

Research progress on magnetic fluid sealing in nuclear irradiation environment

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Abstract: Magnetic fluid sealing (MFS), with advantages such as zero leakage and long service life, has become the core solution for dynamic seals in extreme environments like nuclear energy and aerospace. However, the high-energy irradiation environment where nuclear industry equipment is located is prone to cause the deterioration and alter the frictional behavior of MFS, which restricts its

engineering application. Based on the author's years of research, this paper systematically reviews the irradiation evolution laws and related mechanisms of three core components, namely magnetic fluid (MF), permanent magnets, and lubricants, as well as their overall performance in MFS. Research shows that the agglomeration of magnetic particles (MPs), the desorption of surfactants, and the degradation of base carrier fluid are the core factors leading to the deterioration of MF performance. There are two explanations for the irradiation demagnetization of permanent magnets: the thermal spike effect and the defect pinning effect. Under irradiation, lubricants exhibit degradation behaviors such as abnormal viscosity, increased acid value, gas release, non-crystallization and oxidation. Meanwhile, the existing research has limitations such as mainly analyzing single components, lacking multi-phase coupling mechanisms, and insufficient correlation with overall sealing performance. Based on this, the research team of authors has invented a series of MFS that can withstand radiation dose up to 10MGy, and successfully applying them to nuclear industry equipment. In the future, efforts should be focused on breaking through in areas such as the coupling mechanism of component performance, long-term assessment of dynamic irradiation, modification of irradiation-resistant materials, and quantitative prediction models for frictional properties and sealing lifespan. This paper reveals the evolution mechanism of the tribological behavior of MFS system under nuclear irradiation conditions. A research framework for MFS in nuclear energy equipment has been established, providing theoretical references for material selection, structural optimization and reliability improvement of MFS.

Keywords: Irradiation, magnetic fluid, sealing, permanent magnet, lubricant

1 Introduction

Nuclear energy, as a clean, efficient and economical new energy source, has gained wide international recognition at the application level [1, 2]. With the development of the nuclear power industry, nuclear power plants will produce a large amount of spent fuel containing radioactive

elements such as uranium and plutonium during operation. If not treated in a timely and effective manner, it will cause serious harm to the environment and human health [3-6]. Take a million-kilowatt-class pressurized water reactor nuclear power plant as an example. The spent fuel it generates each year is about 20 to 25 tons [7]. The decay cycle of spent fuel is generally tens of thousands to hundreds of thousands of years. How to safely dispose of these highly radioactive and toxic spent fuels has become a bottleneck restricting the sustainable development of nuclear power [8].

Ionizing radiation in the nuclear power plant environment contains a variety of high-energy particles, such as γ photons, electrons, protons, neutrons and atomic nuclei, etc. [9, 10]. A mixed radiation field is composed of at least two types of particles, usually including γ photons and neutrons. They transfer energy to substances through elastic or inelastic collisions, leading to chemical changes such as molecular bond breakage and free radical generation. The energy deposited per unit mass of substance is called the absorbed dose, and its SI unit is Gray (Gy), with $1\text{Gy}=1\text{J/kg}$. Another commonly used unit is the rad, where $1\text{rad}=0.01\text{Gy}$ [11, 12].

At present, the main safe disposal method for spent fuel internationally is the nuclear fuel cycle, which mainly includes the following two ways [13-17]. One is the closed nuclear fuel cycle, and the other is the open nuclear fuel cycle. For the closed nuclear fuel cycle, spent fuel reprocessing technology is one of the most crucial technologies, playing a significant role in ensuring the safety and economy of nuclear engineering operations [18]. Spent fuel reprocessing technology not only enhances the utilization capacity of nuclear fuel, but more importantly, provides a reliable guarantee for the safe and sustainable development of nuclear power.

In the spent fuel reprocessing process, a large amount of radioactive and corrosive substances are utilized [19]. With the expansion of the scale of spent fuel reprocessing, the requirements for the safety and reliability of various equipment and components during the construction of the reprocessing plant are getting higher and higher [20-22]. Sealing requirements such as zero leakage, radiation resistance and corrosion resistance have been put forward.

Compared with traditional dynamic sealing methods such as mechanical sealing, packing sealing and labyrinth sealing, magnetic fluid sealing (MFS) has advantages such as zero leakage, long service life, high reliability, low friction, no pollution and easy maintenance [23-27]. In 1972, a research report by NASA provided the radiation resistance of some sealing materials [28]. It can be concluded that the radiation resistance of MFS is excellent, far superior to that of commonly used O-ring sealing and V-ring sealing, allowing the cumulative dose of γ radiation to increase by at least two orders of magnitude. It has a very promising development prospect in nuclear engineering applications.

MFS is composed of components such as rotating shaft, pole shoes, magnetic fluid (MF), permanent magnets, rubber rings, and bearings. Currently, it is mainly applied in fields such as nuclear energy, aerospace, electronics, and vacuum [29-35]. MFS adopts a magnetic concentration structure to achieve a non-uniform magnetic field distribution, confining MF in the sealing gap to form a liquid "O" ring [36-39], thereby achieving a sealing effect, as shown in Fig. 1.

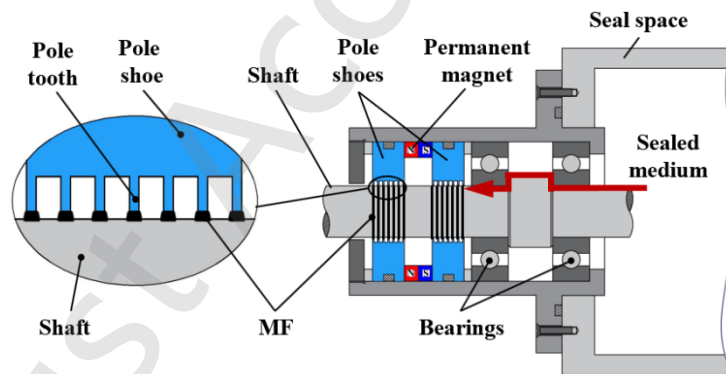


Fig. 1 The principle of MFS.

During the operation of nuclear engineering equipment, materials are exposed to strong nuclear radiation and suffer from irradiation damage. As a result, all components of MFS are damaged to varying degrees, significantly altering the interface frictional behavior, resulting in the failure of interface lubrication, increased wear, and ultimately damaging the integrity and service reliability of the sealing structure. This paper respectively discusses the performance of three types of components related to dynamic seals, namely MF, permanent magnet, and lubricant, after irradiation. And then

discusses the sealing performance of MFS in irradiation environments. This has important engineering guiding significance for how to truly apply MFS to the nuclear energy field.

2 Research progress on the properties of magnetic fluid and their components after nuclear irradiation

The development of MF began in the 1960s. NASA developed MFS to solve the sealing problem of movable joints in spacesuits. Since then, MF has always been a hot topic in academic research [40-42]. MF, also known as ferrofluid, etc., is mainly composed of a mixture of magnetic particles (MPs) with nanoscale diameters, base carrier fluid and surfactant. It is a new type of functional material [43], as shown in Fig. 2. MF has properties similar to those of ordinary colloids in the absence of an external magnetic field. When an external magnetic field is present, MF exhibits superparamagnetism [44], which can be controlled by the magnetic field and possess many unique magnetic, rheological, optical and acoustic properties [45-47]. Due to the fact that MF possesses both the fluidity of liquids and the magnetism of solid magnetic materials, it has high academic value and broad application prospects. It has been applied in fields such as MFS, MF loudspeaker, MF shock absorber, MF heat transfer and wastewater treatment [48-55]. MF is the core of MFS, and its performance after irradiation is of vital importance.

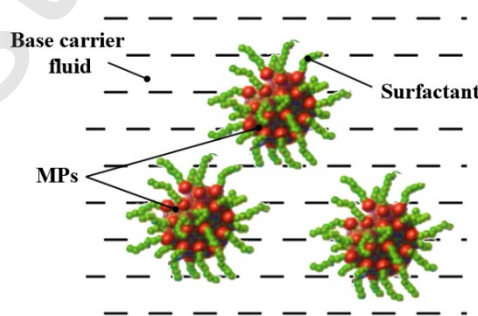


Fig. 2 The composition of MF.

In scenarios such as nuclear reactor maintenance, spent fuel reprocessing, and aerospace radiation environments, MF needs to be exposed to ionizing radiation such as γ rays and electron beams for a long time. The microstructure changes caused by irradiation will significantly affect their service performance. The development of scientific methods for preparing MF and the verification of its

performance in irradiation environments are of great significance for ensuring the long-term reliable operation of nuclear industry equipment. In recent years, scholars have conducted extensive research on the effects of irradiation on MF and its components, revealing the mechanism of radiation damage and the laws of performance regulation. This chapter starts with the irradiation response of each component of MF, summarizes the macroscopic performance evolution of the system after irradiation, and provides a comprehensive reference for the preparation and application of radiation-resistant MF.

2.1 Irradiation response of MPs

MPs are the core functional components of MF, and their magnetic properties directly determine the magnetic response characteristics of MF. Commonly used MPs include Fe_3O_4 、 $\gamma\text{-Fe}_2\text{O}_3$ 、 FeCo 、 Gd_2O_3 , etc. [43] Irradiation can affect their performance by inducing particle defects, size changes and phase structure transitions.

Devi et al. [56] irradiated oleic acid-coated water-based MF (MF1) with 878Gy and 2635Gy of $^{60}\text{Co-}\gamma$. Subsequently, Devi et al. [57] irradiated water-based MF (MF2) and kerosene-based MF (MF3), both using oleic acid as the surfactant and with a concentration of 17.5%, at a dose of 2635Gy. It should be noted that MF1 and MF2 were stabilized by double-layer oleic acid, while MF3 was stabilized by single-layer oleic acid. The average sizes of Fe_3O_4 MPs (MP1, MP2, MP3) in three MF were measured respectively by transmission electron microscopy (TEM) And dynamic light scattering (DLS). The results are shown in Table 1 and Fig. 3.

Table 1 The average particle sizes and growth rate of MP1, MP2, and MP3 under different irradiation doses. Adapted from Ref. [56, 57]

Sample number	Characterization method	Average particle size (nm)			Compared to the size growth rate before irradiation (%)	
		Non-irradiated	878Gy	2635Gy	878Gy	2635Gy
MP1	TEM	8	20	48	150	500
	DLS	15	28	60	86.67	300
MP2	TEM	9	-	45	-	400
	DLS	15	-	60	-	300
MP3	TEM	9	-	18	-	100

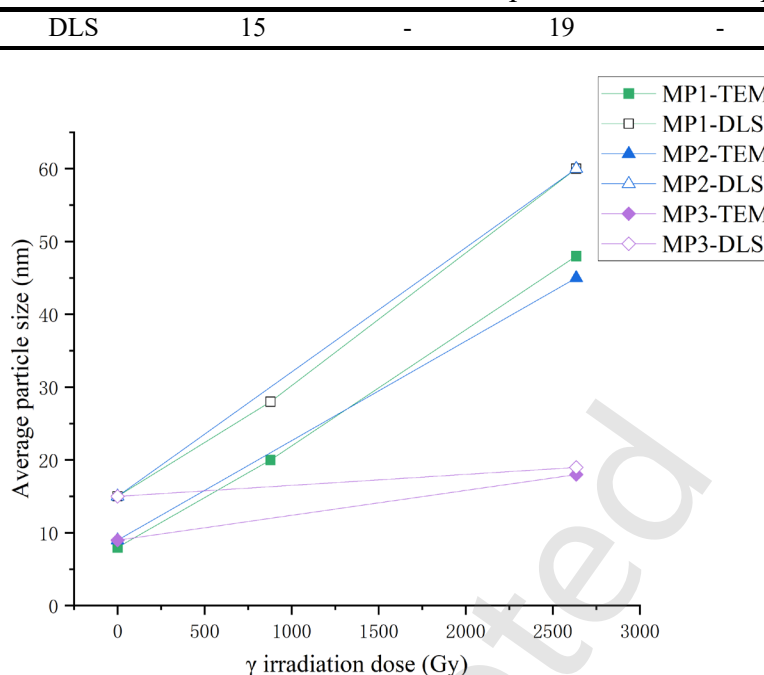


Fig. 3 The average particle sizes of MP1, MP2, and MP3 under different irradiation doses. Adapted from Ref. [56, 57]

From the experimental results, the DLS results are generally larger than the TEM results. This is because TEM reflects the intrinsic morphological size of the particles, while DLS is closer to the actual hydrodynamic behavior size of the particles in the liquid phase. These results all indicate that Fe_3O_4 particles dispersed in MF undergo solid-state recrystallization and particle growth by absorbing the energy of γ irradiation and dissipating it into the surrounding environment, thereby enhancing the formation of chain-like structures. Moreover, with the increase of irradiation dose, the particle size distribution of nanoparticles also increases accordingly. The particle size growth of MP3 is less than that of MP1 and MP2. There could be the following three reasons for this: Firstly, MP3 is single-layer oleic acid chemical adsorption. MP1 and MP2 are double-layer oleic acid stable, with the inner layer being chemical adsorption and the outer layer being physical adsorption. Under irradiation, the physical adsorption layer formed by the intermolecular van der Waals force is more prone to damage, leading to the failure of the stable layer and the aggregation of nanoparticles. Secondly, compared to water, kerosene has a higher viscosity, which to some extent limits the Brownian motion and collisions of nanoparticles, inhibiting excessive growth. Thirdly, the density of water is slightly greater than that

of kerosene, and the energy dissipation in the water phase is more sufficient, which is more conducive to nanoparticles growth.

Alsaieri et al. [58] subjected Fe_3O_4 samples to γ irradiation. According to X-ray diffraction (XRD) analysis, the crystal sizes of the samples without irradiation, 3kGy, 4.5kGy, and 6kGy were 14.67nm, 15.99nm, 16.69nm, and 17.37nm, respectively. This is due to irradiance inducing lattice defects and ion migration, which leads to grain growth and an increase in crystallinity.

Darziyeva et al. [59] investigated the changes of Fe_3O_4 MPs after irradiation with ^{132}Xe heavy ions at 167MeV. It can be seen from Table 2 that after irradiation, with the increase of ion injection, the specific magnetic moment decreases significantly. This phenomenon stems from the destruction of spinel structural integrity by heavy ion irradiation, which in turn disrupts the long-range magnetic order within the crystal thereby weakening the overall magnetism. After irradiation, the Curie temperature of MPs decreases with the increase of injection volume. It indicates that irradiation causes the temperature of the ferromagnetic-paramagnetic phase transition to shift towards a lower temperature.

