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RADIATION SHIELDING PROVIDED BY RESIDENTIAL HOUSES IN JAPAN IN REACTOR ACCIDENTS ACCOMPANIED WITH ATMOSPHERIC RELEASE

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Radiation Shielding Provided by Residential Houses in Japan in Reactor Accidents Accompanied with Atmospheric Release

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The present report describes the radiation shielding effect of houses in Japan against the radioactive cloud resulting from a major reactor accident accompanied with atmospheric release. The shielding factor of houses, the ratio of indoor exposure rate to outdoor one, has been studied for the semi-infinite and finite clouds which contain γ-emitting radionuclides released from a reactor facility.

The shielding factor of houses against γ-rays from the radioactive cloud decreases gradually with release delay time and keeps a minimum during the period from 50 to 1000 hours after reactor shutdown while ^{133}Xe predominates in the cloud. Radioiodines mixed in the cloud raise slightly the shielding factor, and the factor depends little on the shape of the cloud. A set of shielding factors for the use of emergency planning was consequently proposed as 0.4 for simple ferroconcrete residential house and 0.9 for other ordinary ones.

Keywords: Reactor Accident, Atmospheric Release, Radioactive Noble Gas, Radioiodine, Sheltering, Shielding Factor, Residential House, Emergency Planning

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放射性物質の大気放出を伴う原子炉事故時における日本の家屋の放射線遮蔽効果

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（1990年12月17日受理）

本報告は，原子炉事故時において施設外に放出された放射性物質のプルームに対する日本の家屋の放射線遮蔽効果について述べるものである。家屋内の照射線量率に対する家屋外の照射線量率の比として定義される遮蔽係数が，γ線放出核種を含む半無限大プルームおよび有限大のプルームに対して評価された。

放射性プルームに対する家屋の遮蔽係数は事故発生から大気放出までの遅れ時間とともに緩やかに減少し，プルーム中で^{133}Xeが最も支配的になる50～100時間で継続的に最小値となる。プルームへの放射性ヨウ素の混入により遮蔽係数は多少上がるが，プルームの形状によって遮蔽係数が大きく影響されることはない。最後に，緊急時計画を立案する際に指標とすべきプルームに対する家屋の遮蔽係数として、住居用鉄筋コンクリート家屋に対して0.4，その他の一般住居用家屋に対して0.9という値が提案された。

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1. INTRODUCTION

The impact on inhabitants in the neighborhood of nuclear facilities should be minimized in an emergency. Efforts have been made for this purpose preparing the emergency plan, countermeasures and networks for nuclear emergency as well as the safety design of the plant. It is generally said that the sheltering is one of the facile and effective countermeasures, in particular, in the early phase of the accident$^{1)}$. The sheltering means in this case that the inhabitants hide themselves into the neighboring structures, preferably into the inner rooms or areas, closing windows and doors tightly during the passage of the radioactive cloud. The advantages of the sheltering are mitigation of the radiological impact from the radioactive materials in the cloud and prevention of panic by ensuring the annoucement from the emergency headquarters.

In the former advantage of the sheltering, the house provides the protection against both external and internal exposure to radioactive materials, namely reducing the doses due to inhalation and skin-attachment of radionuclides by preventing ingression of the cloud and reducing the whole body external dose by shielding the radiation originating outside the house. Two types of radiation sources are possible for external exposure: the radioactive cloud source and the ground-deposited radionuclides source. The present report considers the shielding effect of houses against the former source which is dominant in the early phase of the accident.

The noble gas such as xenon and krypton and the volatile material such as iodine are most possible to be released in a major reactor accident. The noble gas nuclides are principal external sources because they are unlikely to retain in the human body. On the other hand, the radioiodines are the most dominant sources to the thyroid exposure. Hence the noble gas nuclides should be considered in the shielding study in the fist place.

Many studies$^{2)\sim 9)}$ have been made to assess the structure shielding effect in reactor accidents accompanied with atmospheric release. Burson and Profio$^{2)}$ have studied the radiation shielding provided by vehicle and structure against the radioactive cloud and fallout sources, and then their results have been employed as a guidline in nuclear emergency planning over the world. The building materials used now in Japanese houses are quite different from those which they considered. For this reason, it is important to assess more realistically the radiation shielding effect on the basis of the actual characteristics of houses in Japan.

The present report describes the radiation shielding effect of typical houses in Japan against principally the radioactive noble gas cloud. Some influential factors on the shielding effect will be discussed. The shielding factor of houses for the use of emergency planning will be proposed as a consequence of the study.

2. METHOD OF CALCULATION

2.1 Definition of Shielding Factor of Houses

The shielding factor of houses SF is defined as the ratio of indoor exposure rate $\dot{X}$ $(C \cdot kg^{-1} \cdot s^{-1})$ to outdoor one $\dot{X}_0$ $(C \cdot kg^{-1} \cdot s^{-1})$ and easily shown to be:

$$SF = \frac{\dot{X}}{\dot{X}_0} \qquad (1)$$

The ratio is named confusingly in some different ways, such as reduction factor and protection factor. It was decided for clarification to allocate in this report terms of "shielding factor", "reduction factor" and "protection factor" for the reduction ratio of external dose, for that of both external and internal doses and for the reciprocal of the reduction factor, respectively.

2.2 Model of Houses

Since the houses have actually a complicated structure, it is quite difficult to estimate directly their shielding factors. Thus it must be necessary to make a simple model of the houses for its own sake. There are two important factors that should be considered in modeling: structure of the house and building materials used in it. Of particular interest for modeling, simplification of house structure must be one of the most important subjects.

