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RADIATION EFFECTS ON THE PROPERTIES OF CONCRETE USED IN NUCLEAR POWER PLANTS

EFECTELE RADIAȚIEI ASUPRA PROPRIETĂȚILOR BETOANELOR FOLOSITE ÎN CENTRALELE NUCLEARE

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Abstract: *Inside the concrete used as a material for the protection shields against ionizing radiation coming from the core of the reactor, various processes and physical and chemical reactions have to be taken into account when the efficiency of the shield is analyzed throughout the operation life of the nuclear power plant. The paper looked at how the concrete can be affected by the irradiation with neutrons and gamma radiation under conditions of possible high fluence outside an reactor core.*

Keywords: protection against ionizing radiation, shielding, concrete.

Rezumat: *In interiorul betonului folosit ca material pentru ecranele de protecţie împotriva radiaţiilor ionizante provenite de la zona activă a reactorului au loc diferite procese şi reacţii fizice şi chimice de care trebuie ţinut cont atunci când se analizează eficienţa ecranării pe toată perioada de funcţionare a centralei. In lucrare s-a urmărit modul în care betonul poate fi afectat de iradierea cu neutroni şi radiaţii gamma în condiţiile unor fluenţe posibile în exteriorul zonei active a reactorului.*

Cuvinte cheie: protecţia împotriva radiaţiilor ionizante, ecranare, beton.

1. Introduction

Nuclear/radiological installations are those that use different materials for protection against ionizing radiation. One of the most popular and used materials for this purpose is the concrete. The term "concrete" covers a wide range of

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compositions. Concrete is usually manufactured and poured just where a structure of this type of material is needed.

In the case of concrete used in a nuclear power plant, the purpose is either to provide structures to support the construction or to ensure the biological protection of the workers. The long operating experience provided by the existing nuclear power plants has proven that the concrete, successfully, fulfill both purposes. A concern related to the behavior of the concrete (and not only) aroused when the extension of the operating time of the Cernavoda NPP is asked. It has been observed that the materials suffer over time the so-called aging phenomenon, accentuated under the presence of intense radiation fields: neutrons and gamma. Even if, for the concrete used as shield, no serious changes were observed in terms of shielding performance, it is important to know if a doubling (for example) of the radiation flux to which a concrete is subjected will accentuate the internal changes of this material.

Irradiation of the concrete with ionizing radiation has a direct effect of breaking chemical or crystalline bonds, and it can also amplify the effect of other physical and chemical phenomena by increasing the internal temperature of the concrete.

Therefore, it is important to know the acceptable ranges for different values of characteristic parameters for the concrete, so that it does not significantly change of the required functions.

In this paper we have looked at how the concrete can be affected by the irradiation with neutrons and gamma radiation under the conditions of possible fluxes outside the core of the reactor.

2. Paper contents

In order to evaluate the radiation level in the shielded areas, one starts from defining the radiation source that requires shielding. As is known, some of the types of radiation in the ionizing radiation category do not require sophisticated protection measures due to the short path they have in ordinary materials (as alpha and beta radiation). Other ionizing radiations, those in the penetrating category, raise serious problems in terms of their shielding (as gamma and neutron radiation).

The main objective of the paper was to obtain calculation results that indicate the effect of the radiation state on the properties of the concrete used in the Cernavoda NPP, using the Monte Carlo method implemented in the MCNP6^{TM} ver.1 code [7].

2.1. Interactions of matter with neutrons

Although neutrons are assimilated to ionizing radiation, the fact that they do not have an electrical charge makes them unable to direct ionization because they do not interact with electrons of the atoms shell. Instead, they lose energy by interacting with atomic nuclei. As a result of these interactions, other radiation can be produced, capable of ionizing the atoms of the substance crossed by neutrons. Neutrons have about the same mass as hydrogen atoms, so they can transfer a large amount of their energy to a collision. A neutron-atom frontal collision transfers almost all the energy to the collided atom. Because the hydrogen nucleus is a proton, it will produce dense ionizations in the same manner as alpha particles. When the neutron loses almost all energy, it is easily absorbed into other nuclei.

2.2. Effects of radiation on the properties of concrete used in nuclear power plants

Compared to other building materials, concrete has good shielding properties against nuclear radiation, good long-term durability and high temperature resistance and relatively low construction costs. Therefore, concrete is widely used for primary and secondary shielding structures exposed to radiation and high temperatures in a nuclear power plants. In addition to being a basic material in building, concrete is used to build protective structures and interim storage facilities for spent nuclear fuel. The effects of radiation and temperature on the properties of concrete depend on a number of variables, such as the strenght of the radiation field, the temperature level and the exposure time. In addition to the effects of radiation and temperature, there is also a coupling effect between the two (i.e. the thermal effect is induced by radiation).

There are two types of radiation in nuclear power plants, neutron radiation and gamma radiation. The two types of radiation interact with the concrete in different ways.

In the nuclear power plants a variety of concrete materials, with different types of cement, aggregates and additives have been used. Some concretes are more sensitive to gamma radiation, and others are more sensitive to neutron radiation, depending on the materials used in the mix.

Photons interact with shielding materials in three different ways: photoelectric effect, Compton scattering and pair production. Following the interactions, the temperature of the material can be increased depending on the gamma radiation energy.

Neutron radiation interacts with the nuclei of atoms, however the interaction depends mainly on the kinetic energy of the neutrons. The amount of neutron radiation absorbed is usually determined by the neutron flux and the material type. The rate of neutron radiation is measured in units of flux and is expressed in terms of neutrons per square centimeter per second.

2.3. Input data for performing the concrete irradiation calculations

Calculations were made for neutron and photon sources; the sources were considered both very narrow beams of particles and flat, uniform sourface sources. The value of the source energy was varied for both types of source particles.

Three types of high density concrete, containing heavy elements such as iron, barium, and boron, were used as special additions to their composition.