Table 2 The specific magnetic moment and Curie temperature of Fe_3O_4 MPs irradiated by heavy ions. Adapted from Ref. [59]

Ion injection (ion/cm ²)	Room temperature specific magnetic	
	moment (emu/g)	Curie temperature (K)
0	33.4	655
5.0×10^{12}	17.7	617
5.0×10^{13}	11.7	576
3.83×10^{14}	9.7	560

Devi et al. [60] prepared Gd_2O_3 covering by CTAB (cetyltrimethylammonium bromide) surfactant and dispersed it in ethanol to form a stable MF. Using a ^{60}Co - γ ray source, five irradiation doses were set: 32Gy, 97Gy, 292Gy, 878Gy, and 2.635kGy. Fourier Transform Infrared spectroscopy (FTIR) analysis was conducted on the samples, and the results showed that as the increased of the

irradiation dose of γ rays, the intensity of the vibration peak of Gd-O gradually increased. However, in the sample with an irradiation dose of 878Gy, it was observed that the Gd-O vibration mode exhibited discontinuities and a reduction in intensity distribution. The discontinuous vibration mode is attributed to the presence of intragranular defects (vacancies, dislocations) in Gd_2O_3 particles, which are unevenly distributed along grain boundaries and surfaces.

Paul et al. [61] took Tb^{3+} -doped Gd_2O_3 nanoparticles as the research object and investigated the regulatory mechanism of γ irradiation on them. From the FTIR results, it can be seen that after irradiation with 97Gy and 2.635kGy, the Gd-O stretching vibration peak in the samples shifted to a red position. It indicated that the lattice vibrations have weakened. Under the interaction between high-energy photons and matter, there might be some flaws. The research provides a basis for the preparation and application of functional materials in irradiation environments.

2.2 Irradiation response of surfactant and base carrier fluid

Surfactant is the key to maintaining the stability of MF. It prevents the agglomeration of MPs through multiple effects such as electrostatic repulsion, steric hindrance effect, formation of protective films, and reduction of density differences. Common surfactant includes oleic acid, sodium oleate, CTAB, chitosan, polyethylene glycol (PEG), bovine serum albumin (BSA), etc. The base carrier fluid provides a dispersion medium for MPs. Its viscosity, chemical properties, etc. determine the rheological characteristics and adaptability to the service environment of MF. Common base carrier fluid includes water, kerosene, esters, ethanol, aviation hydraulic oil, etc. Irradiation can cause molecular chain breakage, oxidative degradation or cross-linking of surfactant and base carrier fluid, disrupt the interface modification effect, affect the dispersion stability of MF, and thereby influence the macroscopic properties of the system.

Kopčanský et al. [62] discovered that γ irradiation would disrupt the long polar chains of oleic acid, causing them to break and lose its ability to coat Fe_3O_4 particles, thereby triggering particle agglomeration. Agglomerated particles settle due to gravity, reducing the number of effective particles

in the top sample and lowering the saturation magnetization. Based on this, Kopčanský et al. [63] discovered that the saturation magnetization intensity and the number of MPs in kerosene-based and diester-based MF both decreased with the increase of γ irradiation dose. Moreover, γ irradiation induced MPs agglomeration and deposition with the increase of dose. This is because irradiation can cause the breakage of long molecular chains in the base carrier fluid and oleic acid surfactant, weakening the repulsive force between particles, thereby accelerating coagulation and subsequent precipitation.

Chang et al. [64] found that under γ irradiation, chitosan caused the breakage of intramolecular glycosidic bonds, a decrease in molecular weight, and oxidative degradation of the amino and hydroxyl groups in the molecular chain. However, when chitosan was pre-irradiated and then coated with Fe_3O_4 particles, the interfacial binding force between it and the particles was enhanced. Furthermore, Chang et al. [65] found that after a month of storage, when the chitosan-coated MF was irradiated with 100kGy, the samples showed obvious stratification. This indicated that high-dose irradiation disrupted the chemical bond between chitosan and MPs, leading to particle aggregation and stratification of MF.

Tomasovicova et al. [66] prepared two water-based MF using only sodium oleate as the surfactant and one using both sodium oleate and PEG as the surfactants. The results showed that 1000Gy of electron irradiation reduced the saturation magnetization of MF coated only with sodium oleate by 50%, while it only reduced the saturation magnetization of the MF coated with sodium oleate and PEG by 25%. The reason is that the protective effect of PEG inhibits particle agglomeration and sedimentation. Furthermore, Tomasovicova et al. [67] irradiated water-based MF coated with PEG in different molar amounts with 20Gy electrons. The research found that the saturation magnetization of MF decreased by approximately 10% after irradiation, and the extent of this decrease was independent of the molecular weight of PEG and the mass ratio of $\text{PEG}/\text{Fe}_3\text{O}_4$. The magnetization curves of the samples with different PEG molecular weights all showed similar decreases. The saturation magnetization intensities of samples with different mass ratios of $\text{PEG}/\text{Fe}_3\text{O}_4$ maintained a decrease

of approximately 10% in both the first measurement after irradiation and the remeasurement one month later, with no further changes. It indicated that the system reached stability after the first sedimentation, with no continuous aggregation or sedimentation.

Subsequently, Tomasovicova et al. [68] subjected biocompatible MF containing different masses of BSA to electron irradiation of 1~1024Gy. The results showed that irradiation reduced the saturation magnetization of the sample with a mass ratio of BSA/Fe₃O₄ of 0.25 by approximately 10%, and that of the samples with a mass ratio of BSA/Fe₃O₄ of 1 and 2.5 by approximately 5%. It was demonstrated that a high mass ratio of BSA/Fe₃O₄ could significantly suppress the decrease in saturation magnetization caused by irradiation. Provided experimental evidence for optimizing the irradiation tolerance of MF in medical applications.

Zaharescu et al. [69] investigated the effect of 50kGy-¹³⁷Cs- γ irradiation in air on the thermal oxidation of surfactants and base carrier fluid in MF. This was equivalent to the maximum irradiance during a major nuclear event. γ irradiation could cause oxidation, leading to weak bond breaking and the generation of free radicals. Based on the decrease in the measured oxidation initial temperature value, materials can be classified into three irradiation stability grades: Materials with low irradiation stability (myristic acid, oleic acid - vegetal, octyl stearate), materials with medium irradiation stability (oleic acid - technical, vacuum pump oil), and materials with high irradiation stability (lauric acid, transformer oil, dioctyl adipate). Moreover, the stability of complete MF is superior to that of a simple superposition of its components, and the interaction between MPs and organic media is a key regulatory factor.

Lazič et al. [70] studied the effect of 50Gy irradiation on water-based MF that was double-layer surface-modified with oleic acid. Compared with the reference sample, the average size of the light-scattering entity of the sample irradiated by electrons increased from 132nm to 149nm. However, it was not certain whether it was caused by the aggregation of MPs or oleic acid droplets.

Taheri et al. [71] reviewed the application of ionizing radiation in the fields of hydrocarbon cracking, isomerization, polymerization, desulfurization and catalyst regeneration in the petroleum industry. Kang et al. [72] explored the performance changes of No. 10 and No. 15 aviation hydraulic oils under 0~5MGy γ irradiation. The results are shown in Table 3. At low doses, the performance of the two oils was stable, which could meet the short-term usage requirements in the nuclear environment. At high doses, long-chain alkanes and cycloalkanes were decomposed into unsaturated hydrocarbons, and tertiary alcohols were decomposed into primary alcohols. Moreover, the performance deterioration of No. 15 oil was more significant. The molecular chain breakage and oxidation reactions triggered by γ irradiation were the main causes of performance degradation, and this process was most intense before 1MGy. These mechanisms could provide technical references for the selection of base carrier fluid for radiation-resistant MF.

Table 3 The performance changes of aviation hydraulic oil No. 10 and No. 15 under 0~5MGy γ irradiation. Adapted from Ref. [72]

Irradiation dose	Irradiation response	
	No. 10	No. 15
Low dose (0~100kGy)	At 100kGy, the kinematic viscosity decreased to 55% of that without irradiation.	At 100kGy, the kinematic viscosity decreased to 72% of that without irradiation.
Medium dose (100kGy~1MGy)	At 1MGy, the kinematic viscosity decreased to 35% of that without irradiation, the initial boiling point dropped from 226°C to below 210°C.	At 1MGy, the kinematic viscosity decreased to 40% of that without irradiation.
High dose (1MGy~5MGy)	At 5MGy, the kinematic viscosity returned to 45% of the value without irradiation; after exceeding 2MGy, the initial boiling point dropped sharply from 168°C to 100°C.	At 5MGy, the kinematic viscosity returned to 54% of the value without irradiation; at 2MGy, the initial boiling point decreased from 226°C to below 210°C, and at 5MGy, the initial boiling point dropped to around 100°C.

2.3 Irradiation damage mechanism of MF

The macroscopic properties of MF after irradiation are a comprehensive reflection of the irradiation responses of their various components. As shown in Fig. 4. High-energy irradiation can cause the chemical bonds between surfactant and base carrier fluid in MF to break. At the same time, MPs in MF will absorb the energy of the rays, agglomerate and settle, thereby affecting their saturation magnetization and material stability [62-65, 69], as shown in Fig. 5. Therefore, irradiation damage may be reflected in the data such as the saturation magnetization intensity, viscosity, MPs size and saturation vapor pressure of MF. The performance of different MF systems changes with the irradiation dose as shown in Table 4. The above research results provide experimental basis for the selection and modification of base carrier fluid and surfactant of MF in irradiation environments. However, the mechanism of the influence of irradiation on the chemical, physical properties, rheological properties, etc. of MF is still not very clear and awaits further study.

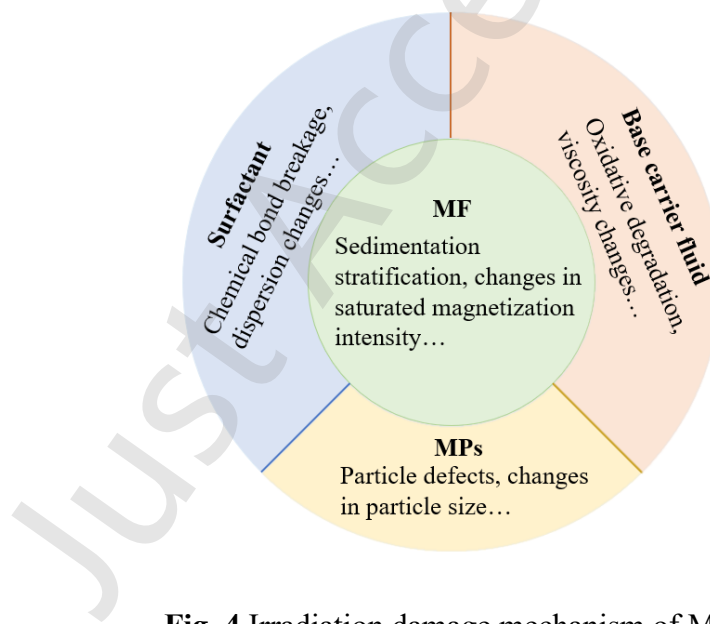


Fig. 4 Irradiation damage mechanism of MF.

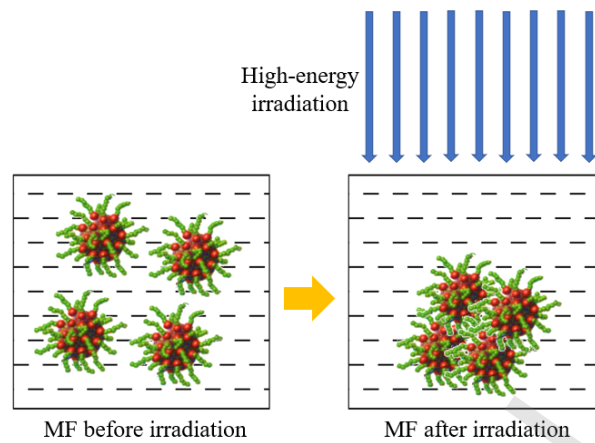


Fig. 5 Microscopic morphology diagram of MF after irradiation.

Table 4 Comparison of the performance of different MF systems with changes in irradiation dose

MPs	Surfactant	Base carrier fluid	Maximum irradiation dose	Type of irradiation	Core irradiation results
Gd ₂ O ₃	CTAB	Ethanol	2635Gy	γ rays	As the irradiation dose increases, the intensity of the Gd-O vibration peak gradually strengthened [60].
		Water / Kerosene	2635Gy		The average particle size increase in water-based MF was greater than that in kerosene-based MF [57].
	Oleic acid	Kerosene	17.3Gy	γ rays	The saturation magnetization intensity decreased from 6.51mT to 4.85mT [62].
	Pre-irradiated		100kGy		The interface bonding strength was enhanced, but after one month of storage, the sample showed obvious layering [65].
Fe ₃ O ₄	chitosan				
	Sodium oleate / Sodium oleate + PEG	Water	1000Gy	Electron beam	PEG provided protection, and the degree of reduction in saturated magnetization compared to the sample without PEG was halved [66].
	Sodium oleate + PEG		20Gy		The saturation magnetization intensity decreased by approximately 10% [67].

Sodium oleate + BSA	1024Gy	β rays	The sample with the highest BSA content showed a
			reduction of approximately 5% in its saturated magnetization intensity [68].
Oleic acid	50Gy	Photon +	After irradiation, the hydrodynamic diameter of the
		Electron beam	particles slightly increased, while the dispersion remained basically stable [70].

In the existing studies, due to the advantages such as simplicity of the model and ease of representation, scholars mostly adopt water-based and kerosene-based MF systems for exploration [57, 70]. In the nuclear engineering environment, high temperature and irradiation exposure often occur simultaneously. Therefore, in actual sealing scenarios, MF with very low evaporation rates must be used. High temperature will intensify molecular thermal oxidation and the thermal cracking of surfactant chains, destroying the coating layer on the surface of MPs. High temperature will also reduce the viscosity of MF and enhance the Brownian motion of MPs, accelerating the formation of large-sized aggregates [34, 73]. High temperature will form a synergistic accelerating degradation effect with irradiation, causing the performance of MF to deteriorate. Most of the existing irradiation-related tests of MF are limited to a single working condition at room temperature. The coupling damage research of the real high-temperature and irradiation coexistence environment in nuclear equipment is still very scarce. No temperature-correction irradiation degradation prediction model has been established, making it difficult to support the design of MFS under nuclear irradiation and high temperature conditions.

The current research on irradiation of MF mainly focuses on the characterization of irradiation degradation behavior. To address these issues, several aspects can be considered to enhance the irradiation resistance of MF. The secondary coating with different surfactants, the introduction of dopant ions, and advanced surface coating technologies [74-77] can effectively improve the irradiation resistance of the system. Perfluoropolyether (PFPE) often be used as the base carrier fluid for long-life MF due to its low saturated vapor pressure and high thermal oxidation stability [78], which can inhibit

irradiation degradation. In recent years, ionic liquid-based carrier fluids [79-81] have developed rapidly, and some anionic liquids have irradiation resistance. As the base carrier fluid, they can reduce the volatilization and free radical generation caused by irradiation. Introducing antioxidants in MF can reduce the active free radicals generated by irradiation [69], and then alleviate the degradation reaction. At the same time, the core-shell nanoparticle structures [82, 83] can isolate the magnetic core from the outside world, and the shell layer can hierarchically dissipate the irradiation energy. Thus, the chemical and irradiation stability of MF can be significantly improved.