Shown in Figure 1 is the model of house proposed for estimating the realistically the radiation shielding effect on the basis of the actual characteristics of houses in Japan.

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Shown in Figure 1 is the model of house proposed for estimating the shielding factor. The model is concerned with single-story houses which are less protective than multi-story ones against the external radiation but which are comparatively popular in the rural region where nuclear power stations are sited. For simplification, the house is represented as a hemispherical shell consisting of three elemental pats: wall, roof and window. Each part has single- or multi-layer of building materials and its specific solid angle subtended at the center of the house; Ω_1, Ω_2 and Ω_3 for window, roof and wall, respectively.

2.3 Calculational Model

It is not realistic to evaluate the shielding factor of houses by the Monte Carlo calculation in many cases because of its considerable computing time. Simplification is of importance in calculation and thus averaging is one of the most useful measures for its sake. In our calculational model, averaging procedure has been applied to obtain the mean values of shielding factors over the elemental parts of the house and over the energies of γ-rays incident to the surface of the house.

The shielding factor of houses as a whole, SF, is given as an average of the shielding factors for the elemental part of the house, $(SF)_i$, and is shown to be:

$$SF = \frac{\Sigma_i\ (SF)_i \cdot \Omega_i}{\Sigma_i\ \Omega_i} \qquad (2)$$

where Ω_i is the solid angle subtended at the center of the house by the elemental part "i" and is used as a weighting factor in averaging. The shielding factor, $(SF)_i$, is given as an average of the shielding factors in each energy group, $\langle SF\rangle_{ij}$, and is given to be:

$$(SF)_i = \frac{\Sigma_j\ \phi(E_j) \cdot \langle SF\rangle_{ij} \cdot \Delta E_j}{\Sigma_j\ \phi(E_j) \cdot \Delta E_j} \qquad (3)$$

where $\phi(E_j)$ is the fluence of γ-ray with energy of E_j and is used as a weighting factor in averaging, and ΔE_j is the energy interval of the energy group "j". Thus the shielding factor of houses as a whole can be evaluated by averaging the factors over the elemental parts of house and γ-ray energies.

The attenuation factor A of γ-ray exposure through the material of single-layer can be written as

$$A = B(E,t) \cdot e^{-\mu(E,t) \cdot t} \tag{4}$$

where B(E,t) and μ(E,t) are the dose buildup factor and the attenuation coefficient of the material for γ-ray of energy E, respectively, and t is the thickness of material. In the case of multi-layered materials, while the exponential part of the formula could be given as a product of those of the single-layer, the buildup factor specified to the multi-layer must be used in the calculation. Although some empirical formulae have been proposed for the buildup factor of muti-layered materials, there is no experimentally positive proof that permits their application to the ordinary building materials. Hence we assumed in the calculation that the attenuation of exposure through the multi-layer would be approximately given as a product of attenuation factors for each of the single layers. Then the shielding factor, $\langle SF \rangle_{ij}$, for the element "i" and for the energy group "j" is just given by

$$\langle SF \rangle_{ij} = \Pi_k \; \{ B(E_j, t_{ik}) \cdot e^{-\mu(E_j, t_{ik}) \cdot t_{ik}} \} \tag{5}$$

where $B(E_j, t_{ik})$, $\mu(E_j, t_{ik})$ and t_{ik} are the dose buildup factor, the attenuation coefficient and the thickness, respectively, of the "k"th building material of the elemental part "i" .

In the calculational model mentioned above, the calculational process is divided into two steps: calculation of energy spectrum of γ-ray incident on the surface of the house and calculation of shielding factor. In the former calculation, of importance are the configuration of house and cloud, and the nuclidic composition of the cloud. In the latter calculation, of importance are the shielding data of building meterials and the house structure. These are going to be mentioned in the following sections.

2.4 Choice of House Structure

Since many different types of house have been built year by year, it is not easy to define a typical house. In addition, it must be true that houses in the urban area are quite different from those in the thinly populated area where nuclear power plants have been constructed. Hence in this study, some typical residential houses were chosen according to the statistical survey on the house structure and building materials$^{10)}$. The houses were classified into three types: wooden, prefabricated and ferroconcrete houses, and the building materials used in the each were selected on the basis of their percentage in the ordinary houses in Japan. The single-story house was focused on because they are still popular in the rural seaside area where all the nuclear power plants are in operation in Japan.

Table 1 gives well used building materials together with their typical density. Table 2 shows typical combinations of materials for each type of house. The shielding factors were evaluated for all the possible combination of materials in Table 1 and the shielding characteristics was investigated for each type in Table 2.

Another important factor in the calculational model is the solid angle Ω_i subtended by wall, window and roof. It is reported that the areal ratio of wall to floor ranges 1.2 ∼ 2.0 m^2/m^2 and the window occupies generally about 20 % of surface of the house in the case of ordinary residential houses$^{10)}$. The solid angle for the elemental part is regarded as the surface area in our house model shown in Figure 1 and then a set of relative solid angle was determined as shown in Table 2.

2.5 Shielding Data of Building Materials

The shielding calculation had been executed so far using the shielding data of the typical shielding materials such as water and concrete because few data are available for ordinary building materials. However it must be favorable to calculate the shielding factor using experimentally positive shieding data. As mentioned in Section 2.3, the shielding data necessary for the calculation are the linear or mass attenuation coefficient and the dose buildup factor for the photon.

