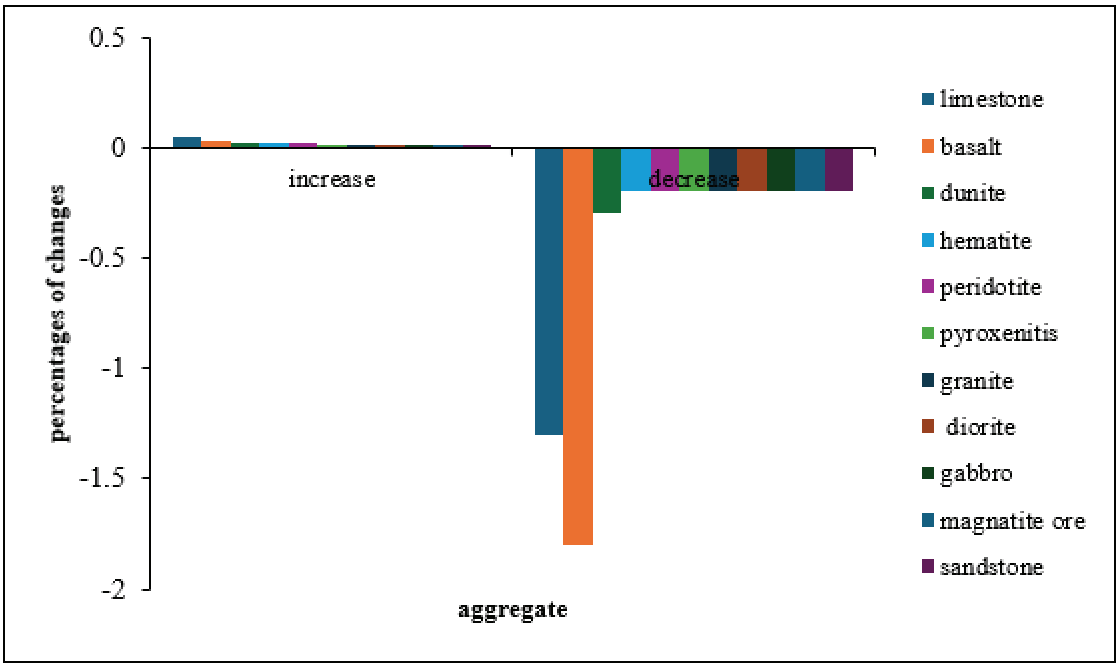

FIGURE 9. Percentage changes in aggregate properties after irradiation at a temperature of 100°C (adapted with improvement from (A. V. Denisov 2020)

According to Bažant (1975), temperature plays an important role in creep. A temperature rise accelerates creep and the hydration events that cause material characteristics to change (aging). Since creep is temperature-dependent, structures exposed to temperature fluctuations across space will be more vulnerable to creep. (England 1980). Creep plays a dual role in structural behavior by redistributing loads and potentially causing substantial displacements from the intended design positions (Khmurovska et al. 2019). The absence of notable volume variations in concrete containments indicates that creep deformation often occurs along with projected design values. Lower creep levels might impede stress relaxation, potentially leading to biological shield damage, while higher creep levels could prompt biological shield movement, affecting pressure vessel positions and potentially disrupting the cooling system or other plant operations (Khmurovska et al. 2019). Understanding concrete creep spans various research domains, ranging from microscopic material levels to engineering perspectives focusing on structural behavior and safety concerns (England 1980). Basic creep contributes significantly to the delayed deformations of prestressed concrete (Jean Michel Torrenti 2016). Accurately estimating creep deformation in prestressed concrete containers is crucial, particularly because it contributes to prestressing loss (Shah and Hookham 1998). Creep represents time-dependent deformation in rock under constant loading, impacting the surrounding rock mass within the insitu stress field. Typically, the surrounding rock mass creeps at a strain rate of 10^{10} s^{1} or less (C. Chen 2018). Whenever stress is applied, the absorption of bias point defects at cavities and along certain dislocation orientations in response to the applied stress leads to the development of irradiation creep (S. J. Zinkle 2012). In addition to regular thermal creep processes, radiation creep also results in dimensional expansion. This phenomenon occurs most significantly at temperatures between the recovery stage and those where thermal creep deformation accelerates (England 1980).

Elevated temperatures and damage in series from an unfortunate incident at a nuclear power station can influence basic creep (Jean Michel Torrenti 2016). The volume of water, notably present in the adsorption layers of concrete, contributes significantly to both creep and shrinkage. These layers, which are only a few molecules thick, reside between solid cement gel particles and layers (Bazant and Hubler 2014; Bažant 1975). As water displaces between cracks, cohesive forces at fracture tips weaken, facilitating crack propagation and generating load-induced drying shrinkage, a behavior observed in acoustic wave studies during creep experiments (Giorla and Dunant 2018). Pignatelli et al. (Pignatelli et al. 2016) proposed a model suggesting the localized dissolution and precipitation of C-S-H crystals under stress, occurring at points where these crystals lack contact. This interaction among C-S-H crystals drives creep, particularly in the long-term, by altering the microstructure through compaction (Pignatelli et al. 2016). Long-term creep involves the compaction and slipping of C-S-H nanostructures under load, wherein the former contributes to a deformation rate proportional to the load, while the latter process elevates the material's apparent viscosity, impeding further deformation (A. B. Giorla and Dunant 2018).