In the future, further exploration of the effects of irradiation dose gradients and mixed radiation fields on the stability of MF can be carried out. In-situ characterization and monitoring methods for the microstructure during the coupling process of high temperature and irradiation should be established. Supplementary data on the performance of MF under the combined effects of high temperature and irradiation should be provided. The preparation methods and protective measures for high-temperature and irradiation-resistant MF should be improved. Long-term performance evaluation of MF under dynamic irradiation conditions should be carried out.

3 Research progress on the properties of permanent magnets after nuclear irradiation

Permanent magnets are materials that can maintain their magnetism for a long time and generate a stable magnetic field without external energy input. It features high residual magnetism, high coercive force and high magnetic energy product, and there are various types with significant performance differences. According to the material composition, permanent magnets are mainly classified into neodymium iron boron permanent magnets (Nd-Fe-B), samarium cobalt permanent magnets (Sm-Co), alnico permanent magnets (Al-Ni-Co), etc. Radiation-induced demagnetization of permanent magnets is an important issue in key applications such as accelerators, nuclear reactors, and space exploration. The failure of permanent magnets can lead to serious consequences and restrict the service life of equipment. Since the 1980s, scholars have used different radioactive sources to study the irradiation characteristics of permanent magnets. The key influencing factors such as irradiation

type, material composition and temperature were analyzed, and the mechanism of irradiation demagnetization was revealed.

3.1 Neutron irradiation effect

Cost et al. [84] found in a reactor that when the irradiation temperature was 77°C and the fast neutron injection rate reached 10^{15}n/cm^2 , the residual magnetic loss of the Nd-Fe-B permanent magnet was approximately 5%. At 153°C, the same amount of irradiation leads to a 10% residual magnetic loss, indicating that high temperatures could intensify neutron demagnetization. After irradiation, the residual magnetism of the permanent magnet could be completely restored by re-magnetization, indicating that irradiation has not significantly changed the metallurgical structure of the material.

In the study, Samin et al. [85] used 10^{15}n/cm^2 fast neutron irradiation. The irradiated samples were cylindrical Nd-Fe-B permanent magnets. The hysteresis loops of Nd-Fe-B permanent magnets before and after irradiation were fitted through the Jiles-Atherton (JA) model. The JA model describes the hysteresis behavior of ferromagnetic materials by considering the domain wall pinning effect (irreversible magnetization) and the bending effect (reversible magnetization), with the core equation being Eq. (1). Among them, the effective magnetic field $H_e = H + \alpha M$, hysteresis magnetization intensity $M_{an}(H_e) = M_s \left[\coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right) \right]$, shape parameter $a = \frac{kT}{\mu_0 m}$, inter-domain interaction parameter α , pinning energy k , reversible magnetization coefficient C , and saturation magnetization intensity M_s .

$$\frac{dM}{dH} = \frac{1}{(1+C)} \frac{1}{\delta k - \alpha(M_{an} - M)} (M_{an} - M) + \frac{C}{(1+C)} \frac{dM_{an}}{dH} \quad (1)$$

Samin et al. determined the parameters of the JA model based on the experimental results. Through the analysis of the fitting parameters, it was found that the shape parameter a in the irradiated samples increased, which reflected the reduction of the regional magnetic moment. The interaction parameter α between magnetic domains and the pinning energy k increased, indicating that the defects introduced by irradiation enhanced the domain wall pinning effect and increased the coercive

force. The reversible magnetization coefficient C decreased, indicating an increase in the proportion of irreversible magnetization. The saturation magnetization intensity M_s increased, which might be due to experimental errors or a change in the crystal structure of the magnet.

In addition, Miyahara et al. [86] irradiated Nd-Fe-B permanent magnets with 10MeV fast neutrons. When the continuous irradiation absorbed doses were 1.1kGy, 3.7kGy, 5.6kGy and 7.4kGy, the magnetic flux losses were 0.6%, 6.9%, 25.2% and 47.3%, respectively. The magnetic flux loss of non-continuous irradiation with a total dose of 7.4kGy (3.7kGy first, then 3.7kGy after 9 months) was 14% less than that of continuous irradiation, which was significantly lower than that of continuous irradiation. It indicates that the dose rate affects the degree of demagnetization, and it is speculated that the defect relaxation during the irradiation interval alleviates the magnetic domain disturbance.

Due to the grain refinement, the neutron irradiation resistance of the fast-quenched melt Nd-Fe-B is significantly better than that of the sintered Nd-Fe-B. The experiments of Brown et al. [87] indicated that after one-hour irradiation with $1.4 \times 10^{16} \text{ n/cm}^2$ fast neutrons, the residual magnetic flux loss of the melt rapidly quenched Nd-Fe-B sample was only 1.5%, while that of the sintered Nd-Fe-B sample reached 4.6%. Because the grains of the fast-quenched melt samples are small, the domain wall pinning effect is stronger. The nucleation of demagnetized domains and the de-nailing effect of domain walls caused by irradiation are suppressed, so the residual magnetism attenuation is slower. The grains of sintered samples are relatively large, and the coercive force depends on the nucleation of demagnetized domains and the nailing of grain boundaries. During irradiation, domain walls can move further, resulting in greater loss of magnetization intensity.

Compared with Nd-Fe-B, Sm-Co permanent magnets have better neutron irradiation tolerance. Brown et al. [88] subjected Nd-Fe-B and Sm-Co permanent magnets to fast neutron irradiation at $1.4 \times 10^{16} \text{ n/cm}^2$. Under the same irradiation conditions, the residual magnetic loss of Sm-Co was less than 0.5%, while the loss of the optimal material Nd-Fe-B was approximately 5%. Moreover, the Nd-

Fe-B permanent magnet had a geometric effect, and the residual magnetic attenuation rate after irradiation decreased with the increase of the length-to-diameter ratio (L/D) of the permanent magnet.

Zhao et al. [89] investigated the effect of neutron irradiation with a dose of $5 \times 10^{14} \text{ n/cm}^2$ on the $\text{Sm}_2\text{Co}_{17}$ permanent magnets. The XRD results showed that no phase transition occurred in the $\text{Sm}_2\text{Co}_{17}$ phase after irradiation. The measured demagnetization curve showed that the residual magnetism remains unchanged after irradiation, the intrinsic coercive force slightly increased from 2130kA/m to 2131.6kA/m, and the magnetic flux slightly decreased from 1331mWb to 1330mWb. The overall magnetic property stability of the Sm-Co permanent magnet after irradiation was good. It indicated that it had good resistance to neutron irradiation.

3.2 Proton and heavy ion irradiation effect

Blackmore [90] discovered that the magnetic properties of Nd-Fe-B permanent magnets were extremely sensitive under 500MeV proton irradiation. Basically, its magnetization performance completely disappeared at $7 \times 10^7 \text{ rad}$ (700kGy), while at $4 \times 10^6 \text{ rad}$ (40kGy), the magnetic loss exceeded 50%. Its relatively low Curie temperature might be the reason for its high sensitivity. For Sm-Co permanent magnets, a relatively low performance loss could still be maintained at $10^9 \sim 10^{10} \text{ rad}$ (10~100MGy). Its high radiation resistance was related to the stability of its crystal structure and magnetic anisotropy.

Ito et al. [91] irradiated Nd-Fe-B permanent magnets with 200MeV protons. It was found that the magnetic flux loss of Nd-Fe-B permanent magnets was logarithmically correlated with the absorbed dose, as shown in Eq. (2), where $\eta = 39 \pm 3\%$. Moreover, the higher the coercive force of the sample, the stronger its radiation resistance. When the coercive force was increased from 1.15MA/m (N48) to 2.5MA/m (N32Z), the absorbed dose corresponding to 20% magnetic flux loss increased from 0.51kGy to 23kGy.

$$\Delta\phi = -\eta \log D + \text{const} \quad (2)$$

Furthermore, Ito et al. [92] found that the damage of 660MeV C⁶⁺ heavy ion irradiation was equivalent to that of 200MeV proton irradiation within the dose range of 50~30kGy. When the absorbed dose reached 1.3~1.4kGy, both irradiations caused a 50% loss of magnetic flux in the Nd-Fe-B permanent magnet. Moreover, after irradiation, the sample could restore its initial magnetic properties through re-magnetization, which proved that the damage does not involve irreversible destruction of the lattice structure.

3.3 High-energy electron and γ -ray irradiation effect

Bizen et al. [93] irradiated Nd-Fe-B with high-energy electrons ranging from 2~8GeV and found that the magnetic flux loss increased with the rise of electron energy, but the growth rate of magnetic field loss slowed down. And the damage was concentrated in the small-volume area near the irradiation axis. Irradiation demagnetization had an energy threshold of approximately 1.7GeV. When the energy was below this threshold, demagnetization could be ignored.

Okuda et al. [94] investigated the effects of 17MeV electron beam irradiation and ⁶⁰Co- γ rays on the magnetic flux of Nd-Fe-B and Sm-Co permanent magnets. The magnetic flux loss of Nd-Fe-B after electron irradiation increased with the increase of dose. When the electron dose was $2.1 \times 10^{-3} \text{C/cm}^2$ (equivalent to an absorbed dose 2.6MGy), the magnetic flux loss of Nd-Fe-B was 9%. When the dose was $1.4 \times 10^{-3} \text{C/cm}^2$ (1.73MGy), the magnetic flux loss of Sm-Co was less than 0.4%. When the absorbed dose of γ rays was 2.8MGy, the magnetic flux losses of both Nd-Fe-B and Sm-Co were less than 0.5%. It is indicated that when the absorbed dose is similar, the damage of γ rays to Nd-Fe-B is weaker than that of electron beams.

Gao et al. [95] irradiated Nd-Fe-B permanent magnets with ⁶⁰Co- γ rays. When the absorbed dose reached 200Mrad (2MGy), the magnetic flux loss was only 0.5-2.5%. When the dose exceeded 100Mrad (10MGy), the loss of thin Nd-Fe-B samples was more significant. It is indicated that the size effect has an impact on the irradiation response.

Zhang et al. [96] pointed out that after being exposed to γ rays, the surface magnetic induction intensity of $\text{Sm}_2\text{Co}_{17}$ permanent magnets increased by 10~40%. This phenomenon occurs because the magnetic domains that were not originally aligned in an orientation are exposed to γ rays, which excite the activity of the magnetic domain atoms. Under the action of the oriented magnetic field lines, some magnetic domains overcome resistance and rotating in a consistent direction, thereby enhancing the magnetic properties of the material.

Yang et al. [97] conducted a study on the γ irradiation effect and magnetic properties of sintered and bonded Nd-Fe-B, sintered SmCo_5 , and rare earth sintered permanent magnets treated with electroless Ni-P plating. When the cumulative dose was approximately 250kGy, the surface magnetic field of these permanent magnets still showed no significant change. It was indicated that both sintered and bonded rare earth permanent magnets had a certain ability to resist γ radiation.

Mesa et al. [98] conducted γ irradiation and temperature tests at 800krad (8kGy) on Nd-Fe-B and Sm-Co permanent magnets. Sm-Co had almost no magnetic property degradation under γ irradiation. The magnetic intensity of Nd-Fe-B dropped sharply at 100°C, showing relatively low thermal stability. The magnetization intensity of Sm-Co decreased linearly and slowly with the increase of temperature within the range of -100~225°C. The thermal stability of Sm-Co is significantly better than that of Nd-Fe-B.

Cheng [99] discovered that after irradiation with a cumulative dose of 1000Mrad (10MGy) of γ rays, the magnetic fluxes of the Al-Ni-Co and Sm-Co showed only a slight attenuation. After irradiation, the magnetic domain morphologies of Al-Ni-Co and Sm-Co did not change much, only reverse domains were formed in some areas. This might be the reason for the slight decrease in magnetic flux.

3.4 Mixed Irradiation Field Effect

The irradiation response of permanent magnets is closely related to the type, energy and dose of irradiated particles. There are significant differences in the degree of damage and mode of action of

permanent magnets caused by different irradiation sources. The actual service environment of permanent magnets is mostly a mixed irradiation field. The synergistic effect of different irradiation sources will aggravate the damage of permanent magnets. The damage caused by each irradiation source is shown in Fig. 6.

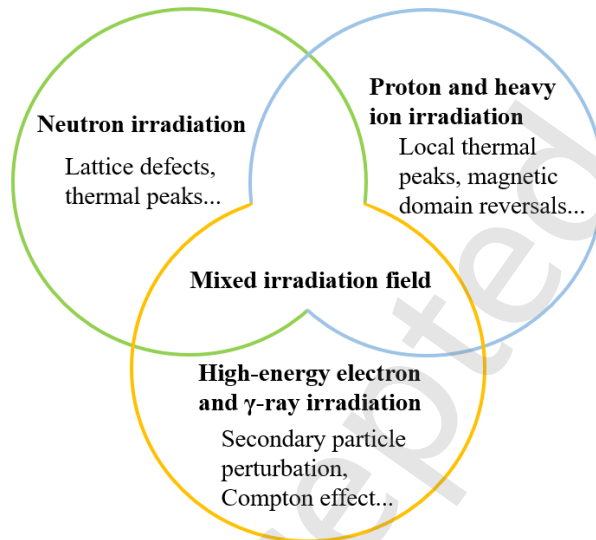


Fig. 6 Summary of damage caused by various irradiation sources.

Bizen et al. [100] proposed that the irradiation-induced demagnetization of permanent magnets could be explained by the magnetic reversal caused by thermal spikes. Thermal demagnetization was directly proportional to coercive force. However, in the case of irradiation demagnetization, this relationship was nonlinear. The mechanism of irradiation demagnetization depends on the irradiation dose of the incident particles. When the irradiation dose is relatively low (at the kGy level), the mechanism of irradiation demagnetization is basically consistent with that of thermal demagnetization.

Yang [101] obtained through a large number of mixed irradiation experiments that the influence of irradiation on Fe-Cr-Co and Nd-Fe-B permanent magnets were mainly manifested as the reduction of magnetic flux loss, while the changes of basic magnetic properties were not obvious. Nd-Fe-B permanent magnet is more sensitive to the temperature during the irradiation process.

Chen et al. [102] investigated the influence of a mixed irradiation field on the magnetic properties of sintered $\text{Nd}_2\text{Fe}_{14}\text{B}$ permanent magnets. When the irradiation dose was 1.56kGy, the magnetic flux loss of the 45SH permanent magnet with high intrinsic coercive force was only 0.2%, while the 52N

permanent magnet was more severely affected by irradiation, with the magnetic flux decreasing by 6.205%. XRD analysis proved that irradiation did not change the crystal structure of the permanent magnet. Wang et al. [103] irradiated two rare earth permanent magnetic materials, $\text{Sm}_2\text{Co}_{17}$ and Nd-Fe-B, with protons of 1~10kGy and neutrons of 10^{15}n/cm^2 . It was found that after the irradiation test, the magnetic properties of the high intrinsic coercive force Sm-Co material did not change significantly. The magnetic properties of Sm-Co materials with low intrinsic coercive force declined by less than 5%. The magnetic properties of Nd-Fe-B material had decreased significantly, with a reduction of more than 30%. It is indicated that the radiation resistance characteristic of rare earth permanent magnets is related to their intrinsic coercive force.

