

Article

Studying Radiation-Induced Degradation of Reinforced Concrete Structures: Review and Numerical Analysis of Reinforcement Corrosion Processes in Concrete

Rustem Omarov *, Vyacheslav Belov * and Andrey Morozenko 

Institute of Hydraulic Engineering and Power Plant Construction, Department of Construction of Thermal and Atomic Power Stations, National Research Moscow State University of Civil Engineering, 26 Yaroslavskoye Shosse, Moscow 129337, Russia; morozenkoaa@mgsu.ru

* Correspondence: omarov383@mail.ru (R.O.); belovvv@mgsu.ru (V.B.)

Abstract: This study addresses the operational degradation of reinforced concrete structures of buildings and facilities where radioactive materials and waste are handled, if degradation is caused by the joint effect of ionizing radiation from materials (substances) handled and factors affecting the overall aging of concrete, reinforcement bars, and their combination. The research focuses on gamma radiation and its physical, chemical, and mechanical effects, triggering corrosion processes in reinforcement bars during the operation of reinforced concrete structures. Changes in the structural behavior of existing and newly built facilities, where radioactive materials and waste (with a focus on highly and moderately radioactive waste) are handled, must be predictable during the extended period of operation. Prognostication methods and assessment models must be accessible to various specialists, including design engineers. Available software packages and numerical analysis tools are used to devise these methods and models. This research project demonstrates the numerical modeling of electrochemical corrosion triggered by oxygen diffusion in concrete. The COMSOL Multiphysics software package was used to develop a model of a reinforced concrete wall segment. This model was used to analyze and prognosticate electrochemical processes in a structure during its future operation. Results of numerical modeling show that corrosion-triggered changes in the original diameter of reinforcement do not exceed tenths (11.2–12.4%) for the predicted service life of 100 years. Studies should be continued in this direction because such factors as radiolysis, carbonization, radiation heating, and changes in the aggregate can have an adverse effect on structures during their operation.

Keywords: radiation-induced corrosion of reinforced concrete; radiolysis; carbonization; effect of gamma radiation on reinforced concrete; numerical evaluation of radiation-induced corrosion of reinforcement bars in concrete; finite element modeling of corrosion; oxygen diffusion in concrete; mechanisms of reinforced concrete degradation; depassivation of reinforcement bars in concrete; structural changes in concrete under the influence of gamma radiation; corrosion and radiation resistance



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1. Introduction

Corrosion of reinforcement in reinforced concrete structures is a main mechanism of their degradation [1–18]. Reinforced concrete structures where nuclear and radioactive materials are handled are not an exception in this case [19].

Reinforcement corrosion is the main cause of aging of concrete structures of nuclear power plants (NPPs), according to [20].

Nevertheless, reinforcement corrosion in concrete is an electrochemical process encompassing the anodic dissolution of iron and the cathodic reduction of oxygen in the absence of chlorides in the external environment [8,21,22]. In the case of their presence, the process encompasses absorption of a chloride ion and formation of soluble ferrous

chloride from insoluble ferrous oxide [21,23–26]. This type of corrosion is usually local, unlike oxygen-induced corrosion [21,22,24,25].

The general mechanism of reinforcement corrosion is triggered in reinforced concrete structures in the case of degradation of the depassivation layer at the interface between a steel rod and concrete, whose pH has high alkalinity [7,8,21,26–30] due to the contact between and the intake of carbon dioxide or chloride ions [7,21,24,26–30]. In the case of carbonization, it is assumed that corrosion is triggered at the moment when carbonization reaches the boundary of reinforcement. That is when the pH value of the protective layer becomes neutral [7,30]. The case of the presence of chlorides is characterized by the recurrent restoration of the layer previously lost to depassivation due to changes in conditions of penetration of chlorides into the structure (clogging of pores with carbonization products; closure of cracks developed under the action of temperature or loading, when the structure is deloaded, etc.). In this case, corrosion is continuous only if chlorides accumulate in the body of the structure [7,29].

As time progresses, corrosion triggers deterioration of the strength characteristics of reinforced concrete structures; it reduces their ability to resist operational and potential special effects due to a reduction in their diameter [1–18,24]. Hence, it is necessary to ensure the predictability of this process as early as at the stage of design of structures and, in some cases, at the time of their regular inspections. In addition, according to [31–34], reinforced concrete structures of buildings and facilities, where nuclear and radioactive materials are handled, need simple practical methods of justification of design solutions, including the methods that are licensed by authorized state and supervisory (regulatory) authorities in accordance with the pre-set procedure.

At present, appropriate models are available. They simulate corrosion of reinforcement in concrete for design conditions to ensure the durability of reinforced concrete structures [21,35–44]. However, advanced methods of predicting radiation-induced corrosion of building structures at stages of design [45–47] and operation [48] are highly conservative. Therefore, radiation-triggered corrosion changes (i) in structures of buildings and facilities where radioactive and nuclear materials are handled, and, (ii) in some cases, in materials for radiation and nuclear waste packaging, are underestimated in terms of the effect of gamma radiation on their future operational degradation, as evidenced by a number of scientific studies [30,45,49–62], including the dissertation study [63]. Gamma radiation accelerates corrosion of steel elements and reinforcement in reinforced concrete structures [56–58,60,61,64–69].

In addition, studies [30,59,60,70–79] report deteriorating strength characteristics of concrete exposed to gamma radiation, which may result in more intensive microcracking under loading and which facilitates the penetration of carbon dioxide and (or) chlorides into the body of a structure. Radiogenic heating has a similar effect [49,72,73].

Radiolysis of residual pore water or moisture penetration into the structure under the action of gamma radiation [73,80] also aggravates the process of reinforcement corrosion.

Moreover, it is found that changes in the concrete of structures exposed to ionizing radiation aggravate as the term of facility operation becomes longer and depend on the value of radiation load [69], as well as accumulated dose values [30,49,52,54,70].

In general, recent research reviews [65] emphasize the need to study conditions and development patterns of the effect of electromagnetic (including gamma) radiation on degradation processes in concrete and reinforcement. It is also noteworthy that designs of structures [81–83] and waste packages [45] need strength and corrosion to be co-analyzed. Models describing the mechanism of aging of reinforced concrete structures should take into account more than one factor [84], and degradation should be prognosticated at the design stage due to the long-term operation of facilities where radioactive and nuclear materials are handled [51].

Therefore, the purpose of this research project is (1) to analyze the effect (including causes, conditions, and implementation mechanisms) of ionizing (mainly gamma) radiation on reinforcement corrosion during the operation of structures and (2) to develop principles

and approaches to the analysis of this process using accessible software tools designed for the numerical analysis of architectural and structural design solutions.

2. Materials and Methods

To achieve the above purpose, the authors analyzed, systematized, and compared information extracted from open-access research and engineering works about the degradation of reinforced concrete structures in general, as well as the causes, conditions, and mechanisms of radiation-induced corrosion in reinforcement bars resulting from the long-term exposure to gamma radiation. Thus, physico-chemical and mechanical conditions of aging of reinforced concrete structures (in terms of anticipated changes in their properties and operating conditions) were identified. Here, the authors consider standard structural monolithic reinforced concrete placed in a structure in the conditions of a construction site. Moreover, for high-strength concrete and reinforced concrete structures produced offsite, reinforcement is less prone to corrosion if the production process involves a steam curing chamber.

Authors proposed methods of predictive evaluation of radiation-induced corrosive degradation of reinforcement bars in concrete, using advanced numerical modeling software and the finite element method (FEM).

