



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
10.08.2011 Bulletin 2011/32

(51) Int Cl.:
G21F 1/10 (2006.01)

(21) Application number: **10152973.3**

(22) Date of filing: **08.02.2010**

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO SE SI SK SM TR
Designated Extension States:
AL BA RS

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(54) **Shielding material and shielding element for shielding gamma and neutron radiation**

(57) Shielding Material and Shielding Element for Shielding Gamma and Neutron Radiation

A material for shielding radiation is disclosed, the material comprising:

- a neutron moderator (13) based on a hydrocarbon,
- a neutron absorber (12) based on B,
- a gamma absorber (11) based on Fe,

wherein the neutron absorber (12), the neutron moderator (13), and the gamma absorber (11) form a mixture, which comprises unbound particles and in which Fe, B

and H have the following partial densities:

- Fe: 2 to 5.5 g/cm³,
- B: 30 to 150 mg/cm³,
- H: 15 to 70 mg/cm³.

The total density of the shielding material ranges from 3.5 to 5.5 g/cm³. The shielding material remains in a particulate form and can be reused several times without reprocessing and does not pose a health hazard while delivering maximum shielding performance for sources that generate a combination of particle and gamma radiation.

FIG 1

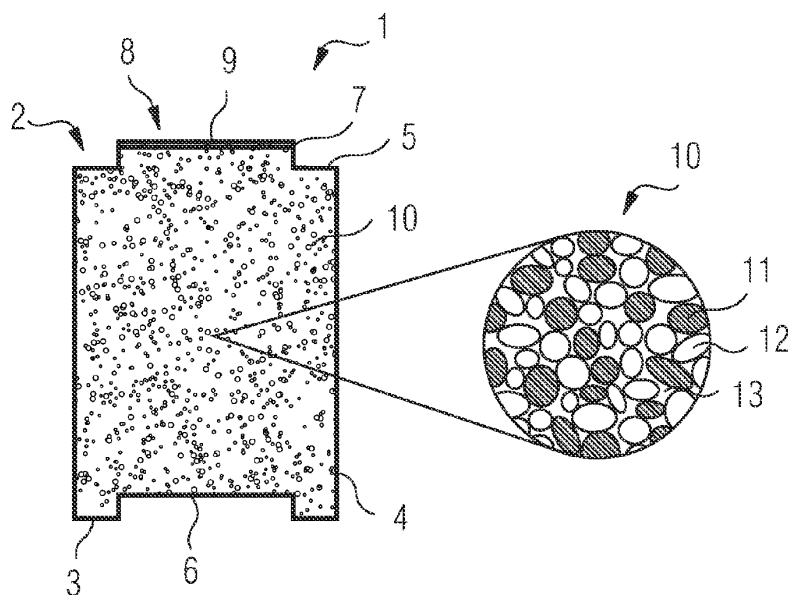
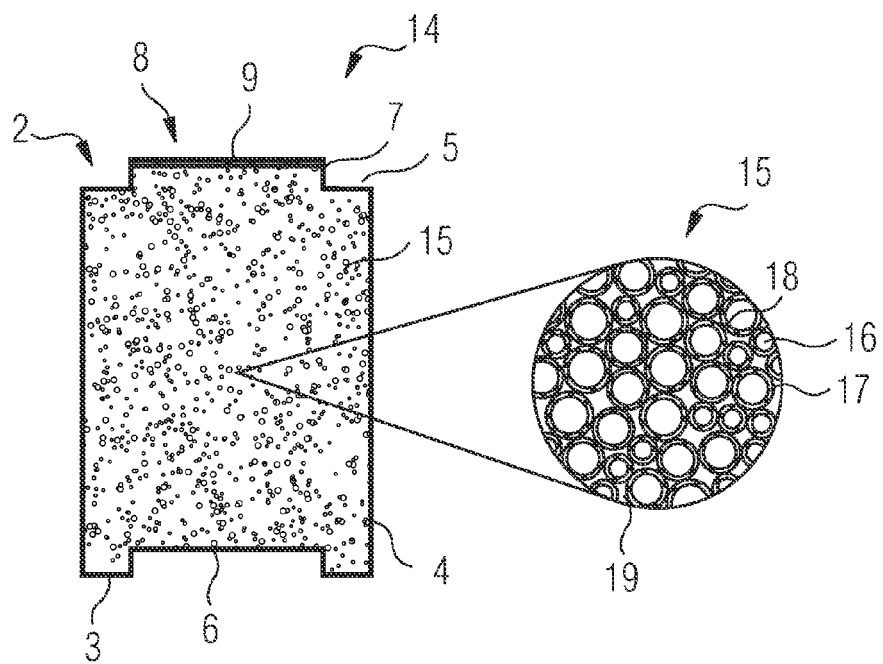


FIG 2



Description

[0001] Shielding Material and Shielding Element for Shielding Gamma and Neutron Radiation

[0002] The invention relates to a material for shielding radiation comprising:

- a neutron moderator based on a hydrocarbon,
- a neutron absorber based on B,
- a gamma absorber based on Fe.

[0003] The invention further relates to a shielding element for shielding neutron and gamma radiation.

[0004] Such a material and such a shielding element is known from DE 10 2004 052 158 A1. The known shielding element is provided with outer support layers. Between the outer support layers a first and a second shielding layer is disposed. The first shielding layer is made from a material that shields gamma radiation and/or high energy particle radiation. Therefore a metallic material is used for the first shielding layer. The second shielding layer is arranged for moderating and absorbing neutrons and is made from material that contains elements such as boron, gadolinium or lithium. For moderating the neutrons the second shielding layer contains also a component that contains hydrogen, such as gypsum.

[0005] Such a shielding element can be used for shielding neutron and gamma radiation. In neutron research facilities all around the world most of all of the biological shielding has to be effective against a combination of neutron and gamma radiation in order to provide the necessary protection of personnel and equipment. Every year considerable investments are made to install suitable shielding for new scientific instrumentation or to upgrade existing ones, as well as for shielding related infrastructure like beam lines and beam ports.

[0006] The known shielding element has the advantage that the shielding material disposed between the outer support layers can be easily recycled and reused if the form of the shielding elements needs to be changed. Further, it can relatively easily be assembled and disassembled.

[0007] The known shielding element has also a number of shortcomings. The assembly of the sequence of layers requires a number of process steps. A further drawback is that the sequence of layers increases the required space.

[0008] A further material and a further shielding element is known from US 5,786,611 A. The known material is a concrete that contains a stable uranium aggregate for attenuating gamma rays and neutron absorbing components. The resulting shielding material has a total density between 4 and about 15 g/cm³.

[0009] A survey on further shielding concretes can also be found in Edwin J. Callan, Concrete for Radiation Shielding, American Concrete Institute, Journal Proceedings, vol. 50, issue 9, pp. 17-44, 1953.

[0010] However, these approaches with cement-based compounds have a number of shortcomings.