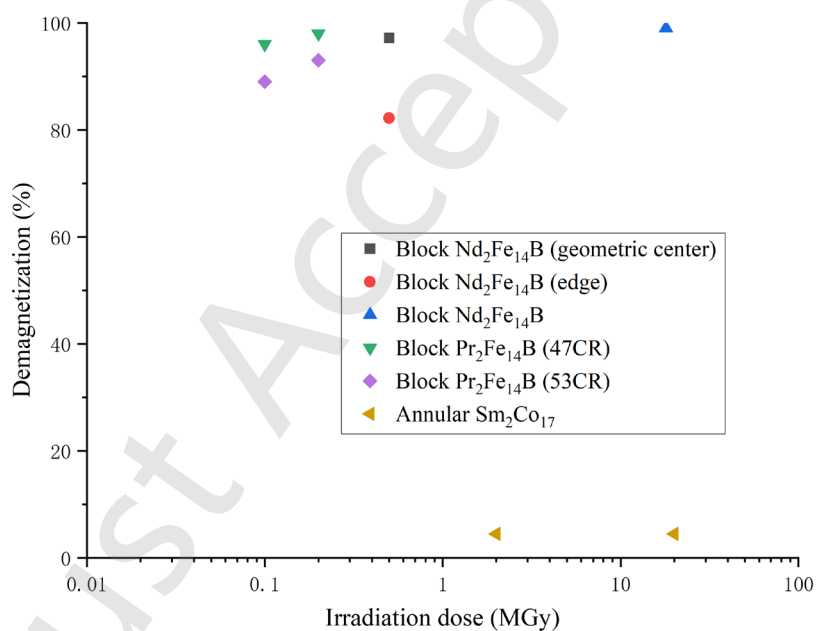


Fig. 7 Demagnetization of different permanent magnets in a mixed irradiation field. Adapted from Ref. [104]

Samin et al. [104] systematically evaluated the demagnetization behavior of three types of permanent magnets in a mixed irradiation field composed of thermal neutrons and fast neutrons, secondary protons, photons and electrons. Studies have shown that the demagnetization of electron return and γ energy flow accounts for only a few percent, so the observed significant loss was believed to be the result of neutron irradiation. The specific results are shown in Fig. 7. The irradiation

sensitivity of $\text{Pr}_2\text{Fe}_{14}\text{B}$ block magnets was higher than that of $\text{Nd}_2\text{Fe}_{14}\text{B}$. The $\text{Sm}_2\text{Co}_{17}$ annular magnet exhibited excellent irradiation tolerance. Due to its high Curie temperature ($>800\text{ K}$) and low boron content, there is no intense nuclear reaction induced by thermal neutrons. The demagnetization degree of $\text{Nd}_2\text{Fe}_{14}\text{B}$ annular magnets at a dose of 0.2MGy was lower than that of block magnets. Because the annular structure removes the high demagnetization area at the center of the block, that is the low magnetic permeability part, the inherent demagnetization driving force is reduced. Furthermore, Samin [105] reviewed the research on permanent magnet irradiation over the past three decades. The influences of irradiation type, magnetic properties and environmental factors on demagnetization were summarized.

3.5 Irradiation damage mechanism of permanent magnets

The irradiation demagnetization of permanent magnets is a complex process involving the coupling of multiple factors such as materials, irradiation and the environment. The essence of the damage caused by irradiation to permanent magnets is the multi-scale interaction between particles and lattice atoms as well as magnetic domains. The currently recognized mechanisms mainly include two types: the thermal spike effect and the defect pinning effect. One type is that when high-energy particles collide with the lattice atoms of permanent magnets, they transfer energy to the primary dissociated atoms (PKA), causing a sudden increase in local lattice temperature, which is known as the thermal peak effect. When the local temperature exceeds the Curie temperature, a ferromagnetic-paramagnetic phase transition occurs in this region, and the magnetic moment arrangement becomes disordered. After cooling, a reverse magnetic domain core is formed and then grows into a reverse magnetic domain, resulting in a loss of macroscopic magnetic flux [85, 100, 106-108]. Another type is that irradiation can form defects such as vacancies, interstitial atoms, and dislocation rings in the lattice of permanent magnets. These defects can cause pinning or migration effects on the magnetic domain walls [84, 106, 109].

For Nd-Fe-B permanent magnets, the defects produced by irradiation will puncture the magnetic domain walls, resulting in a slight increase in coercive force. When the defect density is too high, it will form reverse magnetic domain nucleation sites, causing irreversible demagnetization. For Sm-Co permanent magnets, their closely packed hexagonal lattices make irradiation defects prone to annihilation. Therefore, the disturbance of the defect to the magnetic domain wall is much weaker than that of Nd-Fe-B. Sm-Co permanent magnets exhibit superior radiation resistance. The performance changes of different permanent magnets with respect to the irradiation dose is shown in Table 5.

Table 5 The performance of different permanent magnets changes with the irradiation dose.

Permanent magnet type	Maximum irradiation dose	Type of irradiation	Core irradiation results
Nd-Fe-B	10^{15}n/cm^2	Fast neutron	At 77°C, the residual magnetism loss is approximately 5%, and at 153°C, it is approximately 10% [84].
Nd-Fe-B / Sm-Co	$1.4 \times 10^{16}\text{n/cm}^2$		The residual magnetism loss of Sm-Co is less than 0.5%, while that of Nd-Fe-B is approximately 5% [88].
Nd-Fe-B	700kGy	Proton	The magnetic properties completely disappeared [90].
Sm-Co	100MGy		Maintain a low level of magnetic performance loss [90].
Nd-Fe-B	2.6MGy	Electron beam	The magnetic flux loss is 9% [94].
Sm-Co	1.73MGy		The magnetic flux loss is less than 0.4% [94].
Nd-Fe-B	2MGy	γ rays	The magnetic flux loss is approximately 2.5% [95].
Sm-Co	10MGy		Almost no degradation of magnetic properties [99].
Nd-Fe-B	18MGy	Neutron + Proton + Photon + Electron beam	Approaching complete demagnetization [104].
Sm-Co	20MGy		The magnetic loss is less than 5% [104].

The irradiation tolerance of permanent magnets is jointly determined by the intrinsic properties of the material, irradiation parameters and the external environment. The core influencing factors can be classified into the following categories, as shown in Table 6.

Table 6 The core influencing factors of the irradiation response of permanent magnets.

Influencing factors		Action rules
Intrinsic properties of the material	Coercive force	Coercive force is the core indicator of the radiation resistance of permanent magnets [91, 110]. The magnetic domain walls of samples with high coercive force are more difficult to migrate. An increase in coercive force may lead to better radiation resistance.
	Curie temperature	The higher the Curie temperature, the higher the threshold of magnetic moment disorder caused by thermal spikes [95, 98]. The Curie temperature of Sm-Co is much higher than that of Nd-Fe-B, so its radiation resistance performance is significantly better.
	Grain size	Fine-grained structure can enhance the binding effect of magnetic domain walls [87] and improve radiation resistance.
	Shape	The shape effect of permanent magnets can significantly affect the irradiation response [88, 95, 104].
Irradiation parameters	Type of irradiation	The damage capabilities of different irradiation sources can be roughly ranked as neutrons > protons/heavy ions > electrons > γ rays [85, 94, 95, 105].
	Irradiation dose	Magnetic flux loss usually increases with the increase of irradiation dose and shows a logarithmic dependence [91]. A high dose rate will exacerbate the damage [85].
	Irradiation temperature	High temperature caused by irradiation will reduce the magnetic anisotropy of permanent magnets and intensify irradiation demagnetization [84, 108].
	Post-processing technology	Post-treatment processes such as annealing and reverse magnetic field stabilization can enhance the radiation resistance of permanent magnets [110].
External environment	Re-magnetization	Most irradiation demagnetization can restore magnetic properties through re-magnetization [91, 92], indicating no permanent crystal damage. For irreversible damage, local magnetization or magnet replacement can be adopted for maintenance.

Existing research has clarified the damage laws and core mechanisms of permanent magnets caused by different irradiation sources, providing theoretical support for the selection and design of permanent magnets in irradiation environments. However, there are few studies on the influence of irradiated permanent magnets on the sealing of MF. Moreover, the quantitative prediction model of

irradiation demagnetization and extreme environment experiments still need to be broken through, making it difficult to accurately predict the performance degradation under actual service conditions. Future research can focus on constructing multi-physics field-coupled irradiation damage models, achieving precise prediction of the service life of permanent magnets, developing radiation-resistant modification technologies, and promoting the engineering application of highly radiation-resistant permanent magnets and so on.

4 Research progress on the properties of lubricants after nuclear irradiation

Lubricants are lubricating media used to reduce the frictional resistance of friction pairs and slow down wear. They are widely used in moving parts such as bearings, gears and lead screws. Their performance determines the reliability and service life of the equipment operation. Nuclear industry equipment is exposed to a strong irradiation environment during operation. Lubricants may undergo liquefaction, solidification, acidification, gas release, etc. under high-energy irradiation, leading to equipment failure or shutdown. Therefore, the irradiation sensitivity of lubricants is particularly crucial. Lubricants can be roughly classified into organic wet lubricants and inorganic dry film lubricants according to their forms. The chemical composition and structural differences of various types of lubricants result in significant distinctions in their irradiation tolerance characteristics [111]. Organic wet lubricants are often used in MFS. In recent years, scholars have conducted in-depth research on the tribological behavior and lubrication performance evolution of commercial lubricants in different irradiation fields, and have made remarkable progress. The research on the evolution of lubricant performance under irradiation has gradually deepened from macroscopic phenomenon observation to microscopic mechanism analysis. Radiation resistance modification technology has also evolved from single-component adjustment to multi-scale structural design.

4.1 Irradiation response of lubricants

Arakawa et al. [112] conducted chromatographic measurements on the emitted gases of 20 commercial lubricating oils after irradiation. The samples were irradiated with ^{60}Co - γ rays under

vacuum. As shown in Table 7, it was the irradiation venting product of the lubricating oil base oil. By measuring the total gas release of the lubricating oil base oil at 100Mrad (1MGy) and 1000Mrad (10MGy) under vacuum, the approximate order of the total gas release can be obtained as refined mineral oils > esters > neutral oils > alkyl aromatics > polyphenylene ethers (PPE). The volume of gas evolution increased with the increase of dosage. However, at high doses, mineral oils tended to stabilize, while esters and aromatic compounds increased linearly. Aromatic rings and long-chain alkyl groups can enhance irradiation stability. Therefore, aromatic lubricants with low gas release can be used in high-dose irradiation environments.

Table 7 Irradiation outgassing products of lubricating oil base oil. Adapted from Ref. [112]

Types of lubricating oil base oils	Irradiation exhalation products
Refined mineral oils	Hydrogen is the main product, while methane, ethane and ethylene are secondary products
Esters	Hydrogen is the main product, while carbon monoxide and carbon dioxide are secondary products
Neutral oils	Methane and hydrogen
Alkyl aromatics	Hydrogen is the main product, while methane, ethane and ethylene are secondary products
PPE	Hydrogen is the main product, with trace amounts of benzene and xylene

Stodola et al. [113] conducted electron irradiation on mineral oil, synthetic oil, hydraulic oil and base oil, with the dose range covering mGy to kGy. It was found that the viscosities of synthetic oil and hydraulic oil decreased significantly with the increase of irradiation dose. The reduction in molecular weight was attributed to the breakage of the carbon-hydrogen chain. The viscosity of mineral oil increased by $19.2\text{mm}^2\cdot\text{s}^{-1}$ at a high dose of 223.59kGy, possibly due to the formation of

gel particles through molecular cross-linking. The viscosity fluctuation of the base oil was relatively small, indicating that the additive had a limited influence on the irradiation response.

Wu et al. [114] evaluated the state of dimethyl silicone oil lubricant after irradiation by γ rays at high dose rate of 2.5kGy/h and low dose rate of 0.6kGy/h. After irradiation aging of dimethyl silicone oil, radiation decomposition gases H_2 , CO and CO_2 were produced, and O_2 was consumed, indicating that the material had undergone oxidation. The mass and kinematic viscosity of dimethyl silicone oil both increased after irradiation aging. It was found that under long-term irradiation at a low dose rate and short-term irradiation at a high dose rate, materials with the same cumulative dose would exhibit different irradiation effects.

Yang et al. [115] investigated the influence of 110keV electron beam irradiation on the tribological properties of commercial space grease under vacuum conditions. The sample contained PFPE base oil and polytetrafluoroethylene (PTFE) additives. Through mass spectrometry analysis, it was found that during the electron irradiation process, the PFPE grease decomposed to generate COF_2 gas, low-molecular-weight perfluoroethers and acidic fluoride groups. It indicated that electron irradiation could cause the cleavage of the C-O bond in the acetal unit ($-O-CF_2-O-$) and form free radicals under ionization. Free radicals were unstable and react to form acidic fluoride groups ($-COF$), simultaneously releasing low-molecular-weight gas products. The friction coefficient of the 2Cr13 steel friction pair increased, and the wear amount increased by one order of magnitude. Obvious pitting corrosion appears on the worn surface, which was caused by fluoride corrosion. In addition, the chemical degradation and evaporation of the base oil jointly lead to the loss of oil in the grease and a decline in the load-carrying capacity of the lubricating film. Ultimately, it leads to intensified friction and wear, and a decline in lubrication performance.

Li et al. [116] studied the structural stability and performance variation law of straight-chain PFPE grease under γ irradiation. The base oil of this PFPE grease had a molecular weight of 18,000, and the thickener was PTFE. Before and after irradiation, FTIR spectra showed no new peaks, indicating that

the ether bond was not broken and no new functional groups were generated. Meanwhile, there were no significant changes in the physical and chemical properties of the grease, such as element content, 1/4 working penetration, high-temperature resistance, extreme pressure performance, and corrosiveness, before and after irradiation. It is demonstrated that the straight-chain PFPE grease exhibits excellent radiation resistance stability under 100kGy conditions.

Ferrari et al. [117] selected nine types of commercial greases, as shown in Table 8, and subjected them to mixed neutron and γ irradiation ranging from 0.1~9MGy. According to the changes in the penetration of samples after irradiation, the nine types of lubricating greases could be classified into the following three categories: the rapid degradation group (Lube-1, Lube-3, Lube-7, Lube-9), the medium-speed degradation group (Lube-6, Lube-2, Lube-4), and the stable group (Lube-5, Lube-8). Irradiation causes structural fracture of the grease thickener and destroys the gel structure. Some greases have base oils with similar chemical compositions, but due to the use of different thickeners, they exhibit completely different effects.

Table 8 Data of nine types of grease. Adapted from Ref. [117, 118]

Sample number	Lube-1	Lube-2	Lube-3	Lube-4	Lube-5	Lube-6	Lube-7	Lube-8	Lube-9
Base oil			Mineral oil			Hydrocarbon	PFPE	PPE	Polyglycol
Thickener	Li	Mixed	Li/Ca	Li	Polyurea	-	PTFE	PC	Li

Ferrari et al. [118] further explored and found that Lube-5 grease remained stable at 4.4MGy, only showed slight hardening at 8.9MGy, and hardened to the point where the penetration could not be measured at 13.3MGy. And the Lube-8 grease remained stable at approximately 12MGy, only slightly softening. It is one of the types that can withstand the highest irradiation dose. Considering the cost, this most expensive radiation-resistant product can only be used in high-radiation areas.