A set of attenuation coefficients of 19 building materials was obtained experimentally in the energy range from 44 to 1250 keV (see Table 3)[11]. It is also reported that for energy range from 1250 to 3000 keV, the mass attenuation coefficient of the element having the atomic number corresponding to the building material is available in the shielding calculation[12] (see Table 4).

An experiment[11),12] for the buildup factor for some building materials shows that a linear formula for the buildup factor, $B = 1 + \alpha \mu t$, is available for the thin materials and for photon energy range of interst, where α is a constant fixed dependently on the material and the photon energy range (see Table 5). Since the formula cannot be applied to the materials whose thickness are over one mean free path of the photon, we employed the buildup factors for the infinite medium[13] in the calculation.

2.6 Calculation of Energy Spectrum of γ-Rays Emitted from Cloud

As described in Section 2.3, the energy differential fluence, energy spectrum, at the reference point above the ground was used as a weighting factor in averaging shielding factor over the γ-ray energies. The γ-ray energy spectra were calculated for the radioactive cloud distributed around or over the house. Two types of distribution form of the cloud were chosen for the calcutaion. One is the semi-infinite radioactive cloud distributed uniformly from the ground up to the region where it has little significant effect to the spectrum at the reference point. The other is the overhead cloud in shape of horizontally trailing cylinder with 120 m in height and 50 m in diameter. The dimension of the cloud was determined based on a typical spreading size of Gaussian plume at the border of the site. The spectrum was calculated for both source configurations.

The one dimensional discrete ordinates transport calculation code, ANISN-JR[14], was used in spectrum calculation for the semi-infinite cloud. The γ-ray energy ranging from 20 to 3000 keV was divided into 18 energy groups as given in Table 6, and P_3 and S_{12} (12 angles) approximation was used in the calculation. Figure 2 shows the structure of spatial meshes. The space neighboring the ground was especially divided into small meshes. The space has a white boundary at the upper end where the outgoing photon current balances with incoming one and hence the net current is zero, and a vacuum boundary at the lower end where the incoming photon current is zero in all directions. As the air and soil layers have thickness about ten times and six times the mean free paths of the most energetic γ-ray in them, respectively, the boundaries have no effect to the energy spectrum at the reference point 1 m above the ground.

The two dimensional discrete ordinates transport calculation code, DOT 3.5[15), was used in the spectrum calculation for the cylindrical cloud. The same eneregy group structure as that for the semi-infinite cloud and P_5 and S_6 (48 angles) approximation were used. Figure 3 shows the structure of spatial meshes. Since it is difficult to take into account the effect of reflection of γ-rays by the ground under such a cylindrical condition, the following correction was made. A set of energy-dependent correction factor $\beta(E_j)$ for the ground reflection was obtained by comparing the spectrum over the ground boundary with that over the vacuum boundary in the slab geometry. The spectrum calculation in the slab geometry was made with ANISN-JR code. The energy spectrum over the ground for the cylindrical cloud, $\phi(E_j)$, was obtained as a product of that over the vacuum boundary, and $\beta(E_j)$ as presented below:

$$\phi(E_j) = \phi(E_j)_{vac} \cdot \beta(E_j) \qquad (6)$$

$$\beta(E_j) = \psi(E_j) / \psi(E_j)_{vac} \qquad (7)$$

where $\psi(E_j)_{vac}$ and $\psi(E_j)$ are the specra over the ground and the vacuum boundaries, respectively.

Two different types of cloud contents were supposed. One is a set of monoenergetic γ-ray emitters whose energies were alloted to each energy group in the transport calculation and whose emission intensity was normalized to be one γ-ray per second per cm^3. The other is a mixture of radioactive noble gas nuclides generated in the reactor core during operation. In the tranport calculation, the source concentration was normalized to be 37 kBq(1 μCi) per cm^3. Since the nuclidic composition of the noble gas mixture varies with time after reactor accident or shutdown, the time dependent composition should be considered in the shielding study. Details are to be in the next section.

2.7 Calculation of Nuclidic Composition in Radioactive Cloud

The radioactive cloud resulting from a major reactor accident could be a mixture of various radionuclides with different life time. The noble gas such as xenon and krypton is most possible to be released in reactor accidents and the mean energy of γ-rays emitted from them varies with the release delay time after reactor shutdown.

The isotope generation and depletion code, ORIGEN-JR[16], was used in the calculation of inventory in the reactor core at the moment of reactor shutdown and following moments up to 2000 hours. The calculation was carried out for a typical PWR of 1100 MWe. The initial average uranium enrichment, power density and operating time were determined to be 3.2 %, 30 MW/ton and 500 days, respectively, according to a typical operational condition of PWR.

Eleven nuclides of krypton and xenon shown in Table 7 were chosen for the nuclidic component of the cloud. They could be principle sources of external exposure of inhabitants in reactor accidents. The release of radioiodines was also considered. Although the radioiodine is considered to be a major source of internal exposure of thyroid, they may also be the external source because of its γ-ray emission. Radioiodines in question are also presented in Table 7. In the case of iodine release, it was assumed exaggeratedly that when the whole noble gas in the reactor core would be released, iodine be by 25 %. This is because the iodine gas release must be necessarily accompanied with the release of a large amount of noble gas.