Concrete no. 1 characterized by the fact that barium is the predominant element and has the following characteristics [6]:

Concrete, Barite (Type BA)

Density (g/cm^3) = 3.350000
Total atom density (atoms/b-cm) = 6.547E-02

Table 1. Concrete, Barite (Type BA)

				Atom	
Element	**Neutron ZA**	**Photon ZA**	**Weight Atom Fraction**	**Fraction**	**Density**
H	1001	1000	0.003585	0.109602	0.007175
O	8016	8000	0.311622	0.600189	0.039293
Mg	12000	12000	0.001195	0.001515	0.000099
Al	13027	13000	0.004183	0.004777	0.000313
Si	14000	14000	0.010457	0.011473	0.000751
S	16000	16000	0.107858	0.103654	0.006786
Ca	20000	20000	0.050194	0.038593	0.002527
Fe	26000	26000	0.047505	0.026213	0.001716
Ba	**-**	**56000**	**0.463400**	**0.103983**	**0.006808**
Total			0.999999	1.000000	0.065468

Concrete no. 2 characterized by the fact that barium is the predominant element, but other elements also appear: boron, potassium, zinc.

Concrete, Boron Frits-baryte

Density (g/cm^3) = 3.100000
Total atom density (atoms/b-cm) = 7.064E-02

Table 2. Concrete, Boron Frits-baryte

				Atom	
Element	**Neutron ZA**	**Photon ZA**	**Weight Atom Fraction**	**Fraction**	**Density**
H	1001	1000	0.005626	0.147522	0.010421
B	**-**	**5000**	**0.010449**	**0.025543**	**0.001804**
O	8016	8000	0.339596	0.560939	0.039625
F	9019	9000	0.002311	0.003215	0.000227
Na	11023	11000	0.012157	0.013975	0.000987
Mg	12000	12000	0.002311	0.002513	0.000177
Al	13027	13000	0.006430	0.006298	0.000445
Si	14000	14000	0.033256	0.031293	0.002211
S	16000	16000	0.091932	0.075769	0.005352
K	**19000**	**19000**	**0.001005**	**0.000679**	**0.000048**
Ca	20000	20000	0.062896	0.041474	0.002930
Mn	25055	25000	0.000201	0.000097	0.000007
Fe	26000	26000	0.022003	0.010413	0.000736
Zn	**30000**	**30000**	**0.006631**	**0.002679**	**0.000189**
Ba	- 5	6000	0.403195	0.077592	0.005481
Total			1.000000	1.000000	0.070641

Concrete no. 3 characterized by the fact that iron is the predominant element and contains phosphorus in a high proportion.

Concrete, Ferro-phosphorus

Density (g/cm^3) = 4.800000
Total atom density (atoms/b-cm) = 9.039E-02

Table 3. Concrete, Ferro-phosphorus

				Atom	
Element	**Neutron ZA**	**Photon ZA**	**Weight Atom Fraction**	**Fraction**	**Density**
H	1001	1000	0.005000	0.158643	0.014339
O	8016	8000	0.104000	0.207881	0.018790
Mg	12000	12000	0.002000	0.002632	0.000238
Al	13027	13000	0.004000	0.004741	0.000429
Si	14000	14000	0.034000	0.038715	0.003499
P	15031	15000	0.197000	0.203403	0.018385
Ca	20000	20000	0.042000	0.033514	0.003029
Fe	**26000**	**26000**	**0.612000**	**0.350471**	**0.031678**
Total			1.000000	1.000000	0.090387

The energy deposed in the concrete irradiated with gamma and neutron was calculated mainly as a measure of the dose received by the material. Several energy values of the particles in the range from 50 keV to 2 MeV for gamma and from 10 eV to 2 MeV for neutrons were considered. The concrete recipes from the specialized literature were used [6].

The model of the shield considered was a concrete block with dimensions 50x50x50cm.

The results were the energy averaged deposed in successive volumes of material, with a thickness of 10 cm, in the case of surface sources. When the sources emitted a narrow beam, the results were calculated for smaller volumes, in the direction of the beam, placed 10cm distance from each other.

Depending on the case for which the calculation was done, there have been varied the particle emitted by the source, the geometry of the source, the material of the shielding or the type of the calculated tally (score). In general, it was desired to calculate the energy deposed on the shield, at different depths. In the case of neutron sources, we calculated scores of the energy deposited by the neutrons emitted from the source, but also scores of the total energy deposed that adds the energy due to the secondary photons produced when the neutrons interact with the atoms of the concrete shield. It should be noted that, for all calculated cases, the strength of the particle source was considered 1.

In the specific case of a thermal reactor emitting both neutrons and photons, the doses produced by the neutrons are four to five orders of magnitude smaller than the gamma doses. Therefore, the main contribution to the increase of the temperature in the shielding is due to the energy deposed by the gamma radiation.

2.4. Thermal transfer equations for concrete in a nuclear unit subjected to radiation

An additional calculation was performed for the heat transfer in a volume of concrete subjected to neutron irradiation and gamma radiation to obtain a correlation between the level of irradiation of the concrete and the value of the measurable parameter - temperature. The modeling, assumptions and data used are conservative and generic and ware used for demonstration purposes, only to illustrate the temperature variation within a relatively large concrete slab, with the possibility of constantly maintaining the outside temperatures on both sides of the slab.

The calculations were performed for the case of heat dissipated from a barite concrete plate subjected to irradiation with gamma and neutron radiation.

From the calculations, it can be concluded that in the case of gamma radiation a maximum temperature is reached inside the concrete shield, at a distance from the exposed surface of the shield, slightly higher compared to that reached by the neutron radiation; however, the values of these distances being very close we can say that a maximum of the temperature in the material is reached about 10 cm from the irradiated surface

The maximum temperatures obtained by conservative hypotheses do not exceed 100°C so that an acceptable safety margin is maintained relative to the temperature of degradation of the concrete which is about 150 °C.

3. Results

The results obtained from the calculations with the MCNP code are summarized in the form of tables and figures. The figures associated with the types of sources used represent the energy deposed inside the protection shield.