The COMSOL Multiphysics v. 6.2 software package was selected to simulate corrosion of reinforcement bars in concrete; this software package was used to implement the finite element mechanism of electrochemical corrosion. Researchers who analyzed problems of reinforcement corrosion in concrete considered this software package more suitable than conventional electrochemical methods for evaluating the state of steel elements in the medium [85]. A higher value of the air permeability coefficient was selected, depending on the water–cement ratio, temperature, and humidity under pre-set carbonation conditions to simulate the contribution of gamma radiation to degradation processes (since neither software tool can simulate it when evaluating corrosion in reinforced concrete structures), because of concomitant processes, such as carbonation and radiolysis, that are underway in concrete. The coefficient value was selected on the basis of the results of experiments reported in the research literature. The general modeling algorithm included creating the geometry for a wall segment, setting planes of contact with the environment and conditions of interaction with the environment, setting the density of current for an oxidative reaction of reinforcement in compliance with experimental values obtained for irradiated, non-irradiated, and carbonized concrete specimens with steel reinforcement at the relative humidity RH of 50% [69,86], an setting functions to describe changes in concrete resistivity and the oxygen diffusion coefficient depending on pore saturation PS%, also based on experimental values [87,88]. Thereafter, the time period needed for concrete carbonization to reach the reinforcement boundary was identified analytically using Formula (1) [89]. As a result, the initial oxygen diffusion coefficient was recalculated (reduced by a factor of 1.1) according to the experimental data reported in [88] for carbonized concrete. In turn, concrete resistivity and current density were increased for the oxidative reaction of reinforcement according to [86]. The COMSOL Multiphysics package was employed for finite element modeling. The findings were compared with the experimental data extracted from research and engineering sources of information.

3. Research Results and Discussion

3.1. Analysis of Degradation of Reinforced Concrete Structures Exposed to Gamma Radiation from the Standpoint of Reinforcement Corrosion

3.1.1. Concrete Degradation Due to Exposure to Ionizing Radiation, Contributing to Corrosion of Reinforcement Bars

The main effects of ionizing radiation on concrete shields for nuclear power plants and radioactive and nuclear waste storage facilities include [70]: (1) an increase in temperature (“radiogenic heating”); (2) activation of concrete components (moreover, according to [70], this type of effect matters solely for the decommissioning of buildings and structures

where radioactive and nuclear materials were handled, and it is also characteristic of direct interaction with neutrons [70]); (3) higher expansion coefficients and swelling of the material; (4) changes in air and water permeability coefficients; (5) carbonization of the cement matrix (primarily due to gamma radiation) and accompanying changes in properties and structure (for example, lower porosity, shrinkage, and others); as well as (6) radiolysis of water.

Radiation-Related Structural Changes in Concrete

Currently, most studies on the degradation of concrete in facilities where nuclear and radioactive materials are handled focus on the effect of neutrons (or mixed neutron and gamma radiation fields, where neutron radiation plays a predominant role). This effect is greatest for the above-mentioned material [70–72,90–117]. However, despite the (1) dry storage of radioactive waste, (2) appropriate handling of radioactive materials, preventing neutron bombardment, and (3) gamma radiation being the main type of effect [118–120], destruction of concrete structures, such as waste storage packages, can still be premature [59].

In general, changes in the physico-mechanical properties of concrete composites are due to the presence and magnitude of radiation-triggered deformations of elements that comprise the composite of elements. They are different for the binder, rock, and minerals of aggregates. Experiments prove that it is the large fraction of concrete fillers that triggers its radiation-induced deformations. Fine filler does not have a significant effect on this process. Moreover, a relative increase in linear dimensions (“radiation-induced swelling”) is caused mainly by neutron radiation, rather than gamma radiation [117,121].

In turn, authors of [122] report that gamma radiation has little effect on the properties of the filler and that much greater changes should be expected in the cement dough.

The threshold value at which mechanical properties of concrete deteriorate is an accumulated dose of gamma radiation exceeding 10^8 Gy [30,60,70,72–75]. If a dose exceeds 10^9 Gy, there is evidence of a 25–60% decrease in the compressive strength of concrete [73]. One study reports an extreme (50%) decrease in the strength of concrete at a dose above 1 GGy [59,123]. However, a number of studies show that even at lower values of the accumulated dose (several MGy), gamma ray quanta are capable of affecting the properties of concrete [70,76–78], in particular, at the early stage of the cement stone strength gain and hardening [53,74,122–125].

Hence, the study [70] cites the work of Wodak et al. (2005) [78], which reports that even if the accumulated dose is $5 \cdot 10^5$ Gy, the strength of concrete decreases by 10%, according to an experimental study of specimens irradiated with gamma radiation for 90 days. The authors of a study [70] report the experiments conducted by Soo and Milian (2001). They evidence a relative decrease in strength at accumulated values of 10^5 and 10^7 Gy [74], and in general, this decrease did not depend on the radiation dose (at relatively low (31 Gy/h) and higher ($3.8 \cdot 10^3$ Gy/h) exposure rates [70]. In turn, higher intensity values translated into an increase in strength at a total absorbed dose of 10 MGy [60]. The study [71] has a similar reference to the research conducted by Soo P. and Milian L.M. in 2001. This work reports a 15% decrease in compressive strength of cement stone at an absorbed dose of 22 MGy. However, Khmurovska Y. and Štemberk P. report that the mechanism of this strength decrease is still unclear [71].

Results of experimental studies conducted by Khmurovska Y. et al. in 2019 using the isotope Co^{60} with a gamma irradiation dose in the range of 3.9 to 4.71 kGy/h [79], and a total absorbed dose of 12.0 to 15.0 MGy, show that gamma radiation greatly reduces the compressive strength of cement mortar specimens (by 20% on average) whose composition is close to that of the structural concrete mix that has no coarse aggregate at the age of 72 days of hardening.

The study [126] provides information that a decrease in compressive strength was detected at lower dose rates (1.36 kGy/h) for “older” concrete specimens (which were older before exposure to gamma radiation). However, this effect was not observed at

ionizing irradiation of 2–8 Gy/h. This conclusion is also confirmed by the study [74], which reports its experimentally derived conclusion that if a dose is up to 10 Gy/h, the age of concrete before irradiation does not have any effect on the decrease in strength. A similar dependence was identified at a rate of 1 kGy/h and described in the work of Potts A. et al. [126], that is, the older the concrete before irradiation, the greater its loss of strength [74].

In addition, amorphization of the cement phase under the effect of high accumulated doses (130 MGy) of gamma radiation was reported in [126]. Other authors report prognostic (based on calculated assumptions) anticipations of the greatest radiation-induced changes in silicate minerals and rocks of concrete fillers under the effect of gamma radiation of 5 MeV and an accumulated dose of 10^{10} – 10^{11} Gy at a temperature of 30 °C [121].

Authors of [59] provide information about the oxygen-induced dislocation of groups of silicon oxides as a result of exposure of silicon atoms to gamma radiation if the accumulated dose is 10 kGy [59]. Although such changes were discussed above in the context of neutron-induced radiation with a density of 10^{19} neutrons/cm² [117]. Obviously, independent studies are needed to detect changes in the physical and mechanical properties of silicate minerals used as additives in concrete composites subjected to gamma radiation.

At this stage, processes of reinforcement corrosion in concrete can be comprehensively taken into account by discussing the research and engineering information, namely, the concrete specimens testing results considered in this work. Summarized results are provided in Table 1.

Table 1. Summarized information provided in recently published sources containing data on the testing of concrete and cement mortar specimens under the effect of gamma radiation [75,79,126,127].

Research, Year	Composition of the Mixtures of the Studied Specimens	Accumulated Dose of Gamma Radiation	Gamma Radiation Rate	Research Results
Khmurovska Y. et al., 2019 [79]	cement (CEM I 42.5R)—33.5%; water—12.7%; sand (0–4 mm)—53.5%; superplasticizer (Glenium ACE 442)—0.3%	12.0–15.0 MGy (accelerated tests conducted using isotope Co ⁶⁰)	3.9–4.71 kGy/h	Gamma irradiation greatly reduces compressive strength by an average of 20%
Anopko D.V. et al., 2020 [127]	steel fiber cement mixture	10 MGy, which corresponds to the shelter-type protective structure during 300 years of operation (accelerated testing conducted using isotope Cs ¹³⁷)	20.0 kGy/h (energy—1.25 MeV)	Higher compressive strength and stable flexural strength limit values
Zbyněk Hlaváč et al., 2021 [75]	mixed Portland cement SPC 325—22.2%; quartz sand (0–2.5 mm)—66.7%; water—11.1%	0.8–1.8 MGy (accelerated testing conducted using isotope Co ⁶⁰)	1.6 kGy/h (energy—1.17 and 1.33 MeV)	A 30% decrease in strength due to microcracks, bending strength—by 26.3%, compression strength—by 5.3%, and tensile strength—by 30%. The authors attribute these effects to radiolysis
Potts A. et al., 2021 [126]	portland cement—8.5%; fly ash—5.6%; limestone as a coarse aggregate (fraction—10 and 20 mm)—46.4%; sand—32.3%; water—7.1%; superplasticizer (Sika 130)—0.1%	35.8 MGy, which corresponds to storing specimens in a storage facility for 30+ years	134.4 Gy/h	No decrease in compressive strength was observed

The above data (Table 1) suggest that recently published sources of research and engineering information have contradictory information about the effect of gamma radiation on strength if the effect of gamma radiation on concrete and cement mortar is addressed. Authors of [75,126,128] emphasize that this process is largely associated with radiolysis and carbonization, and tests of control specimens irradiated in conditions of a radioactive waste storage facility do not show any changes in strength characteristics [126].