LONG TERM PROPERTIES

ALKALI SILICA REACTION (ASR)

Nuclear containments and shields are not vulnerable to design accident pressure loads; rather, they are engineered to withstand pressures within reactor buildings (Józwiak-Niedzwiedzka, Glinicki, and Gibas 2016). The endurance of these materials is tested by operational, environmental, and aging stressors, including material deterioration, such as the alkali–silica reaction (ASR), which collectively diminishes their capabilities and increases failure rates over time (Lukschová, Přikryl, and Pertold 2009; Józwiak-Niedzwiedzka, Glinicki, and Gibas 2016). ASR causes pattern cracking in unreinforced concrete; on the other hand, broad fractures that run parallel to the longitudinal reinforcement appear in reinforced concrete, while sporadic tiny cracks are observed to span between longitudinal cracks (Dubey et al. 2018; Lukschová, Přikryl, and Pertold 2009). Cracks are classifi ed into four sizes: cryptocracks, microcracks, fi ne cracks, and macrocracks (French 1991; Jana and Erlin 2007). The frequency of crack occurrences, measured in cracks per meter, is commonly observed on polished plates or thin sections (French 1991). Although visible to the naked eye in cores, cracks resulting from alkali-aggregate reactions are often referred to as microcracks (French 1991).

The ASR refers to a chemical reaction within concrete involving alkali hydroxides from highly alkaline cement paste and reactive amorphous silica present in various aggregates under suffi cient moisture (Dubey et al. 2018). As this reaction progresses, a swelling gel of CSH is produced, resulting in the expansion of the affected aggregate (przemyslaw czapik 2020; Ichikawa and Kimura 2007; Dubey et al. 2018). In the presence of moisture, this ASR gel undergoes volume expansion, exerting internal pressure within the material. As a result, the nonuniform moisture distribution induces nonhomogeneous swelling, causing cracks to grow from the microscale to the macroscale and leading to spalling (Dubey et al. 2018; Pomaro 2016). Through these calcium silicate shells, the alkaline solution penetrates through the aggregates, dissolving even more SiO_2 in the solution (Pomaro 2016). The combined pressures from aggregate expansion and alkaline solution penetration, on the other hand, accumulate behind strong silicate shells, causing the aggregates to expand and eventually crack (Ichikawa and Koizumi 2014; Pomaro 2016). The ASR in concrete, under conditions of sufficient moisture, is primarily caused by the interaction of alkali hydroxides (K+ and Na+) present in highly alkaline cement paste with the reactive amorphous silica (S2+) found in common aggregates (przemyslaw czapik 2020). This interaction over time leads to the creation of a swelling gel, calcium silicate hydrate (C-S-H), which causes expansion of the affected aggregate (Mariaková et al. 2022; Józwiak-Niedzwiedzka, Glinicki, and Gibas 2016). ASR is a chemical phenomenon that occurs when silica-rich aggregates contact alkaline solutions in concrete micropores, leading to significant and progressive degradation of concrete structures (Ichikawa and Kimura 2007). ASR occurrence requires three critical components: adequate alkalis, reactive silica in the aggregate, and sufficient moisture (Menendez et al. 2020; Ichikawa and Miura 2007). ASR-induced cracking typically manifests within or between these particles, in the interfacial transition zone (ITZ), and throughout the bulk cement paste, forming alkali-silica gel and other secondary reaction products (. Sanchez et al. 2016; Farny and Kerkhoff 1997) (Fig. 10).

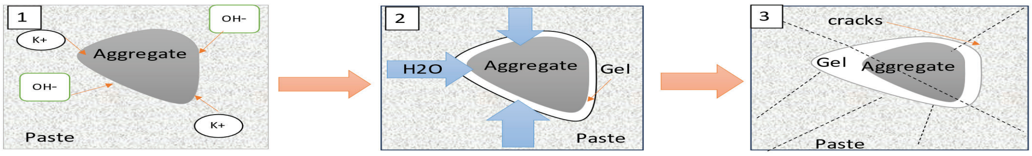

FIGURE 10. The process of ASR-induced cracking in concrete (raw data adapted from (Farny and Kerkhoff 1997; Dubey et al. 2018; Ichikawa and Miura 2007))

It is suggested that the ASR could be one of the dominant degradation factors in the concrete used in an NPP (Naus et al. 1992). The concrete around the reactor pressure vessel encounters the most substantial nuclear radiation exposure within nuclear power plant (NPP) structures, approximately $2x10^{17}$ Gy/year for beta and gamma rays and $1x10^{18}$ n/cm^2/year for fast neutrons (H.K.Hilsdorf, J. Kropp, and H. J. Koch 1978; Yuliia Khmurovska et al. 2019). The properties of concrete remain unaffected by gamma rays up to a dose of 10^{10} Gy (Saouma and Hariri-Ardebili 2014; Mohammed et al. 2004). On the other hand, irradiation with fast neutrons exceeding ~10^{19} n/cm^2 leads to the deterioration of concrete (Józwiak-Niedzwiedzka, Glinicki, and Gibas 2016; Saouma and Hariri-Ardebili 2014). The critical radiation dose required to trigger ASR has been a topic of debate among various authors (Table 6).