Gamma surface source/concrete samples. Analyzing the values presented in Table 1-1 it can be seen that the energy deposed in the shield depends on the value of the energy of the source particles and the distance traveled by them inside the shield. When the energy is low (100 keV) only a very thin layer of the shield surface is affected by radiation (see Figure 1-1 a). When the energy of the radiation increases, the entire thickness of the shield is traversed but the value of the energy deposed decreases towards its external face.

Comparing the behavior of the concretes used, it can be seen that concrete no. 3 (iron content) is slightly less affected by radiation compared to the others (see Figure 1).

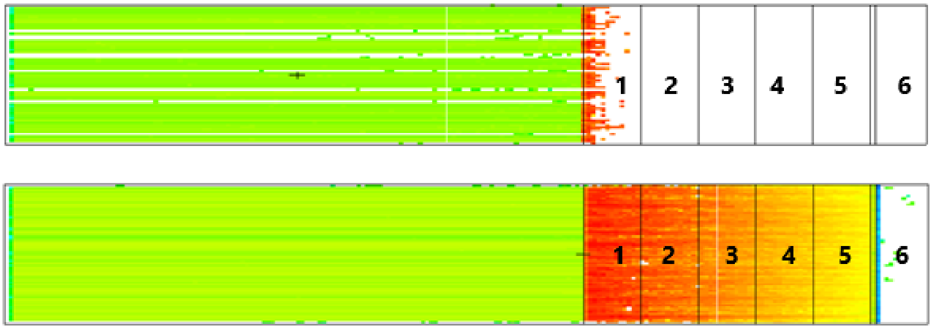

Figure 1. Gamma surface source/slice samples
a) energy 100 keV; b) energy 2 MeV

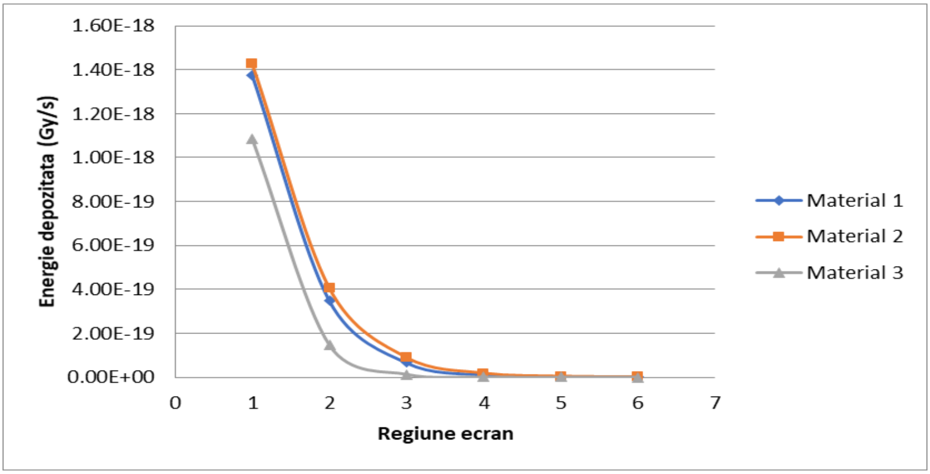

Figure 2. Variation of the energy deposed in the protection shield material for a surface gamma source with an energy of 1 MeV

Table 4. Energy deposed in concrete shield cells for a surface gamma source

Material	**Radiation energy**	**Energy deposed [Gy/s]**				
		100 keV	**500 keV**	**1MeV**	**1.5MeV**	**2MeV**
Material 1	Cell 1	1.83457E-19	8.15974E-19	1.37406E-18	1.85787E-18	2.31976E-18
	Cell 2	0.00000E+00	8.30661E-20	3.48492E-19	6.27205E-19	8.99769E-19
	Cell 3	0.00000E+00	5.95225E-21	6.69918E-20	1.70842E-19	2.92375E-19
	Cell 4	0.00000E+00	3.67574E-22	1.15706E-20	4.26319E-20	8.74651E-20
	Cell 5	0.00000E+00	2.11103E-23	1.88226E-21	1.00027E-20	2.48921E-20
	Cell 6	0.00000E+00	1.37994E-24	4.40055E-22	3.46031E-21	1.02521E-20

Material	Radiation energy	Energy deposed [Gy/s]				
		100 keV	500 keV	1MeV	1.5MeV	2MeV
Material 2	Cell 1	1.97978E-19	8.52750E-19	1.42576E-18	1.91522E-18	2.38424E-18
	Cell 2	0.00000E+00	1.08209E-19	4.03525E-19	7.05613E-19	9.93568E-19
	Cell 3	0.00000E+00	9.81548E-21	8.86343E-20	2.12318E-19	3.52244E-19
	Cell 4	0.00000E+00	7.96880E-22	1.73193E-20	5.86317E-20	1.15388E-19
	Cell 5	0.00000E+00	5.57580E-23	3.22874E-21	1.52856E-20	3.59659E-20
	Cell 6	0.00000E+00	5.52232E-24	8.23472E-22	5.62610E-21	1.57126E-20
Material 3	Cell 1	1.24308E-19	5.69386E-19	1.08540E-18	1.54361E-18	1.96634E-18
	Cell 2	0.00000E+00	3.36426E-20	1.46446E-19	3.02279E-19	4.69916E-19
	Cell 3	0.00000E+00	1.06704E-21	1.31574E-20	4.31419E-20	8.72577E-20
	Cell 4	0.00000E+00	2.93572E-23	1.03732E-21	5.39093E-21	1.44627E-20
	Cell 5	0.00000E+00	6.96364E-25	7.38638E-23	6.19177E-22	2.23250E-21
	Cell 6	0.00000E+00	6.41306-26	1.11809E-23	1.38794E-22	6.63657E-22

Gamma beam / concrete samples. From the analysis of the results obtained in this case, it can be seen that the values have a similar behavior to the previous ones, the difference is that the energy values deposed in successive cells decrease more because the statistics are made on much smaller volumes, where the calculated value is constant (see Figure 3 and Table 5).