3. RESULTS AND DISCUSSION

3.1 Monoenergetic γ-Ray Sources

3.1.1 γ-Ray Energy Spectrum at 1 m above the Ground

γ-ray energy spectra at the reference point 1 m above the ground were calculated for monoenergetic γ-ray sources of submersion and overhead plume. Figure 4 shows γ-ray energy spectra for three γ-ray energy source groupes: 3rd (1000 ~ 1400 keV), 7th (300 ~ 400 keV) and 11th (100 ~ 130 keV) energy groups presented in Table 6. The spectra are shown normalized at their source

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The spectrum for the overhead plume source has larger component of scattered γ-rays than that for the submersion source. It is merely because γ-rays emitted from the overhead plume have higher probability of scattering during their passage to the reference point than those emitted from the submersion. In other words, while the overhead plume source is distributed more than 100 m far from the reference point, in case of submersion the γ-ray emitting cloud spreads to just beside the reference point. This feature appears the more conspicuous for the lower energy source.

3.1.2 Shielding Factor against Monoenergetic γ-Ray Cloud

The shielding factor has been estimated for monoenergetic γ-ray sources of submersion and overhead plume. Figure 5 shows shielding factors as a function of γ-ray source energy for three different types of house . The shielding factor increases consistently with the source energy. Reflecting scattered component, the shielding factors for overhead plume are a little less than those for submersion but difference between them is not notable. As can be seen in the figure, since the distribution form of cloud does not affect the shielding factor of houses, the factor for submersion may be allowed to give a typical shielding factor in a reactor accident.

The shielding protection rises in the order of prefabricated, wooden and ferroconcrete houses. The prefabricated house provides feeble shielding protection, but the wooden house is effective in shielding. While ALC(Autoclaved Light Weight Concrete) panels used in the prefabricated house do not contribute so much to the shielding because of their low density (ρ = 0.58 g/cm^3), clay rooftiles and mortar used in the wooden house have a great contribution to the shielding because of their comparatively high densities (ρ = 1.93 and 2.35 g/cm^3, respectively). Since the materials described just above have the almost same corresponding atomic number, the density of the building material can be concluded to be one of the important factors in shielding. The ferroconcrete house provides more effective shielding protection than those discussed above. This is because concrete used in the wall and roof has high density of 2.35 g/cm^3 and large thickness of 15 cm.

The shielding factor of the ferroconcrete house decreases with the source energy differently from others in the energy region less than 200 keV. While the buildup factor for the infinite concrete medium was used for the ferroconcrete house, the buildup factors in slab geometory were employed for the prefabricated and wooden houses. In most cases, the buildup factor in the infinite medium exceeds that in the slab geometry in low energy region because of the backscattered γ-ray component in the medium. For the above reason, the shielding factor of the ferroconcrete house is concluded to be overestimated in the energy range less than 200 keV. In other words, more shielding protection must be expected for the ferroconcrete house in this energy region.

3.2 Radioactive Noble Gas Sources

3.2.1 Nuclidic Composition in Radioactive Noble Gas Cloud

A noble gas inventory in the reactor core was computed using ORIGEN-2 code to evaluate nuclidic fractions in the cloud. Table 8 shows a set of nuclidic fractions (in %) of krypton and xenon in the core at 0.05 ～ 800 hours after reactor shutdown, which results from a 500-day operation. A noteworthy nuclide in the table is ^{133}Xe. It predominates in the noble gas cloud and attains over 90 % of fraction from 50 to several hundreds hours after reactor shutdown. It can be said from this that ^{133}Xe is the overwhelming source for external exposure one day after the accident. Although ^{85}Kr becomes a major nuclide in the cloud after a thousand hours, it must be noteless in terms of external exposure because of its very feeble γ-ray emission (0.43 % per disintegration).

Since the noble gas is chemically inactive, its relative nuclidic fraction in the atmospheric environment is expected to be the same as in the reactor core. If we consider the period from reactor shutdown to plume arrival to the house, we can obtain a set of nuclidic fractions at any moment of exposure from Table 8.

3.2.2 Energy Spectrum and Mean Energy of γ-Rays from Cloud

γ-ray energy spectra at the reference point 1 m above the ground have been calculated for submersion and overhead plume of noble gas nuclides. Figure 6 shows a series of spectra at 0.05, 3.0, 20, 125 and 800 hours after reactor shutdown. The spectra in the figure are shown being normalized at the energy group indicated by an arrow. As time passes, higher energy portion disappears gradually in the spectrum. Major portion of γ-rays after 125 hours is considered to result from ^{133}Xe which emits γ-ray of 81 keV. As in the case of monoenergetic γ-ray cloud sources, the spectra for submersion include less scattered component of γ-rays than those for overhead plume do.

Figure 7 shows the mean energies of γ-rays at the reference point 1 m above the ground, drawn as a function of time after reactor shutdown. Both submersion and overhead plume have lower mean energy than that of the direct γ-rays at the reference point because of the component of scattered and energy-lessened γ-rays. The mean energy of the source itself decreases with time and attains less than 100 keV about 100 hours after reactor shutdown. Since the overhead plume includes much scattered γ-ray component than the submersion does, the mean energy of the former is less than that of the latter but they become close each other after 100 hours. Then the shielding factor is considered to vary with time accordingly.

3.2.3 Shielding factor against Radioactive Noble Gas Cloud

The shielding factor of houses was estimated for the two types of radioactive noble gas cloud of which the nuclidic fraction, energy spectrum and mean energy of γ-rays at the reference point were discussed above. Figure 8 shows shielding factors as a function of time after reactor shutdown for three different types of house. As in the case of monoenergetic γ-ray cloud sources, the shielding protection rises in the order of prefabricated, wooden and ferroconcrete houses.

