

Use of Concrete as a Biological Shield from Ionising Radiation

Some aspects of the Utilisation of Nuclear Energy and its feasibility and Sustainability

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ABSTRACT

The controversy over the use of nuclear energy fundamentally arises from the three main considerations: from its safety, from its long term sustainability, and finally from its potential to reduce greenhouse gas emissions. Following the Fukushima nuclear plant accident, caused by the exceptionally strong earthquake and tsunami, the potential for the safe use of the nuclear energy in Japan became of concern to the authorities, to the industry and to the population in general. The current paper addresses the problem of safety of nuclear plants, and specifically the design and construction of reliable biological shields, capable of protecting public from the ionising radiation. The explicit emphasis is made on the potential use of local materials, including Portland cements, Pozzolans, admixtures and additives, and the variety of natural aggregates, as well as heavy weight aggregates, consisting of the industrial steel by-products. Both the theory and practice of shield construction are discussed.

Keywords: Nuclear plants, radiation shielding, design and construction, safety aspects, use of local materials.

SUSTAINABILITY AND NUCLEAR ENERGY

The report compiled in October 2006 by Sir Nicholas Stern, a former Chief Economist with the World Bank claims that without an immediate reduction in global greenhouse gas emissions the world is heading for the period of economic and social instability, which will exceed the aftermath of combined effects of the two World Wars and the Great Depression. Peaceful use of nuclear energy may then become an important part of replacing fossil fuels with solar, wind and hydraulic power plants. The estimated global uranium reserves are of the order of two million tonnes, with the mining cost averaging some US\$80 per kilogram of ore. On the negative side there are concerns about the safety of Nuclear Reactors and the contravention of the Nuclear Explosions (Prohibition and Inspections) Act of 1998. Recent explosion of the atomic bomb in North Korea seems to prove that the Act can be violated without any major consequences for the offender. There are of course immense benefits to humanity in the use of Nuclear Medicine. Thus, the protection of personnel from the possible exposure to ionising nuclear radiation is of paramount importance. Proper design and construction of biological shields as a protection from radiation is essential, if the industrial and medical use of nuclear energy is to succeed. (Samarin, August 2001).

NECESSARY AND SUFFICIENT CONDITIONS FOR RADIATION SHIELDING CONCRETE

Although by comparison with other construction materials used in nuclear reactors concrete has many advantages when it is utilised as a radiation shield, a set of conflicting requirements must be met in the selection of ingredients and mix proportions of concrete designed for the optimum attenuation of both gamma and neutron radiation.

Gamma rays can be attenuated by photoelectric absorption, electron-pair production and Compton absorption and scattering. The Compton Effect, in general, is greatest for medium energy quanta and in absorbers of relatively low atomic weight. At lower energies photoelectric absorption is more prevalent, and at high energies pair-production predominates. In concrete, for gamma ray energies in the range from one to ten MeV, attenuation is almost entirely due to Compton absorption and scattering. At energies greater than 10 MeV, the pair-production process becomes increasingly important. For similar thickness of steel and concrete, gamma rays are weakened approximately in proportion to the density of material.

In addition to absorbing gamma rays, reactor shields have to attenuate neutrons. Neutrons are usually classified according to their energy. In a reactor high-energy free neutrons are those, which possess energies of greater than 10 MeV. Neutrons with energies in the range of 10 MeV to 20 keV are fast neutrons, from 20 keV to 100 eV they are known as intermediate, from 100 eV to 0.025 eV neutrons are epithermal, and at 0.025 eV they are classified as thermal or slow neutrons. The intensity of neutron radiation is described by the neutron flux, which is the number of neutrons passing through unit area in unit time, or the product of number of neutrons per unit volume and their mean speed. In a nuclear reactor the flux is generally of the order of 10^{16} to $10^{18} \text{ m}^{-2} \text{ s}^{-1}$. For efficient neutron shielding, concrete must contain some heavy elements, which are capable to slow down fast neutrons, and a sufficient quantity of hydrogen to slow down the intermediate and to absorb the slow neutrons.