Senajova et al. [10] stated that the operation of the accelerator at CERN generates a variety of high-energy particles such as photons, electrons, and neutrons. The irradiation dose absorbed by mechanical components mainly comes from high-energy neutrons and photons, with a typical cumulative dose ranging from 0.1~15MGy. The results showed that among different types of base oils,

PPE was the most radiation-resistant, while silicone oil had the highest irradiation sensitivity.

Irradiation degradation affects friction behavior by altering the properties of the lubricating film, including boundary lubrication failure, increased friction coefficient, and grease liquefaction, etc.

4.2 Irradiation damage mechanism of lubricants

Existing research indicates that the irradiation performance of organic wet lubricants is jointly determined by the base oil and additives, and the tolerated dose is positively correlated with the stability of the molecular structure. The chemical composition of organic wet lubricants contains carbon and hydrogen or organic molecules with heteroatoms, and their irradiation damage is mainly caused by ionization. When high-energy particles pass through lubricants, they transfer energy to molecules, causing them to be excited or ionized, generating a large number of active free radicals and triggering two types of chemical reactions. As shown in Fig. 8. One is the breakage of molecular chains. Chemical bonds such as C-C, C-O, and C-H in organic molecules break due to energy overload, generating gases such as small-molecule hydrocarbons (CH_4 , C_2H_6), H_2 , CO, and CO_2 , while also producing low-molecular-weight polymer fragments [112, 114, 115]. The chain-breaking reaction directly leads to a decrease in the viscosity of the lubricant and an increase in its volatility. Sometimes, with the release of a large amount of gas, it can also cause a sudden increase in pressure in the sealed system, threatening the safety of the equipment. Another type is molecular chain cross-linking. The free radicals generated by irradiation promote the formation of new covalent bonds between molecular chains, constructing a network cross-linked structure [117, 118]. Cross-linking reactions can cause the lubricant to lose its fluidity and prevent the formation of a continuous lubricating film. These further triggers dry friction wear of the friction pair. In addition, the synergistic damage caused by irradiation and oxidation is also one of the important triggers for the failure of organic wet lubricants. Irradiation can enhance molecular activity and accelerate the adsorption and reaction of oxygen molecules. The generation of acidic substances such as carboxylic acids and peroxides leads to an increase in the total acid value of the lubricant and simultaneously corrodes the surface of the metal friction pair [112, 117].

The comparison of the performance changes of different organic wet lubricants with respect to the irradiation dose is shown in Table 9.

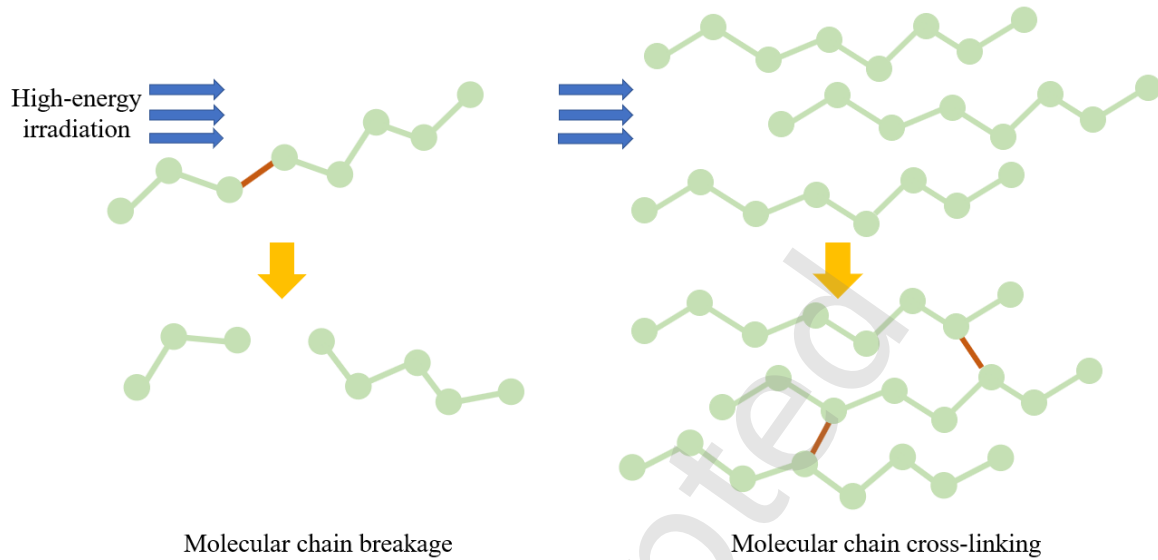


Fig. 8 The influence of irradiation damage on lubricants.

Table 9 The performance of different organic wet lubricants changes with the irradiation dose.

Lubricant type	Maximum irradiation dose	Type of irradiation	Core irradiation results
Mineral oil	223.59kGy	Electron beam	The viscosity increased from $12.5 \text{ mm}^2 \cdot \text{s}^{-1}$ to $19.2 \text{ mm}^2 \cdot \text{s}^{-1}$ [113].
PFPE lubricating grease	$1 \times 10^{16} \text{ e/cm}^2$		The friction coefficient of the 2Cr13 steel friction pair increased from 0.12 to above 0.45, and the wear amount increased by one order of magnitude [115].
Dimethyl silicone oil	500kGy	γ rays	At 300kGy, it changes from a liquid state to a gel-like state, and the viscosity increases by 700% at 100°C . At 500kGy, it becomes a jelly-like state and completely loses its usability [114].
PFPE lubricating grease	100kGy		The physical and chemical properties of the grease did not show any significant changes [116].
PPE lubricating grease	11.4MGy		Maintain stability and only slightly soften [118].

Polyurea thickened mineral oil	13.3MGy	Neutron + γ rays	At 8.9MGy, only slight hardening occurred, while at 13.3MGy, the hardening reached a point where the indentation measurement could no longer be measured [118].
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Macha et al. [111] reviewed the damage mechanism of irradiation on lubricants, the changes in material properties, and the research progress of radiation-resistant lubrication systems. The behavioral differences of dry film lubricants, lubricating oils and greases under ionizing radiation were analyzed emphatically. The damage of irradiation to lubricants was a multi-mechanism coupled process, involving atomic displacement, lattice defects, chemical degradation and structural reconstruction, etc. In dry film lubricants, the friction coefficient of PTFE significantly increased at the kGy dose level, and surfaced cracking and peeling occur at the MGy dose level. Molybdenum disulfide was prone to oxidation and failure. Graphite could self-repair through thermal annealing at doses of kGy, and it might still maintain its lubricating properties at doses of MGy. Carbon-based nanomaterials such as graphene and nano-diamonds exhibited excellent radiation resistance potential.

Through the above research, it can be found that the degradation form of lubricants after irradiation is specifically manifested as follows: organic wet lubricants cause viscosity changes, acid value increases and gas release through chain breaking and cross-linking reactions. Inorganic dry film lubricants can cause atomic shifts and lattice defects, leading to crystallization and oxidation. The degree of its influence depends on the total dose of high-energy irradiation. Moreover, the energy transfer methods of different irradiations vary significantly, resulting in different damage effects. Photons and electrons mainly cause ionization damage, which significantly disrupts organic wet lubricants. Neutrons and heavy ions have both ionization and displacement damage, which have a greater impact on inorganic dry film lubricants. These achievements provide an important basis for evaluating the irradiation stability of lubricants and their application selection. Future research can focus on dose threshold verification in mixed irradiation fields and long-term exposure experiments in irradiation environments. And the influence of the combined effect of multiple factors such as temperature, vacuum and load on the irradiation effect. This will further enhance the reliability and

safety of nuclear industry equipment to support the development of advanced nuclear energy technologies.

5 Research progress on the properties of magnetic fluid sealings after nuclear irradiation

MFS, as a sealing technology that combines advantages such as zero leakage, self-healing, and low friction, is shown in Fig. 1. It has broad application prospects in fields related to irradiation environments such as the nuclear industry, neutrino detection, and aerospace. γ rays, neutrons and other substances in the irradiation environment can affect the core components of MFS, leading to degradation or even failure of sealing performance. In previous studies, scholars have conducted extensive research on the dispersive irradiation performance of the three core components of sealing systems: MF, permanent magnets, and lubricants. Based on the relevant research results in recent years, this chapter takes the MFS after high-energy irradiation as the research object. Summarize the evolution law of its overall sealing performance systematically and deeply analyze the performance attenuation characteristics and coupling effects of each key component. This chapter reviews the influence of irradiation on the key components of MFS, the sealing performance under different irradiation scenarios, and the optimization strategies. At the same time, the research progress of the author's research group is also be introduced. To provide a reference for the research and development and application of MFS technology in extreme irradiation environments.

5.1 Irradiation response of MFS and their component couplings

Xiao et al. [119] studied the effects of magnetic devices under irradiation conditions. Neutrons could cause permanent damage to magnetic materials, mainly because the interaction between high-energy neutrons and the materials led to a displacement effect of lattice atoms. γ irradiation could cause ionization effects, which could cause instantaneous interference to materials and devices, and even permanent damage. Static experiments had demonstrated that when the neutron flow rate reached 10^{18} neutron/cm² and the γ irradiation dose rate was 10^8 rad/s (1MGy/s), the performance of magnetic devices did not change significantly.

Yu [120] explored the feasibility of using MFS in the primary circuit equipment of sodium-cooled fast reactors. As the preferred reactor type of the fourth-generation advanced nuclear energy system, the dynamic seal on the reactor vessel of the sodium-cooled fast reactor was the key factor affecting the overall sealing performance. Considering the working conditions where the primary circuit sealing medium of the fast reactor is argon gas, the operating pressure is low, the rotational speed is not high, and the temperature and radioactivity levels are relatively low, the MFS has good applicability. Especially in the application of sodium pumps, there have been development cases of oil-free sodium pumps in India.

Zhang et al. [121] explored the application research of MFS in aerospace equipment under severe environments such as high vacuum, high irradiation, and high and low temperature thermal cycles. Due to the excellent properties of MFS such as zero leakage and self-healing, its application feasibility in extreme space environments is constantly increasing.

Liu et al. [122] studied and designed an ultra-clean and highly reliable MFS system. Through the synergistic effect of multi-stage MFS, secondary sealing with magnetic grease and intelligent protection auxiliary system. Ultimately, the content of radioactive elements in the sealed cavity should be less than 10^{-15} g/g. MFS has become a key dynamic sealing technology in neutrino detection devices, providing new ideas for solving the problem of ultra-clean sealing in irradiation environments. However, there is still a lack of specific research on the impact of irradiation doses on its performance.

Yoshida et al. [123] irradiated MFS for vacuum rotary actuators with a total dose of 0.7~1.8Gy of γ -ray sources. Unlike Fig. 1, in this MFS, instead of rectangular pole teeth, inclined triangular pole teeth were adopted, as shown in Fig. 9. The degradation of MF was tested by observing the formation of MF spikes at the pole teeth and measuring the changes in viscosity, surface tension and colloidal stability of MF. No significant changes were observed.

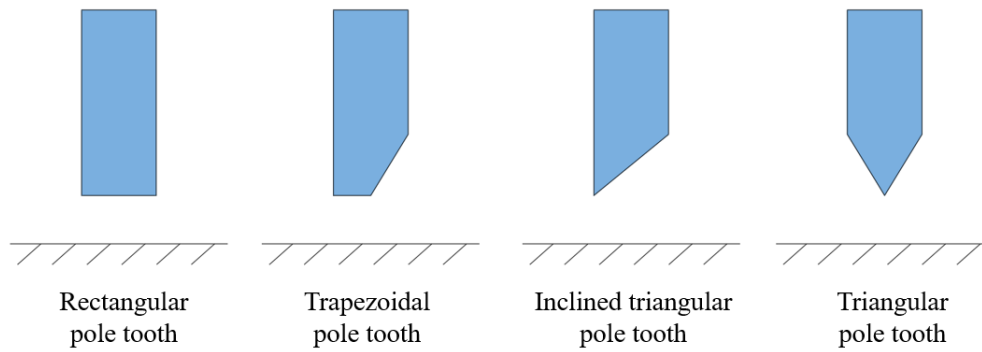


Fig. 9 Schematic diagram of the structures of different pole tooth in MFS.

Shinichi et al. [124] studied the irradiation characteristics of the T0 chopper assembly. Irradiation experiments with doses of 1, 10 and 100kGy were conducted on the key components of the T0 chopper using the ^{60}Co - γ ray source of the Japan Atomic Energy Agency. Simulate the cumulative irradiation effect in actual operation, the experimental results are shown in Table 10. This research provides experimental basis for the material selection and protective design of precision moving parts under strong irradiation fields.

Table 10 Irradiation response of the T0 chopper component. Adapted from Ref. [124]

Irradiated object	Performance after irradiation
Bearing grease (PTFE thickener and PTFE base oil)	Within the range of 1~100kGy, the friction coefficient of the irradiated samples decreased to 82~75% of that of the unirradiated samples. The acceptable load of the grease after irradiation decreased to approximately 80%. The bearing life was shortened by half.
MFS	The viscosity coefficients and evaporation rates of the unirradiated samples and the 100kGy irradiated samples were both $0.3\text{N}\cdot\text{s}/\text{m}^2$ and $1.2\times 10^{-4}\text{g}/\text{cm}^2\cdot\text{h}$. The sealing performance was not affected.
Mechanical components	Under 100kGy γ irradiation, there was no significant degradation in the key properties of the material, and the service life met the maintenance requirement of one year.
Semiconductor components	There was irradiation damage, and effective irradiation protection was required.

Furthermore, Simos et al. [125] tested the operational performance of MFS under irradiation of 0.2, 2, and 20MGy. Table 11 summarizes the performance degradation laws of MFS at different

irradiation doses. It was found that the device performance was stable at a dose of 0.2MGy. Although there was MF damage at a dose of 2MGy, it could still operate, but it completely failed at a dose of 20MGy. It was believed that the main problem of seal leakage under irradiation was the degradation of the fragile components of MFS caused by irradiation.

Table 11 The performance degradation law of MFS under different irradiation doses. Adapted from Ref. [125]

Irradiation dose	0.2MGy	2MGy	20MGy
State of permanent magnet	Nd ₂ Fe ₁₄ B, no significant demagnetization	Sm ₂ Co ₁₇ , no significant demagnetization	Sm ₂ Co ₁₇ , still maintain stability
State of MF	The properties of MF had not deteriorated.	The MF showed signs of damage but had not lost its sealing function.	The viscosity of MF increased significantly, particles aggregated, and base carrier fluid decomposed.
Vacuum sealing performance	There was no leakage at both static and dynamic (5000 rpm), the leakage rate $\approx 23 \times 10^{-3} \text{ Pa} \cdot \text{L/s}$.	The dynamic leakage rate increased by 37%, that is $\leq 15 \times 10^{-3} \text{ Pa} \cdot \text{L/s}$.	There is a serious leakage of MF.
Torque performance	The initial starting torque was relatively high, but after the rotational cycle, it dropped to a level close to the unirradiated level, with no significant change in the rotational torque.	The starting torque increased by 70% compared with the unirradiated sample, while there was no significant change in the rotational torque.	Torque testing cannot be conducted.