Indeed, Table 1 has information on standard structural monolithic reinforced concrete or cement mortar. There are no test data for higher-strength concrete or reinforced concrete structures produced offsite using a steam curing chamber.

Authors of [59] propose four types of interaction between a gamma photon and atoms in a cement hydrate, namely, dislocation of atoms (with or without the rupture of chemical bonds) in the solid structure of the cement phase, hydrolysis of water, causing the formation of reactive particles, and thermal shrinkage with dehydration.

In turn, the above trend makes it obvious that the type of interaction between gamma radiation and concrete composite is largely determined by the energy potential of the acting gamma quanta, the rate, and the accumulated radiation dose. In this case, it is necessary to establish parameters of the operation of protective walls and ceilings of buildings and structures where radioactive materials are handled. As for high-activity waste storage facilities, the predicted accumulated dose is estimated at up to 9 MGy, with a maximum rate of 23 Gy/h for the concept of a super-container designed for the final isolation of high-activity radioactive waste packages during their anticipated operation for 300 years [74]. Although M. Dąbrowski et al. [60] further specify a figure of 120 MGy for the design service life of elements of a high-activity waste container. At the same time, they consider a container for the final isolation of spent nuclear fuel. Potts A. et al. [126] emphasize that the accumulated dose corresponds to 35.8 MGy at a rate of 134.4 Gy/h for concrete specimens in a high-activity waste storage facility designed for 30+ years of storage. For example, if conditioned and cemented waste containing isotope Cs^{137} ($3.7 \cdot 10^{10}$ Bq/kg) is stored [129], the absorbed dose reaches ~1 MGy for the cement stone (not even packaging) in case of a nearly complete decay of the isotope activity of ~2 MGy during the half-life of the radionuclide (30,17 years). The protective structure of the Shelter facility will accumulate up to 10.0 MGr over the course of 300 years of operation [127].

Since the purpose of this work is to consider protective structures of buildings and facilities where radioactive materials and waste are handled, the effect on them should be expected to be even smaller than the one specified above, since the above effects mainly refer to the packaging structures and waste cementation materials. For example, the design requirements applied to the dose rate for structures of unattended rooms of NPPs (located in the internal subshell space of the reactor island containment) are set at around 1.008 Gy/h [130], which corresponds to ~0.9 MGy for 100 years of their operation. The average energy of the gamma spectrum in the concrete shield of NPPs was measured; it reached 1.93 MeV for WWER 1000 [75].

Authors Medvedev V. and Pustovgar A. [30] emphasize that if a service life of an NPP is 60 years, the calculated accumulated dose should not be expected to exceed 10^9 Gy. They assume that under such conditions one should not actually expect any great changes in the physical and mechanical properties of concrete itself [30]. Moreover, as for the zone near the reactor space (the reactor shaft), the study [60] provides information on the possible value of the absorbed dose of 100 MGy for the case of a planned service life of 50 years. Hence, the effects manifested as structural changes may be significant enough.

A study [122] reports that when the effects of radiogenic heating are monitored, gamma radiation does not have a great effect on the strength characteristics and elastic modulus of cement stone, and this conclusion is consistent with the conclusions made in [70], because the above-mentioned threshold values of the dose (10^8 Gy) accumulated in protective reinforced concrete shields of buildings and structures where radiation materials are handled are, as a rule, not achieved during their operation, and therefore, one

should not expect dislocation of atoms and, as a consequence, chemical reorientation of bonds, respectively.

Therefore, as for the effects on the corrosion of reinforcement in reinforced concrete structures of protective walls and ceilings of nuclear power plants and radioactive waste storage facilities during predictive modeling of the future operational degradation, the least importance should be attached to the effects of reduced strength resulting from direct exposure to gamma radiation, although the effect of gamma radiation on individual filler minerals requires further experimental studies.

Radiogenic Heating

The process of interaction between gamma radiation and reinforced concrete structures of concrete shields of buildings where radioactive materials are handled is primarily characterized by radiogenic heating. Hence, when passing through the material of protective walls or ceilings, the kinetic energy of gamma quanta is converted into heat, which raises the temperature of concrete and reinforcement or triggers radiogenic heating [70,131,132]. Nearly all absorbed radiation is converted into heat [133]. Such heating has an adverse effect on the mass, dimensionality, and mechanical properties of cement products [49,72,73], silicate minerals and filler rock (at 30 °C for a gamma flux with the energy of 5 MeV and an accumulated dose of 10^{10} – 10^{11} Gy, respectively [121]). Moreover, according to the author of [121], an increase in the absorbed dose boosts the total amount of changes, and an increase in temperature causes its considerable reduction. Moreover, temperature can also have a significant effect on the corrosion of steel elements [64,133]. Winsley R.J., Smart N.R. et al. [64] studied corrosion processes in irradiated carbon steel immersed in an alkaline solution (pH = 13.4) at a temperature of 25 °C and 80 °C and a gamma radiation dose rate of 25 Gy/h, with an exposure duration of up to 6000 h. They found that the initial corrosion rate was higher at 80 °C than at 25 °C [64]. In general, an increase in temperature contributes to an increase in the depth of cracks and, in general, to cracking, due to different values of the coefficient of linear thermal expansion of steel elements, aggregates, and the binder concrete composite, as well as possible “pore cleaning”, which, in turn, contributes to greater penetration of CO₂, an increase in the depth of carbonation [59,134], and to the penetration of chlorides from the external environment to the surface of reinforcement and, as a consequence, to the acceleration of corrosion of the reinforcement [135].

As a rule, concrete containers for high-activity radioactive waste are heated by gamma radiation during 5–10 years to 100 °C [136], which can be considered gamma heating.

However, the effect of this temperature on some elements of buildings and structures, such as protective walls and ceilings (shields), may be insignificant. Hence, according to open-access materials on the license authorizing the extension of operation of NPP Braidwood (units 1 and 2), posted on the official U.S. NRC website, the effect of gamma-induced radiogenic heating for reinforced concrete structures of nuclear power plants is limited to a temperature change of approximately 1.12 °F [137]. In other words, it is insignificant, which is consistent with conclusions of the IAEA report [19].

When analyzing the deterioration of reinforced concrete structures due to corrosion, one should take into account an increase in temperature due to radiogenic heating, both for the purpose of strength analysis and analysis of acceleration of corrosion processes, while the contribution of gamma radiation to the heating of protective structures should be analyzed separately in each individual case, depending on the calculated parameters of the dose rate and, accordingly, the energy of gamma quanta. In this finite element model, temperature conditions were taken into account for the prognostic threshold of 10–45 °C, but different temperature values can be applied because the COMSOL software package allows for multi-physical computations needed to take into account the additional effect of temperature.

Radiolysis

Radiolysis has a great effect on the corrosion conditions of reinforcement since it facilitates the process of release and diffusion of oxygen. Aqueous solutions, exposed to ionizing radiation, can decompose into oxidizing and reducing components (OH , H_2O_2 , $\cdot\text{O}_2^-$, e^- , $\text{H}\cdot$, H_2 [138]) near the steel reinforcement and in pores. As a result, a protective passivation layer of steel reinforcement is exposed to the effect of radiolysis products with an increase in the rate of solubility of the latter, which directly affects the acceleration of corrosion [139].