[0011] For shielding pure neutron radiation a mixture of compounds containing neutron absorbing elements such as Boron, Lithium or Gadolinium and some matrix material that provides mechanical cohesion is common practice. For shielding gamma radiation this type of material is mostly inefficient, though. In order to gain this capability in a shielding structure heavy elements such as iron or lead have to be added. Such a sandwich is very effective and can be adapted to a large spectrum of shielding problems. For larger structures, however, like instrument enclosures or beam line shielding this approach is not cost effective. In addition to the price of the actual shielding material the support structure required to keep such a sandwich in place and to provide the mechanical stability of the entire setup has to be taken into account. For that reason in large scale applications so called heavy concrete is widely used, either in form of reinforced concrete blocks that can be stacked on top of each other or as filling for tailor-made steel containers that form the radiation barrier.

[0012] Special formulations of such concrete have been examined to address this particular shielding problem. Examples can be found in the book of Karl-Heinz Lindackers, "Praktische Durchführung von Abschirmberechnungen", München, 1962, p. 56 ff.

[0013] Cement-based heavy concrete is filled to a high degree with iron granules and / or other minerals that have a high specific density, such as Hematite, to provide effective gamma absorption properties. In addition it contains substances that absorb neutrons well, such as colemanite or other boron compounds. In combination with the water enclosed in the structure of the concrete that acts as a moderator for faster neutrons this material mix is very effective in slowing down and absorbing neutrons and reducing the intensity of gamma radiation. It can be tailored over a wide range to fit the spectrum of the radiation source at hand by adjusting the amounts of the individual ingredients. The density of such heavy concrete varies between 3.5 and 6.2 g/cm³ depending on the intensity and energy of the gamma source. The heavier the concrete the better are its shielding properties against gamma radiation. The neutron absorption capability depends mainly on the amount of neutron absorber and neutron moderator for higher-energy neutrons in the concrete, which is not correlated to the density.

[0014] The main attractions of the concrete based shielding approach are the comparatively low initial costs for the heavy concrete and the nearly unlimited design options when it comes to planning large shielding structures. Metal

containers filled with concrete provide extremely rugged building blocks for virtually any type of structural shielding. Attachment points for moving the blocks are easily integrated, intricate details like small openings, gaps and overlaps can be designed as needed and the outer surface can be coated in such a way as to allow for decontamination.

[0015] However, there are a number of disadvantages to a heavy concrete shielding:

At the end of their service life custom-made blocks that make up the shielding have to be dismantled and disposed of. Even if the blocks are not contaminated or activated this is a costly procedure, especially so when the concrete is encased in steel containers. Here the cost of disposal may well be in the range of the original purchase price.

[0016] A further disadvantage is that the reuse of the salvaged concrete is very difficult because it requires separation of the various ingredients so most often the material is discarded.

[0017] Shielding blocks made of steel containers are commonly filled with concrete off-site and then transported to their final destination. Given the large size and consequently high weight of these elements this can be a difficult task, most notably if a suitable crane is not available to place all the elements in the desired position.

[0018] During the filling with heavy concrete the steel container is subjected to a considerable hydrostatic pressure, owing to the liquid nature of the concrete and its high density. To avoid permanent deformation of the container it has to be suitably reinforced inside which adds to the cost of design and manufacture.

[0019] In combination these points show that there is a significant potential for improvement. Addressing some or all of those shortcomings not only saves a lot of money in the long run but also helps addressing logistical and ecological problems. These days the demand to design a product with the end of its life cycle in mind does not only apply to consumer products but also to scientific instrumentation as well.

[0020] Proceeding from this related art, the present invention seeks to provide an improved shielding material for shielding a combination of neutron and gamma radiation. The invention further seeks to provide an improved shielding element.

[0021] These objects are achieved by a shielding material and a shielding element having the features of the independent claim. Advantageous embodiments and refinements are specified in claims dependent thereon.

[0022] In one embodiment of the shielding material, the neutron absorber, the neutron moderator, and the gamma absorber form a mixture, which comprises unbound particles and in which Fe, B and H have the following partial densities:

- Fe: 2 to 5.5 g/cm³,
- B: 30 to 150 mg/cm³,
- H: 15 to 70 mg/cm³.

[0023] In this context, particles should be understood to be a solid agglomeration of a plurality of molecules, ions and / or atoms, and unbound particles should be understood to be particles which are not embedded in a continuous solid phase.

[0024] If H is provided in form of a hydrocarbon, the partial density of C may typically range between 90 and 420 mg/cm³.

[0025] In order to obtain a neutron shielding material of high efficiency, materials with a

- high inelastic neutron scattering cross section
- high elastic neutron scattering cross section
- high neutron absorption cross section

have been combined.

[0026] By inelastic neutron scattering fast neutrons are moderated effectively down into the epithermal energy range. Moderation is continued by elastic down scattering to the thermal region. Within the thermal energy range neutrons are captured by the absorbing material. As neutron absorber a material is selected that does not produce high energy gamma radiation.

[0027] As a high background of gamma radiation occurs in most neutron beams, the shielding material contains also a component that shields gamma radiation.

[0028] The shielding material described herein relies on the properties of the following elements: Fe is a suitable material for inelastic neutron scattering and is also a gamma shielding material, H scatters neutrons elastically and B is used for neutron absorption.

[0029] The optimal fractions of the material components depend on the neutron spectrum, in particular on the ratio of fast to thermal neutron flux, and on the ratio between the neutron and the gamma flux. The actual composition can then be adjusted to the local requirements.

[0030] The range of the partial densities listed above typically results in a shielding material that can absorb neutrons and gamma radiation in an effective way. The material comprising the listed densities generally contains a sufficiently

large number of Fe, B and H atoms per unit of volume for resulting in an effective gamma and neutron shielding that can be easily produced at moderate costs and allows reducing the required space. Since the average atomic mass of these elements is known, the number of atoms per unit of volume can also be expressed as a partial density that is basically the product of the average atomic mass and the number of atoms per unit of volume.

[0031] In one particular embodiment, the neutron absorber, the neutron moderator, and the gamma absorber form a mixture, in which Fe, B and H have the following partial densities:

- Fe: 3 to 5.5 g/cm³,
- B: 50 to 85 mg/cm³,
- H: 30 to 60 mg/cm³.

[0032] If H is provided in form of a hydrocarbon, the partial density of C may typically range between 180 and 360 mg/cm³.

[0033] Such a material shows a particularly good performance for absorbing neutron and gamma radiation.

[0034] The total density of the mixture generally ranges between 3.5 and 5.5 g/cm³ for ensuring a sufficient number of absorbing and moderating atoms per unit of volume.

[0035] In another particular embodiment, the neutron absorber, the neutron moderator, and the gamma absorber form a mixture, in which Fe, B and H have the following partial densities:

- Fe: 4 to 4.5 g/cm³,
- B: 75 to 85 mg/cm³,
- H: 40 to 60 mg/cm³.