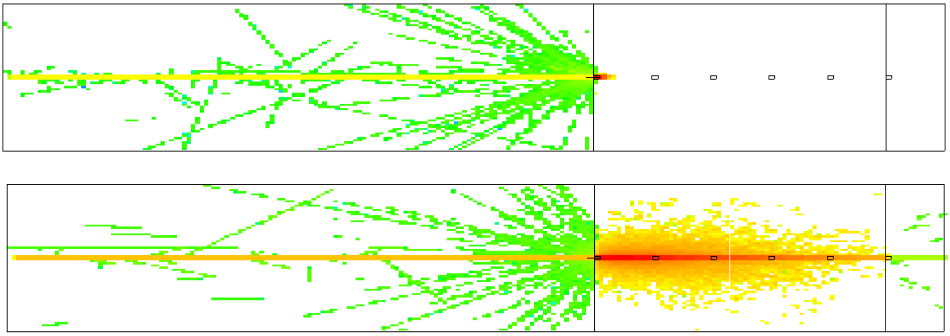

Figure 3. Gamma beam source / slice samples

a) energy 100 keV; b) energy 2 MeV

b)

Table 5. Energy deposed in the concrete shield cells for a gamma beam source

Material	Radiation energy	Energy deposed [Gy/s]				
		100 keV	500 keV	1MeV	1.5MeV	2MeV
Material 1	Cell 1	4.45947E-15	3.14520E-15	4.41685E-15	5.79002E-15	7.17532E-15
	Cell 2	0.00000E+00	1.70895E-16	6.54425E-16	1.24033E-15	1.85707E-15

Material	**Radiation energy**	**Energy deposed [Gy/s]**				
		100 keV	**500 keV**	**1MeV**	**1.5MeV**	**2MeV**
	Cell 3	0.00000E+00	6.75616E-18	8.43915E-17	2.55329E-16	4.46400E-16
	Cell 4	0.00000E+00	4.63442E-19	1.02140E-17	4.72718E-17	1.06931E-16
	Cell 5	0.00000E+00	0.00000E+00	1.68703E-18	8.30410E-18	2.44708E-17
	Cell 6	0.00000E+00	0.00000E+00	2.88959E-19	1.11158E-18	6.21116E-18
Material 2	Cell 1	4.66119E-15	3.04353E-15	4.41608E-15	5.82616E-15	7.21862E-15
	Cell 2	0.00000E+00	2.09436E-16	7.40902E-16	1.37118E-15	2.04654E-15
	Cell 3	0.00000E+00	1.26553E-17	1.15276E-16	2.94935E-16	5.53938E-16
	Cell 4	0.00000E+00	7.62368E-19	1.74144E-17	6.51326E-17	1.55583E-16
	Cell 5	0.00000E+00	0.00000E+00	3.04118E-18	1.42339E-17	4.06402E-17
	Cell 6	0.00000E+00	0.00000E+00	3.64302E-19	3.35037E-18	1.12988E-17
Material 3	Cell 1	1.90371E-15	2.30003E-15	4.12053E-15	5.64695E-15	7.03796E-15
	Cell 2	0.00000E+00	4.91456E-18	2.58130E-16	6.03109E-16	9.97119E-16
	Cell 3	0.00000E+00	1.03594E-18	1.45757E-17	5.71218E-17	1.28848E-16
	Cell 4	0.00000E+00	0.00000E+00	5.73323E-19	6.08518E-18	1.66950E-17
	Cell 5	0.00000E+00	0.00000E+00	2.59176E-20	8.16350E-19	2.91504E-18
	Cell 6	0.00000E+00	0.00000E+00	0.00000E+00	1.38794E-22	1.89684E-19

Surface source neutrons / slice samples. The calculations performed for the neutron source considered obtaining two energy deposed tally, one produced by neutrons and the other produced by neutrons together with photons produced by interaction with the atoms of the shielding material.

For fast neutrons (over 1 MeV), the total energy is almost twice as high as the energy due to neutrons alone.

It can also be seen that the results for neutrons are approximately the same order of magnitude as those obtained for the gamma source, provided that the source intensity expressed in particles per second has the same value.

From Figure 6 it can be seen that concrete no. 2 absorbs more neutron energy than other materials, a phenomenon that can be explained by the fact that that concrete contains boron which has a large neutron capture section (see Figure 5). Unlike this, concrete no. 1 has a much smaller neutron absorption section (see Figure 6) which makes it less efficient for neutron attenuation but instead accumulates less energy.

Regarding the deposed of energy in the shielding material, it can be seen from the tables 6 – 9 that the energy due to secondary gamma radiation is relatively higher than that due to neutrons, more obviously in the case of thermal neutrons.

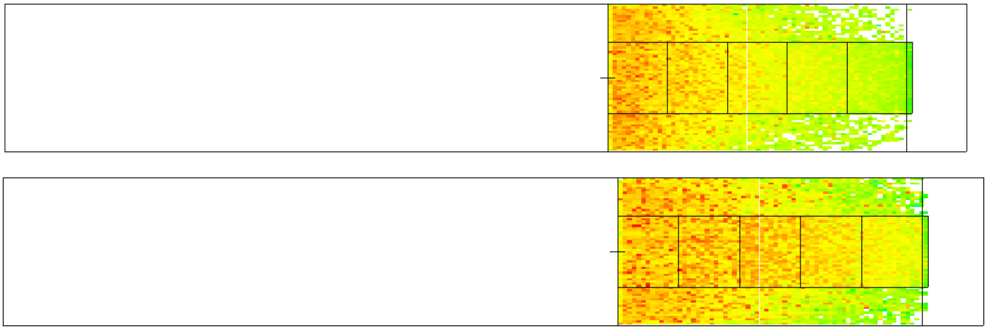

Figure 4. Surface neutron source / slice samples
a) energy 100 keV; b) energy 2 MeV