In this case, a reduction in concrete strength described in this paper may be directly related to the radiolysis of residual water [73]. Since at temperatures around 100 °C, physically or chemically bound water is lost due to effects of radiation [131]. However, as Robira M. et al. prove in their study [77], deterioration of mechanical properties is greater for dry concrete specimens than for those in the humid state. Hence, they conclude that water radiolysis may not play a leading role in degradation at low doses of gamma radiation.

When corrosion-triggered degradation of reinforcement in a reinforced concrete structure is analyzed, it becomes obvious that radiolysis will be one of the leading processes. Thus, authors of a study [80] assume that the direct effect of ionizing radiation on corrosion is generally insignificant (in an oxygen-free/oxygen-free aqueous environment). The majority of radiation-triggered cases of damage and corrosion processes occur due to the reaction of materials with water radiolysis products.

Carbonization

According to the review article written by Medvedev V. and Pustovgar A. [30], carbonation, or the process of formation of calcium carbonate from calcium hydroxide, is a key factor reducing the durability of reinforced concrete in the course of operation. It also boosts the strength of concrete products [126] and modifies the alkaline reaction of the concrete stone environment to neutral [30,140,141], which may boost corrosion of reinforcement in concrete.

It is generally assumed that depassivation of steel commences at a pH below 11.8, while a decrease in pH to 9 is observed during carbonization [30,59].

For most civil buildings, the process of carbonation is mainly characterized by the external sorption of carbon dioxide. This process is quite slow (up to 1 mm per year), since the concentration of carbon dioxide in the air is not high [30]. In turn, gamma radiation accelerates the process of carbonation in concrete structures and triggers its relatively ubiquitous development in concrete. It also reduces porosity but boosts cracking [30,54,60,69,70,77,142]. In general, carbonation products include calcite and vaterite/aragonite [30,143]. Cement matrix pores are filled with vaterite, and this is the main reason why the strength properties of the cement matrix improve [142]. However, it is found that gamma irradiation (at a dose of 1.5 MGy) causes microstructural changes in the hardened cement mass, characterized by a change in the carbonation phase from vaterite to calcite [60], which, in turn, is explained by the fact that different molar volumes change porosity and can accelerate carbonation [60]. The equilibrium between calcium hydroxide and calcite depends on irradiation [143], while the proportion of calcite increases due to irradiation [128]. As calcite is formed in the pore space, the structure of pores changes, and the total effective porosity decreases; it contributes to a decrease in mass transfer through the cement stone or a decrease in access of aggressive substances to the reinforcement [59]. The difference between the unit volume of calcite and calcium hydroxide can lead to shrinkage of the cement stone and, accordingly, cracking [59].

Moreover, carbonation is accelerated by limestone [60], used as a plasticizer in the process of concreting, as well as an aggregate for protective reinforced concrete structures of shields.

An increase in the relative humidity of the structure boosts carbonation. The highest carbonation rate was observed in the range of 55% to 70% [144–146]. At the same time,

the rate of corrosion decreases if the structure is in a humid state due to a decrease in the oxygen diffusion process in concrete [147,148]. However, this occurs at a relative humidity of 70% [149]. The diffusion coefficient of oxygen in air (open pores) is approximately 104 times greater than in the liquid phase (pores filled with water) [147].

The rate of reinforcement corrosion of carbonated mortar or concrete can also be reduced by decreasing the water–cement ratio: experimental results show that a decrease in the water–cement ratio from 0.8 to 0.55 results in a 2.5-fold decrease in the surface current density at a relative humidity of 100% [150]. However, as a rule, protective reinforced concrete structures of buildings and facilities where radiation and nuclear materials are handled have much lower water–cement ratios due to the need to meet strict strength requirements. The following trend is revealed in [151], whose authors study water–cement ratios close to those used in nuclear energy facilities (0.25, 0.3, and 0.35): as the water–cement ratio decreases, so does the overall probability of corrosion. However, prevailing factors include the extent of pore saturation and the effective area of contact between steel and water-filled pores [144].

Hence, processes of radiation-triggered heating, carbonization, and radiolysis of chemically bound and unbound pore water are of predominant importance in the mechanistic modeling of processes reinforcing steel corrosion in concrete. Moreover, a general decrease in crack resistance (caused by carbonization) facilitates greater penetration of CO₂ due to cracking and, consequently, causes an increase in the carbonization depth [134]. Similarly, the process of carbonization is accelerated by high temperatures [134].

Thus far, no carbonization prediction models have been developed under conditions of exposure to ionizing radiation [30].

3.1.2. Corrosion of Reinforcement in Reinforced Concrete Structures Under the Effect of Gamma Radiation

Reinforced concrete structures are characterized by the formation of a passivating layer with a pH of 13 at the interface between the reinforcement and concrete, which prevents the general corrosion of reinforcement steel [152].

Carbonization, radiolysis, and chloride ions penetrating into concrete can destroy this passivating layer. As a result, the process of general corrosion will occur [153]. In this case, operating temperature conditions have a great effect [152]. And the same about penetrating chlorides, which retain moisture inside the concrete structure and reduce the specific electrical potential of concrete resistance, in addition to the chemical reaction [153].

The immediate effect of gamma radiation on the corrosion rate of steel elements in various environments is studied in several works [56–58,60,61,64,66–69,154–157].

Thus, the preliminary evaluation of corrosion of carbon steel container packages under aerobic conditions shows that gamma irradiation increases the corrosion potential [155]. On the contrary, the study [57] provides information that the corrosion rate of carbon steel increases six-fold under the effect of water and gamma radiation.

Smart N.R. et al. (2008) examine the effect of gamma radiation (at a dose rate of 11 Gy/h and 0.3 kGy/h and temperatures of 30 and 50 °C, respectively) on steel corrosion in groundwater environments. Their conclusion is that corrosion processes are accelerated, and some oxidation is observed at higher dose rates [58]. Hence, gamma radiation accelerates steel corrosion processes in the media that facilitate radiolysis.

In [67], low-carbon steel X65 was irradiated with a gamma radiation source of Co⁶⁰ under aerobic groundwater conditions until the accumulated values of 1, 2, and 3 MGy were attained. According to Canshuai Liu et al. [67], gamma radiation boosts the number of defects in the lattice structure of metals, reduces the overall electrical potential, and accelerates processes of local and general corrosion. In the review section of their study, the authors [67] found that, in general, gamma radiation accelerates the corrosion of carbon steel at dose rates of 3 kGy/h but decelerates this process at higher rates exceeding 13 kGy/h.

According to [68], a dose rate of more than 5 Gy/h is needed to accelerate the general corrosion of corrosive materials. However, some authors claim that the corrosion rate was comparable with that without irradiation at a dose rate of 11 Gy/h [61].

It follows from an earlier review [158] of works on steel corrosion that the effect of gamma radiation, even at high dose rates (about 10^5 R/h), is insignificant for carbon steel during corrosion in aqueous solutions with a low degree of salinity and low magnesium content, but if chlorides are present, such an effect is insignificant up to a dose rate of $3 \cdot 10^2$ R/h. In environments saturated with magnesium ions, high doses (10^5 R/h) lead to a significant increase in the corrosion rate. For dose rates in the range of 10 to 10^3 R/h, the corrosion rate can decrease under the action of gamma radiation, which, as Shoesmith D.W. and King F. suggest, is associated with the ability of the radiation field to cause crystallization of protective iron deposits.

Table 2 contains a summary of studies on the corrosion of metal structures subjected to the effect of gamma radiation in various environments and at various temperatures.

Table 2. Review of sources of research and engineering information on corrosion tests of specimens under the effect of gamma radiation [58,64,67,154,156,159,160].