TABLE 6. Critical dose and time for concrete deterioration due to ASR-induced damage

Ref	Mineral	Critical dose of beta and gamma irradiation (Gy)	The critical time of beta and gamma irradiation (year)	Critical dose of fast neutron irradiation (n/cm^2)	The critical time of fast neutron irradiation (year)
(Ichikawa and Kimura 2007)	Plagioclase	$1x10^8$	5 years	$1x10^{16}$	4 days
(Ichikawa and Kimura 2007)	Amorphous quartz	$1x10^{12}$	50,000 years	$1x10^{20}$	100 years
(Ichikawa and Koizumi 2002)	Crystalline quartz	$5x10^{11}$	-	$5x10^{19}$	-
	Amorphous quartz	0.5×10^{11}	-	1×10^{19}	-

Alkali-aggregate interactions typically lead to damage in concrete structures within the initial ten years of an NPP lifespan (Rasheed et al. 2022). However, radiation-induced ASR can manifest as soon as a plant begins operation (Ichikawa and Kimura 2007). ASRs have been identified in NPP concrete structures across various regions, such as Belgium, Canada, the United States, and Japan (Rasheed et al. 2022). In France, a study was conducted with a focus on NPP operations beyond 40 years, potentially extending up to 60 years (Gallitre and Dauffer 2011). ASR has been identified as one of the key factors contributing to age-related issues as structural aging becomes a concern (Gallitre and Dauffer 2011; Saouma and Hariri-Ardebili 2014).

Exposure to irradiation leads to the expansion of aggregates and the contraction of cement paste (Ichikawa and Koizumi 2002; Ichikawa and Miura 2007). Ichikawa and Koizumi's research (Ichikawa and Koizumi 2002) suggested that nuclear irradiation may heighten the reactivity of silica-rich aggregates, thereby potentially increasing the risk of ASR in concrete structures. They specifically examined the effects of electron-beam irradiation on the ASR reactivity of plagioclase, a mineral typically found in volcanic rocks (Ichikawa and Koizumi 2002). Their observations revealed that under a 30-keV electron beam and at doses exceeding 0.9×10^9 Gy, amorphous plagioclase becomes 35 times more reactive to alkali than its crystalline counterpart. This heightened reactivity implies that aggregates, which are usually ASR inert, might contribute to the degradation of irradiated concrete via the alkali–silica reaction. Furthermore, they noted that gamma rays do not significantly alter concrete properties until 10^{10} Gy are reached (Mohammed et al. 2004; Saouma and Hariri-Ardebili 2014).

Research by (Sanchez et al. 2016; Dunant and Scrivener 2012; Józwiak-Niedzwiedzka, Glinicki, and Gibas 2016; Lukschová, Přikryl, and Pertold 2009) has demonstrated that silica-rich aggregates become more reactive to alkalis when exposed to nuclear radiation. The higher the SiO^2 content in the aggregates was, the lower their resistance to nuclear radiation was. This implies an acceleration in ASR-induced deterioration in such contexts. Top of Form

Aggregates can be classified as normally reactive (those reacting within 5 to 20 years) or slowly reactive (those reacting after 15-20 years) (Castro and Wigum 2012). In fact, irradiated α-quartz exhibited a >700-fold increase in reactivity at 1×10^{12} Gy beta and gamma rays and at 1×10^{20} n/cm^2 fast neutrons (Jóźwiak-Niedźwiedzka and Lessing 2019). In an experiment by Shin et al. (Shin, Struble, and Kirkpatrick 2015), three types of cracks were identified in mortar bars containing silica glass with 0.8% total alkali content, and it was found that in aggregate grains filled with ASR gel, cracks formed in the paste or at the interface. These cracks predominantly appeared in weaker regions, such as the paste or the aggregate-paste interface, which often fractured due to shrinkage (Mohammed et al. 2004; Saouma and Hariri-Ardebili 2014). A multitude of voids, many with angular shapes, were observed in the exterior sections of the samples. The voids appeared to be the holes that were left behind when the aggregate particles disintegrated. This suggests that aggregate particle disintegration is a step in the deterioration process (Thomas et al. 2008; Lukschová, Přikryl, and Pertold 2009).

ELEVATED TEMPERATURE

The concrete structure is acknowledged as an excellent fire-resistant material (Hussin et al. 2015). Structures often confront the common risk of fire or exposure to high temperatures throughout their lifespan (Salahuddin et al. 2020). It is also known that when concrete structural elements are exposed to fire, their response is influenced by the deformation and thermal and mechanical characteristics of the concrete used in their construction (Anupama Krishna, Priyadarsini, and Narayanan 2019). The deformation, thermophysical and mechanical properties of concrete undergo substantial changes within the range of temperatures experienced during building fires. Various factors influence concrete behavior at elevated temperatures, encompassing the rate at which temperatures escalate and the nature and stability of the aggregate (Dhabale and Telang 2023). These qualities change with temperature and are determined by the composition and features of the concrete (Wu, Lin, and Zhou 2020; Anupama Krishna, Priyadarsini, and Narayanan 2019).