In recent years, MFS technology has developed rapidly, but there are relatively few reports on the application of MFS in nuclear irradiation environments. Existing studies have clearly demonstrated the feasibility of MFS under low-dose irradiation. However, the mechanism of action of high-dose and mixed irradiation still needs to be further explored. Moreover, most of the existing studies are limited

to the independent performance analysis of a single component, while ignoring the system characteristics of the multiphase coupling in MFS, including the magnetic field, fluid and solid. The correlation mechanism between the performance variation of components under irradiation environment and the overall sealing reliability has not yet been established. It is difficult to support the full life cycle design and evaluation of sealing devices under extreme irradiation conditions. Future research can focus on the following aspects: conducting a comprehensive analysis of how the deterioration of MF, permanent magnets, and lubricants collectively leads to the failure and performance degradation of the sealing system. Establish multi-field coupling simulation models to accurately predict the degradation law of sealing performance under the combined effect of irradiation, temperature, and magnetic field. The key point is to clarify the influence path of performance coupling between MFS components on the overall service performance of the sealing system. Carry out long-term irradiation tests inside the reactor to verify the service life of the sealing system in the actual nuclear industry environment. It provides theoretical basis and data support for the structural optimization, material selection and reliability improvement of MFS in high-energy irradiation environments.

5.2 Relevant research of author's research group

The research group of authors has been dedicated to exploring the irradiation damage mechanism of MFS. They have conducted studies on the engineering applications of MFS under nuclear irradiation conditions and have achieved many results.

Due to the poor stability of traditional MF such as water-based and kerosene-based ones in strong radiation environments, the research group chose PFPE with high bond energy C-F bonds as the base carrier fluid to prepare radiation-resistant MF. Using perfluoropolyether carboxylic acid (PFPE-CA) surfactant that is similar in solubility to the base carrier fluid, they enhanced the stability of the MF. The prepared MPs and MF were subjected to γ irradiation at doses of 0.1, 1, 3, and 10MGy.

The appearance of $\text{Fe}_3\text{O}_4@\text{PFPE-CA}$ MPs before and after different doses of irradiation were observed. The pictures were taken as shown in Fig.10. It can be seen that there were no obvious changes.



Fig.10 Pictures of $\text{Fe}_3\text{O}_4@\text{PFPE-CA}$ MPs before and after irradiation with different doses.

The FTIR spectra of PFPE-CA and $\text{Fe}_3\text{O}_4@\text{PFPE-CA}$ before and after strong nuclear radiation were tested, as shown in Fig.11.

As can be seen from Fig.11(a), before and after different doses of irradiation, the ether bond C-O-C asymmetric stretching vibration peak of PFPE-CA appears at around 1128 cm^{-1} , indicating the presence of fluorine-containing ether chain structure in PFPE-CA. The C-F bending vibration peak at around 981 cm^{-1} and the C-F stretching vibration peak at around 1230 cm^{-1} indicate that there are a large number of C-F bonds in PFPE-CA, making it have extremely strong hydrophobic and hydrophobic properties, chemical stability and high-temperature resistance. At 0.1MGy, 1MGy, 3MGy, and non-irradiated, the C=O stretching vibration peak appears at around 1774 cm^{-1} , confirming the presence of carboxylic acid groups in PFPE-CA. When the cumulative irradiation dose reaches 10MGy, the C=O stretching vibration peak shifts from 1774 cm^{-1} to 1886 cm^{-1} , showing a blue shift. This may be due to the degradation caused by irradiation, which leads to the dissociation of the carboxylic group structure in PFPE-CA, generating by-products such as carbon fluoride (COF_2). The vibration of the C=O group in these by-products produces a new peak at around 1886 cm^{-1} .

From Fig.11(b), it can be seen that before and after irradiation with different doses, $\text{Fe}_3\text{O}_4@\text{PFPE-CA}$ all exhibited a strong lattice vibration peak of Fe-O at around 582 cm^{-1} , confirming that the Fe_3O_4 MPs remained intact. The asymmetric stretching vibration peak of the ether bond C-O-C at around

1137 cm^{-1} verified the integrity of the perfluoropolyether chain. The C-F bending vibration peak at around 983 cm^{-1} and the C-F stretching vibration peak at around 1238 cm^{-1} indicated that the perfluorinated ether chain was covering the surface of MPs. Compared with Fig.9(a), the peaks at 1774 cm^{-1} and 1886 cm^{-1} of the free carboxylic acid disappeared, while the symmetric and asymmetric vibration peaks of carboxylate-COO- at 1429 cm^{-1} and 1651 cm^{-1} appeared, indicating that PFPE-CA formed a bond with the hydroxyl functional group-OH on the surface of Fe_3O_4 through the carboxyl functional group-COOH, removing one molecule of water H_2O to form carboxylate-COO-, which is a chemical adsorption. The O-H stretching vibration peak at around 3415 cm^{-1} indicated that water was adsorbed on the surface of MPs. Thus, it can be confirmed that PFPE-CA surfactant was still modified on the surface of the Fe_3O_4 MPs before and after irradiation with different doses.

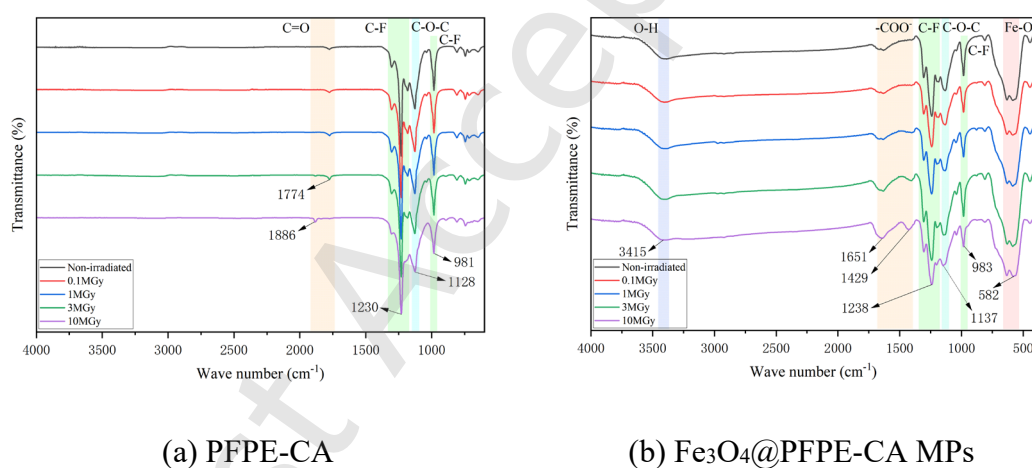


Fig.11 FTIR of PFPE-CA and Fe_3O_4 @PFPE-CA MPs before and after different doses of strong irradiation.

The magnetic properties of Fe_3O_4 @PFPE-CA MPs and MF before and after different doses of irradiation were analyzed using a vibrating sample magnetometer. The magnetization intensity was measured and the magnetization curves were plotted, as shown in Fig.12. The MPs themselves possess a permanent magnetic moment. However, in the absence of an external magnetic field, the orientation of MPs magnetic moments is random, resulting in no macroscopic magnetism. Under the influence of an external magnetic field, the MPs magnetic moments gradually align along the direction of the

external magnetic field, causing MPs and MF being measured to exhibit macroscopic magnetism. Moreover, the magnetization intensity increases with the increase of the external magnetic field. When the external magnetic field reaches about 5000Oe, it basically reaches saturation. Further increasing the external magnetic field, the magnetization intensity of MPs and MF does not increase significantly. And regardless of whether they are irradiated or not, the magnetization curves of MPs and MF are all S-shaped, indicating that the prepared MPs and MF are superparamagnetic before and after different doses of irradiation.

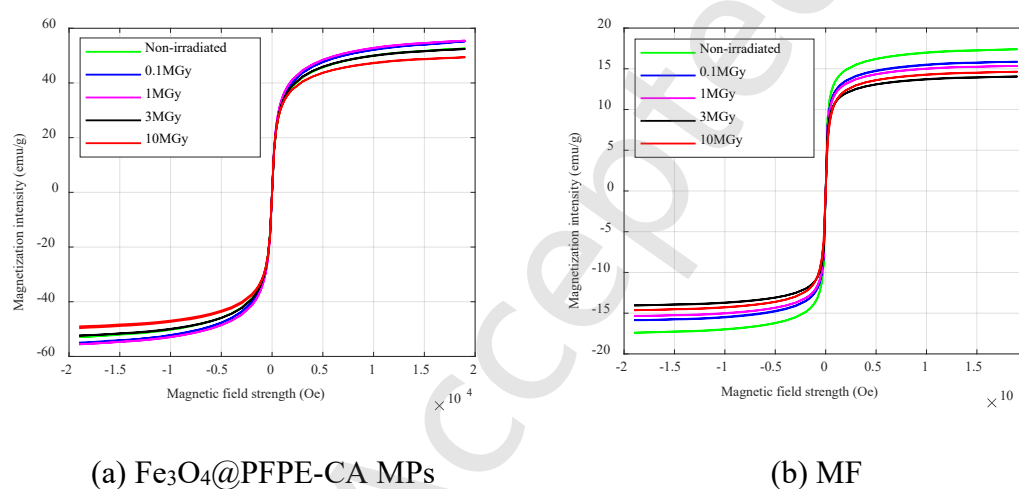


Fig.12 Magnetization curves of MPs and MF before and after exposure to different doses of intense radiation.

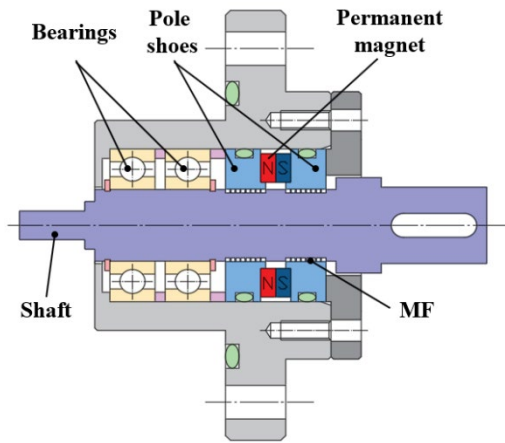
The magnetic properties of MPs and MF before and after different doses of irradiation are listed in Table 12. The relationship of the saturation magnetization intensity of the magnetic particles before and after different doses of irradiation is as follows: 1MGy > 0.1MGy > non-irradiated > 3MGy > 10MGy. It is speculated that irradiation at doses of 0~1MGy can improve the crystallinity of MPs, leading to local grain growth and thereby increasing the saturation magnetization intensity. However, at doses of 1~10MGy, the accumulated irradiation defects may cause the crystal structure to be disrupted, destroying the long-range order of the lattice, and thus reducing the saturation magnetization intensity. It is calculated that the change of the saturation magnetization intensity of MPs compared to the unirradiated state after different doses of irradiation does not exceed 6.10%.

The relationship of the saturation magnetization intensity of the MF before and after different doses of irradiation is as follows: non-irradiated > 0.1MGy > 1MGy > 10MGy > 3MGy. As the irradiation dose increases, the saturation magnetization intensity of the prepared MF shows a pattern of first decreasing, reaching the lowest point at 3MGy, and then slightly recovering at 10MGy. It is speculated that during the 0~3MGy, the deteriorating effect of irradiation dominates, and the PFPE based carrier fluid undergoes slight degradation, causing particle agglomeration, thereby reducing the saturation magnetization intensity. From 3~10MGy, the PFPE based carrier fluid may have undergone cross-linking polymerization under irradiation, enhancing the colloid stability and inhibiting further agglomeration. This is conducive to the recovery of magnetism and slightly increases the saturation magnetization intensity. It is calculated that the change of the saturation magnetization intensity of MF compared to the unirradiated state after different doses of irradiation does not exceed 19.3%. The above tests have demonstrated that the prepared MPs and MF possess excellent radiation resistance, which supports their potential application in the nuclear industry environment.

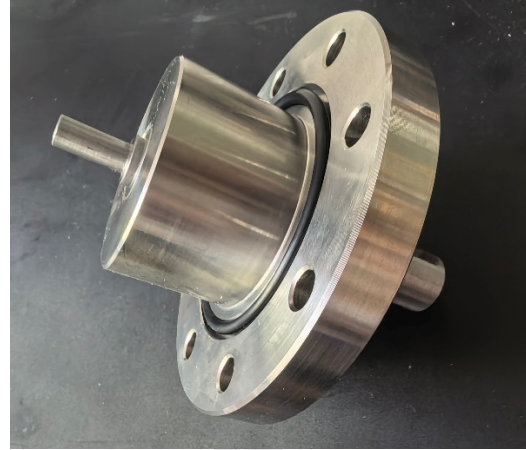
Table 12 The magnetic properties of MPs and MF before and after different doses of irradiation.

Irradiation dose	Saturation magnetization intensity (emu/g)	
	Fe ₃ O ₄ @PFPE-CA MPs	MF
Non-irradiated	52.76	17.406
0.1MGy	55.27	15.860
1MGy	55.55	15.341
3MGy	52.40	14.047
10MGy	49.54	14.635

The MFS structure as shown in Fig.13 was designed. For the MF, the irradiation-resistant MF prepared above was used. For the permanent magnets in MFS, the existing Sm₂Co₁₇ ring-shaped magnet with the maximum coercivity of grade 33H was employed. For the bearing lubricating grease in MFS, the PPE-based lubricating grease with the good irradiation resistance was used.



(a) Structural diagram



(b) Physical picture

Fig.13 The designed MFS for irradiation environments.

The designed MFS, after processing, cleaning and assembly, has reliable sealing performance in the nuclear irradiation environment. Eventually, it was applied in the post-processing equipment for spent fuel in nuclear power plants, fully meeting the sealing requirements of the equipment and achieving excellent application results. This provided theoretical and experimental support for the engineering application of MFS in the nuclear irradiation environment.

6 Conclusion

This paper systematically reviews and summarizes the research on the core components and overall performance of MFS in nuclear irradiation environments in recent years. The irradiation evolution characteristics and mechanisms of three key components, namely MF, permanent magnets, and lubricants, as well as the overall performance of the seal, have been clarified. Meanwhile, the limitations of the current research were analyzed and the future research directions were pointed out. The following main conclusions are drawn:

(1) Under high-energy irradiation, MF will undergo weak bond breakage between surfactant and base carrier fluid, as well as agglomeration and sedimentation of MPs. This further leads to a decrease in saturation magnetization and a reduction in material stability.

(2) Irradiation demagnetization of permanent magnets is a complex process involving multiple factors. There are two core mechanisms. The thermal peak effect and the defect pinning effect.