Research, Year	The Medium in Which the Study was Conducted	The Temperature for Testing Procedures, °C	pH of the Medium	Gamma Radiation Dose, kGy/h	Test Time, Days	Key Findings
Badet et al., 2014 [154]	Pure water (anoxic conditions)	25	6.5	0.3	up to 99	In experimental media, acceleration of corrosion was observed under the effect of high-dose gamma radiation. The corrosion rate nearly tripled. The dose rate at which an increase in the corrosion rate was observed is significantly higher than that selected for storage of radioactive waste.
	Water with carbonates (anoxic conditions)		7.1	0.3	15, 109, and 340	
				1.0	109 and 340	
Smart N.R. et al., 2008 [58]	Artificial groundwater	30	8.8	0.011	166	Gamma radiation increases the rate of anaerobic corrosion of carbon steel in artificial groundwater. At 11 Gy/h the increase lasts only about 7000 h, but at 300 Gy/h it lasts longer and may be continuous.
		50	10.4			
Aljohani T. et al., 2019 [159]	Sodium chloride	not specified	7.0	4.0	37.5 and 62.5	Specimens exposed to high doses of radiation of 150 and 250 kGy showed accelerated corrosion.
Marsh G. P. et al., 1988 [156]	Groundwater contacting granite	90	9.4	1.0	100 and 200	In slightly saline groundwater contacting granite, at the gamma radiation dose rate of 1.0 kGy/h and a temperature of 90 °C, the corrosion rate increased from less than 0.1 µm/year to 3 µm/year, at a factor of 30.
Winsley et al., 2011 [64]	Artificial pore water with high alkali content (anaerobic)	80	13.4	0.025	230 and 250	The corrosion rate did not change. The authors believe that apparently the dose rate of 25 Gy/h is not sufficient to accelerate corrosion in general. The presence of chlorides accelerates corrosion, but this acceleration is insignificant.
	Artificial pore water with high alkali content, with chlorine added (anaerobic)					
	Artificial pore water with high alkali content (anaerobic)	25	13.4		223	
Giannakandropoulou S.I. et al., 2022 [160]	Ultrapure deaerated water (anaerobic)	not specified	7.0	0.050	15 and 16	Gamma radiation causes a slight decrease in the corrosion rate of carbon steel.
Canshuai Liu et al., 2018 [67]	Groundwater (aerobic)	25	-	3.0 (energy—1.25 MeV)	14.28 and 42 (absorbed doses—1, 2, and 3 mGy, respectively)	Gamma radiation increases lattice defects and reduces the overall electrical potential, accelerating the process of both local and general corrosion.

Table 2 shows that gamma radiation increases the corrosion rate in the presence of chlorides at elevated temperatures and also under conditions of high accumulated radiation doses (above 150 kGy). The threshold value of 0.3 kGy/h shows the onset of the effect of gamma radiation.

Dabrowski (2022) [60,69] and Dewynter-Marty V. (2017) [66] investigate changes in corrosion properties of low-carbon steel reinforcement exposed to gamma irradiation.

Dewynter-Marty V. et al. examine the behavior of unalloyed steel in cement mortar from the standpoint of radiolysis triggered by gamma radiation (about 15 Gy/h). These researchers did not reveal a great effect of gamma irradiation on the corrosion rate up to the accumulated dose of 0.3 MGy [66]. Dabrowski M. et al. consider cylindrical specimens filled with cement mortar (Portland cement CEM I 52.5 R) with a steel rod (S235JR with a diameter of 6 mm) in the middle, irradiated for 8 months at different relative humidity levels (50% and 100%). The values of absorbed doses of gamma radiation were close to 1.8 MGy. The following conclusions were made [60,69]: in all cases gamma irradiation shifts corrosion potential to negative values, which shows an increase in the probability of a reduction in corrosion resistance; as for specimens in a medium with 100% relative humidity, gamma radiation caused a slight increase in current density (by 1.1–1.3 times), while at 50% humidity, higher current density values (by 4–12 times) were observed; the gamma radiation dose up to 2 MGy reduces protective properties of the passivating layer of reinforcing steel; no significant effect of the limestone aggregate on the process of steel corrosion was revealed; in turn, the presence of fly ash in the specimens caused an insignificant increase in the corrosion rate. The process itself was characterized by Dabrowski [60] as electrochemical. It is consistent with the observation of degradation of steel elements used in nuclear power plants; Rasheed P. A. et al. [54] emphasize that the main problem is electrochemical corrosion.

The research studies of Dabrowski (2022) [60,69] and Dewynter-Marty V. (2017) [66] demonstrate that gamma radiation has little effect on reinforcement, although the passive layer in irradiated specimens is more unstable. Probably, irradiation has a greater effect on the composition of the pore fluid due to water radiolysis and due to more accelerated carbonation of the solution in the near-surface layer, triggering changes in the near-surface layer of the reinforcement. Conclusions made in [69] show that the effect of gamma radiation on steel corrosion is significantly stronger in an atmosphere with a content of 1% CO₂ and moderate relative humidity (50%) than with a content of 1% CO₂ and a fully saturated atmosphere (relative humidity—100%).

3.2. Modeling of Chemical Radiation-Induced Corrosion Processes Using the COMSOL Software Package

The first step of the research is the analysis of an extensive list of factors affecting the process of reinforcement corrosion in concrete, mainly under the effect of gamma radiation. Given the fact that the physics of the phenomenon and the mechanism of corrosion under gamma radiation conditions are not implemented by any of the finite element modeling platforms or other proven software numerical analysis methods for building structures [161–165], this paper proposes a mechanism for taking into account the effect of ionizing radiation in the form of oxygen diffusion. To implement this effect, oxygen concentration was increased in the software package by 1.1 times. This allows us to get as close as possible to the characteristic parameters of reinforcement exposed to gamma quanta, taking into account the accompanying processes occurring in the concrete of the structure [69].

In this case, gamma radiation can be replaced by oxygen diffusion in the concrete structure, which leads to similar values of current density observed during irradiation. This approach ensures more accurate results, close to the experimental data reported in [60,69].

However, it is noteworthy that at different periods of time conditions affecting the process of reinforcement corrosion are different. In general, they depend on the oxygen input into a structure, residual water in concrete, the external environment, damping conditions (the number and presence of empty pores), carbonization, gamma radiation (gamma heating), as well as the resistance of concrete and the boundary of the passivating layer.

The review of open-access sources of research information reported in Section 3.1 of this paper suggests that the following mechanism is implemented at different periods of operation of reinforced concrete structures. This mechanism serves as the basis for

modeling performed in the COMSOL software package, and it encompasses the following stages (see Figure 1):