[0036] If H is provided in form of a hydrocarbon, the partial density of C may typically range between 240 to 360 mg/cm³.

[0037] Such a shielding material typically has a total density between 4 and 5 g/cm³.

[0038] For evenly distributing the components of the material over the available volume, the neutron absorber, the gamma absorber and the neutron moderator form a homogeneous, unlayered and unbound mixture.

[0039] In one particular embodiment, the neutron absorber and the gamma absorber are in the solid state and the neutron moderator is in the liquid state, if the shielding material is at room temperature. By using a liquid material the voids between the solid components can effectively be filled, so that the shielding material is particularly compact.

[0040] The neutron moderator is a fluid generally based on alkanes. These fluids, such as paraffin oil, are available in large quantities and at relatively low costs. In addition, these materials protect other components from corrosion.

[0041] The neutron absorber can be based on ferroboration which has a similar specific weight as pure iron so that the neutron absorbing material and the gamma absorbing material will not segregate if a gamma absorber based on Fe is used.

[0042] In another embodiment, the neutron absorber, the gamma absorber and the neutron moderator are in the solid state, if the shielding material is at room temperature. Such an embodiment has the advantage, that the material is free flowing and therefore can easily be filled into a shielding structure and can easily be removed from the shielding structure. The shielding material can also easily be stored because the shielding material is essentially in a dry state.

[0043] In such an embodiment, the neutron moderator can be made from a hydrocarbon such as polyethylene, which comprises a relatively high hydrogen density in comparison to its C content.

[0044] As neutron absorber a material based on boron carbide is typically used because of its higher content of B.

[0045] Since the neutron absorber such as boron carbide and since the neutron moderator such as polyethylene have a significantly lower density than the gamma absorber such as iron the segregation of the neutron absorber, neutron moderator and gamma absorber can be prevented by coating the neutron absorber and the neutron moderator on the particles of the gamma absorber. Simply mixing the neutron absorber, the moderator and the gamma absorber does not work due to the large differences in the specific densities of these materials. The particles do not mix properly because the gamma absorber segregates and ends up at the bottom of the container. By coating particles of the gamma absorber with a mixture of neutron moderator and neutron absorber this problem can be overcome. With spherical particles a sufficient packing density of the coated particles can be achieved.

[0046] In most embodiments of the shielding material the gamma absorber is an iron alloy or iron.

[0047] The shielding material can particularly be used for filling an outer container with the shielding material. Thus a shielding element is obtained that can be assembled to form a complex shielding structure.

[0048] These shielding structures can then be used for shielding radiation originating from a variety of radiation sources, such as nuclear reactors, fission reactors, fusion reactors and spallation sources.

[0049] Further advantages and properties of the present invention are disclosed in the following description, in which exemplary embodiments of the present invention are explained in detail based on the drawings:

Figure 1 shows a cross section of a shielding element that is filled with a shielding material for shielding neutron and gamma radiation;

Figure 2 shows a cross section of a further shielding element that is filled with a further shielding material for shielding neutron and gamma radiation;

Figure 3 illustrates the geometry that has been assumed for simulating the attenuation of neutron and gamma radiation within the shielding material;

Figure 4 shows the spectrum of the neutron radiation used for simulating the attenuation of neutron and generated gamma radiation within the shielding material;

Figure 5 shows the spectrum of the primary gamma radiation used for simulating the attenuation of gamma radiation within the shielding material;

Figure 6 is a diagram that illustrates the resulting shielding performance of various materials;

Figure 7 is a diagram that shows the total dose per source neutron inside the sphere as a function of the distance to the source.

[0050] Figure 1 shows a shielding element 1 that comprises a container 2 having a metallic bottom 3, metallic walls 4 and a metallic cover 5. In the bottom 3, a recess 6 is formed that fits into a bulge 7 of the cover 5. Thus, the shielding elements 1 can be stacked in order to form a wall-like shielding structure. Instead of the recesses 6 and bulges 7, the container 2 can also be provided with other fixing elements that are suitable for forming a particular shielding structure. The container 2 is further provided with an inlet 8 that can be closed by a cap 9. Via the inlet 8, the container 2 can be filled with a shielding material 10. The inlet 8 may further be used for removing the shielding material 10 from the container 2. Additional components may be provided for facilitating the removal of the filling or emptying of the container 2.

[0051] The shielding material 10 consists of a powder and / or granulate material comprising iron (Fe) particles 11 and ferroboration (FeB) particles 12. These materials both have a very similar density so that the particles 11 and 12 will not segregate. The volume in between the iron particles 11 and the ferroboration particles 12 is filled by a liquid hydrocarbon 13 to fill the volume in between the particles 11 and 12. Except for the carbon contained in the hydrocarbon 13 all elements present in this compound are active in the shielding process. The boron atoms are finely and evenly dispersed within this mixture, and so are the iron atoms and the hydrogen atoms. By such a wet filling of the container 2 the shielding efficiency is maximized in a very simple and cost effective way. It should be noted that the liquid hydrocarbon protects the iron particles 11 and the ferroboration particles 12 from corrosion.

[0052] The iron acts as a gamma absorber and as a neutron moderator, the boron acts as a neutron absorber and the hydrogen contributes to the absorption of the neutrons by moderating the neutrons. These materials are specified according to their predominant function in the shielding material 10. It is however not excluded under all circumstances that a neutron moderator or a neutron absorber also absorbs gamma radiation or that a gamma absorber also moderates or absorbs neutrons.

[0053] Figure 2 shows a cross section of a further shielding element 14. In the shielding element 14, the container 2 is filled with a dry shielding material 15, that consists of granular iron particles 16 of larger size (2-8 mm) and more or less spherical shape, which are provided with a polyethylene coating 17, which contains small boron carbide particles 18. Instead of polyethylene and boron carbide also any other materials containing boron and hydrogen can be used. For instance, polypropylene, paraffin or stearin may be used instead of polyethylene, provided that the melting point is sufficiently high above the ambient temperature of the shielding material 15. Also polyamide or other waxes may be used instead of polyethylene. Boron carbide may finally be replaced by calcium hexaboride (CaB_6), titanium diboride (TiB_2), zirconium diboride (ZrB_2) or boron nitride (BN) or similar boron compounds.

[0054] Here the hydrocarbon acts as a matrix material for the boron or the boron compound. The advantage of that solution is improved handling, especially for emptying the containers 2, since the shielding material 15 is composed of solid components resulting in a dry mixture. It comes with increased cost, though, since the coating process adds another step to the formulation of the filling and usually requires more expensive material grades. Another drawback is that the mixture inevitably comprises voids 19.