Water, which is the main source of hydrogen in concrete, can be present in cement paste in a free, adsorbed and chemically combined state. Some aggregate may also contain water, as part of constituent minerals. Physical adsorption involves only van der Waals forces, and in a chemical adsorption, or chemisorption transfer of electrons also takes place.

Free water, which is not chemically combined in the process of cement hydration, will be ultimately lost, through the process of diffusion. The process will be accelerated, if the temperature of concrete is increased above 100°C . Some of the adsorbed water may also be lost at high temperatures.

The amount of chemically bound water is influenced by the mineral composition of Portland cement, by the age of cement paste, by the water-cement ratio of concrete and the environment (temperature, humidity) to which this concrete is exposed.

The chemically bound water W_b can be approximately calculated, using the following relationship (Copeland, L.E, *et al*, 1960): -

$$W_b/C = a_1(C_3S) + a_2(C_2S) + a_3(C_3A) + a_4(C_4AF)$$

where C is the cement content, and C_3S , C_2S etc, are the calculated fractional contents of the tricalcium silicate, dicalcium silicate, etc., respectively.

For example, at the water-cement ratio of 0.6 the parameters a_i for a 13 year old concrete are: $a_1 = 0.230$, $a_2 = 0.196$, $a_3 = 0.522$ and $a_4 = 0.109$.

For a typical Australian Portland cement composition, the calculated value of W_b becomes approximately 21%. This is slightly less than the value of 23% by weight of cement, which is generally considered as common for well-matured pastes of ordinary Portland cements, and represents about half of the hydrogen content required for the optimum neutron attenuation in concrete. In such case it is important to prevent the build up of heat in the radiation shield, in order to retain as much of the adsorbed water as possible. Theoretical relationship between diffusivity, cement pore structure, temperature and humidity can provide an indication of the

extent to which evaporable water can be retained in a given concrete at the specific severity of exposure (Samarin, 1985).

Radiation in a nuclear reactor can be divided into three types: direct, scattered and leakage. The calculation of thickness of a reactor shield is usually based upon the concept of half-thickness and the cumulative effect of succeeding layers of different materials, such as lead, steel and concrete, each of which halves the intensity of radiation penetrating it. As neutron radiation penetrates concrete, the neutrons are absorbed producing heat and the secondary gamma rays are emitted. All bodies, including air, which are subjected to primary radiation become radioactive and subsequently emit secondary radiation, potentially damaging to health. The absorption of secondary gamma rays in concrete together with any incident gamma rays also produces heat, and due to low thermal conductivity of concrete, this can result in a significant temperature rise. Temperatures of the order of 250⁰ C have been reported.

Concrete in a biological shield must be thoroughly compacted to exclude the entrapped air as much as possible. There should not be any measurable segregation of paste and aggregate – a demanding task, as the differences in the densities of these two phases in dense weight concrete are quite large.

Unlike entrapped air, small amounts of deliberately entrained air can be beneficial in reducing the rate and the total volume of water bleeding to the surface of fresh concrete. This helps to prevent the formation of capillaries and to retain some of the free water, thus assisting the process of cement hydration. The ultimate loss of adsorbed water can also be reduced. Void size distribution in air-entrained concrete is usually in the range from about 1µm to 3000µm in radius. However, vibration at high frequencies and low amplitude has the potential of removing the air bubbles with the radius above 1000µm. Up to 1% of air-entrainment with average radius of the bubble of 500µm should not adversely affect the shielding effectiveness of dense weight concrete. Commonly used aggregates include industrial waste materials such as scrap iron, steel punchings, iron shot and ball bearings, with the bulk densities of the order of 7500 kg/m³. Natural heavy weight aggregates include ilmenite haematite, magnetite, goethite and limonite. Please note that goethite and limonite contain chemically bound water, which should assist the attenuation of fast neutrons, but they are not as dense as ilmenite, haematite and magnetite. Fixed water in goethite is estimated at about 10 to 11 percent and in limonite at between 8 and 9 percent by mass. Barytes has also been used as aggregates for dense weight concrete, but barytes are of friable nature and decrepitate if heated beyond 350⁰ C. The hardness of this aggregate is also low. An investigation of Australian dense weight aggregate for radiation shielding concrete was carried out by Professor Campbell-Allen during the construction of the High Flux Australian Reactor (Campbell-Allen, D., 1958).