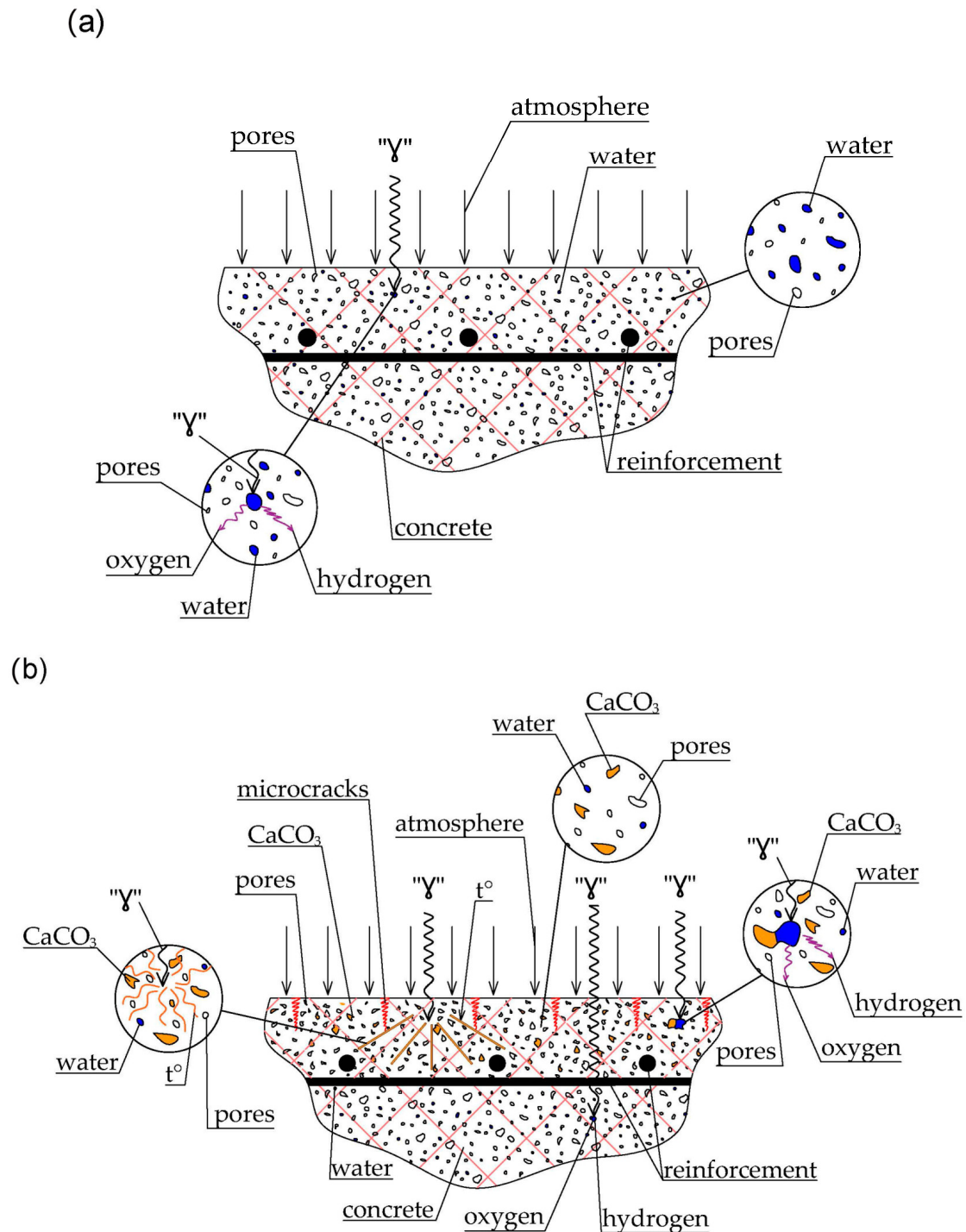


Figure 1. Conceptual scheme of mechanisms evolving in time (during different periods of operation of a reinforced concrete structure) and relevant for corrosion of the reinforcement exposed to gamma radiation, which serves as the basis for simulation in the COMSOL software package, for a segment of a reinforced concrete wall, where (a) is the initial time period (the onset of operation), and (b) is the period of substantial carbonization.

- *Initial period (the onset of operation):* the structure contains residual water (chemically bound and in pores); this period is characterized by high (relative to the carbonization period) diffusion of external oxygen together with carbon dioxide in the air; electrical resis-

tance of concrete is low; corrosion currents are low; a reliable passivation layer is formed around reinforcement bars. At this time, some residual water continues to participate in the hydration reaction in concrete; it is also subjected to accompanying radiolysis under the action of gamma radiation, which leads to the release of oxygen in the structure. Therefore, oxygen saturation of the structure is high at this stage. Calcium hydroxide gradually enters into a reaction with carbon dioxide, which leads to the formation of calcium carbonate and water. Hence, calcium carbonate fills the pores and reduces the permeability of the structure, but the water resulting from the reaction is decomposed due to radiolysis, and the structure, including its inner layers, becomes saturated with oxygen, while its permeability goes down (refer to [88] for a comparison between oxygen diffusion in carbonized and non-carbonized concrete), while the electrical resistance of concrete increases, the passivating layer of reinforcement degenerates, and corrosion currents intensify.

- *Period of substantial carbonization:* this period is characterized by micro-cracking, as the pores filled with calcium carbonate can no longer compensate for deformations in concrete (induced by loading or temperature, including radiation heating). Consequently, the infeed of oxygen and other gases contained in the air increases near the interface between the reinforcement and concrete. The corrosion current in the reinforcement goes up significantly; the total electrical resistance of concrete also increases, and the passivation layer deteriorates. In the course of further carbonization, the number of cracks increases, the number of free pores decreases, the resistance of concrete increases, and radiolytic processes move deeper into the structure due to the absence of water. This period is characterized by permeability mainly due to micro-cracking of concrete, enhanced by radiogenic heating, which leads to the accelerated corrosion of the reinforcement and carbonization.

The authors employed the COMSOL software to simulate half of a reinforced concrete wall using the principle of symmetry. The arrangement of reinforcement whose diameter is 25 mm is shown in Figure 2a. The interaction between the wall faces and the external environment is shown in Figure 2b.

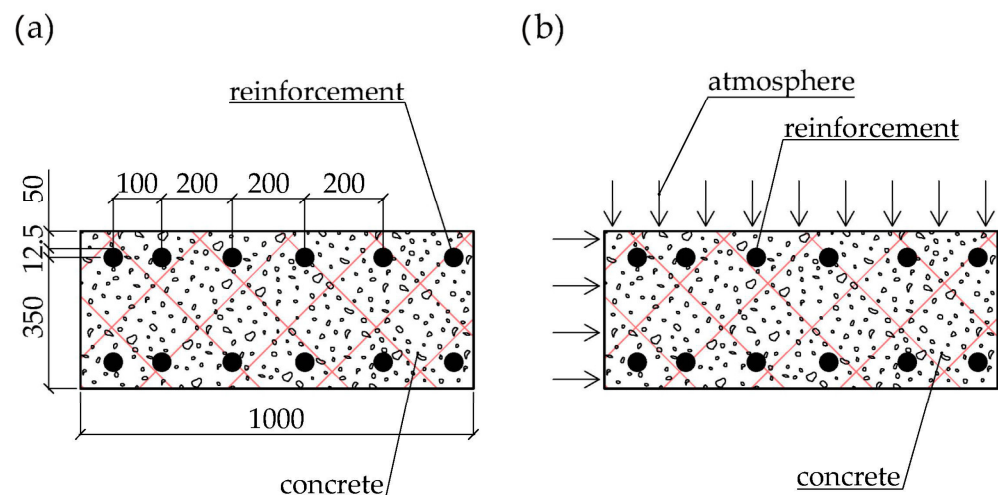


Figure 2. Scheme of a wall segment modeled in the COMSOL software package, where (a) is the geometry of a modeled segment of a reinforced concrete wall (dimensions are shown in mm), and (b) shows boundaries of a concrete wall segment interacting with the surrounding atmosphere.

Oxygen enters the structure and diffuses through the concrete, reacting with the reinforcement. In the steady state, the governing equation describing oxygen transport states that the divergence of the space-dependent effective oxygen diffusion (D_{O_2}) multiplied by the oxygen concentration gradient (∇C_{O_2}) must be equal to zero for all points in concrete [87]:

$$\nabla \cdot D_{O_2}(\nabla C_{O_2}) = 0 \quad (1)$$

Oxygen transport through concrete depends on many factors, including pore tortuosity and size distribution, wall adsorption capacity, capillary effects, and the moisture content in concrete. Experimental values of the effective oxygen diffusion in concrete as a function of the moisture content (or pore saturation) are presented in Table 3.

Table 3. Specific resistivity of concrete ρ and effective oxygen diffusion D_{O_2} as a function of pore saturation PS% [87].

PS (%)	Concrete Resistivity ρ ($\Omega \cdot m$)	Effective Diffusivity of Oxygen $D_{O_2} \cdot 10^{10}$ (m^2/s)
20	5.727	152
30	1.227	115
40	500	83
50	205	49
55	170	39
60	142	28
65	125	20
70	102	15
75	80	10
80	64	8.5

Table 3 shows that as a consequence, D_{O_2} values vary with pore saturation. In all cases, the local equilibrium between the aqueous phase and the pore phase oxygen is assumed, and the C_{O_2} symbol denotes the concentration of oxygen in the pore phase.

The charge transport in concrete is also important because the corrosion process is electrochemical. Ions dissolved in the concrete pore solution act as charge carriers in the presence of an electric field. The electric field is due to the electric potential difference (φ) in concrete. In the steady state, the charge transport equation means that the divergence of the reciprocal of space-dependent resistivity ($1/\rho$) multiplied by the gradient of the electric potential is zero for all points in concrete [87]:

$$\nabla \cdot \frac{1}{\rho} (\nabla \varphi) = 0 \quad (2)$$

The electrical resistance of concrete (ρ) is used to reduce the complex phenomenon of ion transport to a single parameter. The value of ρ is a function of pore saturation and is determined experimentally [166]. Table 3 shows values of ρ as a function of pore saturation [87]. Since the solution in the pores facilitates the travel of ions, specific resistance varies in inverse relation to the pore saturation.