[0055] By selecting the size and the shape of the powder particles the resulting bulk density of the Fe-FeB powder mix can be adjusted between 45% (fine powders, ground particles) and 65% (larger, spherical particles). This allows for tailoring the compound to the radiation source at hand. For a less intense and / or lower energy gamma source the amount of iron can be reduced, resulting in a final mixture with a density of approximately 3.7 g/cm^3 . For the maximum gamma reduction the density can be brought up to approximately 5.2 g/cm^3 by using only spherical powders. The

attenuation of neutrons is excellent in both cases due to the amount of neutron moderator (Fe and H) and neutron absorber (B) present in the materials 10 and 15. A mixture of iron, boron carbide, and polyethylene granules will therefore result in an effective shielding material.

[0056] Simulations with Monte Carlo based programs such as MCNP ("A General Monte Carlo N-particle Transport Code" by the Los Alamos National Laboratory) have shown that a shielding compound exclusively composed of active elements such as iron, boron and hydrogen performs significantly better than existing heavy concrete mixtures. However, due to the huge differences in specific weight simply mixing suitable powders does not work. The heavier particles segregate from the lighter ones and end up at the bottom of the pile. The materials 10 and 15, however, represent a homogenous and stable mixture that is easy to produce, whose quality can be controlled reliably, that is easy and safe to handle and which is also economically feasible.

[0057] Heavy concrete as shielding has the disadvantage that some elements contribute little to the shielding effect. But they are necessary to ensure the mechanical strength of the concrete. This applies for example for the oxygen content of the cement and the hematite, too. With the embodiments of the shielding materials 10 and 15 as described herein the shielding effect is enhanced since these materials 10 and 15 are mainly composed of specific substances which contribute to the shielding effect. To achieve a homogeneous mixture, the individual substances are used in form of powder and / or granulated material. Thus, in combination with a suitable metal container 2 that acts as the load-bearing element a similar mechanical strength as with heavy concrete form elements can be achieved using the powder mixture.

[0058] As useful elements in the shielding material may be considered:

- Iron as inelastic neutron scattering material, which exhibits a high density of resonances in the energy range of fast neutrons and which is a suitable material for shielding gamma radiation;
- Boron as an absorber for thermal neutrons, wherein boron produces no high-energy gamma radiation while absorbing neutrons;
- Hydrogen as an elastic neutron scattering material and moderator for fast neutrons.

[0059] For determining the optimum mixing ratio of iron, boron and hydrogen the following model was considered:

This model is depicted in Figure 3. In the center of a sphere 20, a point-like neutron source 21 was assumed, which emits neutrons isotropically and has a spectrum as it occurs in the beam channel SR4A of the research nuclear reactor FRM II of TU München, Germany. The radius of the sphere 20 was assumed to be 60 cm. The sphere was further assumed to be filled with a homogenous mixture of the elements of the shielding material 10 and 15, respectively. Thus, it was assumed that the elements of the compounds are evenly distributed over the volume of the sphere 20, but the concentration and thus the partial density of the elements and the air fraction was varied.

[0060] The neutron dose per source neutron was determined by a detector 22 on the outer surface of the sphere 20. The neutron spectrum used for the simulation is shown in Figure 4.

[0061] Similarly, the dose of gamma radiation caused by neutron absorption and inelastic neutron scattering in the mixture is determined on the outer surface of the sphere 20 relative to one source neutron. This kind of dose is called generated gamma dose.

[0062] To determine the dose caused by primary gamma radiation, an analog model was used, in which the neutron source 21 was replaced by a gamma radiation source with the corresponding spectrum of gamma rays in the beam channel SR4A. This gamma spectrum is shown in Figure 5. In this context, the primary gamma radiation should be understood to be the prompt gamma radiation from fission in the reactor core and the prompt gamma radiation originating from neutron absorption and inelastic neutron scattering by structural elements in the moderator vessel and the beam tube. However, the primary gamma radiation does not include the delayed gamma radiation originating from the decay of fission products and the gamma radiation from the decay of activated nuclei in the structure materials.

[0063] The results obtained by calculating the primary gamma radiation were finally multiplied with the gamma/neutron ratio ($= 0.315$) in the beam channel SR4A.

[0064] Several simulations based on the model described above were carried out considering different shielding materials and different densities of the shielding materials. The shielding performance of heavy concrete was compared to the shielding performance of an ideal powder mixture, in which iron fills 60%, polyethylene 35% and boron 5% of the volume of the sphere 20.

[0065] In a first basic simulation for evaluating the feasibility of the concept, a bulk density of 100% was assumed. However, a bulk density of 100% is hardly achievable in reality. In the case that all additives that are being used are ball-shaped and of equal size, the additives would occupy 74% of the available space at best. In fact, since the additives are added as spheres of different sizes, a higher bulk density above 74% can be achieved. To determine the influence of bulk density on the dose at the outer surface of the sphere 20, a simulation was performed in which the ideal powder

mixture with a bulk density of 70% was used. The overall density of the mixture is then only 3.6 t/m³ and lies well below the density of heavy concrete. As can be seen from Table I, the dose at the outer surface of the sphere 20 is nevertheless barely above the corresponding values which are obtained by using heavy concrete. At a bulk density of 100% of the optimum powder mixture, the doses are an order of magnitude below the values that are achieved by heavy concrete at the surface of the sphere 20.

[0066] More specific simulations were performed for evaluating the shielding effect of a mixture of steel, ferroboration, and paraffin oil as depicted in Figure 1. In the simulations, the shielding of the neutron and gamma radiation by the material 10 was determined. In principle, the material 10 can fill up to 100% of the available volume within the container 2. But in reality the material 10 will generally contain some amount of air so that the shielding material 10 fills less than 100% of the available volume.

[0067] In Table II to IV the mixtures comprising steel, ferroboration and paraffin oil are listed. The volume fractions of steel and ferroboration are identical in all mixtures. Only the paraffin oil-volume fraction was varied.

[0068] The same kind of calculation was also performed for a heavy concrete produced by the company Schielein, Germany, with a density of 4.5 g/cm³. This type of concrete contains hematite and colemanite as additives. For this sort of concrete the manufacturer guarantees the overall density of 4.5 g/cm³. In fact, however, a density of about 4.7 g/cm³ can be achieved. For the simulations an overall density of 4.5 g/cm³ was adopted.

[0069] Figure 6 shows the results of the calculation. All mixtures of steel, ferroboration and paraffin oil achieve a lower neutron dose at the outer surface of the sphere 20 (R = 60 cm) than heavy concrete. Even if the mixture reaches only a bulk density of 90%, the neutron dose is by a factor of 6.3 lower than the neutron dose associated with a heavy concrete with a density of 4.5 g/cm³.

[0070] If the mixture of steel, ferroboration and paraffin oil is used with a bulk density of 90%, the dose of generated gamma radiation is by a factor of 4.8 smaller than the corresponding dose by using heavy concrete with a density of 4.5 g/cm³. For higher bulk densities of the mixture the dose of generated gamma radiation is even lower. The contribution of primary gamma radiation is shielded better by a factor of 1.1 by using mixtures of steel, ferroboration and paraffin oil with a bulk density of 90% than by using heavy concrete.