His findings can be summarised as follows: “The need for accurate alignment of instruments and handling facilities passing through a radiation shield makes dimensional stability an important property. The concrete in place must be homogenous and free from any segregation or slumping under inserts, because these defects may lead to leakage paths. When heavy aggregates are used, the difference in densities between the paste and the aggregate is much more marked than in conventional concrete, and segregation is more difficult to prevent. Concrete can be made with densities up to 5600 kg/m³ using economically available materials. For concrete densities over 4000 kg/m³ it is necessary to use metallic aggregates, as commercial ores with the necessary density are not economically available. Possible sources are steel shot and steel punchings. Mixes made with No.7 and No.18 steel shot require very high cement content of about 550 kg/m³ to fill the voids. Compressive strengths over 30 MPa were obtained, but during testing preliminary failure, indicated by spalling, occurred at loads about one-half to one third of the ultimate strength.

A considerable reduction in cost and some increase in density were achieved by using ilmenite sand as a fine aggregate. Ilmenite occurs virtually as a waste product in the processing of mineral beach sands. It is very fine black sand, with over 90% between 300µm and 150µm and nothing smaller than 75µm. Ilmenite used with steel shot enabled the cement content to be reduced to 325 kg/m³ and the density of hardened concrete was 5540 kg/m³. The compressive strength was 18 MPa. For concrete densities between 3000 and 4000 kg/m³, mineral ores which

can be processed and handled in the same way as conventional dense aggregates, will serve. Although barytes has been used, it is expensive and of variable quality. Iron ores, either magnetite or haematite, are the most economical aggregates in most parts of Australia. When haematite fine aggregate is used, large amounts of material down to clay sizes form a coating on the aggregate which is difficult to remove and which increases the water demand of the mix inordinately. Ilmenite sand is better fine aggregate in this range of densities”.

MANUFACTURE, PLACEMENT AND CONSOLIDATION OF HEAVY WEIGHT CONCRETE

The problem of segregation with steel aggregate experienced by Campbell-Allen can be practically eliminated, if densities of below 3500 kg/m^3 are considered adequate. A reasonably homogenous mix can be achieved by blending well-graded steel and conventional aggregates. Samarin (Ready Mixed Concrete Industries Limited, Central Research Laboratory, Special Report No.31: “Concrete for Nuclear Reactors”, October 14, 1969) reported on the production of heavy weight concrete in which steel punchings (20 mm to 10 mm in size) were combined with crushed river gravel (also 20 mm down to 10 mm in size) to produce concrete with plastic density of 3370 kg/m^3 . It contained (per m^3 of concrete) 185 kg of pit sand, 470 kg of river sand, 530 kg of gravel, 1535 kg of steel punchings, 330 kg of Portland cement and 170 litres of water. This concrete has shown no visible signs of segregation at a slump of 80 mm, and held 1% of air. Prior to use, the steel punchings were washed in alkaline solution, to remove all traces of oil and grease. Compressive strength in excess of 25 MPa at 28 days was achieved, and concrete remained durable and maintenance free for the entire designed life cycle of the structure. It may be prudent to apply the Law of Parsimony or Ockham’s razor principle in the process of selection of an optimum method of manufacturing, placing and consolidation of heavy weight concrete. The law was formulated by William Ockham (1285 – 1349) as follows: “*Entia non sunt multiplicanda praeter necessitatem*”. Translated loosely into the technical English, it will read: “Technical solutions should not be made increasingly intricate, beyond an absolute necessity”. The tried and proven methods of radiation shielding construction, using heavy weight concrete, are: (1) by puddling or aggregate immersion, (2) by grout intrusion or prepacked concrete, and (3) by conventional mixing and placing. In the aggregate immersion method, interlocking blocks of the required shapes are cast by feeding and consolidating steel punchings into cement mortar made with Portland cement, water reducing-plasticising admixture and steel filings or iron-shot aggregate. The formwork used in precast yards is usually heavy duty. It reduces the risk of distortion under the hydraulic pressure of heavy weight concrete, and being reusable minimises the cost. Concrete with a bulk density of 6000 kg/m^3 can thus be made.