The neutron shielding properties are crucially influenced by the operating temperature and are affected by the loss of water content and microcracking (Dubrovskii V. B. et al. 1967). Within a reactor core, the heat generated from nuclear fission in fuel elements is transferred to a heat exchanger, generating steam that drives a turbine (Ho et al. 2019). Heat is also produced when the nuclear radiation from the reactor core is attenuated and absorbed by surrounding elements (Ho et al. 2019). This massive amount of heat is passed outwardly to neighboring materials (coolant, structural materials such as concrete shields) via conduction, convection and radiation (El-Sayed Abdo and Amin 2001). In addition, heat is also released during the hydration of cement in the concrete (Salahuddin et al. 2020). An elevated concrete temperature causes (1) dehydration, which results in a reduced moisture content and shrinkage, and (2) increased porosity, which results in excessive pore pressure that subsequently leads to strength loss, thermal expansion, thermal creep, and thermal spalling (Anupama Krishna, Priyadarsini, and Narayanan 2019; Graves et al. 2014). The acceleration of the basic creep effect might occur due to prestressing loss, which could induce tensile stresses in certain structural areas, potentially initiating cracks (Jean Michel Torrenti 2016).

In the case of a catastrophic accident, such as the loss of the reactor's cooling agent, the pressure and temperature of the nuclear vessel could increase to 0.5 MPa and 180°C, respectively, within a two-week span, potentially accelerating creep damage in concrete (Jean Michel Torrenti 2016). Given the low thermal conductivity of concrete, dissipating the heat generated within the shield is challenging (Horszczaruk, Sikora, and Zaporowski 2015), as this process causes uneven temperature distributions and consequential differential thermal strains. These fluctuations provoke varying volume changes in concrete constituents (Table 7), leading to cracking and diminished durability (Horszczaruk, Sikora, and Zaporowski 2015; Anupama Krishna, Priyadarsini, and Narayanan 2019). Elevated temperatures resulting in the loss of prestress can expedite the progression of fundamental creep. Consequently, specific structural areas might experience tensile stresses, potentially causing the formation of cracks that compromise the structural integrity (J. M. Torrenti et al. 2007; Steven J. Zinkle, Tanigawa, and Wirth 2019; Jean Michel Torrenti 2016). Even Tan and Nicholas (Tan and Nichols 2004) have proven that curing at high temperature (steam curing) causes a decrease in concrete strength after 28 days of curing. One of their samples exhibited a decrease in strength from 32 MPa after normal curing to 26.5 MPa after steam curing.

Elevated temperatures during curing contribute to chemical and physical deterioration via the separation of calcium hydroxide (CH) from CSH, which destroys both the interlayer and chemically bonded water above the Form(Hussin et al. 2015). This elevated temperature results in relatively high thermal stresses within the concrete shielding, affecting its thermal properties, such as thermal diffusivity, thermal expansion, thermal conductivity and specific heat (Fig 11).

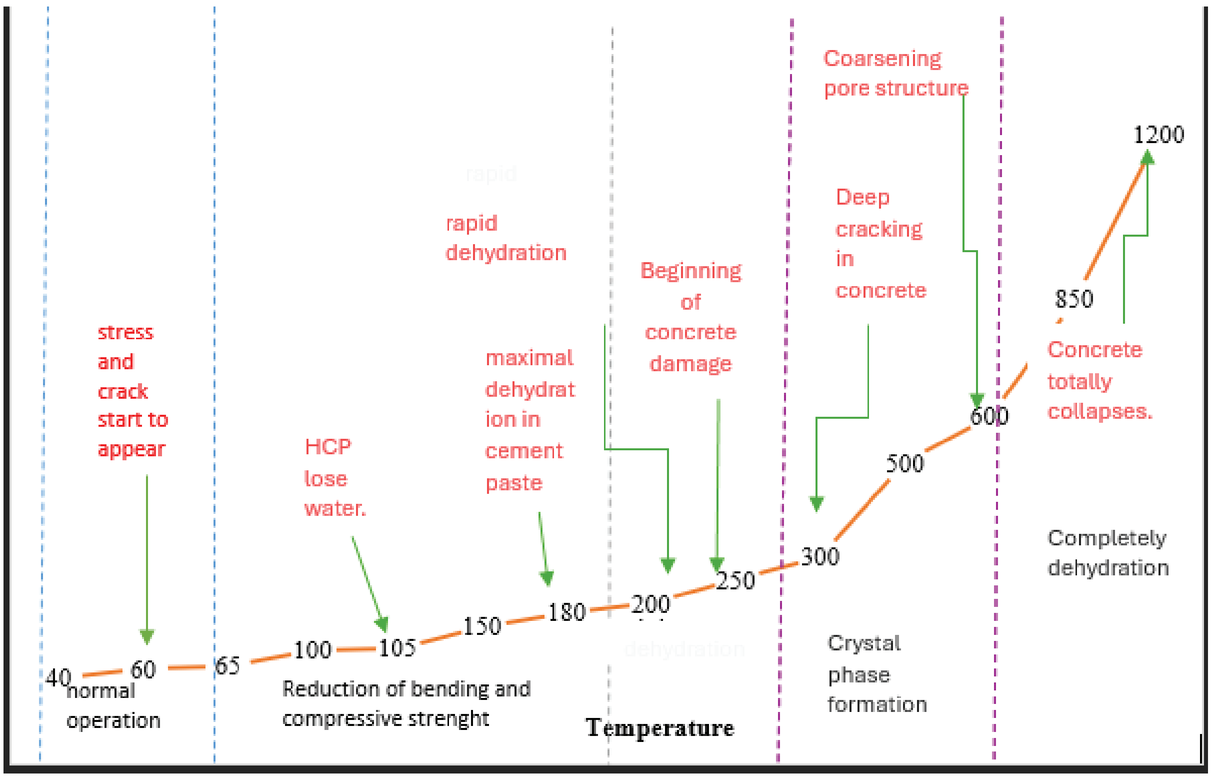

FIGURE 11. Relationships between temperature and concrete constituents during the operation of NPP