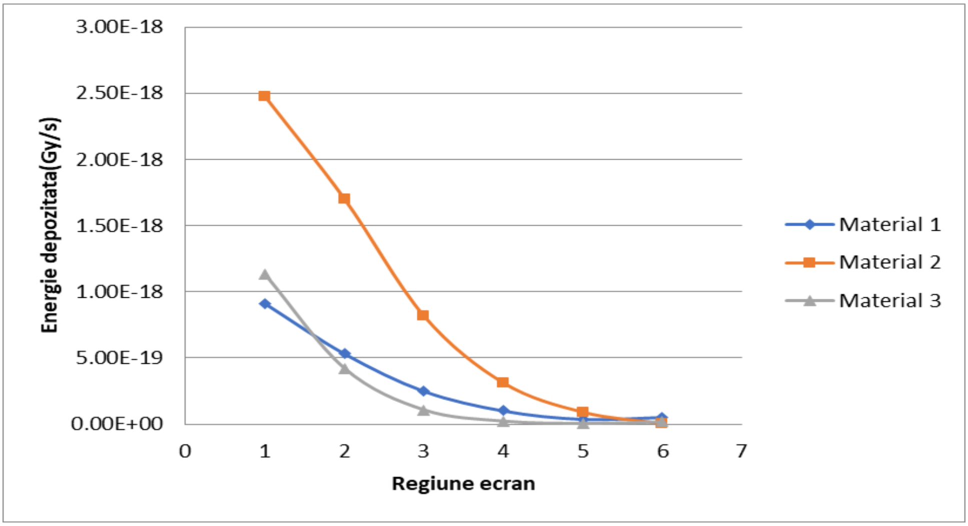

Figure 5. Variation of energy deposed in the shielding material
by neutrons with energy of 1 MeV

Neutron beam / concrete samples. The results obtained for this case have a behavior similar to those for the surface neutron source.

In order to be able to state some considerations related to the limits of concrete irradiation proposed by international entities, we make some observations related to a real exposure situation, correlated with the results obtained in this paper.

Table 6. Energy deposed in concrete shield sections for a surface neutron source with energy from 0.5 eV to 500 eV

Material and cell nr.	**Radiation energy**	**Energy deposed [Gy/s]**				
		0.5 eV	**1 eV**	**10 eV**	**100 eV**	**500 eV**
Material 1 Cell 1	neutrons	4.88228E-21	4.92646E-21	5.02870E-21	5.99077E-21	6.28929E-21
	n+gamma	3.19923E-18	3.11216E-18	2.97714E-18	2.15141E-18	2.02373E-18
Material 1 Cell 2	neutrons	1.87228E-21	1.94158E-21	2.03757E-21	2.67953E-21	2.95081E-21
	n+gamma	1.89920E-18	1.86414E-18	1.76207E-18	1.46651E-18	1.39106E-18
Material 1 Cell 3	neutrons	5.56241E-22	5.94329E-22	6.36393E-22	9.84210E-22	1.03333E-21
	n+gamma	7.20107E-19	7.16207E-19	6.88406E-19	6.46483E-19	6.06536E-19
Material 1 Cell 4	neutrons	1.54068E-22	1.68289E-22	1.87212E-22	2.81152E-22	3.39167E-22
	n+gamma	2.42589E-19	2.43657E-19	2.41260E-19	2.33594E-19	2.31575E-19
Material 1 Cell 5	neutrons	3.89183E-23	4.63967E-23	5.00895E-23	7.84499E-23	1.01820E-22
	n+gamma	7.23657E-20	7.41900E-20	7.43321E-20	7.95626E-20	7.73415E-20
Material 1 Cell 6	neutrons	5.83582E-21	3.04288E-21	2.67435E-26	6.26940E-27	1.33286E-20
	n+gamma	2.91981E-20	2.60018E-20	2.23368E-20	2.73483E-20	3.87071E-20
Material 2 Cell 1	neutrons	4.83285E-18	4.67068E-18	4.08561E-18	4.21726E-18	3.50936E-18
	n+gamma	5.48157E-18	5.32237E-18	4.68143E-18	4.68590E-18	3.90167E-18
Material 2 Cell 2	neutrons	1.07004E-20	2.62598E-20	1.88193E-19	4.46828E-19	6.57668E-19
	n+gamma	4.62358E-20	6.85209E-20	2.70551E-19	5.58088E-19	7.93851E-19
Material 2 Cell 3	neutrons	0.00000E+00	4.34286E-23	5.32103E-21	1.91635E-20	4.69277E-20
	n+gamma	3.73867E-21	2.56926E-21	1.17248E-20	3.02108E-20	6.51251E-20
Material 2 Cell 4	neutrons	0.00000E+00	0.00000E+00	3.32393E-23	9.16425E-22	3.03924E-21
	n+gamma	4.26041E-22	4.16154E-22	4.00013E-22	1.79949E-21	5.25676E-21
Material 2 Cell 5	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	3.14773E-23	2.83439E-22
	n+gamma	1.15360E-22	2.97312E-22	3.21059E-24	4.26462E-23	9.42865E-22
Material 2 Cell 6	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	0.00000E+00	2.58024E-22	0.00000E+00	3.77267E-25	2.15153E-24
Material 3 Cell 1	neutrons	4.19389E-22	3.98214E-22	3.42344E-22	3.89357E-22	8.03041E-22
	n+gamma	3.35883E-18	3.22291E-18	2.79995E-18	2.43919E-18	2.15633E-18
Material 3 Cell 2	neutrons	1.74977E-23	2.21333E-23	3.24870E-23	4.62863E-23	5.89155E-23
	n+gamma	6.19120E-19	6.32599E-19	7.01937E-19	7.88715E-19	8.23822E-19
Material 3	neutrons	3.26348E-25	4.22401E-25	9.21501E-25	1.69335E-24	2.87866E-24