The shielding factor decreases gradually with time and keeps a minimum after 50 hours, which corresponds to the time-dependent change of γ-ray mean energy. The houses provide a little greater shielding protection agaist the overhead plume than against the submersion. This is also because the overhead plume includes more fraction of scattered γ-ray than the other.

It is suggested that there be delay time before the occurence of uncontrolled release of radioactive materials in the accident and the delay varies from about half an hour to one day depending on the plant and accident sequence[17]. It should be taken into consideration that the change of γ-ray mean energy and accordingly the shielding factor of houses decreases with delay time of release.

3.3 Consideration to Release of Radioiodines

Iodine is another possible principal material to be released in reactor accidents because of its high volatility. It is expected that the amount of iodine to be released is much less than that of noble gas because it may be reduced by wash-out and fixation during leakage. The iodine gas release must be necessarily accompanied with the release of a large amount of noble gas. The shielding factor of houses were calculated under a hypothesis that a quarter of iodine and all of noble gas in the reactor core would be released.

Figure 9 shows comparison of energy spectra between due to noble gas cloud and iodine-mixed one. Although mixture of radioiodines into the noble gas cloud has no significant effect in the spectrum immediately after the accident, the difference between two spectra becomes noticeable as time passes. While the compoment of γ-ray over 100 keV can be observed in the spectrum for iodine-mixed noble gas cloud after 300 hours, it is not observed in the spectrum for pure noble gas cloud. Figure 10 shows comparison of γ-ray mean energy between due to noble gas cloud and iodine-mixed one as a function of time after reactor shutdown. The mean energy for iodine-mixed noble gas cloud is less than that for pure noble gas cloud till several hours later but this relationship reverses after then. The difference between the two is estimated to be about 100 keV at and after 50 hours.

Figure 11 shows the shielding factors of houses against the iodine-mixed noble gas submersion as a function of time after reactor shutdown, in comparison of those against pure noble gas one. The house provides less shielding protection against the iodine-mixed submersion than the pure one because of higher energy component of γ-rays due to radioiodines. The release of radioiodines affects the shielding factor also in its decreasing manner as being more gradual. As can be seen in the figure, the shielding factor rises slightly again after several hundreds hours. A quarter of iodine activity in the core was assumed to be released in the calculation but this hypothesis is fairly radical in the case of accident of water reactor . It was reported that while 96 PBq(2.5 × 10^6 Ci) of noble gas were released into the atmosphere, only about 555 GBq(15 Ci) of iodine were released in the accident of TMI-2. It can be expected from this that the difference between the two shielding factors for each house would be smaller in actual cases than that shown in Figure 11.

3.4 Effect of Window Portion on Shielding Factor

This section describes how the window portion of the house affects the shielding factor in the case of noble gas release. It is important to consider this effect because the window provides very feeble shielding protection and any residential house is windowed for lighting rooms. Figure 12 shows the shielding factor of ferroconcrete house as a function of Ω_{win} , relative solid angle subtended by window at the center of the house (see Figure 1). The shielding factors are plotted for two types of submersion whose nuclidic composion are those at 3 and 300 hours after the accident. The houses of $\Omega_{win} = 0.0$ and $\Omega_{win} = 1.0$ can be regarded as a greenhouse and a protective shelter, respectively. Since Ω_{win} can be treated as a linear factor to the shielding factor in our calculational model, the shielding factor increases linearly with Ω_{win} as a matter of course. What we have to take notice of is drastic change of the shieling factor, i.e. from 0.1 to 0.95 and from 0.01 to 0.93 for the submersions at 3.0 and 300 hours, respectively. This means that if inhabitants hide themselves behind the internal wall, protective effect can be expected more than that shown in Figures 8 and 11 because of substantial zero of Ω_{win} .

4. SHIELDING FACTOR AS A GUIDELINE IN EMERGENCY PLANNING

The shielding factor of houses in reactor accident has been investigated and its characteristics has been discussed about so far. This chapter descibes a guideline of shielding factor in emergency planning, which would facilitate decision making and execution of countermeasures for the public around the facilities. It is obvious from the above discussion that the shielding factor the core was assumed to be released in the calculation but this hypothesis is fairly radical in the case of accident of water reactor . It was reported that while 96 PBq(2.5 × 10^6 Ci) of noble gas were released into the atmosphere, only about 555 GBq(15 Ci) of iodine were released in the accident of TMI-2. It can be expected from this that the difference between the two shielding factors for each house would be smaller in actual cases than that shown in Figure 11.

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The shielding factor of houses decreases monotonously with time after reactor shutdown as can be seen in Figures 7 and 11. Considering any timing of release of radioactive materials from the facilities, it is reasonable to adopt values of shielding factor in the very early time of the accident. From Figures 7 and 11, shielding factors of 0.9, 0.7 and 0.4 would be fixed as conservatively rounded value for prefabricated, wooden and ferroconcrete houses, respectively. It is obvious from the discussion in the preceding sections that the shielding factors must not exceed these specific values in any case of release. Shielding calculation was executed for them against the noble gas cloud. Since there are some common building meterials used in both wooden houses and prefabricated ones, it is better to classify the house into ferroconcrete house and others to consider a generalized guideline. It can be derived from the above discussion that the shielding factor of ferroconcrete house never exceed 0.4 at any time of release in the accident. Considering the demandes for simplicity and wide applicability of the guideline in emergency use, it can be concluded that shielding factors of 0.4 and 0.9 are applicable for ferroconcrete house and other ordinary houses, respectively. Finally, it is important to note that both factors include a margin and then they may lead an overestimation for the inhabitants' projected dose.