Excessive heating may even lead to the complete deterioration of concrete shielding (Azreen et al. 2018). Nevertheless, in general, high temperatures can cause the weakening of concrete mechanical properties and spalling (Jóźwiak-Niedźwiedzka and Lessing 2019). The deterioration of the mechanical properties of concrete due to thermal effects can be attributed to several factors, including physicochemical changes in the cement paste and aggregates, as well as the thermal compatibility of its constituents and thermal properties at both the structural and microstructural levels (Jóźwiak-Niedźwiedzka and Lessing 2019). Elevated temperatures impact both the chemical and physical stability of cementitious composites (Öztürk 2022; Naus And Graves 2006). When Subjected to High Temperatures, Cracks Develop in Cementitious Composites due to the varying thermal strain behaviors among their components. This discrepancy results in mismatched thermal stresses, contributing to the deterioration of material strength (Öztürk 2022). One of the most significant effects is the dehydration of the cement paste, which leads to a reduction in strength and an increase in porosity, in addition to other effects, including changes in thermal expansion, pore pressure, strength, moisture content, thermal cracking due to incompatibility, thermal creep, and thermal spalling due to excessive pore pressure (Anupama Krishna, Priyadarsini, and Narayanan 2019).

Naus et al. (1992) stated that concrete behavior at elevated temperatures strongly depends on the aggregate type. Standard aggregate materials are capable of enduring temperatures of up to 350°C (Naus et al. 1992). The concrete shield surrounding the nuclear reactor core experiences noticeable temperature increases during reactor operation. The combination of high temperature and irradiation heat accelerates concrete drying and shrinkage (Rosseel et al. 2016). Moreover, 66°C is suggested as the threshold temperature at which water-molecule bonds begin to break, whereas at 100°C, the strength of concrete starts to decrease rapidly (Sakr, K., & EL-Hakim 2005; El-Sayed Abdo and Amin 2001). At temperatures ranging between 100°C and 200°C, the approximate decrease in compressive strength amounted to 25%, whereas the decrease in tensile strength might reach as high as 80% (A. Giorla et al. 2015). At a temperature of 200°C, where the concrete on the interior surface faces the reactor core, serpentine and aluminate cement pastes were subjected to a neutron fluence ranging from $1.2x10^{19} \sim 1.2x10^{20}n/cm^2$. This exposure led to rapid dehydration and a significant reduction in bending strength of 50%. At 280°C, with a neutron fluence of approximately 10^{20} n/cm^2, concrete samples within a heavy water reactor experienced heavy damage (Basu and Gupchup 2004)

Recent research has highlighted the susceptibility of concrete to explosive spalling at high temperatures. This phenomenon is attributed to thermal stress caused by rapid temperature rise and water vapor, which can lead to high pore vapor pressure (Steven J. Zinkle, Tanigawa, and Wirth 2019; Jean Michel Torrenti 2016; Rasheed et al. 2022). Recent tests conducted on ordinary Portland cement concrete have notably demonstrated significant heat-induced damage (Ali, Khan, and Hossain 2008; Celik et al. 2015; Hussin et al. 2015). For safety purposes, the temperature in the reactor building is generally kept at <65°C. During operation, the concrete inside the cooling tower may be subjected to temperatures of approximately 40°C, with allowable peaks reaching up to 93°C at 100% relative humidity. (Rowcliffe et al. 2018; Naus and Graves 2006). In dry casks, the maximum expected temperature in the worst-case scenario is 200°C (Y. Le Pape 2015b). Biological shield structures or reactor pressure vessel support systems are usually engineered to operate at an average temperature of approximately 65°C, with the capacity to withstand peak temperatures up to approximately 93°C. Top of Form

However, during accelerated irradiation experiments, the temperature can reach 150°C (Naus and Graves 2006). When the concrete is heated to 200 degrees Celsius, it gains 2-8% of its compressive strength (Ghazy, Elaty, and S. elkhoriby 2015). Temperatures up to 300°C demonstrate no discernible impact on cement-based composites; in fact, such elevated temperatures can potentially enhance or expedite cement hydration reactions (Öztürk 2022). However, temperatures between 350 and 550°C cause the material's strength to deteriorate because that temperature range results in the decomposition of CH into lime and water, and further elevated temperature ranges (700-900°C) result in the decomposition of CSH (Öztürk 2022; Hussin et al. 2015). At 400°C, a marginal decrease in compressive strength, ranging between 5 and 8%, was observed. This reduction continued to increase, reaching approximately 54-68% at 600°C. Subsequently, a substantial decrease of 85-90% in compressive strength was recorded at 800°C (Ghazy, Elaty, and S.elkhoriby 2015).