Typical cement content is of the order of 400 kg/m^3 , and with water-cement ratio of 0.4, compressive strength of 40 MPa and a flexural of 3.5 MPa at 28 days is usually achieved. A steel-trowelled finish can be easily applied, ensuring closely fitted and well-bonded joints. In the grout intrusion or prepacked method, aggregate is placed into the formwork and grout is continuously pumped under pressure into the interconnecting system of voids. Grouting hoses of 20 mm diameter are kept immersed in the grout in 50 mm diameter slotted sounding tubes, which are used for checking the level of the grout. Vent pipes allow for the escape of air as the grout rises. If there are obstructions to pouring concrete into the formwork, such as steel inserts in the radiation shielding concrete, the prepacked method of placing has considerable advantages over the conventional. The shield constructed in this way is usually composed of a homogenous, void-less and crack free concrete. Aggregate in sizes from minimum of 14 mm and up to 125 mm can be used in prepacked concrete, which, when packed *in situ*, results in the void system of some 33 to 40 percent by the volume of aggregate. The grout usually consists of one part of Portland cement to one and a half parts of heavy aggregate, all passing 0.6 mm screen, a water reducing-plasticising admixture to achieve a water-cement

ratio of 0.5, and a foaming agent (such as aluminium powder) to ensure that all the voids are filled under pressure. Prepacked concrete, made with properly sized steel aggregate and with grout containing magnetite, goethite or limonite has a density of some 6000 kg/m³. Even higher densities can be obtained, if steel filings or steel shot is used as filler in the grout.

When heavy weight concrete is mixed, placed and consolidated using conventional methods, particular attention should be given to the increasing tendency for mixes to segregate. Standard batching and mixing equipment can be used for high-density concrete. However, the batch sizes should be reduced inversely proportional to densities, as compared with the conventional structural concrete. To avoid segregation, the use of long rigid chutes or drop pipes should be avoided. If concrete is placed in narrow forms or through restricted openings, a short, flexible drop chute should be used to prevent segregation of concrete, by restricting the distance of its free fall. Heavyweight concrete should not be placed in layers of more than 300 mm thick, which will assist in the pressure reduction on the formwork. Formwork must also be braced to withstand the extra hydraulic pressure induced by high density concrete. Openings for fittings must be effectively sealed against the loss of cement paste. Internal vibration is usually supplemented with external. Radiation shielding concrete must be consolidated to obtain its maximum potential density, and to remain free from segregation and entrapped air.