5. CONCLUSIONS

The shielding factor of houses in major reactor accident was studied for the monoenergetic γ-ray cloud source and radioactive noble gas cloud source. The followings were concluded from this shielding study.

1) The spreading shape of cloud source barely affects the shielding factor,
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1) The spreading shape of cloud source barely affects the shielding factor,
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gradually with release delay time and keeps a minimum during the period from 50 to 1000 hours after reactor shutdown , while ^{133}Xe predominates in the cloud,

3) Mixing of radioiodines into the noble gas cloud raises the shielding factor insignificantly,
4) Even if the radioactive noble gas cloud ingresses the house, it would barely affect the shielding factor,
5) Shielding factors of 0.4 and 0.9 were proposed for ferroconcrete house and other ordinary ones, respectively, as a guideline in emergency planning.

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Table 1 Building materials used well in Japan and their typical density

Building Material	Density (g/cm³)	Building Material	Density (g/cm³)
Cedar Board	0.38	Asbestos Cement Sheet	1.5 ～ 1.6
Plaster	1.1	Gypsum Board	0.95 ～ 1.4
Mud	1.1 ～ 1.3	Gypsum Lath Board	0.93 ～ 1.4
Mortar	2.0 ～ 2.15	Sheet Glass	2.5
Concrete	2.3 ～ 2.35	Clay Rooftile	1.73
Lightweight Concrete	1.6	Fibreboard	0.99
Autoclaved Lightweight Concrete	0.6	Pressed Cement Roof Tile	2.29
Hollow Concrete Block	1.21	Coated Iron Sheet	7.86
Plywood Board	0.63		

Table 2 Building materials used in the typical houses in Japan and relative solid angles (Ω_i) subtended at the center of the house by wall, roof and window

Type of House	Ω_i	Building Material (thickness)
Wooden House	Wall 0.6	Mortar(3.2cm) + Cader board(1.2cm) + Gypsum board(0.9cm)
	Roof 0.2	Clay rooftile(2.8cm) + Cedar board(1.2cm) + Gypsum board(0.9cm)
	Window 0.2	Sheet glass(0.3cm)
Prefabricated House	Wall 0.6	Autoclaved lightweight concrete(5.0cm) + Gypsum board(0.9cm)
	Roof 0.2	Asbestos cement sheet(0.45cm) + Cedar board(1.2cm) + Gypsum board(0.9cm)
	Window 0.2	Sheet glass(0.3cm)
Ferroconcrete House	Wall 0.6	Concrete(20cm)+ Gypsum board(0.9cm)
	Roof 0.2	Concrete(20cm)+ Gypsum board(0.9cm)
	Window 0.2	Sheet glass(0.3cm)

Table 3 Linear attenuation coefficients of various building materials

	Building Material	Density (g/cm^3)	Linear Attenuation Coefficient (cm^{-1})						
			*44 keV	59.5 keV	*84 keV	*105 keV	320 keV	662 keV	1250 keV
1	Cedar Board	0.38	0.0803±0.0004	0.0745±0.0003	0.0585±0.0002	0.0560±0.0003	0.0392±0.0006	0.0288±0.0002	0.0217±0.0004
2	Lauan Board	0.54	0.1244±0.0004	0.1066±0.0002	0.0909±0.0002	0.0837±0.0003	0.0598±0.0005	0.0436±0.0001	0.0332±0.0002
3	Plywood Board	0.65	0.1445±0.0008	0.1229±0.0003	0.1016±0.0005	0.0992±0.0005	0.0678±0.0012	0.0514±0.0006	0.0378±0.0010
4	Particleboard	0.70	0.1532±0.0004	0.1322±0.0003	0.1149±0.0002	0.1066±0.0002	0.0738±0.0006	0.0522±0.0002	0.0411±0.0004
5	Insulation Fibreboard	0.30	0.0663±0.0004	0.0569±0.0003	0.0475±0.0002	0.0447±0.0002	0.0317±0.0005	0.0217±0.0003	0.0188±0.0005
6	Hard Fibreboard	0.99	0.2246±0.0007	0.1992±0.0007	0.1694±0.0004	0.1602±0.0004	0.1132±0.0010	0.0788±0.0005	0.0627±0.0008
7	TATAMI	0.34	0.0892±0.0003	0.0672±0.0003	0.0577±0.0002	0.0509±0.0002	0.0361±0.0004	0.0257±0.0002	0.0194±0.0003
8	Wood-Wool Cement Board	0.54	0.2772±0.0006	0.1632±0.0004	0.1071±0.0002	0.0998±0.0002	0.0513±0.0004	0.0392±0.0002	0.0299±0.0003
9	Wood-Chip Cement Board	1.11	0.6138±0.0013	0.3681±0.0009	0.2383±0.0005	0.1973±0.0006	0.1164±0.0007	0.0852±0.0003	0.0674±0.0004
10	Asbestos Cement Sheet A	1.49	0.9761±0.0020	0.5232±0.0012	0.3261±0.0005	0.2677±0.0005	0.1576±0.0010	0.1167±0.0005	0.0901±0.0005
11	Asbestos Cement Sheet B	1.70	1.192 ±0.0025	0.6597±0.0015	0.4021±0.0006	0.3266±0.0007	0.1862±0.0014	0.1347±0.0007	0.1027±0.0011
12	Autoclaved Lightweight Concrete	0.58	0.3190±0.0006	0.1851±0.0004	0.1263±0.0002	0.1015±0.0002	0.0570±0.0004	0.0442±0.0001	0.0335±0.0002
13	Hollow Concrete Block	1.52	0.8624±0.0022	0.5205±0.0013	0.3184±0.0005	0.2357±0.0005	0.1452±0.0009	0.1106±0.0003	0.0806±0.0005
14	Pressed Cement Roof Tile	2.31	1.347 ± 0.0031	0.7864±0.0020	0.5002±0.0009	0.4149±0.0010	0.2442±0.0020	0.1858±0.0008	0.1329±0.0012
15	Gypsum Board	0.70	0.4177±0.0010	0.2404±0.0006	0.1561±0.0003	0.1266±0.0003	0.0747±0.0006	0.0560±0.0002	0.0415±0.0004
16	Gypsum Lath Board	0.66	0.4203±0.0009	0.2465±0.0008	0.1530±0.0004	0.1226±0.0004	0.0759±0.0007	0.0529±0.0004	0.0335±0.0005
17	Clay Rooftile A	1.93	0.9281±0.0021	0.5540±0.0007	0.3669±0.0006	0.3048±0.0007	0.1837±0.0013	0.1368±0.0005	0.1016±0.0007
18	Clay Rooftile B	1.65	0.8178±0.0019	0.4931±0.0006	0.3390±0.0006	0.2776±0.0006	0.1762±0.0012	0.1282±0.0005	0.0945±0.0007
19	Sheet Glass	2.34	1.347 ± 0.0031	0.6370±0.0019	0.4480±0.0011	0.3819±0.0012	0.2372±0.0026	0.2058±0.0011	0.1354±0.0016