All system boundaries that are not steel reinforcement require natural (isolating) boundary conditions [87]:

$$\vec{n} \cdot \nabla C_{O_2} = 0 \quad (3)$$

$$\vec{n} \cdot \nabla \varphi = 0 \quad (4)$$

where $\vec{n}$ is the unitary normal vector to the surface. These boundary conditions state that gradient vectors must always be perpendicular to the normal vector at the insulating boundaries; that is why no transport occurs across the surface. It is assumed that the oxygen concentration at the concrete–anode interface is equal to the atmospheric oxygen concentration (i.e., the anode itself does resist the oxygen transport) [87]:

$$C_{O_2}(0, y) = C_{O_2}^* \quad (5)$$

where $C_{O_2}(0, y)$ is the concentration of oxygen at the concrete–reinforcement interface, and $C_{O_2}^*$ is the concentration of oxygen in the atmosphere, which is a constant value.

An interpolation relationship containing a multiplier (a coefficient of proportionality) was additionally formulated to take into account changes in the electrical conductivity of concrete over the time interval of 100 years. Subsequently, the value of the initial function

of electrical conductivity will be multiplied by the appropriate coefficient depending on the time of oxidation (over the initial period of time— $(1/10^7)$; 9 years— $(1/45)$; 50 years— $(1/14)$; and 100 years— $(1/2.8)$).

Determining the relationship between the moisture content and temperature/humidity in concrete is of great importance for an accurate prediction of the durability of reinforced concrete structures [167].

The results show that the water saturation of pores, considered as a characteristic of the moisture content, changes nonlinearly depending on the relative humidity of concrete. Its change pattern is greatly affected by the water–cement ratio and temperature [166]. Jiang J. and Yuan Y. developed a model conveying the relationship between pore water saturation, temperature, and relative humidity in concrete. In addition, they experimentally verified it by an independent test [166]. Hence, dependencies specified in [166] were used to link temperature, water–cement ratio of concrete, humidity, and water saturation in further computations. In this case, the temperature range was 10 to 45 °C.

Computation parameters entered into the COMSOL software package are shown in Table 4.

Table 4. The list and standard values of parameters used in computations made by the COMSOL software package.

Parameter *	Expression
A_{Fe}	0.41 [V]
A_{H2}	−0.15 [V]
A_{O2}	−0.18 [V]
C_{O2_ref}	9.46 [mol/m ³]
$C_{O2_ref_9_100}$	8.6 [mol/m ³]
E_{eq_Fe}	−0.76 [V]
E_{eq_H2}	−1.03 [V]
E_{eq_O2}	0.189 [V]
I_{0_Fe}	7.1×10^{-5} [A/m ²]
I_{0_H2}	1.1×10^{-2} [A/m ²]
I_{0_O2}	7.7×10^{-7} [A/m ²]
L	3.175×10^{-2} [m]
$R_{reinforcement\ bar}$	0.635×10^{-2} [m]
S	2.54×10^{-2} [m]
W	6.35×10^{-2} [m]
PS	0.6

* letter designations are given in Appendix A.

Three of many possible chemical reactions that can occur at the interface between the reinforcement and concrete (actively corroding reinforcement) are considered: oxygen reduction, oxidation of the steel reinforcement (here represented as iron oxidation), and hydrogen evolution due to water reduction.

When atmospheric oxygen diffuses and reaches the surface of the reinforcement, it can be reduced to hydroxide ion in the aqueous solution [87,168]:



Corrosion occurs when iron in the steel reinforcement undergoes oxidation. The corrosion reaction is described by the model [87,168]:



Finally, pore water adjacent to the reinforcement can be reduced to form hydrogen gas [87]:



Corresponding boundary conditions are added to COMSOL using the “electrode reaction” function.

The value equal to $-0.07 \mu\text{A}/\text{cm}^2$ is taken as the initial parameter of current density for the oxidative reaction of the reinforcement. It corresponds to the experimental values provided in [69]. The period of time needed for concrete carbonization to reach the boundary of the reinforcement is 9 years; it was calculated by the authors in accordance with Formula (1) [89]:

$$C = k \cdot \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \beta_1 \cdot \beta_2 \cdot \beta_3 \cdot \sqrt{t}; \quad (9)$$

where C is carbonation depth (cm); t is time (years); K is the coefficient; α_1 is the coefficient depending on the type of concrete; α_2 is the coefficient depending on the type of cement; α_3 is the coefficient depending on the water–cement ratio; β_1 is the coefficient depending on temperature; β_2 is the coefficient depending on humidity; β_3 is the coefficient depending on CO_2 concentration. [89]

In the aftermath of 9 years of carbonization of a 50 mm thick protective layer of reinforcement, the initial coefficient of oxygen diffusion is recalculated by the authors (reduced by a factor of 1.1) in compliance with the experimental data provided in [88] for carbonized concrete. In turn, the current density of the oxidative reaction of the reinforcement is increased by a factor of 10 according to [86].

In addition, a logical Expression (10) is entered into the D_c settings responsible for oxygen diffusion in the COMSOL software package:

$$\text{if}(t < 2.838\text{e} + \frac{8, D_{O2(PS)}}{1000, D_{O2(PS)}}); \quad (10)$$

where $D_{O2(PS)}$ is the dependence between the effective oxygen diffusion coefficient and pore saturation (see Table 3), and c is the name of the atmospheric oxygen concentration variable.

Expression (10) sets the value of the oxygen diffusion coefficient in the concrete material for the first 9 years (i.e., $2.838\text{e}+8$ s) as $1/1000$ of the initial one at the pre-set moisture content in concrete pores. After 9 years, the value of the diffusion coefficient will be equal to the initial value determined by the D_{O2} function (Table 3).

A change in the value of current density for the oxidative reaction of the reinforcement as a result of the accumulation of the gamma radiation dose is taken in proportion to experimental values for gamma-irradiated concrete specimens with steel reinforcement at relative humidity RH 50% in accordance with the data extracted from the study [69] ($0.24 \mu\text{A}/\text{cm}^2$, with the accumulated dose of 1.8 MGy for 6 months of irradiation). The dose value is 11.4 Gy/h, which corresponds to values of radioactive waste specified in [74].

A change in parameters of current was mainly achieved due to a change in concrete resistance.

In turn, the specific concrete conductivity function of the moisture content in pores ((ρ) , see Table 3) was entered into the electrolyte conductivity field of COMSOL, taking into account a change in conductivity throughout the calculation interval by multiplying it by the interpolation function with proportionality coefficients shown in Figure 3.

In addition, the density of current, accompanying the reaction of iron oxidation before “significant carbonization” (i.e., before the expiry of 9 years ($2.838\text{e}+8$ s)), is determined by the expression $c/C_{O2_ref} * I_{0_O2}$, and after 9 years by the expression $c/C_{O2_ref_9_100} * I_{0_O2}$. Towards this end, Expression (11) is entered into the COMSOL “exchange current density” field:

$$\text{if}(t < 2.838\text{e} + 8, \frac{c}{C_{O2_ref} * I_{0_O2}}, \frac{c}{C_{O2_ref_9_100} * I_{0_O2}}); \quad (11)$$

where c is the name of the atmospheric oxygen concentration variable.