(3) Under high-energy irradiation, the organic wet lubricants undergo chain breakage and cross-linking caused by ionization, while the inorganic dry film lubricants are confronted with crystal structure destruction caused by displacement damage.

(4) Current research mostly focuses on the independent performance analysis of a single sealing component, generally ignoring the multiphase coupling characteristics of magnetic field, fluid and solid in MFS. The correlation mechanism between the performance variation of components under irradiation environment and the overall sealing reliability has not yet been established. Moreover, there are relatively few application research reports on MFS in nuclear irradiation scenarios. It is difficult to predict the evolution of the frictional behavior of the sealing system under extreme irradiation conditions, as well as to conduct the full life cycle design, assessment and maintenance of the system.

Based on these requirements for the sealing system proposed by the research team of authors for the post-processing equipment of spent nuclear fuel, they have conducted in-depth research over the years. They prepared irradiation-resistant MPs and MF, subjected them to γ irradiation at doses of 0.1, 1, 3, and 10MGy, and tested their performance before and after irradiation. They revealed the mechanisms of the effects of different doses of nuclear irradiation on the prepared MPs and MF. They invented MFS systems that can withstand an irradiation dose of up to 10MGy and successfully applied them to nuclear industrial equipment. Provide comprehensive theoretical basis and data support for the engineering application of MFS in high-energy irradiation scenarios.

Regarding the current research status, future breakthroughs need to be made from multiple dimensions:

Firstly, it is necessary to systematically explore the interaction patterns of high-temperature irradiation coupling, irradiation dose gradients, and mixed ionizing radiation fields on the frictional behavior of MF. A platform for in-situ spectroscopy and real-time microscopic morphology

characterization during the irradiation process should be established. Dynamic irradiation aging experiments should be conducted to quantify the performance degradation patterns of MF under long-term irradiation and cyclic conditions. A performance evolution model capable of predicting the long-term service life should be developed.

Secondly, it is necessary to establish a quantitative prediction model for the irradiation demagnetization of permanent magnets that can adapt to different irradiation types, temperatures, and stress coupling conditions. Quantify the impact of the deterioration of the magnetic performance of the permanent magnet on the magnetic field distribution in the sealing gap of MFS. Clarify the collaborative failure mechanism between the demagnetization of the permanent magnet and the attenuation of the magnetic properties of MF, providing a calculation basis for the optimization design of the radiation-resistant in MFS magnetic circuit.

Thirdly, it is necessary to establish a standardized evaluation system for lubricants under multiple working conditions such as irradiation, high temperature, vacuum, and load, based on the actual operating environment of nuclear equipment. Different base oils and additives should be evaluated for their performance under combined extreme conditions. The evolution characteristics of friction and wear, critical failure irradiation doses, and temperature thresholds of the lubricants should be clarified. A stable lubrication system suitable for high-energy irradiation scenarios should be established.

Fourthly, it is necessary to clarify the multi-scale performance coupling mechanism of the entire component of MFS under irradiation conditions. Quantify the regulatory laws of the interaction between components on the sealing pressure-bearing capacity, leakage rate, and service life. Incorporate multiple physical field parameters such as magnetism, flow, heat, and irradiation to establish a comprehensive performance evaluation system for MFS under irradiation conditions. Achieve the prediction of the entire process of sealing failure risks.

Fifthly, it is necessary to develop a new type of radiation-resistant MFS and establish standardized design guidelines for radiation-resistant MFS. At the material level, optimize processes such as

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surfactant compounding and protective coating, and develop new MF materials with excellent radiation resistance. At the structural level, design radiation shielding layers, gradient magnetic field confinement structures, and heat insulation and buffering composite sealing structures, etc.

Sixthly, it is necessary to conduct prototype deployment and verification based on real nuclear systems such as nuclear reactors, irradiation test circuits, and nuclear energy equipment. This will provide comprehensive theoretical support and measured data references for the engineering implementation of MFS under high-energy irradiation.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

References

- [1]Wu H S, Li C X Global nuclear power is poised for takeoff [J]. Foreign Nuclear News, 2022, (11): 20-2 (in Chinese).
- [2]Abram T, Ion S. Generation-IV nuclear power: A review of the state of the science [J]. Energy Policy, 2008, 36(12): 4323-30.
- [3]Liu H J, Chen X L. Research status of spent fuel reprocessing technology at home and abroad [J]. Energy-saving technology, 2021, 39(04): 358-62 (in Chinese).
- [4]Liu H D. Research on Radiation Monitoring Methods and Evaluation of Nuclear Security Incidents in Spent Fuel Reprocessing Facilities [D]: Nanhua University, 2022 (in Chinese).
- [5]Ishikawa T. Radiation Doses and Associated Risk From the Fukushima Nuclear Accident: A Review of Recent Publications [J]. Asia-Pacific Journal of Public Health, 2017, 29: 18S-28S.

- [6] Jaunich M, Goral M, Wolff D, et al. Overview of metal seal tests performed at BAM and implications for extended interim storage [J]. *Kerntechnik*, 2020, 85(6): 440-3.
- [7] Liu M, Shi A Q, Li Z H, et al. Approach spent fuel from nuclear power plants [J] *Environmental economy*. 2020: 38-9 (in Chinese).
- [8] Qin Z, Fan F L, Tian W, et al. Research on Spent Fuel Recycling and Regeneration in Accelerator-driven Advanced Nuclear Energy Systems [J] *Nuclear chemistry and radiochemistry*. 2022: 489-99 (in Chinese).
- [9] Zheng W K, Liu Y, Wu G P, et al. The influence of gamma-ray irradiation on the properties of sintered materials for mechanical seals [J] *Journal of Tribology*. 2019: 381-6.10.16078/j.tribology.2018110 (in Chinese).
- [10] Senajova D, Dini D, Kershaw K, et al. Effect of radiation on lubrication performance and the consequences for mechanical equipment at CERN [J]. *Engineering Failure Analysis*, 2025, 167.
- [11] PODGORSK E B. *Radiation Oncology Physics: A Handbook for Teachers and Students* [M]. Vienna: International Atomic Energy Agency, 2005.
- [12] BIPM. *The International System of Units (SI)* [M]. 9th ed.: Bureau International des Poids et Mesures, 2019.
- [13] Sun X Z, Luo C H. The Current Situation and Analysis of Global Spent Fuel Reprocessing [J]. *Nuclear safety*, 2016, 15(02): 13-6 (in Chinese).
- [14] Forsberg C. Coupling the Back End of Fuel Cycles with Repositories [J]. *Nuclear Technology*, 2012, 180(2): 191-204.
- [15] Xu J, Wang W, Huang Q Y, et al. A Comparative Study on Spent Fuel Storage Methods of Nuclear Power Plants Abroad [J] *China Nuclear Power*. 2021: 901-9 (in Chinese).
- [16] Liu Q, Zhang H L, Han S Y. Research and Analysis on Spent Fuel Management Strategies of Foreign Nuclear Power Plants [J]. *China Electric Power Industry*, 2019, (04): 77-9 (in Chinese).

- [17] Lu W H. The Current Situation and Analysis of Spent Fuel Reprocessing in the World [J]. Jiangxi Chemical Industry, 2018, (06): 10-2 (in Chinese).
- [18] Duan H. Research on the New Indirect Maintenance Technology of Bench Transfer [D]: Nanhua University, 2018 (in Chinese).
- [19] Zhang C L, Dong Y C, Lv D, et al. Research and Implications on Equipment Corrosion in Spent Fuel Reprocessing Plants in Japan [J] Nuclear chemistry and radiochemistry. 2022: 575-88 (in Chinese).
- [20] Xiao R, Guo X F, Wang G K. The application of valves in spent fuel reprocessing technology [J]. Valve, 2022, (03): 240-4 (in Chinese).
- [21] Wei C, Xu S, Zou S, et al. Risk Analysis and Evaluation of Nuclear Security Radiation Events in Spent Fuel Reprocessing Plants [J]. Sustainability, 2023, 15(1).
- [22] Raj B, Chellapandi P, Mudali U K. Life Cycle Management of Structural Components of Indian Nuclear Reactors and Reprocessing Plants; proceedings of the 4th International Conference on Through-Life Engineering Services (TESConf), Cranfield Univ, Cranfield, ENGLAND, F 2015 Nov 03-04, 2015 [C]. 2015.
- [23] Li D C, Hao D. Research Progress on Key Issues of Magnetic Fluid Rotary Seals [J]. Journal of Vacuum Science and Technology, 2018, 38(07): 564-74 (in Chinese).
- [24] Wal K, Ostayen R, Lampaert S. Ferrofluid rotary seal with replenishment system for sealing liquids [J]. Tribology International, 2020, 150.
- [25] Liu J W, Li D C, Cai J C, et al. Theory analyses and experimental study on starting torque and seal capacity of field-control magnetic fluid seal [J]. Tribology International, 2024, 191.
- [26] Li D C. Theory and Application of Magnetic Fluid Sealing [M]. Beijing: Science Press, 2010 (in Chinese).
- [27] Rosensweig R E. Ferrohydrodynamics [M]. New York: Cambridge University Press, 1985.
- [28] Hotz G M. A survey of actuator shaft sealing techniques for extended space missions [R], 1972.

- [29] Wang Z Z. Research on Sealing Liquid Media with Magnetic Fluid [D]: Beijing Jiaotong University, 2019 (in Chinese).
- [30] Zhu S, Yang X, Huang Y, et al. Study on the Technology of Combined Seal of Magnetic Fluid Seal and Mechanical Seal; proceedings of the 4th International Conference on Sensors, Mechatronics and Automation (ICSMA), Zhuhai, PEOPLES R CHINA, F 2016 Nov 12-13, 2016 [C]. 2016.
- [31] Hao D, Li D C, Chen J W, et al. Theoretical analysis and experimental study of the characteristics of magnetic fluid seal with a large diameter at high/low temperatures [J]. International Journal of Applied Electromagnetics and Mechanics, 2018, 58(4): 531-50.
- [32] Parmar S, Ramani V, Upadhyay R V, et al. Design and development of large radial clearance static and dynamic magnetic fluid seal [J]. Vacuum, 2018, 156: 325-33.
- [33] Kubik M, Pavlicek D, Machacek O, et al. A magnetorheological fluid shaft seal with low friction torque [J]. Smart Materials and Structures, 2019, 28(4).
- [34] Chen Y, Li D, Zhang Y, et al. The Influence of the Temperature Rise on the Sealing Performance of the Rotating Magnetic Fluid Seal [J]. Ieee Transactions on Magnetics, 2020, 56(11).
- [35] Qiao Y J, Li D C, Ge Y, et al. Numerical and experimental investigation of magnetic fluid sealing under high-speed conditions [J]. Vacuum, 2025, 239.
- [36] Gao W M. Research on the Design and Performance of Magnetic Fluid Seals in Space Environments [D]: Beijing Jiaotong University, 2014 (in Chinese).
- [37] Cheng H H. Research on Magnetic Fluid Sealing of Reaction Vessel Equipment [D]: Beijing Jiaotong University, 2016 (in Chinese).
- [38] He X Z, Li D C, Wang H J. The influence of gravity on the sealing performance of magnetic fluid [J]. Journal of Vacuum Science and Technology, 2014, 34(11): 1160-3 (in Chinese).
- [39] Liu S J, Li D C, He X Z, et al. Structure design study of vacuum magnetic fluid seal [J]. Frontiers in Materials, 2022, 9.
- [40] Li D C, Li Y W, Li Z X, et al. Theory analyses and applications of magnetic fluids in sealing [J].

- [41] Rosensweig R E. Magnetic fluid seals: U.S. Patent 3620584, Nov.1971.
- [42] Moskowitz R. Dynamic sealing with magnetic fluids [J]. Tribology Transactions, 1975, 18: 135-43.
- [43] Li D C. Theory and Application of Magnetic Fluid [M]. Beijing: Science Press, 2003 (in Chinese).
- [44] Li D C. Magical magnetic fluid [M]. Beijing: Science Press, 2016 (in Chinese).
- [45] Yang J L, Huang W. A brief introduction to the progress of magnetic fluid lubrication technology [J]. Surface technology, 2017, 46(06): 61-8 (in Chinese).
- [46] Wang X Y, Zhao Y, Liu H C, et al. Influence of external magnetic field on the tribological performance of magnetic fluids in different lubrication regimes [J]. Friction, 2025, 13(7).
- [47] Li L, Guo Y Q, Qi Z Q, et al. The sealing pressure variance originated from volume of ferrofluids in magnetic fluid seal [J]. Tribology International, 2024, 200.
- [48] Li J, Dai Q, Huang W, et al. Feasibility study of magnetic fluid support and lubrication behaviors on micro magnet arrays [J]. Tribology International, 2020, 150.
- [49] Yao J, Li D C, Chen X Z, et al. Damping performance of a novel ferrofluid dynamic vibration absorber [J]. Journal of Fluids and Structures, 2019, 90: 190-204.
- [50] Karami A H, Horestani F K, Kolahdouz M, et al. Rotation Sensor Based on Magnetic Microrods [J]. Ieee Sensors Journal, 2018, 18(1): 77-82.
- [51] Bao L F, Dong X Y, Zhang S Q, et al. Magnetic Field Sensor Based on Magnetic Fluid-Infiltrated Phase-Shifted Fiber Bragg Grating [J]. Ieee Sensors Journal, 2018, 18(10): 4008-12.
- [52] Khalafalla S. Beneficiation with magnetic fluids—magnetic separation of the second kind [J]. Mineral Processing and Extractive Metallurgy Review, 1985, 2(1-2): 21-55.
- [53] Zhang Y J, Chen Y B, Li D C, et al. Experimental Validation and Numerical Simulation of Static Pressure in Multi-Stage Ferrofluid Seals [J]. Ieee Transactions on Magnetics, 2019, 55(3).