TABLE 7. Radiation effects on different concrete constituents

Constituents	Phase	Effects of neutron radiation	Effects of gamma radiation	Ref.
Cement paste	Liquid	Changes of properties due to the decomposition initiated by radiation during drying.	Changes of properties due to the decomposition initiated by radiation during drying. Morphological change in calcium silicate hydrate (CSH), Gas release (H_2 and O_2) and large shrinkage. Transformation of properties resulting from exposure to hydrogen peroxide and radicals.	(F. Sanchez and Kosson 2018; Yann Le Pape, Giorla, and Sanahuja 2016; Bouniol and Bjergbakke 2008; A. B. Giorla and Le Pape 2015)
	Solid	Deformed hydrates due to the neutron blasts Minimal effect on CSH's physical characteristics Pore water mends distorted hydrates through the solution-precipitation phenomenon	Cement paste reduction because of gamma-induced heating Morphological, physical and Ph changes due to severe drying deformed Si-O-Si and other covalent bonds due to radiolysis blasts. Oxygen in Si-O-Si and covalent bonds knocked-out by electrons	(Yuliia Khmurovska and Štemberk 2021; Yann Le Pape, Giorla, and Sanahuja 2016; Fillmore 2004; Maruyama et al. 2018)
Aggregate	Liquid	Intensified RIVE and diminished mechanical properties owing to neutron-induced amorphization of crystalline minerals within the aggregates	Gamma heating leads to the loss of crystalline water and the evaporation of adsorbed water. The contraction of clay minerals and similar layered structures occurs because of the drying process.	(Field, Remec, and Pape 2015; Rosseel et al. 2016; Yann Le Pape, Giorla, and Sanahuja 2016; Y. Le Pape, Field, and Remec 2015; S. J. Zinkle 2012)
	Solid	Neutron-induced metamictization of rock-forming minerals; some are healed by thermal effect. Consecutive metamictization and swelling of rock-forming minerals because of secondary gamma-rays; α-quartz demonstrates significant responsiveness to neutrons, leading to a notable increase in its metamictized state.	Metamictization affects Si-O-Si bonds and other covalent structures, leading to changes in volume. Certain deformations and metamictized states are repaired by the thermal effects. Crystal structures experience atom displacement due to the impact of secondary electrons.	(Maruyama et al. 2017; Bamigboye et al. 2022)
Concrete		Expansion due to metamictization of aggregates Diminution and fissures in mortar and cement paste due to aggregate's opposition. Reduced strength and young's modulus according to crack formation from aggregates' expansions	Cracking in the mortar surrounding aggregates is caused by drying or heating effects. Unreacted cement undergoes chemical reactions at higher temperatures due to gamma heating. Changes in strength and cracking occur cause by different volumetric changes between mortar and aggregates. The opening of cracks leads to a reduction in Young's modulus.	(Huo and Wong 2006; Masenwat et al., n.d.; Sasano et al. 2020; Maruyama and Muto 2016)

EXPECTED CONCRETE CONDITIONS ATER 80 YEARS

LIFE EXTENSIONS

Numerous countries are actively pursuing the establishment or expansion of nuclear power programs, recognizing the multifaceted benefits of nuclear energy in addressing climate change, environmental mitigation, energy supply security, and socioeconomic policies (Voyevodin et al. 2021). To meet the future energy demands of the nation while simultaneously curbing greenhouse gas emissions, national regulators, nuclear power plant (NPP) operators, and researchers have stepped up their focus on aging management (Fig. 13). This comprehensive approach includes thorough examination, inspection, maintenance, and testing of essential components. In certain cases, this approach also involves considering the possibility of extending the operational life of these critical elements Top of Form M.rosseel et al. 2016). The Atomic Energy Act of 1954 USNRC 2015) and the NRC regulations (Saouma and Hariri-Ardebili 2014) declare that operating licenses for commercial power reactors are granted for an initial period of 40 years and that the licenses can be renewed for an unlimited number of periods for an additional 20 years. In section 103, Commercial Licenses, c., specifically addresses (Hull, Hiser, and Lindo-Talin 1989) that "each such license shall be issued for a specified period, as determined by the Commission, depending on the type of activity to be licensed, but not exceeding 40 years from the authorization to commence operations."

Typically, new nuclear facilities are granted a 40-year operating license, with the opportunity to seek a further 20-year extension through an initial license renewal (LR) and, if eligible, a subsequent license renewal (SLR). This process enables the long-term operation (LTO) of these facilities for up to 80 years (Kurtis et al. 2017). The initial 40-year operating license for new facilities was determined based on antirust and economic considerations rather than being constrained by technical factors (USNRC 1991; USNRC 2015; Rosseel et al. 2016). Numerous facilities have subsequently been requested and been granted a 20-year life extension. In 2019, four reactors received SLR approval, extending their life to 80 years (Rosseel et al. 2016). As of June 15, 2023, 87 out of the 92 nuclear reactors currently in commercial operation in the U.S. have had their licenses extended to 60 years, and 16 reactors have been applied for SLR to potentially operate for an additional 20 years beyond the initial 60-year period (Aaron Larson 2023). As of February 2022, the Nuclear Regulatory Commission cancelled the approval for SLR for Turkey Point Units 3 and 4 and Peach Bottom Units 2 and 3 due to technical issues, despite previously granting SLRs for these reactors (Aaron Larson 2023). Conversely, the initial operating license duration for an aboveground storage chamber spans 20 years. However, there is potential for extension beyond a century, comprising the first 15 years housed in a spent nuclear fuel pool, followed by the subsequent 85 years within dry cask storage facilities. This extension period continues until a permanent repository becomes available (Reches 2019). The NRC general review of plant aging management systems is documented in the general Aging Lessons Learned for Subsequent License Renewal report (GALL-SLR), which serves as guidance for SLR applicants. The GALL-SLR Report serves as a foundational document for the assessment of aging management plans, offering guidance and criteria that are vital for the long-term operation and safety of NPPs (IAEA 2022). Compressive strength, an important parameter, plays a role in future life extensions, as it provides an overview of the material's performance at the macro level (Potts et al. 2021). According to the Agency-wide Documents Access and Management System database, a fast neutron fluence exceeding 1.0×10^{19} n/cm^2 up to 6×10^{19} n/cm^2 can be expected on the external vessel of pressurized water reactors after 80 years of operation. Several NPPs in Japan exceeded the $1x10^{19}$ n/cm^2 threshold after just 40 years of operation (M.rosseel et al. 2016). The threshold value is predicted to be slightly lower ($<1.0\times10^{19}$n/cm^2) for boiling water reactors. It was also suggested that a 20-30% lower cutoff value from the aforementioned number be applied at the concrete biological shield for safety (Field, Remec, and Pape 2015). It should be noted that the neutron