In the COMSOL boundary condition settings, we select two outer boundaries of the model that are in contact with the atmosphere. In the field for the numerical value of the concentration, we specify a logical Expression (12):

$$if(t < 2.838e + 8, C_{O2_ref}, C_{O2_ref_9_100}); \quad (12)$$

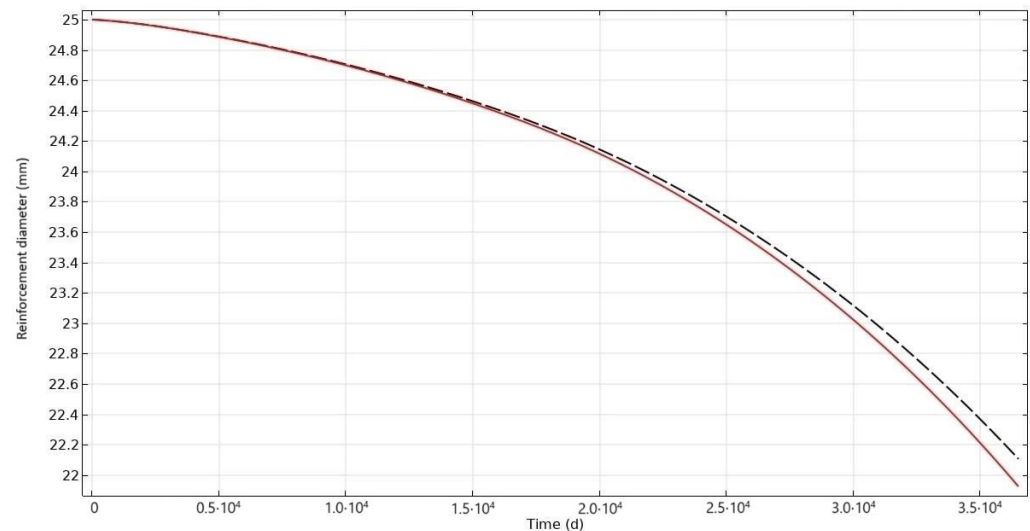


Figure 3. A change in the diameter of the reinforcement over time (the dashed black line shows the reinforcement located closer to the wall surface; the red line shows the reinforcement on the opposite face).

The computation performed in the COMSOL software package shows that the diameter of the reinforcement changes within tenths of its original diameter in the course of the oxygen diffusion in concrete. In 100 years, the approximate diameter change will reach 2.8–3.1 mm, which is 11.2–12.4% of the initial diameter of the reinforcement (see Figure 3).

The values obtained by the authors are consistent with the corrosion rate provided in the Oak Ridge National Laboratory (NRC U.S.) Report [48], which says that the rate of the reinforcement corrosion is 0.001 to 0.03 mm/year (0.1 to 3.0 mm in 100 years, respectively), and exceed those provided in the IAEA Report [19], or 0.001–0.005 mm/year (0.1–0.5 mm in 100 years). In addition, values obtained by the authors do not comply with the experimental results obtained in accelerated tests by Shiro Mitsugi et al. [89], or 6.4×10^{-6} %/day (0.234% for 100 years, which corresponds to the residual diameter of reinforcement of approximately 24.97 mm).

At the same time, the corrosion acceleration process is observed, which is in agreement with the conclusions drawn in the study of Smart N.R. et al. (2008) [58] at the gamma radiation dose rate of 11 Gy/h. Furthermore, Dabrowski M. et al. [60,69] draw conclusions that in all cases gamma radiation shifts the corrosion potential to the negative domain, which shows an increase in the probability of reducing corrosion resistance.

The above method can adequately predict the process of reinforcement corrosion in concrete during operation, provided that reinforced concrete structures are exposed to gamma radiation.

4. Conclusions

The review of open-access research undertakings, performed in this work, shows that, according to the majority of authors, the gamma radiation dose rate, exceeding 300 Gy/h, is the threshold value for the acceleration of corrosion processes in steel elements. In this case, corrosion itself is caused by the process of radiolysis. However, the rate of anaerobic corrosion of carbon steel increases even at lower dose rate values of 11 Gy/h

in accelerated tests limited in time. The time of exposure to ionizing radiation has a great effect on corrosion processes in steel elements in different environments. Hence, steel corrosion accelerates in the presence of chlorides if the accumulated dose exceeds 150 kGy. Higher accumulated doses, exceeding 0.3 MGy at the radiation rate of about 15 Gy/h, show the effect on corrosion processes (its acceleration) in unalloyed steel in cement mortar. At an accumulated dose exceeding 1.8 MGy, the corrosion of reinforcement accelerates in concrete specimens in the air. In addition, accumulated doses of several MGy trigger microscopic changes in concrete (microcracks, larger pores, greater brittleness), which promote the penetration of gases from the environment deeper into concrete and accelerate corrosion processes.

In general, the following factors are important for processes of reinforcement corrosion in reinforced concrete structures:

- Operating environments, namely, the presence of chlorides, ions of magnesium and carbon; temperature and humidity characteristics (higher radiolytic damage and accelerated carbonization were observed in the RH range of 50 to 75%, and similarly corrosion processes accelerated in steel elements in concrete under the combined effect of temperature (including radiation heating).
- Conditions of oxygen supply to a structure.
- Presence of residual water (initial water–cement ratio).

Operational conditions for steel reinforcement in concrete, subjected to gamma radiation, are characterized by the effect of various factors during the initial period of operation of structures and further (at a high accumulated dose of ionizing radiation). Hence, radiolysis and carbonization processes prevail in the initial period, while the subsequent period is characterized by their consequences, such as brittleness, the formation of microstructural changes, and reduction in external pore permeability.

In this work, the authors took into account the above degradation changes occurring under the effect of gamma radiation in reinforced concrete structures by varying the corresponding resistance of concrete and diffusion of oxygen in different time periods.

As a result, the retrospective numerical analysis performed in the COMSOL software package for 100 years of operation of the structure shows that the anticipated change in the diameter of the reinforcement (from 2.8 to 3.1 mm) is quite consistent with corrosion rates presented in the Oak Ridge National Laboratory (NRC U.S.) report [48]; they contradict the data provided in the IAEA report [19] and some results of studies that involved accelerated corrosion tests conducted under the effect of gamma radiation.

It is obvious that the modeling of corrosion processes under the effect of gamma radiation is a truly challenging research task. Despite the fact that the authors substantiated the viability of using standard software in the numerical modeling of corrosion processes by means of replacing the effect of gamma radiation by (1) oxygen diffusion and (2) a change in the resistance of concrete, development of a comprehensive analytical model requires further experimental studies, taking into account all factors of corrosion and radiation-triggered degradation of reinforced concrete structures under the extended exposure to gamma radiation.

5. Future Directions

A retrospective analysis of facilities to be decommissioned will be performed in the course of further research and evaluation of provisions serving as the basis for this study. The dose rate, the point of the specimen extraction, the duration of exposure to gamma radiation, and conditions of the operating environment should be reliably identified for the point of sampling. Real corrosion values and depth of the carbonized concrete layer should be found; permeability and structural changes should be identified in specimens extracted from such facilities.

In addition, a set of long-term tests should be made for (i) relatively low and medium threshold values of gamma radiation dose rates and (ii) temperature and humidity conditions close to the operating environment, including loading conditions, to verify the rate of

carbonization of concrete specimens with reinforcement under the action of ionizing radiation.

It is necessary to experimentally evaluate the saturation of pores in environments close to the operating environment under conditions of exposure of specimens to gamma radiation, since part of the moisture is subjected to radiolysis.

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Marov Rustem: software modeling and preparation of literary sources of research information, their primary analysis. Belov Vyacheslav Vasilievich: development of research methodology, preparation of the initial draft of the research. Morozenko Andrey Aleksandrovich: editing of research materials, their critical evaluation, funding arrangements.

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Appendix A

A_{Fe}	iron oxidation on the Tafel slope;
A_{H_2}	hydrogen evolution on the Tafel slope;
A_{O_2}	oxygen reduction on the Tafel slope;
$C_{O_2_ref}$	oxygen reference concentration;
$C_{O_2_ref_9_100}$	oxygen concentration after 9 years;
E_{eq_Fe}	equilibrium oxidation potential of iron;
$E_{eq_H_2}$	equilibrium potential of hydrogen evolution;
$E_{eq_O_2}$	equilibrium potential of oxygen reduction;
I_{0_Fe}	exchange current density of iron oxidation;
$I_{0_H_2}$	current density of hydrogen evolution;
$I_{0_O_2}$	current density of exchange during oxygen reduction;
L	length of concrete segment;
$R_{reinforcement\ bar}$	reinforcement radius;
S	thickness of concrete;
W	width of concrete segment;
PS	pore saturation.

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