Material and cell nr.	Radiation energy	Energy deposed [Gy/s]				
		0.5 eV	1 eV	10 eV	100 eV	500 eV
Cell 3	n+gamma	8.88329E-20	8.88829E-20	1.10673E-19	1.13813E-19	1.28390E-19
Material 3 Cell 4	neutrons	3.62239E-27	7.83556E-27	8.78307E-27	3.25523E-26	4.34288E-26
	n+gamma	1.47086E-20	1.34286E-20	1.60536E-20	1.55463E-20	2.06675E-20
Material 3 Cell 5	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	4.79796E-28	9.16360E-28
	n+gamma	3.24572E-21	1.66695E-21	2.02725E-21	2.01511E-21	4.31403E-21
Material 3 Cell 6	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	1.72361E-21	1.32004E-22	4.05637E-22	3.22617E-22	2.25928E-21

Table 7. Energy deposed in concrete shield sections for a surface neutron source with energy from 100 keV to 2 MeV

Material and cell nr.	Radiation energy	Energy deposed [Gy/s]				
		100 keV	500 keV	1 MeV	1.5 MeV	2 MeV
Material 1 Cell 1	neutrons	8.37210E-20	3.22659E-19	5.62399E-19	7.45515E-19	9.13436E-19
	n+gamma	3.66254E-19	5.99338E-19	9.01352E-19	1.18426E-18	1.50014E-18
Material 1 Cell 2	neutrons	2.47621E-20	1.66136E-19	3.06818E-19	4.36109E-19	5.33628E-19
	n+gamma	3.41767E-19	4.70911E-19	6.42970E-19	8.28367E-19	1.03467E-18
Material 1 Cell 3	neutrons	7.13556E-21	6.52581E-20	1.28228E-19	1.98381E-19	2.50366E-19
	n+gamma	2.36394E-19	3.01241E-19	3.63675E-19	4.72381E-19	5.81828E-19
Material 1 Cell 4	neutrons	2.19863E-21	2.33916E-20	4.92430E-20	8.12375E-20	1.01960E-19
	n+gamma	1.26996E-19	1.75520E-19	1.93884E-19	2.42734E-19	2.92052E-19
Material 1 Cell 5	neutrons	6.81121E-22	7.60383E-21	1.65588E-20	2.94176E-20	3.78674E-20
	n+gamma	5.55878E-20	8.06084E-20	8.25830E-20	1.01701E-19	1.23220E-19
Material 1 Cell 6	neutrons	1.29722E-20	3.95239E-20	7.89576E-21	2.58164E-20	2.36611E-20
	n+gamma	3.11291E-20	6.47432E-20	3.05437E-20	5.10213E-20	5.24283E-20
Material 2 Cell 1	neutrons	1.64827E-18	1.95022E-18	1.72697E-18	2.18605E-18	2.47585E-18
	n+gamma	1.84231E-18	2.10025E-18	1.81106E-18	2.29338E-18	2.58971E-18
Material 2 Cell 2	neutrons	8.48808E-19	1.15687E-18	7.54770E-19	1.49705E-18	1.70268E-18
	n+gamma	9.76967E-19	1.30565E-18	8.35868E-19	1.62514E-18	1.82872E-18
Material 2 Cell 3	neutrons	1.79409E-19	3.64982E-19	2.63305E-19	6.82801E-19	8.18979E-19
	n+gamma	2.15256E-19	4.26119E-19	3.00336E-19	7.57607E-19	8.96110E-19
Material 2	neutrons	2.75892E-20	8.03412E-20	7.05141E-20	2.45512E-19	3.13622E-19

Material and cell nr.	**Radiation energy**	**Energy deposed [Gy/s]**				
		100 keV	**500 keV**	**1 MeV**	**1.5 MeV**	**2 MeV**
Cell 4	n+gamma	3.41370E-20	9.77362E-20	8.17299E-20	2.77445E-19	3.49106E-19
Material 2 Cell 5	neutrons	2.62990E-21	1.25115E-20	1.42598E-20	6.78940E-20	9.17125E-20
	n+gamma	3.53669E-21	1.73164E-20	1.74746E-20	7.82685E-20	1.03389E-19
Material 2 Cell 6	neutrons	3.22317E-24	1.22168E-24	8.23328E-26	8.85613E-21	4.99008E-21
	n+gamma	2.55088E-22	3.94721E-22	9.00545E-22	1.02598E-20	6.50945E-21
Material 3 Cell 1	neutrons	1.09350E-19	4.77642E-19	7.28081E-19	9.51129E-19	1.13285E-18
	n+gamma	1.96422E-18	2.00479E-18	1.88684E-18	2.34113E-18	2.49976E-18
Material 3 Cell 2	neutrons	6.28412E-21	9.31243E-20	1.38034E-19	3.63894E-19	4.21816E-19
	n+gamma	1.23776E-18	1.60070E-18	1.23481E-18	1.91106E-18	1.86078E-18
Material 3 Cell 3	neutrons	2.02105E-22	1.02228E-20	2.03329E-20	9.07517E-20	1.07437E-19
	n+gamma	3.19088E-19	5.95317E-19	4.65757E-19	8.86116E-19	8.74932E-19
Material 3 Cell 4	neutrons	6.56267E-24	9.63902E-22	2.82010E-21	1.96345E-20	2.22595E-20
	n+gamma	5.62714E-20	1.51526E-19	1.34140E-19	3.01786E-19	2.93406E-19
Material 3 Cell 5	neutrons	1.90046E-25	9.49108E-23	3.26778E-22	3.57527E-21	3.87305E-21
	n+gamma	1.11317E-20	2.99717E-20	3.02216E-20	7.53510E-20	7.50977E-20
Material 3 Cell 6	neutrons	0.00000E+00	1.08286E-23	0.00000E+00	0.00000E+00	1.59405E-20
	n+gamma	3.58474E-21	7.53927E-21	7.90282E-21	1.76538E-20	3.63903E-20

Following the results obtained for particles (neutrons and gamma) with an energy of 1MeV, because this value is a reasonable average of the energies of the particles emitted by a thermal reactor, it can be seen that the energy stored in cell 1 is the largest, in the range of 1.E-15Gy/s.