spectra are similar for two-loop and three-loop PWRs. However, a two-loop reactor would experience double to quadruple doses of neutron fluence than would a three-loop reactor, as depicted in Fig. 9 (Bruck et al. 2019). Moreover, the total gamma radiation dose in light water reactors after 80 years of operation is expected to reach 50 to 200 MGy, for a dose rate of approximately 5 to 20 kGy/h (Murty and Charit 2013). Maruyama et al. (Maruyama et al. 2017) outlined the expected gamma-ray dose and neutron flux over 60 years of operation within Japanese nuclear reactors, specifically focusing on the interior surface of the initial biological shielding wall for PWRs, as depicted in Fig. 12.

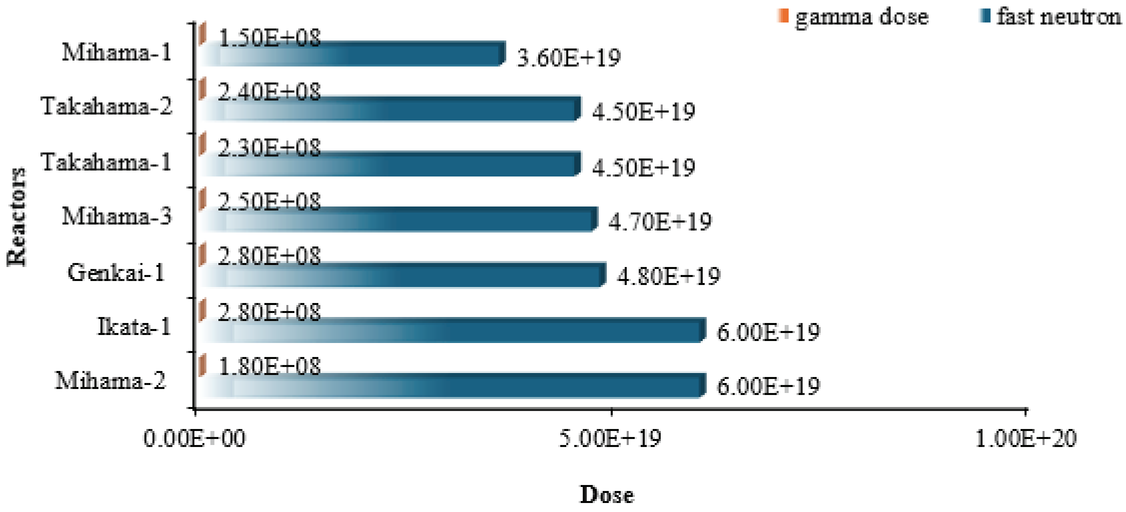

FIGURE 14. Dose fluence of Japan's power plants after 60 years of operation (adapted from (Maruyama et al. 2017)

POTENTIAL POLICY IMPLICATION

Given the expectation for nuclear power plants (NPPs) to operate for extended periods, it is crucial to update or change regulations and standards for materials used in these facilities. This is essential for enhancing safety, economic efficiency, and longevity. The findings from this study could significantly influence policies and regulations regarding materials used in nuclear facilities.

SAFETY

Revised Material Standards: New standards could mandate or recommend the use of high-density aggregates like barite in critical areas of nuclear facilities to enhance radiation protection. Ensuring that materials can withstand long-term radiation exposure helps prevent structural failures that could lead to catastrophic events and accidents.

ECONOMIC EFFICIENCY

Cost-Effective Longevity: Updated policies should focus on extending the service life of materials. Materials that better withstand radiation and other stressors help maintain the structural integrity of the facility over time, reducing maintenance costs and preventing expensive, unplanned outages.

LONGEVITY AND DURABILITY

Long-Term Monitoring Requirements: Policies should include regular monitoring of concrete structures for signs of cumulative radiation damage. This ensures timely maintenance and repair, preventing structural failures and extending the service life of the facility.

ENVIRONMENTAL CONSIDERATIONS

Incorporating Environmental Factors: Regulations should account for the impact of environmental conditions such as temperature, humidity, and chemical exposure on the shielding properties of concrete. This ensures that materials can withstand real-world conditions over extended periods, enhancing the overall durability of the facility.

FUTURE-PROOFING AND SUSTAINABILITY

Adaptability to Future Advances: Updated standards can ensure that NPP facilities can adapt to and accommodate future advancements in nuclear safety protocols. Choosing materials that are more durable and resistant to radiation contributes to the sustainable operation of nuclear facilities by reducing the need for frequent repairs and replacements.

By implementing these updates, NPPs can enhance their safety, reduce operational costs, and ensure their longevity, ultimately leading to more sustainable and efficient nuclear energy production.