* Values obtained with heavily filtered X-rays

Table 4 Corresponding atomic number(Z_{cor}) and classification of building material

Building Material	Density (g/cm^3)	Z_{cor}	Material Group
Cedar Board	0.38	7	I (7 ～ 9)
Lauan Board	0.54	8	
Plywood Board	0.65	8	
Particleboard	0.70	7	
Insulation Fibreboard	0.30	8	
Hard Fibreboard	0.99	8	
TATAMI	0.32	9	
Wood-Wool Cement Board	0.54	14	Ⅱ (13 ～ 16)
Wood-Chip Cement Board	1.11	14	
Asbestos Cement Sheet A	1.49	15	
Asbestos Cement Sheet B	1.70	16	
Autoclaved Lightweight Concrete	0.58	14	
Hollow Concrete Block	1.52	14	
Pressed Cement Roof Tile	2.31	15	
Gypsum Board	0.70	15	
Gypsum Lath Board	0.66	15	
Clay Rooftile A	1.93	13	
Clay Rooftile B	1.65	14	
Sheet Glass	2.34	13	

Tabel 5 Constant α in linear formula of dose buildup factor for building material group and incident photon energy range

Material Group	Constant α		
	68 ～ 100 keV	100 ～ 662 keV	662 ～ 1250 keV
I	1.3	1.0	0.7
Ⅱ	0.7	0.7	0.7

Table 6 Energy group structure in γ-ray spectrum calculation

Group No.	γ-Ray Energy Range (keV)
1	3000.0 ～ 2000.0
2	2000.0 ～ 1400.0
3	1400.0 ～ 1000.0
4	1000.0 ～ 700.0
5	700.0 ～ 520.0
6	520.0 ～ 400.0
7	400.0 ～ 300.0
8	300.0 ～ 230.0
9	230.0 ～ 170.0
10	170.0 ～ 130.0
11	130.0 ～ 100.0
12	100.0 ～ 80.0
13	80.0 ～ 62.0
14	62.0 ～ 50.0
15	50.0 ～ 40.0
16	40.0 ～ 33.0
17	33.0 ～ 26.0
18	26.0 ～ 20.0

Table 7 Radionuclides composing radioactive cloud

Krypton	^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{89}Kr
Xenon	^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe, ^{138}Xe
Iodine	^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I

Table 8 Nuclidic fraction (in %) of mixed noble gas at different time after reactor shutdown resulting from 500-day operation

Nuclide	Time After Reactor Shutdown (hour)								
	0.05	1.00	3.00	8.00	20.0	50.0	125	300	800
^{85m}kr	4.37	6.37	5.10	2.62	0.50	0.01	—	—	—
^{85}kr	0.09	0.16	0.17	0.19	0.23	0.33	0.50	1.28	15.64
^{87}kr	0.08	0.09	0.03	—	—	—	—	—	—
^{88}kr	11.89	15.82	10.59	3.48	0.23	—	—	—	—
^{131m}Xe	0.16	0.27	0.29	0.33	0.40	0.55	0.81	1.72	8.82
^{133m}Xe	0.93	1.57	1.70	1.88	2.15	2.33	1.49	0.39	0.01
^{133}Xe	30.50	50.83	55.45	61.57	73.09	91.72	97.19	96.59	75.53
^{135m}Xe	5.59	6.97	6.04	3.99	1.38	0.08	—	—	—
^{135}Xe	7.98	15.65	20.61	25.95	22.02	4.98	0.03	—	—
^{137}Xe	16.27	—	—	—	—	—	—	—	—
^{138}Xe	22.14	2.29	0.01	—	—	—	—	—	—