[0071] The stratification of steel and borated polyethylene has the same neutron shielding effect as the mix of steel, ferroboration and paraffin oil with a bulk density of 100%. All other components of radiation (gamma rays) are somewhat better shielded by a layered sequence of steel and borated polyethylene than by the mixture of steel, ferroboration and paraffin oil, even if a bulk density of 100% is used.

[0072] The mixture of steel, ferroboration and paraffin oil achieved a lower total dose than heavy concrete. This is already true at a bulk density of 90%. The mixture will not only achieve a lower total dose, but each radiation component will be better shielded than by heavy concrete. In particular, this can be recognized from Figure 7, in which the total dose is depicted as a function of the distance from the source.

[0073] Looking at the dose from neutron radiation and generated gamma radiation, the mixture of steel, ferroboration and paraffin oil with a thickness of about 50 cm and a bulk density of 95% achieves the same shielding effect as heavy concrete with a thickness of 60 cm.

[0074] Looking at the primary gamma rays, the mixture of steel, ferroboration and paraffin oil shows no higher shielding efficiency than heavy concrete. However, if the radiation is composed as assumed for the simulations, in particular with a gamma/neutron ratio as in the direct beam on SR4, the primary gamma radiation transmitted through the shielding material of the sphere plays a minor role.

[0075] Therefore, using the mixture of steel, ferroboration and paraffin oil with a bulk density of 95% the thickness of the shielding structure can be reduced to 50 cm in comparison to the thickness of 60 cm that will be needed if the shielding structure is made from heavy concrete.

[0076] If, however, structural materials are inside the shield and if these structural materials produce high-energy gamma rays by neutron absorption (e.g. Al, Fe), the gamma radiation produced in this way has the same effect with respect to the shielding material as primary gamma radiation. This type of radiation therefore acts as an additional component of primary gamma radiation whose spatial distribution might be inhomogeneous. Therefore, the actual shielding efficiency must be examined for each case individually.

[0077] The shielding materials 10 and 15 have a number of advantages:

Since the filling of the shielding container never solidifies it can be removed from the container whenever the need arises. At the end of their service life the metal containers can be scrapped separately from the filling. The amount of potentially contaminated material to be disposed is drastically reduced thus cutting disposal costs accordingly.

[0078] After removal from the container the shielding mixture can be immediately reused in other shielding applications, no post processing of any kind is required. Corrosion is not a problem because of the hydrocarbon that acts as a very effective barrier against oxidation. There is no limit to the number of recycling cycles. That way the initial investment is well protected over a long period of time.

[0079] Heavy concrete used for conventional shielding elements usually contains quite a large percentage of elements that do not actively participate neither in the moderation and absorption of neutrons, nor in the reduction of gamma radiation, such as Calcium, Carbon, Oxygen, Silicon and Aluminum. Therefore heavy concrete is not as efficient for a given volume as could be. A filling containing only effective elements performs significantly better, allowing for a reduction in shielding thickness for a given radiation source. This in turn leads to lighter shielding elements that put less stress on the supporting floor. In a number of existing neutron research facilities the maximum permitted floor load of 10 t/m² makes it difficult to meet the requirements for radiological effectiveness while at the same time staying within the given load limits for the building. Increasing the efficiency of the shielding compound allows for thinner and consequently lighter shielding structures. In the application at hand at the nuclear research reactor FRM II of TU München in Germany a reduction of the thickness of 20% is possible which translates into just about the same weight saving given the very similar density of both materials. This reduction in thickness makes it possible to increase the available floor space inside the shielding by 10 cm on each side.

[0080] Filling of the shielding steel containers can happen on-site since all the equipment required to mix the ingredients is portable and no health hazards are associated with handling the three components of the mixture. This allows for placing the empty and therefore much lighter containers in their final position before adding the weight of the filling. Testing the setup for fit and quality becomes much easier, too, since it can be done with empty containers on- or off-site. For dismantling the containers can be first emptied and then moved away in the empty state, again saving a lot of effort when proper lifting equipment is not available or cannot be used to good effect.

[0081] Due to its high internal friction the new shielding mixture does hardly exert any hydro-static pressure on the walls of the metal container. Consequently the container can be designed without most of the internal stiffeners required in a design for heavy concrete, saving cost in labor and material.

[0082] From an economic point of view the shielding material 10 described herein is attractive not only in the long term perspective. In the current version all three ingredients are off-the-shelf products that are readily available and do not require any further processing. At current market prices the shielding materials may be more costly than conventional heavy concrete. Taking into account the savings in material, logistics and time for assembly, however, the economic benefit even at the point of installation nearly offsets the higher cost for the filling. Looking further along the time axis there are no future costs to be taken into account. Setting up the next generation of shielding installations requires only the design and manufacture of new metal containers and the transfer of the filling material into the new formwork - a considerable saving compared to buying a completely new shielding structure and paying dearly for scrapping the old one.

[0083] In summary, material 10 offers the best shielding efficiency, but the handling of material 10 is more complicated than the handling of material 15 since material 10 is wet and is therefore not free flowing. In contrast to material 10, material 15 that contains no liquid component is free flowing and can therefore be handled easily, but its shielding efficiency is lower than the shielding efficiency of material 10. In addition, the production of material 15 is more expensive than the production of material 10.

[0084] It should be noted that the partial densities of the materials 10 and 15 have been optimized for shielding a particular neutron and gamma spectrum. The particular neutron spectrum contains a relatively small percentage of fast neutrons, because the beam tubes are arranged in a tangential way with regard to the reactor core. If, however, the portion of fast neutrons is higher than it is the case in most research reactors of older design, where the beam tubes are arranged towards the reactor core, the percentage of the neutron moderator generally needs to be higher in order to provide a sufficient number of scatter centers for inelastic collisions in the resonance region of the iron nuclei and for bringing the fast neutrons down into the epithermal energy region. If, however, the radiation that needs to be shielded originates from a fusion reactor, the relative percentage of hydrogen atoms must be increased, since the neutron flux will have a sharp peak at 2.5 MeV, which is well above the resonance region of the iron nuclei being around 1 MeV. Under these circumstances, the neutrons with a kinetic energy well above 1 MeV must be brought into the resonance region of the iron nuclei by elastic scattering on hydrogen.

[0085] Throughout the description and claims of this specification, the singular encompasses the plural unless the context otherwise requires. In particular, where the indefinite article is used, the specification is to be understood as contemplating plurality as well as singularity, unless the context requires otherwise.

[0086] Features, integers, characteristics, compounds or groups described in conjunction with a particular aspect, embodiment or example of the invention are to be understood to be applicable to any other aspect, embodiment or example described herein unless incompatible therewith.