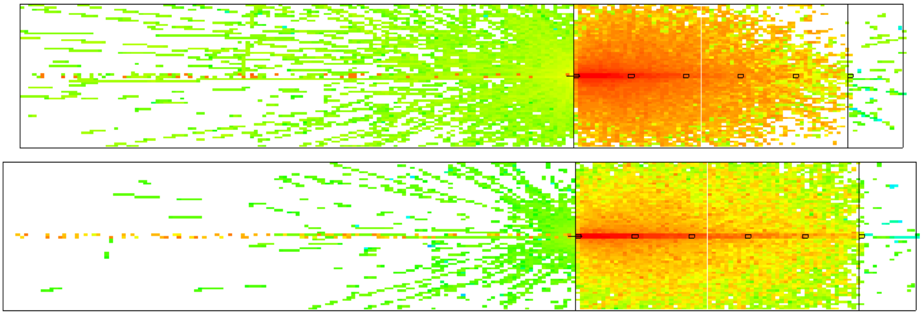

Figure 6. Narrow beam neutron source / slice samples
a) energy 100 keV; b) energy 2 MeV

Table 8. Energy deposed in the cells of the concrete shield for a neutron source beam with energy from 0.5 eV to 500 eV

Material and cell nr.	**Radiation energy**	**Energy deposed [Gy/s]**				
		0.5 eV	**1 eV**	**10 eV**	**100 eV**	**500 eV**
Material 1 Cell 1	neutrons	9.85008E-18	9.83549E-18	9.83096E-18	1.00445E-17	1.05813E-17
	n+gamma	5.31836E-16	5.18744E-16	4.93125E-16	2.80398E-16	2.78202E-16
Material 1 Cell 2	neutrons	1.83792E-18	1.83523E-18	1.86193E-18	1.91409E-18	2.04255E-18
	n+gamma	1.50700E-16	1.46644E-16	1.41951E-16	7.90305E-17	8.12870E-17
Material 1 Cell 3	neutrons	3.37644E-19	3.43667E-19	3.44587E-19	3.66256E-19	3.95139E-19
	n+gamma	2.62756E-17	2.40849E-17	2.45726E-17	1.48594E-17	1.52173E-17
Material 1 Cell 4	neutrons	5.44260E-20	5.96772E-20	6.21011E-20	6.40608E-20	7.13886E-20
	n+gamma	4.84528E-18	5.67312E-18	5.43611E-18	3.73630E-18	3.83140E-18
Material Cell 5	neutrons	8.13354E-21	1.14569E-20	1.45770E-20	1.23156E-20	1.17160E-20
	n+gamma	9.44030E-19	1.24363E-18	1.23547E-18	7.82850E-19	4.62410E-19
Material 1 Cell 6	neutrons	1.86208E-18	9.39047E-25	3.17022E-24	0.00000E+00	0.00000E+00
	n+gamma	1.92219E-18	9.37764E-25	7.79546E-22	0.00000E+00	0.00000E+00
Material 2 Cell 1	neutrons	3.56383E-14	2.67440E-14	9.50939E-15	6.50176E-15	2.90107E-15
	n+gamma	3.61685E-14	2.71582E-14	9.67080E-15	6.55240E-15	2.92511E-15
Material 2 Cell 2	neutrons	2.05187E-17	4.78351E-17	8.53630E-17	1.05707E-16	6.90131E-17
	n+gamma	2.25291E-17	5.06231E-17	9.16465E-17	1.10677E-16	7.18916E-17
Material 2 Cell 3	neutrons	0.00000E+00	0.00000E+00	1.27068E-18	2.63660E-18	2.08930E-18
	n+gamma	0.00000E+00	0.00000E+00	1.28930E-18	2.71504E-18	2.19215E-18
Material 2 Cell 4	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Material 2 Cell 5	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Material 2 Cell 6	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Material 3 Cell 1	neutrons	5.13670E-19	3.77710E-19	1.81115E-19	5.99249E-19	8.03041E-22
	n+gamma	4.95778E-16	3.74529E-16	1.39977E-16	5.17870E-17	2.15633E-18
Material 3 Cell 2	neutrons	1.12389E-21	1.44720E-21	1.43760E-21	1.63972E-21	5.89155E-23
	n+gamma	1.40661E-17	1.33309E-17	1.60057E-17	1.12433E-17	8.23822E-19
Material 3 Cell 3	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	4.19014E-23	2.87866E-24
	n+gamma	1.92272E-18	1.16427E-18	3.03272E-19	1.11987E-18	1.28390E-19
Material 3 Cell 4	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	4.34288E-26
	n+gamma	0.00000E+00	0.00000E+00	6.03098E-19	9.93335E-19	2.06675E-20
Material 3 Cell 5	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	9.16360E-28
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	4.31403E-21
Material 3 Cell 6	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	2.25928E-21

Table 9. Energy deposed in concrete shield cells for a neutron source beam with energy from 100 keV to 2 MeV