- [54] Rosensweig R E, Hirota Y, Tsuda S, et al. Study of audio speakers containing ferrofluid [J]. Journal of Physics-Condensed Matter, 2008, 20(20).
- [55] Li Y W, Han P D, Li D C, et al. Typical dampers and energy harvesters based on characteristics of ferrofluids [J]. Friction, 2023, 11(2): 165-86.
- [56] Devi M, Das R, Mohanta D, et al. Enhanced magneto-optic activity of magnetite-based ferrofluids subjected to gamma irradiation [J]. Applied Physics a-Materials Science & Processing, 2012, 106(3): 757-63.
- [57] Devi M, Mohanta D, Saha A. Comparative study of microscopic, spectroscopic and magneto-optic response of ferrofluids subjected to gamma-radiation [J]. Indian Journal of Physics, 2015, 89(2): 115-21.
- [58] Alsaiani N S, Rakha A, Shaheen B, et al. Tuning of structural and optical parameters of Fe₃O₄ by gamma irradiation for evaluation of photocatalytic activity for removal of drugs [J]. Journal of Radioanalytical and Nuclear Chemistry, 2025.
- [59] Darziyeva T A, Alekperov E S, Jabarov S H, et al. Influence of Heavy Ions on the Magnetic Properties of Fe₃O₄ Nanoparticles [J]. Integrated Ferroelectrics, 2023, 232(1): 127-33.
- [60] Devi M, Paul N, Mohanta D, et al. Characteristic spectroscopic properties of gamma-irradiated rare-earth oxide-based ferrofluids [J]. Journal of Experimental Nanoscience, 2012, 7(5): 586-95.
- [61] Paul N, Hazarika S, Saha A, et al. Optical emission, vibrational feature, and shear-thinning aspect of Tb³⁺-doped Gd₂O₃ nanoparticle-based novel ferrofluids irradiated by gamma photons [J]. Journal of Applied Physics, 2013, 114(13).
- [62] Kopcansky P, Cernak J, Tima T. The effect of gamma-radiation on the magnetization of the kerosene based ferrofluid [J]. Radiation Physics and Chemistry, 1989, 34(5): 817-8.
- [63] Kopcansky P, Cernak J, Tima T, et al. γ -Radiation induced sedimentation of magnetic particles in magnetic fluids [J]. Journal of Magnetism and Magnetic Materials, 1990, 85(1-3): 103-6.
- [64] Chang K P, Cheng C H, Chiang Y C, et al. Irradiation of synthesized magnetic nanoparticles and

its application for hyperthermia; proceedings of the International Conference on Multifunctional Materials and Structures, Hong Kong, PEOPLES R CHINA, F Jul 28-31, 2008 [C]. 2008.

[65] Chang K P, Lin Z Y, Hung M C, et al. Effects of Irradiation on Chitosan-coated Nanoparticles for Hyperthermia; proceedings of the International Conference on Advanced Design and Manufacturing Engineering (ADME 2011), Guangzhou, PEOPLES R CHINA, F Sep 16-18, 2011 [C]. 2011.

[66] Tomasovicova N, Haysak I, Koneracka M, et al. Radiation stability of biocompatible magnetic fluid [J]. arXiv preprint arXiv:10043448, 2010.

[67] Tomasovicova N, Haysak I, Koneracka M, et al. Magnetic Properties of Biocompatible Magnetic Fluid after Electron Irradiation [J]. Acta Physica Polonica A, 2012, 121(5-6): 1302-4.

[68] Tomasovicova N, Haysak I, Kovac J, et al. Radiation Stability of the BSA Modified Biocompatible Magnetic Fluid [J]. Acta Physica Polonica A, 2014, 126(1): 262-3.

[69] Zaharescu T, Setnescu R, Borbath I. Thermal oxidation of irradiated magnetic fluids and their component surfactants and dispersing oils [J]. Central European Journal of Chemistry, 2014, 12(7): 782-7.

[70] Lazic D, Malaescu I, Bunoiu O M, et al. Investigation of therapeutic-like irradiation effect on magnetic hyperthermia characteristics of a water-based ferrofluid with magnetite particles [J]. Journal of Magnetism and Magnetic Materials, 2020, 502.

[71] Taheri A, Shirmardi S P. Applications of ionizing irradiation in oil industry: a review [J]. Reviews in Chemical Engineering, 2025, 41(3): 241-68.

[72] Kang D N, Luo R R, Huang C, et al. The effects of high gamma-irradiation on hydraulic oils [J]. Fusion Engineering and Design, 2025, 216.

[73] Zaripov A K, Ubaidi A. Dependence of the Viscosity of Magnetic Fluids on the Concentration of Magnetic Particles, Temperature, and a Magnetic Field [J]. Russian Journal of Physical Chemistry A, 2021, 95(10): 2141-7.

- [74] Anekratmontre T, Wongsawaeng D, Kongprawes G, et al. Enhancement of surface tribology, mechanical, and electrical properties of UHMWPE via graphene nanoplatelets coating and electron beam irradiation [J]. Rsc Advances, 2025, 15(33): 26756-65.
- [75] Kruglyakov M A, Kudiiarov V N, Laptev R S, et al. Influence of Chromium Coating on Microstructure Changes in Zirconium Alloy E110 Under High-Temperature Hydrogenation and Kr Ion Irradiation [J]. Coatings, 2025, 15(2).
- [76] Wang R D, Ge C T, Yu P, et al. Enhancing the irradiation resistance of Cr coating via periodic insertion of nanochannel CrAlSiN layers that act as elastic unsaturated "sponges" [J]. Corrosion Science, 2025, 246.
- [77] Si Y X, Li J L, Zhang F X, et al. Silicon carbide (SiC) as antioxidant coating in solid-state lithium target for accelerator-based boron neutron capture therapy (AB-BNCT) [J]. Annals of Nuclear Energy, 2026, 235.
- [78] Cui H C, Li D C. Fabrication and properties research on a novel perfluoropolyether based ferrofluid [J]. Journal of Magnetism and Magnetic Materials, 2019, 473: 341-7.
- [79] Okabe T, Kondo Y, Yoshimoto S, et al. Outgassing performance of an ionic liquid-based magnetic fluid [J]. Vacuum, 2019, 164: 34-40.
- [80] Okabe T, Sasaki S, Kondo Y, et al. Hydrostatic ionic liquid-lubricated fluid film bearing for a rotational electron-beam lithography system [J]. Precision Engineering-Journal of the International Societies for Precision Engineering and Nanotechnology, 2020, 61: 194-203.
- [81] Jia J J, Yang G B, Zhang C L, et al. Effects of magnetic ionic liquid as a lubricant on the friction and wear behavior of a steel-steel sliding contact under elevated temperatures [J]. Friction, 2021, 9(1): 61-74.
- [82] Chaudhuri R G, Paeia S. Core/Shell Nanoparticles: Classes, Properties, Synthesis Mechanisms, Characterization, and Applications [J]. Chemical Reviews, 2012, 112(4): 2373-433.
- [83] Zhang W, Wang K K, Zeng Y F, et al. Low-Diffusion Fricke Gel Dosimeters with Core-Shell

Structure Based on Spatial Confinement [J]. *Materials*, 2021, 14(14).

[84] Cost J R, Brown R D, Giorgi A L, et al. Effects of Neutron Irradiation on Nd-Fe-B Magnetic Properties [J]. *Ieee Transactions on Magnetics*, 1988, 24(3): 2016-9.

[85] Samin A, Kurth M, Cao L R. An analysis of radiation effects on NdFeB permanent magnets [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2015, 342: 200-5.

[86] Miyahara N, Honma T, Fujisawa T. Irradiation effects of a 10 MeV neutron beam on a Nd-Fe-B permanent magnet [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2010, 268(1): 57-61.

[87] Brown R D, Cost J R, Meisner G P, et al. Neutron irradiation study of Nd-Fe-B permanent magnets made from melt-spun ribbons [J]. *Journal of Applied Physics*, 1988, 64(10): 5305-7.

[88] Brown R D, Cost J R. Radiation-induced changes in magnetic-properties of Nd-Fe-B premanent-magnets [J]. *Ieee Transactions on Magnetics*, 1989, 25(4): 3117-20.

[89] Zhao X, Li J Y, Wang L, et al. Effects of neutron irradiation and high temperature on structure and magnetic properties of Sm₂Co₁₇ permanent magnet [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2023, 538: 179-84.

[90] Blackmore E W. Radiation effects of protons on samarium-cobalt permanent-magnets [J]. *Ieee Transactions on Nuclear Science*, 1985, 32(5): 3669-71.

[91] Ito Y, Yasuda K, Ishigami R, et al. Magnetic flux loss in rare-earth magnets irradiated with 200 MeV protons [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2001, 183(3-4): 323-8.

[92] Ito Y, Yasuda K, Ishigami R, et al. Magnetic flux loss in Nd-Fe-B magnet irradiated with 660 MeV carbon ion beam [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2006, 245(1): 176-9.

[93] Bizen T, Asano Y, Marechal X M, et al. High-energy electron irradiation of NdFeB permanent

magnets: Dependence of radiation damage on the electron energy [J]. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2007, 574(3): 401-6.

[94] Okuda S, Ohashi K, Kobayashi N. Effects of electron-beam and γ -ray irradiation on the magnetic flux of Nd-Fe-B and Sm Co permanent magnets [J]. Nuclear Instruments & Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 1994, 94(3): 227-.

[95] Gao R S, Zhen L, Li G A, et al. Effect of γ -ray irradiation on the magnetic properties of NdFeB and Fe-Cr-Co permanent magnets [J]. Journal of Magnetism and Magnetic Materials, 2006, 302(1): 156-9.

[96] Zhang J X, Gan H Y, Huang W X. The influence of gamma rays on the magnetic properties of samarium cobalt 2:17 [J]. Aviation precision manufacturing technology, 1992, (02): 25-6 (in Chinese).

[97] Yang S Q, Zhang W L, Gong J, et al. Research on the Gamma Irradiation Effect of Rare Earth Permanent Magnets [J] Functional materials. 2000: 250-1+4 (in Chinese).

[98] Mesa J L, Fernandez A B, Hernando C, et al. Effects of gamma-ray radiation on magnetic properties of NdFeB and SmCo permanent magnets for space applications; proceedings of the IEEE Radiation Effects Data Workshop (REDW) is part of the Nuclear and Space Radiation Effect Conference (NSREC), Paris, FRANCE, F Jul 14-18, 2014 [C]. 2014.

[99] Cheng M H. The influence of temperature/irradiation on the microstructure and properties of Alnico and SmCo alloys [D]: Harbin Institute of Technology, 2021 (in Chinese).

[100] Bizen T, Asano Y, Marechal X M, et al. Idea of mechanism and protection of radiation damage on undulator permanent magnet; proceedings of the 9th International Conference on Synchrotron Radiation Instrumentation (SRI 2006), Daegu, SOUTH KOREA, F May 28-Jun 02, 2006 [C]. 2007.

[101] Yang L. Research on Irradiation Effects and Structural Evolution of Several Magnetic Materials [D]: Harbin Institute of Technology, 2010 (in Chinese).

[102] Chen J, Zhang X F, Zhou L, et al. The influence of a mixed irradiation field on sintered

- Friction* <https://mc03.manuscriptcentral.com/friction>
Nd₂Fe₁₄B permanent magnets [J] *Metallic functional materials*. 2018: 22-6.10.13228/j.boyuan.issn1005-8192.2018077 (in Chinese).
- [103] Wang L, Li J Y, Yuan T, et al. Research on the Radiation Resistance of Rare Earth Permanent Magnetic Materials [J] *Magnetic materials and devices*. 2021: 46-9.10.19594/j.cnki.09.19701.2021.01.010 (in Chinese).
- [104] Simos N, Ozaki S, Mokhov N, et al. Demagnetization of Nd₂Fe₁₄B, Pr₂Fe₁₄B, and Sm₂Co₁₇ Permanent Magnets in Spallation Irradiation Fields [J]. *Ieee Transactions on Magnetics*, 2018, 54(5).
- [105] Samin A J. A review of radiation-induced demagnetization of permanent magnets [J]. *Journal of Nuclear Materials*, 2018, 503: 42-55.
- [106] Samin A, Cao L. Monte Carlo study of radiation-induced demagnetization using the two-dimensional Ising model [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2015, 360: 111-7.
- [107] Bizen T, Marechal X M, Seike T, et al. Radiation damage in permanent magnets for ID [J]. *Radiation Measurements*, 2006, 41: S260-S4.
- [108] Kahkonen O P, Makinen S, Talvitie M, et al. Radiation damage in Nd-Fe-B magnets: temperature and shape effects [J]. *Journal of Physics-Condensed Matter*, 1992, 4(4): 1007-14.
- [109] Yang L, Zhen L, Xu C Y, et al. Effects of proton irradiation on electronic structure of NdFeB permanent magnets [J]. *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, 2009, 267(18): 3084-6.
- [110] Bizen T, Asano Y, Hara T, et al. Introduction of the high radiation resistance of undulator magnet; proceedings of the 8th International Conference on Synchrotron Radiation Instrumentation (SRI 2003), San Francisco, CA, F 2004 Aug 25-29, 2003 [C]. 2004.
- [111] Macha M, Senajova D, Giles T, et al. Effects of Radiation Dose on Lubricants: A Review of Experimental Studies [J]. *Acs Applied Materials & Interfaces*, 2025, 17(10): 14773-800.
- [112] Arakawa K, Hayakawa N, Nakanisha H. Radiation-Induced Gas Evolution from Commercial

Lubricant Base Oil [J]. Nuclear Technology, 1983, 61(3): 533-9.

[113] Stodola J, Stodola P. Controlled Degradation of Lubricating Media by Means of an Accelerated Electron Beam [J]. Processes, 2020, 8(11).

[114] Wu H H, Liu Y C, Zhang B T, et al. Preliminary Study on the Irradiation Effect of Lubricating Oil [C] The 2022 Science and Technology Annual Conference of the Chinese Society for Environmental Sciences - Environmental Engineering Technology Innovation and Application Subforum. Nanchang, Jiangxi, China. 2022: 5.10.26914/c.cnkihy.2022.042841 (in Chinese).

[115] Yang J, Li X, Liu Y, et al. The effect of electron irradiation on the tribological property of perfluoropolyether grease in vacuum [J]. Journal of Fluorine Chemistry, 2015, 175: 114-20.

[116] Li Q, Xin H, Li X T, et al. Investigation on the Gamma Irradiation Resistance of Linear Perfluoropolyether Lubricating Grease [J]. Synthetic Lubricants Materials, 2025, 52(03): 10-5 (in Chinese).

[117] Ferrari M, Zenoni A, Hartl M, et al. Experimental study of consistency degradation of different greases in mixed neutron and gamma radiation [J]. Heliyon, 2019, 5(9).

[118] Ferrari M, Senajova D, Kershaw K, et al. Selection of radiation tolerant commercial greases for high-radiation areas at CERN: Methodology and applications [J]. Nuclear Materials and Energy, 2021, 29.

[119] Xiao D S, Zhang G M. Dynamic effects of magnetic devices under nuclear radiation conditions [J] Nuclear electronics and Detection technology. 1982: 32-4 (in Chinese).

[120] Yu T J. Feasibility Study on the Use of Magnetic Fluid Sealing in the Primary Circuit Equipment of Fast Reactors [J]. Technological innovation and application, 2015, (22): 9-10 (in Chinese).

[121] Zhang Y C, Li X F, Wang Y P, et al. A Preliminary Study on Magnetic Fluid Lubrication/Sealing in Space Environments [J] Lubrication and Sealing. 2023: 147-56.10.3969/j.issn.0254-0150.2023.03.020 (in Chinese).

[122] Liu L F, Li D C, Li L, et al. Design and study of sealing performance for ultra-clean and highly

reliable magnetic fluid seals [J]. Tribology International, 2026, 213.

[123] Yoshida A, Suda T, Ohtsuki T, et al. Status and overview of production target for BigRIPS separator at RIKEN [J]. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2008, 590(1-3): 204-12.

[124] Itoh S, Ueno K, Ohkubo R, et al. Irradiation properties of T0 chopper components [J]. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2011, 654(1): 527-31.

[125] Simos N, Fernades S, Mittag W, et al. Performance degradation of ferrofluidic feedthroughs in a mixed irradiation field [J]. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2017, 841: 144-55.



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