When high-range water- reducing admixtures are used, concrete is sometimes incorrectly labelled “self-compacting”. In concrete of “normal” consistency (say 40 to 100 mm slump) vibration should consist of two stages. During the first stage, concrete should become sufficiently fluid and cohesive to flow into the formwork and fill the space without entrapping large pockets of air and without segregation. Vibrations at frequencies greater than 50 Hz and amplitudes of about 1 mm are ideal for this first stage of consolidation. Relatively large aggregate particles respond to these frequencies and amplitudes. When concrete is in place, the remaining entrapped air can be removed by agitating particles of fine sand and cement in the paste. Sand particles best respond to frequencies of about 100 Hz and amplitudes of 0.2 mm, and cement particles to frequencies of 200 – 230 Hz and to amplitude of 0.1 mm. Commercial poker vibrators with diameters 50 to 150 mm, operate at frequencies in the range of 100 Hz to 250 Hz. High slump concrete with high-range water-reducing admixture will require little or no low frequency high amplitude vibration, but high frequency low amplitude vibration is essential, to remove the entrapped air. When compacting heavyweight concrete, poker vibrators must be inserted at closely spaced intervals. It is desirable to use high frequency vibration, but for a shorter than normal periods. There will be a natural tendency for the high density aggregate to settle and excessive cement paste and bleed water may build up on the surface. This layer must be removed whilst the concrete is still plastic to prevent potential delamination in hardened concrete.

Pumping concrete imposes additional requirements on heavyweight concrete. It is now an accepted practice for conventional structural concrete to be pumped, and very high pumping pressures are commonly reached to deliver concrete up some 300 metres. When ordinary concrete is pumped vertically, extra force of the order of 23 kPa per metre of lift is required to overcome gravity. There are three basic types of concrete pumps, viz: - piston pumps, pneumatic pumps and squeeze pumps. Concrete pipelines can be made of either rigid pipe or heavy-duty flexible hose. Careful and detailed planning of pump location, pipeline layout, placing sequence and the continuous supply of uniform concrete are prerequisites to efficient performance. The pipelines must be firmly supported with a minimum of bends. Concrete moves as a cylindrical plug when it is pumped, separated from the pipe wall by a thin lubricating film of cement paste. Thus, the line should be initially primed by starting the pump with a properly designed mortar, which must lubricate the entire length of the pipes. A preliminary pump-test run should be made before the commencement of the actual pour. For concrete to be pumped satisfactorily it must meet, in addition to the normal requirements of a well-designed mix the following criteria: -

- it should be sufficiently mobile at the point of entry to the pump to ensure effective filling of the pump hopper during the suction stroke,
- it should be sufficiently cohesive so as not to segregate during pumping, and
- it should be self-lubricating at the interface between pipe and concrete.

Heavyweight concrete, which can comply with all of the above preconditions, will require an extra special attention to detail in its design, production and delivery stages.

Consolidation of pumped concrete usually results in the increased settlement per unit depth of the pour, as compared with concrete placed by conventional means. Pre-setting cracks may be caused by the differential settlement, either above an obstruction in the concrete, or because of significant difference in concrete depths, due to the configuration of the bottom formwork.

The most common obstacles that are likely to cause the pre-setting cracks in concrete are: reinforcing bars or mesh, service pipes or ducts and protrusions from the formwork. Pre-setting cracks above the obstructions are most likely to occur, when the concrete cover above an obstacle is one third or less of the depth of the concrete, and particularly if the cover depth is ranging between 100 mm and 300 mm (Samarin, A., 1985).

Change in the mix consistency, such as the reduction of slump due to traffic hold up of a delivery truck, can have a dramatic effect on the pump pressures and may result in the pipeline blockage. Because pumping pressures also increase when pipeline temperatures rise significantly above normal, hot pipelines can also cause blockage. It is therefore recommended that, in hot weather, pipelines should be cooled by whatever practical means possible.

In the event of a pipeline blockage, lifting gear must be at hand to expediently clear the affected section and to emptying and flush the pipes. Availability of compressed air and water under pressure is essential.

PROPERTIES OF HARDENED CONCRETE

Apart from the general structural requirements, heavy weight radiation shielding concrete should also be capable to maintain its structural integrity and effectiveness as a biological shield over a period of 50 years. Attenuation of radiation results in a rise of temperature of the shielding concrete, as the absorbed energy is converted into heat. Since the energy of absorption, and therefore the heat, varies in an inverse exponential relationship with the distance, the greatest amount of heat is generated in the part of the shield closest to the source of radiation. In addition to the above, the inner face of the concrete shield is often exposed to the direct heat from the reactor core. Concrete has relatively low thermal conductivity, which makes it difficult to remove the heat generated in the shield. As a result, the temperature distribution throughout concrete is non-uniform and the differential thermal stresses arise (Bakos, G.C., 2001). To avoid local damage or even, in the extreme case, a structural failure, it is necessary to establish a relationship between the maximum incident energy flux and the allowable, differential compressive and tensile stresses in concrete.