Table I:

Dose [pSv] per Source Neutron at the Surface of the Shielding			
	Heavy Concrete	Fe-B ₄ C-PE-Mixture	Fe-B ₄ C-PE-Mixture

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(continued)

Dose [pSv] per Source Neutron at the Surface of the Shielding						
	Density: 4.5g/cm ³		70% Bulk Density Density: 3.6g/cm ³		100% Bulk Density Density: 5.138g/cm ³	
Neutrons	3.87E-07 ±	4.19E-08	4.29E-07 ±	1.15E-08	2.26E-08 ±	3.54E-10 0
Generated Gammas	1.02E-07 ±	1.12E-08	1.24E-07 ±	1.76E-08	1.08E-08 ±	1.02E-09
Primary Gammas	2.01E-09±	4.09E-10	8.53E-08 ±	3.36E-09	6.64E-09 ±	8.37E-1
Total	5.09E-07 ±	4.33E-08	6.39E-07 ±	2.13E-08	4.00E-08±	1.09E-09

Table II A:

Data with respect to a Mixture of Steel, Ferrobor und Paraffin Oil at a Bulk Density of 90%			
Additives	Density of the Additive [g/cm ³]	Volume Share in the Mixture	Density of the Additive in the Mixture [g/cm ³]
Ferroboron (FeB)	6.6000	0.0750	0.4950
Steel (Fe)	7.8600	0.4750	3.7335
Paraffin Oil (CH ₂)	0.8500	0.3500	0.2975
Total		0.9000	4.5260

Table II B:

Densities of the Elements in the Mixture of Ferrobor, Steel und Paraffin Oil [g/cm ³] (Bulk Density 90%)					
	H	B	C	Fe	Total
Ferroboron (FeB)		0.0803		0.4147	0.4950
Steel (Fe)				3.7335	3.7335
Paraffin Oil (CH ₂)	0.0428		0.2547		0.2975
Total	0.0428	0.0803	0.2547	4.1482	4.5260

Table III A:

Data with respect to a Mixture of Steel, Ferrobor und Paraffin Oil at a Bulk Density of 95%			
Additives	Density of the Additive [g/cm ³]	Volume Share in the Mixture	Density of the Additive in the Mixture[g/cm ³]
Ferroboron (FeB)	6.6000	0.0750	0.4950
Steel (Fe)	7.8600	0.4750	3.7335
Paraffin Oil (CH ₂)	0.8500	0.4000	0.3400
Total		0.9500	4.5685

Table III B:

Densities of the Elements in the Mixture of Ferrobor, Steel und Paraffin Oil [g/cm ³] (Bulk Density 95%)					
	H	B	C	Fe	Total
Ferroboron (FeB)		0.0803		0.4147	0.4950
Steel (Fe)				3.7335	3.7335

(continued)

Densities of the Elements in the Mixture of Ferrobor, Steel und Paraffin Oil [g/cm ³] (Bulk Density 95%)					
	H	B	C	Fe	Total
Paraffin Oil (CH ₂)	0.0489		0.2911		0.3400
Total	0.0489	0.0803	0.2911	4.1482	4.5685

Table IV A:

Data with respect to a Mixture of Steel, Ferrobor und Paraffin Oil at a Bulk Density of 00%			
Additives	Density of the Additive [g/cm ³]	Volume Share in the Mixture	Density of the Additive in the Mixture [g/cm ³]
Ferrobor on(FeB)	6.6000	0.0750	0.4950
Steel (Fe)	7.8600	0.4750	3.7335
Paraffin Oil (CH ₂)	0.8500	0.4500	0.3825
Total		1.0000	4.6110

Table IV B:

Densities of the Elements in the Mixture of Ferrobor, Steel und Paraffin Oil [g/cm ³] (Bulk Density 100%)					
	H	B	C	Fe	Total
Ferroboron (FeB)		0.0803		0.4147	0.4950
Steel (Fe)				3.7335	3.7335
Paraffin Oil (CH ₂)	0.0550		0.3275		0.3825
Total	0.0550	0.0803	0.3275	4.1482	4.6110

Claims

1. A material for shielding radiation comprising:

- a neutron moderator (13, 17) based on a hydrocarbon,
- a neutron absorber (12, 18) based on B,
- a gamma absorber (11, 16) based on Fe,

characterized in that the neutron absorber (12, 18), the neutron moderator (13, 17), and the gamma absorber (11, 16) form a mixture, which comprises unbound particles and in which Fe, B and H have the following partial densities:

- Fe: 2 to 5.5 g/cm³,
- B: 30 to 150 mg/cm³,
- H: 15 to 70 mg/cm³.

2. The material according to Claim 1

wherein the neutron absorber (12, 18), the neutron moderator (13, 17), and the gamma absorber (11, 16) form a mixture, in which Fe, B and H have the following partial densities:

- Fe: 3 to 5.5 g/cm³,
- B: 50 to 85 mg/cm³,
- H: 30 to 60 mg/cm³.

3. The material according to Claim 1 or 2

wherein the total density of the mixture ranges between 3.5 and 5.5 g/cm³.

4. The material according to any one of Claims 1 to 3 wherein the neutron absorber (12), the neutron moderator (13), and the gamma absorber (11) form a mixture in which Fe, B and H have the following partial densities:

- Fe: 4 to 4.5 g/cm³,
 - B: 75 to 85 mg/cm³,
 - H: 40 to 60 mg/cm³.

5. The material according to any one of Claims 1 to 4 wherein the total density of the mixture ranges between 4 and 5 g/cm³.

6. The material according to any one of Claims 1 to 5 wherein the neutron absorber (12), the gamma absorber (11) and the moderator (13) form a homogenous, unlayered mixture.

7. The material according to any one of Claims 1 to 6 wherein, at room temperature, the neutron absorber (12) and the gamma absorber (11) are in the solid state and the neutron moderator (13) is in the liquid state

8. The material according to Claim 7 wherein the neutron moderator (13) is a fluid based on alkanes.

9. The material according to Claim 7 or 8 wherein the neutron absorber (12) is based on ferrobaboron.

10. The material according to any one of Claims 1 to 6 wherein, at room temperature, the neutron absorber (18), the gamma absorber (16) and the neutron moderator (17) are in the solid state.

11. The material according to Claim 10 wherein the neutron moderator (17) is based on a hydrocarbon that is solid at room temperature.

12. The material according to Claim 10 or 11 wherein the neutron absorber (18) is based on a boron compound.

13. The material according to any one of Claims 10 to 12 wherein the neutron absorber (18) and the neutron moderator (17) are coated on the particles of the gamma absorber.

14. The material according to any one of Claims 1 to 13 wherein the gamma absorber (16) is iron or an iron alloy.

15. A shielding element comprising an outer container (2) filled with the shielding material according to any one of Claims 1 to 14

16. Use of the shielding element according to Claim 15 for shielding radiation originating from a source that generates particle as well as gamma radiation.