Material and cell nr.	Radiation energy	Energy deposed [Gy/s]				
		100 kev	500kev	1 MeV	1.5 MeV	2 MeV
Material 1 Cell 1	neutrons	1.68816E-16	6.04750E-16	1.04897E-15	1.36950E-15	1.72014E-15
	n+gamma	2.07653E-16	6.40731E-16	1.09380E-15	1.42280E-15	1.80563E-15
Material 1 Cell 2	neutrons	1.31697E-17	1.34985E-16	2.31985E-16	3.37962E-16	4.27707E-16
	n+gamma	1.68514E-17	1.47579E-16	2.45758E-16	3.58669E-16	4.60816E-16
Material 1 Cell 3	neutrons	9.26589E-19	2.83608E-17	5.47580E-17	8.36475E-17	1.05344E-16
	n+gamma	1.39513E-18	3.09921E-17	5.79899E-17	8.90920E-17	1.13731E-16
Material 1 Cell 4	neutrons	6.15167E-20	5.89906E-18	1.03903E-17	2.00214E-17	2.56941E-17
	n+gamma	3.29121E-19	6.50317E-18	1.12862E-17	2.19227E-17	2.82062E-17
Material 1 Cell 5	neutrons	2.72046E-21	1.24744E-18	2.29280E-18	5.00629E-18	6.12193E-18
	n+gamma	2.60741E-19	1.45843E-18	2.50561E-18	5.42395E-18	7.26500E-18
Material 1 Cell 6	neutrons	1.77879E-18	1.08734E-20	1.35017E-18	1.36784E-18	6.72123E-19
	n+gamma	1.82318E-18	4.18108E-20	1.34833E-18	1.36597E-18	6.71870E-19
Material 2 Cell 1	neutrons	6.57342E-16	1.35042E-15	3.11419E-15	2.36754E-15	3.00951E-15
	n+gamma	6.59730E-16	1.35058E-15	3.11276E-15	2.36810E-15	3.01122E-15
Material 2 Cell 2	neutrons	2.48085E-17	8.44508E-17	5.35882E-17	4.07273E-16	6.05265E-16
	n+gamma	2.58725E-17	8.58802E-17	5.41268E-17	4.07981E-16	6.06469E-16
Material 2 Cell 3	neutrons	1.82224E-18	5.44622E-18	1.37159E-18	6.80905E-17	1.16868E-16
	n+gamma	2.24703E-18	6.11540E-18	1.36971E-18	6.84337E-17	1.17132E-16
Material 2 Cell 4	neutrons	3.60838E-20	6.76370E-19	2.29387E-19	1.17722E-17	2.30443E-17
	n+gamma	7.29665E-20	7.96675E-19	3.80995E-19	1.19262E-17	2.32047E-17
Material 2 Cell 5	neutrons	1.84059E-20	2.58869E-21	3.59377E-20	1.47563E-18	5.16009E-18
	n+gamma	1.94303E-20	2.58515E-21	3.60700E-20	1.47546E-18	5.22964E-18
Material 2 Cell 6	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
Material 3 Cell 1	neutrons	3.57838E-16	9.30960E-16	1.74273E-15	1.63132E-15	1.92369E-15
	n+gamma	3.71770E-16	9.38598E-16	1.80289E-15	1.68252E-15	2.01893E-15
Material 3 Cell 2	neutrons	5.64200E-18	6.13523E-17	5.26334E-17	2.53483E-16	2.43631E-16
	n+gamma	1.48546E-17	7.20114E-17	6.14887E-17	2.71092E-16	2.65113E-16
Material 3 Cell 3	neutrons	1.17749E-19	3.89577E-18	1.26204E-18	3.67117E-17	2.73571E-17
	n+gamma	3.42472E-18	7.75754E-18	3.15030E-18	4.41184E-17	3.25150E-17
Material 3 Cell 4	neutrons	5.92894E-23	1.98695E-19	1.11864E-19	5.04796E-18	2.74563E-18
	n+gamma	7.93135E-19	1.02216E-18	1.15594E-18	6.21614E-18	4.45705E-18
Material 3 Cell 5	neutrons	0.00000E+00	2.09552E-20	1.40126E-21	5.98168E-19	3.02777E-19
	n+gamma	6.24890E-20	7.28019E-20	1.69472E-19	1.27446E-18	9.37602E-19
Material 3 Cell 6	neutrons	0.00000E+00	0.00000E+00	0.00000E+00	1.14183E-18	0.00000E+00
	n+gamma	0.00000E+00	0.00000E+00	0.00000E+00	1.14244E-18	0.00000E+00

In the case of the CANDU reactor, the neutron flux in the area where the concrete vault is placed is approximately 1.0 E +14 n/cm^{2}s. The gamma radiation flux emitted by the irradiated fuel is higher than that of neutrons, but for the present discussion we will consider that it is of the same order of magnitude as the neutron flux. Under conditions of equal intensity of particle sources, we can approximate that the storage of total energy in cell 1 of the shield is about 5.6Gy/s, which means a dose of about 4.84 E+5 Gy/year.

Under the most restrictive conditions proposed by ANSI [1], it follows that the concrete studied here could be irradiated for about 207 years or that a concrete that would be subjected to a neutron flux of 1.0 E+19 n/cm2 would receive a dose due to neutrons with energy average of 1MeV, of the order of thousands of Gy.

At this level of radiation exposure, the temperature of the concrete of the reactor vault will increase most in the exposed region closest to the radiation source, cell 1, which is about 10cm thick. Under normal operating conditions, the concrete caisson is permanently cooled so that the temperature at the surface of the inner wall is about 50 °C, which ensures that the temperature inside the shield will not reach values above the allowable limits.

It should be noted that in this paper we have addressed the irradiation of concrete that can be used as a structural or shielding material in nuclear / radiological installations only in terms of increasing the internal temperature in conditions of exposure to neutron flux and gamma radiation. The effect of irradiating materials is much more complex and consists of physical and chemical phenomena that can contribute more to internal degradation: breaking of chemical bonds, uneven expansion of constituent components, loss of water from internal pores, etc. From the strict point of view of irradiation (especially with neutrons), an important phenomenon is the activation of constituent elements, a phenomenon that can affect the ability to attenuate radiation.

It could be seen from the results that the radiation attenuation properties were maintained in all cases of exposure, so the simple heating of the concrete does not affect the qualities of radiation protection shield.

4. Conclusions

The energy deposed at different depths inside a concrete plate was calculated considering neutrons and photons emitted from an external source. Radiation sources were modeled as a narrow beam or as a surface source.

Three types of special concrete were used, but no significant variation of the calculated values determined by the composition of the concrete was observed; a slight increase in the energy deposed in the concrete containing boron is normal because boron is a good neutron absorber.

The conclusion of the paper was that the concrete exposed to radiation, under conservative but realiste conditions, will not suffer temperature increases above the permitted limits and will not affect the radiation shielding qualities for periods of time comparable to the life of a nuclear power plant.

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