For example, (Thomas, D. R., 1965) a 1370 mm thick reinforced concrete shield was capable to resist, without any apparent damage, the incident energy flux of 23g-cal/hr cm^2 , which resulted in a temperature rise of 52°C .

The magnitude of the temperature rise seems to be practically independent of the nature of radiation, be it gamma rays or neutrons. However, without the reinforcement a flux of only 2.8g-cal/hr cm^2 , produced a temperature rise of 8.9°C leading to cracking of the outer concrete surface. A temperature rise of about 65°C produced internal compressive stresses of the order of 7 MPa in this particular shielding concrete. The permissible internal stresses in a concrete shield should always be as low as practically possible, as it is important to insure that no local cracking or deterioration takes place. The desirable properties of radiation shielding concrete are: high thermal conductivity to minimise the build up of heat, low coefficient of thermal expansion to minimise strains due to temperature gradients, and low drying shrinkage to minimise differential strains. The coefficient of thermal expansion should be as close as possible to that of the reinforcing steel and steel inserts, again to minimise the differential

strains. Creep in certain cases may actually reduce the internal stresses (Please refer: Samarin: “Concrete Shrinkage – Causes and Effects to be Considered in a Structural Design”, *University of Wollongong*, 1996). To evaluate the accuracy of creep and shrinkage predictions for Australian Concrete, please refer to the paper by McDonald, Roper and Samarin, 1988 (see the References).

RADIATION DAMAGE

Potentially harmful effects of irradiation on the properties of hardened concrete have been investigated for more than 50 years. Some of the results are non-conclusive and others conflicting. One of the reasons seems to be the difficulty of separating the effects of irradiation from the changes, which take place at high temperatures in concrete subjected to high intensity radiation. Another possible reason is that the extent of damage for a similar exposure varies with the concrete aggregate type and mix composition. For example, (Batten, A.W.C., 1960): - when ordinary Portland cement 1 to 3 mortar, with a water-cement ratio of 0.45 was exposed to the $10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$ neutron flux, there was strength reduction of about 30% after six months of irradiation. Temperature was maintained constant at about 50°C . However, further exposure of up to three years produced no additional loss of strength. Companion specimens stored in an oven at 200°C , produced similar decrease in strength. Gamma radiation doses of up to 10^{10} rd. (Alexander, S.C., 1963) seem to have no apparent effect on the compressive strength of concrete. In another study, at a gamma ray dose of 10^{11} rd., reduction of between 25% and 60% in concrete strength was reported. Exposure to an integrated flux of between 3 and $8 \cdot 10^{19} \text{ cm}^{-2} \text{ sec}^{-1}$, resulted in the 31% strength reduction in barytes mortar, and 20% reduction in magnetite mortar (Van der Schaaf, C.F., 1969). Tests carried out at the Atomic Energy Research Establishment at Harwell in the United Kingdom between 1953 and 1956, have shown an increase of 17% in transverse rupture of concrete subjected to a neutron flux of $0.5 \cdot 10^{19} \text{ cm}^{-2} \text{ sec}^{-1}$. (Price, B.T., 1957). Number of investigations concerning with the effects of both fast and slow neutrons on the compressive strength of concrete were unable to draw a clear distinction between the two. At an integrated neutron flux of $5 \cdot 10^{18} \text{ cm}^{-2} \text{ sec}^{-1}$ the compressive strength of uncooled irradiated specimens varied from a decrease of about 20% to an *increase* of almost 20%, when compared with the compressive strength of companion specimens which were neither irradiated nor heated (Hilsdorf, H.K., *et al*, 1978). Gas is generated when concrete is exposed to gamma and neutron radiation (Elleuch, L.F., 1972). The gas is produced as a result of radiolysis of water, and consists mainly of hydrogen, oxygen, nitrogen, carbon monoxide and carbon dioxide. The generation of gas does not seem to adversely affect the properties of hardened concrete, but some components of it may have corrosive effect on steel inserts or on concrete reinforcement. From the experimental data, it seems impossible to generalise the exact effects of irradiation on concrete. However, at one end of the scale, neutron doses of up to $0.5 \cdot 10^{18} \text{ cm}^{-2} \text{ sec}^{-1}$ seem to have negligible effect on the properties of hardened concrete (BS 4975). At the other end of this scale, according to the USA Code for Concrete Reactor Vessels and Containments (American Society of Mechanical Engineers, 1980), concrete should never be subjected to the integrated neutron flux of $10 \cdot 10^{20} \text{ cm}^{-2} \text{ sec}^{-1}$, or greater.