FIG 1

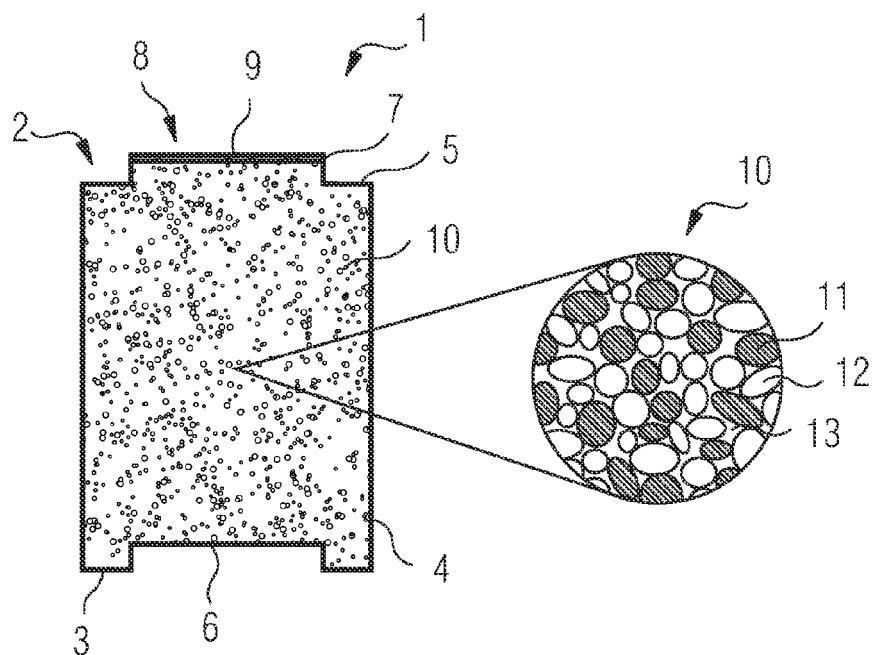


FIG 2

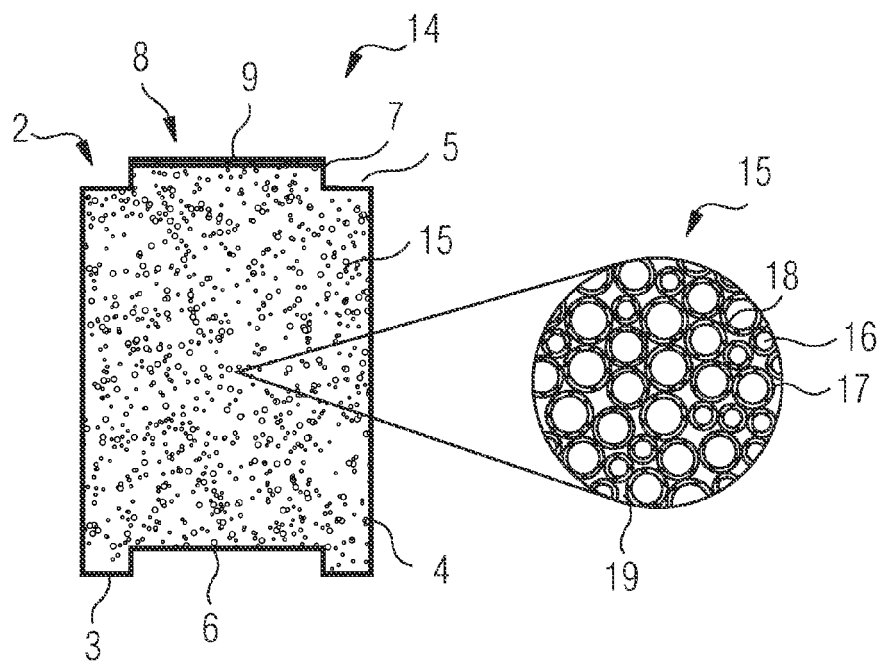


FIG 3

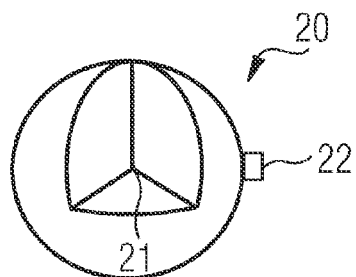


FIG 4

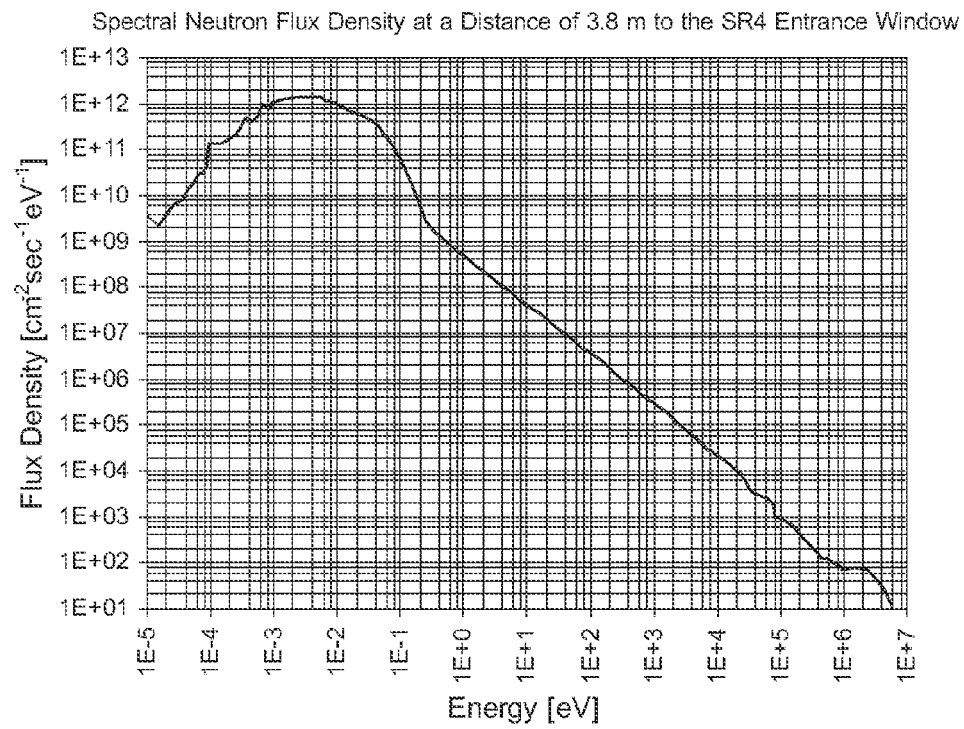


FIG 5

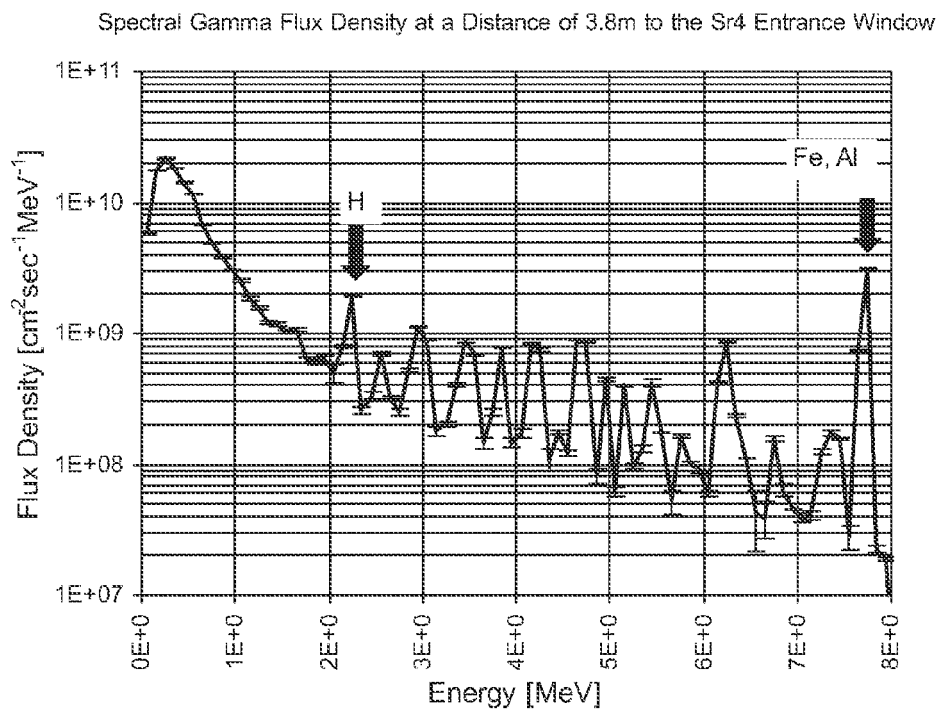


FIG 6

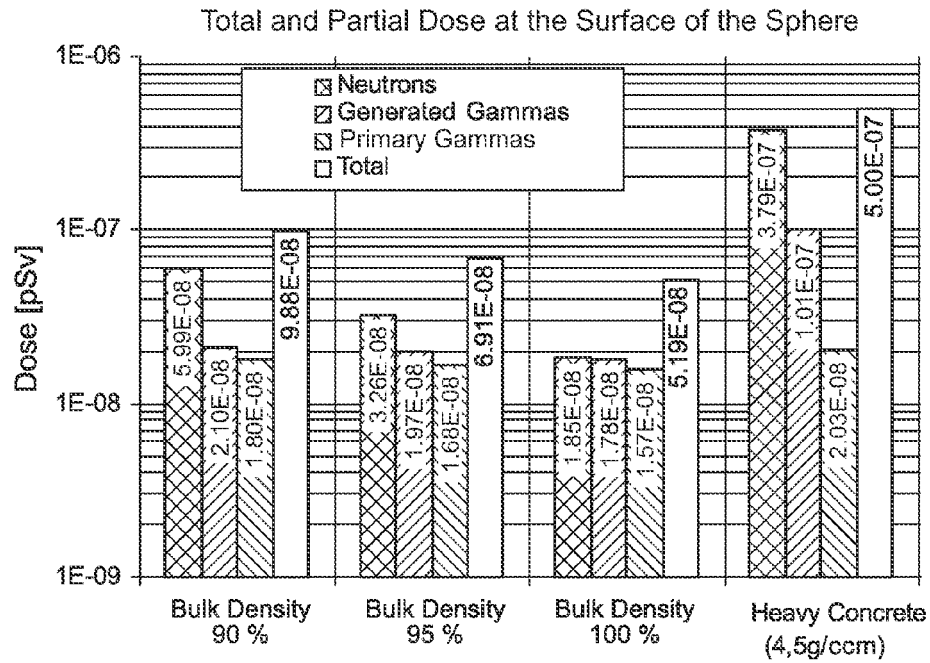
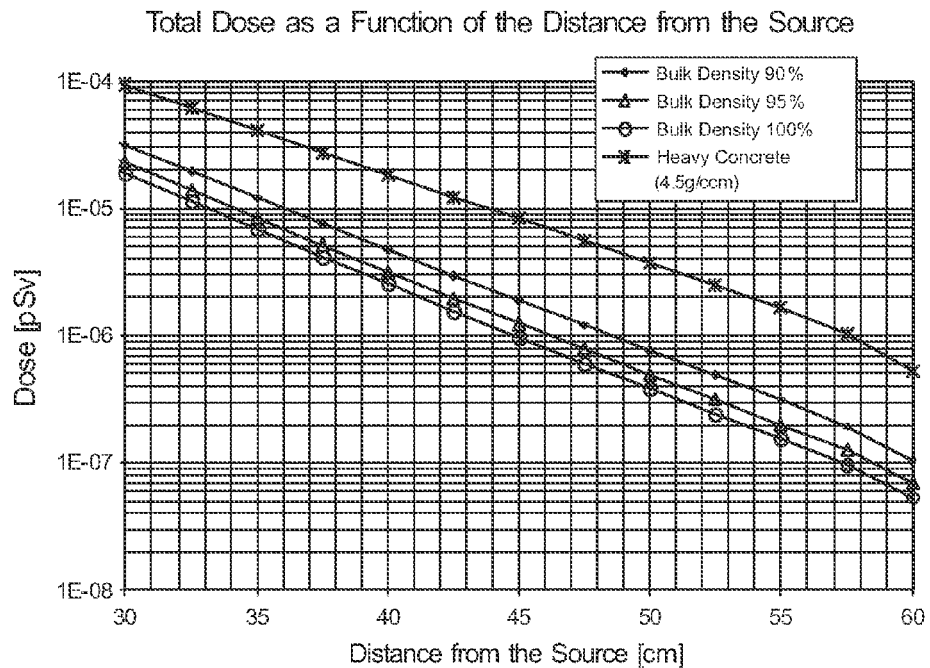


FIG 7





EUROPEAN SEARCH REPORT

Application Number
EP 10 15 2973

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 4 123 392 A (HALL WILLIAM C ET AL) 31 October 1978 (1978-10-31) * abstract * * column 3, lines 19-35 * * column 4, lines 6-27 * * column 4, line 65 - column 5, line 10 * * column 7, lines 23-32 * * column 8, lines 13-64; table 2 * * examples 4 and 8 * * column 16, lines 34-44 * -----	1-16	INV. G21F1/10
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A	GB 1 409 263 A (ELLIOTT BROTHERS LONDON LTD) 8 October 1975 (1975-10-08) * figure 1 * * page 1, lines 45-69 * * page 1, line 92 - page 2, line 31 * * page 2, lines 68-83 * -----	1-16	
A	US 2005/112375 A1 (SCHADE CHRISTOPHER T [US] ET AL SCHADE CHRISTOPHER T [US] ET AL) 26 May 2005 (2005-05-26) * abstract * * paragraphs [0010], [0025], [0026], [0031] * -----	1-14	G21F
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 16 July 2010	Examiner Manini, Adriano
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

 2
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**ANNEX TO THE EUROPEAN SEARCH REPORT
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