CONCLUSION

This comprehensive review elucidated the multifaceted impact of nuclear radiation on concrete biological shields in NPPs, a significant consideration in assuring the safety and longevity of these facilities. Understanding radiation-induced damage to concrete is essential for the nuclear power industry due to its implications for safety, longevity, and economic viability. Ensuring the structural integrity and durability of concrete under radiation exposure helps maintain the safe and efficient operation of nuclear power plants, reduces maintenance costs, and supports regulatory compliance. By investing in research and development of more radiation-resistant concrete, the industry can enhance the resilience and sustainability of nuclear power infrastructure, ultimately contributing to the safe and sustainable generation of nuclear energy

This review highlights key findings regarding the detrimental effects of radiation, particularly neutron fluence and gamma-rays, on reactor concrete's structural integrity and durability. It is evident that radiation exposure, particularly at high neutron fluence, precipitates a significant degradation in the structural capabilities of concrete, with the DPA process inducing point defects and extensive damage. The magnitude of strength reduction, which can reach 90%, is alarmingly proportional to the neutron fluence, underscoring the necessity for rigorous and ongoing inspection of reactor concrete. This degradation is further exacerbated by RIVE, alterations in mechanical and physical properties, and ASR. Radiogenic heating also presents a significant challenge, as it impacts concrete compressive and tensile strengths and can lead to substantial damage at elevated temperatures. Given the critical purpose of concrete in ensuring the efficiency and safety of NPP, future research should focus on developing radiation-resistant concrete materials. The includes exploring innovative compositions and additives that can enhance the resilience of concrete against radiation-induced degradation. Advanced modeling and simulation techniques should also be employed to forecast concrete's long-term behavior more accurately under radiation exposure, thus aiding in the formulation of more robust and durable concrete mixtures.

Moreover, the review underscores the need for meticulous and advanced inspection techniques to monitor the condition of reactor concrete over time. Early detection of degradation signs could allow timely maintenance and replacement, thereby preventing catastrophic failures. Enhanced monitoring and predictive maintenance strategies would significantly contribute to the secure functioning of nuclear power facilities. Moreover, in addition to material innovations and advanced monitoring, this review calls for a holistic approach to managing the risks associated with radiation exposure in NPPs. This approach considers the interplay of various factors, such as environmental conditions, reactor design, and operational protocols, that collectively influence the performance of concrete biological shields.

In conclusion, while concrete remains a vital material for biological shielding in nuclear reactors, its susceptibility to radiation-induced damage necessitates a concerted effort in research, development, and monitoring. Addressing these challenges is crucial for ensuring the safety and efficiency of presently operating nuclear power facilities and for paving the path for the next generation of nuclear energy systems. As nuclear power becomes a progressively sought-after clean and dependable energy source worldwide, safeguarding the durability and sustainability of concrete biological shielding has emerged as a crucial factor in fully harnessing the potential of this technology.

SUGGESTION FOR FUTURE RESEARCH DIRECTION

Based on the current understanding of the challenges and gaps in the knowledge about radiation-induced damage to concrete biological shielding materials, several potential hotspot research topics emerge that could be of great interest for further studies by researchers, enginer and policy maker worldwide. These topics not only address the immediate concerns related to nuclear power plants but also pave the way for advancements in materials science, nuclear engineering, and safety protocols. Several research areas are suggested:

-Long-Term Durability Studies: Conduct extensive research focusing on the long-term durability of concrete, new composite materials, or additives that can increase the radiation resistance of concrete under continuous radiation exposure. Assess potential cumulative damage over extended periods to provide comprehensive data on their longevity. As policy maker, Updated Material Standards and regulations for materials used in nuclear facilities to include requirements for high-density aggregates in critical shielding applications. Ensure that the standards reflect the latest research findings on material durability and radiation resistance.

-Microstructural Analysis: Utilize advanced imaging techniques such as synchrotron radiation to gain deeper insights into the microstructural changes in concrete due to irradiation. This can help in understanding the fundamental mechanisms of degradation and guide the development of more resilient materials. This research could involve the use of computational methods to simulate radiation effects on concrete at the molecular or atomic levels, the use of sensors, artificial intelligence (AI) algorithms, or imaging technologies to monitor the integrity of reactor concrete in real-time, thereby aiding in the design of more durable materials.

-Environmental Impact Studies: Investigate the effects of environmental factors such as temperature, humidity, and chemical exposure on the radiation shielding properties of concrete. This research could provide insights into how elevated temperatures combined with radiation affect the structural integrity of concrete. Simulating real-world conditions will provide more accurate data for developing durable concrete mixtures.

-Comparative Material Studies: Conduct comparative studies on a wider range of aggregates and binders to identify materials that offer superior radiation resistance. This can include exploring new or unconventional materials and examining the optimization of the concrete composition and design for maximal radiation shielding efficiency. This could involve balancing factors such as density, hydrogen content, and structural strength. that might provide better shielding properties.

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DECLARATION

The authors declare that artificial intelligence (AI) tools, specifically language processing algorithms, were utilized during the preparation of this manuscript to enhance grammatical accuracy. The AI assistance primarily focused on identifying and rectifying grammatical errors, ensuring clarity and coherence in the presented content. It is imperative to acknowledge that while AI tools played a role in refining the language mechanics, the overall intellectual content and interpretation remain the responsibility of the authors.

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