CONCLUSIONS

In shielding concrete, designed to provide the highest attenuation of gamma and neutron radiation, a delicate balance must be achieved between the proportion of high density aggregate and the ingredients, which contain hydrogen in a form of chemically bound or adsorbed water. For gamma rays the law of exponential (or nearly an exponential) attenuation of radiation as a function of the thickness of the shielding material can be expressed as follows:

$$I = I_0 \exp(-x / l_n)$$

where I_0 is the initial intensity of radiation, I is the attenuated radiation, x is thickness of the shield and l_n is a material constant, such that the radiation intensity is reduced by the factor of n . For gamma radiation the values of l_{10} (mm) (i.e attenuation of the intensity of radiation by the factor of 10) are approximately as follows:

	Energy 3 MeV	Energy 6 MeV
Water	580	830
Ordinary concrete, with the density of 2300 kg/m ³	274	372
Iron	82	96
Lead	49	46*

* Reduction is due to the electron-pair production.

For neutrons with the energies of the order of 2 MeV, approximate values of l_{10} are:
 For ordinary concrete (2300 kg/m³) - 250 mm, For water - 200 mm, For high density concrete (4300 kg/m³) - 120 mm.

The use of high density concrete is particularly attractive, if the layout of the nuclear plant imposes restriction on the size of the concrete radiation shield.

Some of the most recent research, however, indicates that the attenuation differences of dense and ordinary concretes can be significantly affected by the specific selection of aggregate and by the mix composition. When comparing ordinary, hematite-serpentine, ilmenite-limonite, basalt-magnetite, ilmenite, steel-scrap and steel-magnetite concrete (Bashter, I.I., 1996), the latter was found to be the best radiation attenuator from the shielding point of view.

On the other hand, the addition of iron punchings to the previously investigated ilmenite concrete (Makarious A.S., *et al*, 1995) became the main source for the production of the most penetrating hard capture secondary gamma rays (7.7 MeV), which may have resulted in a significant generation of heat in the reactor shield. Yet, in another research (Abulfaraj, N.H., *et al*, 1994) it was reported that ordinary concrete provided better biological protection, when compared with Ilmenite-Serpentine concrete. Of the methods used in construction of dense weight concrete shield, the aggregate immersion and the grout intrusion systems seem to contain fewer operations during which things can go wrong. Aggregate immersion of course, demands facilities of a special precast yard, and the grout intrusion, although carried out on a building site, requires certain expertise, which the contractor may not have. Placement of dense weight concrete by pump increases the risk of pour interruptions, should the pump blockages occur, and these can lead to the formation of "cold joints" in the concrete shield. If this happens, the affected concrete must be removed. Provided the contractor is prepared to take this risk, and in the event replace the faulty structure, placing of concrete by pump can become one of the options in the construction methods, listed above.

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