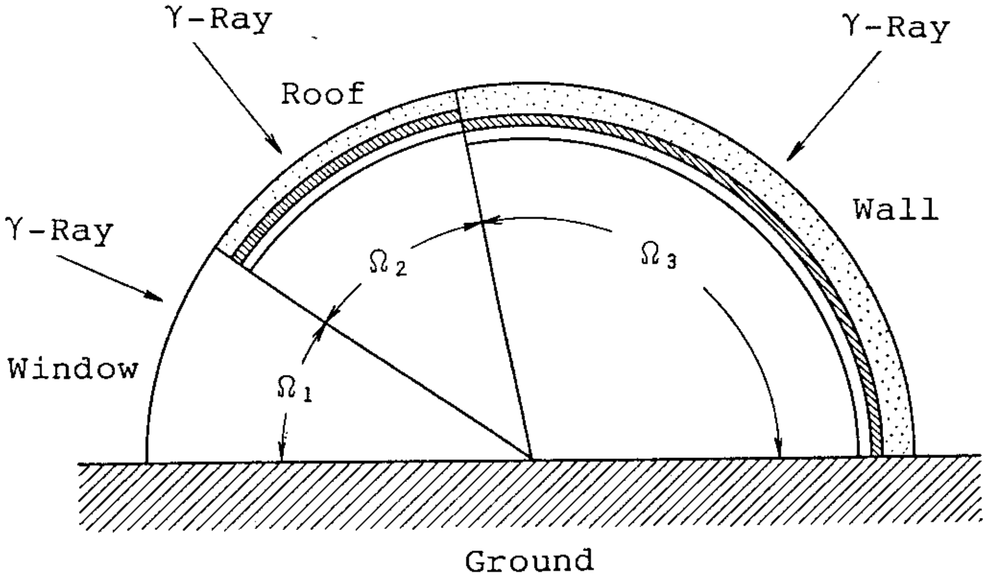

Fig. 1 Diagram of house model. Roof and wall consist of different building materials.

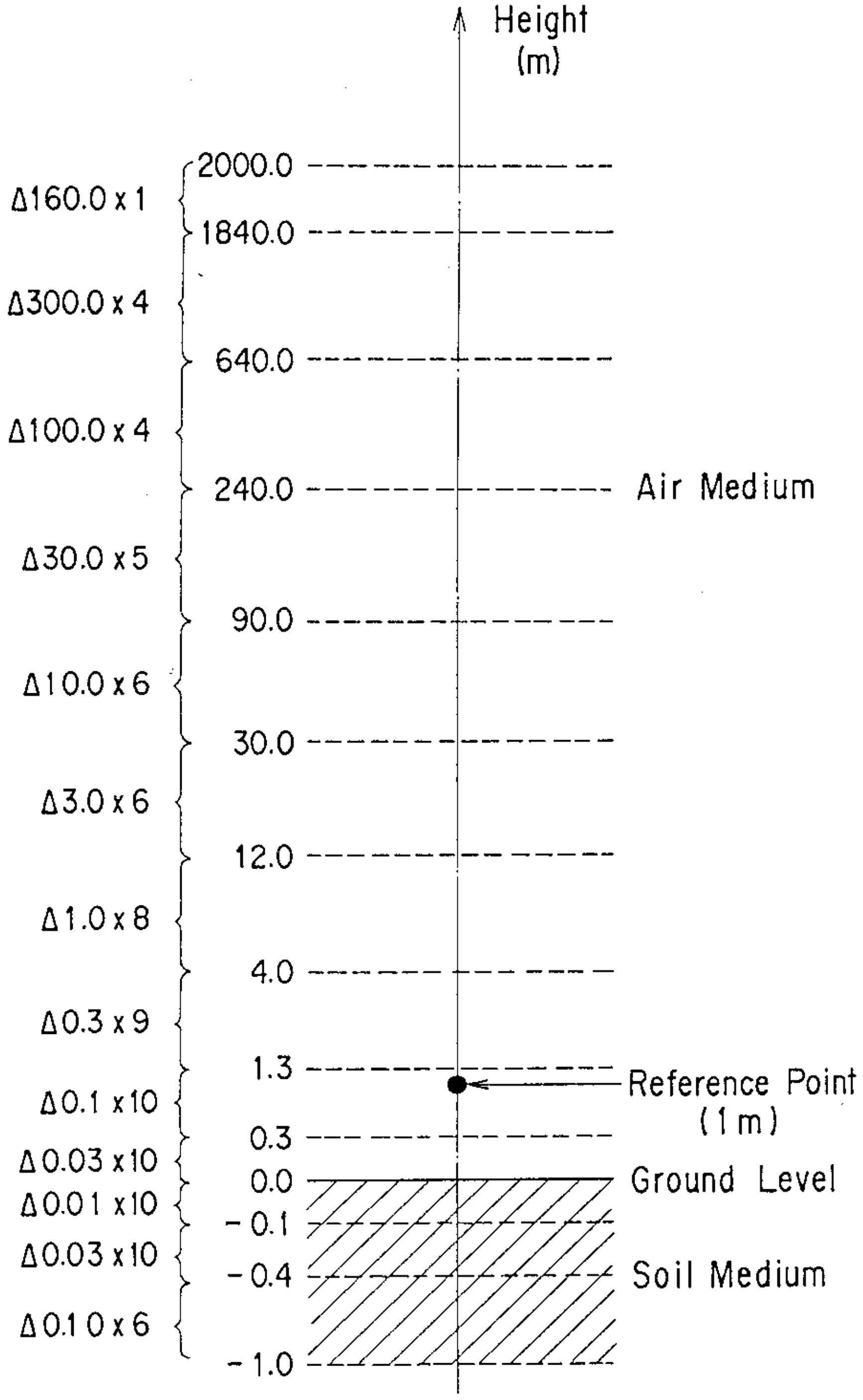

Fig. 2 Spatial mesh structure in one dimensional transport calculation.

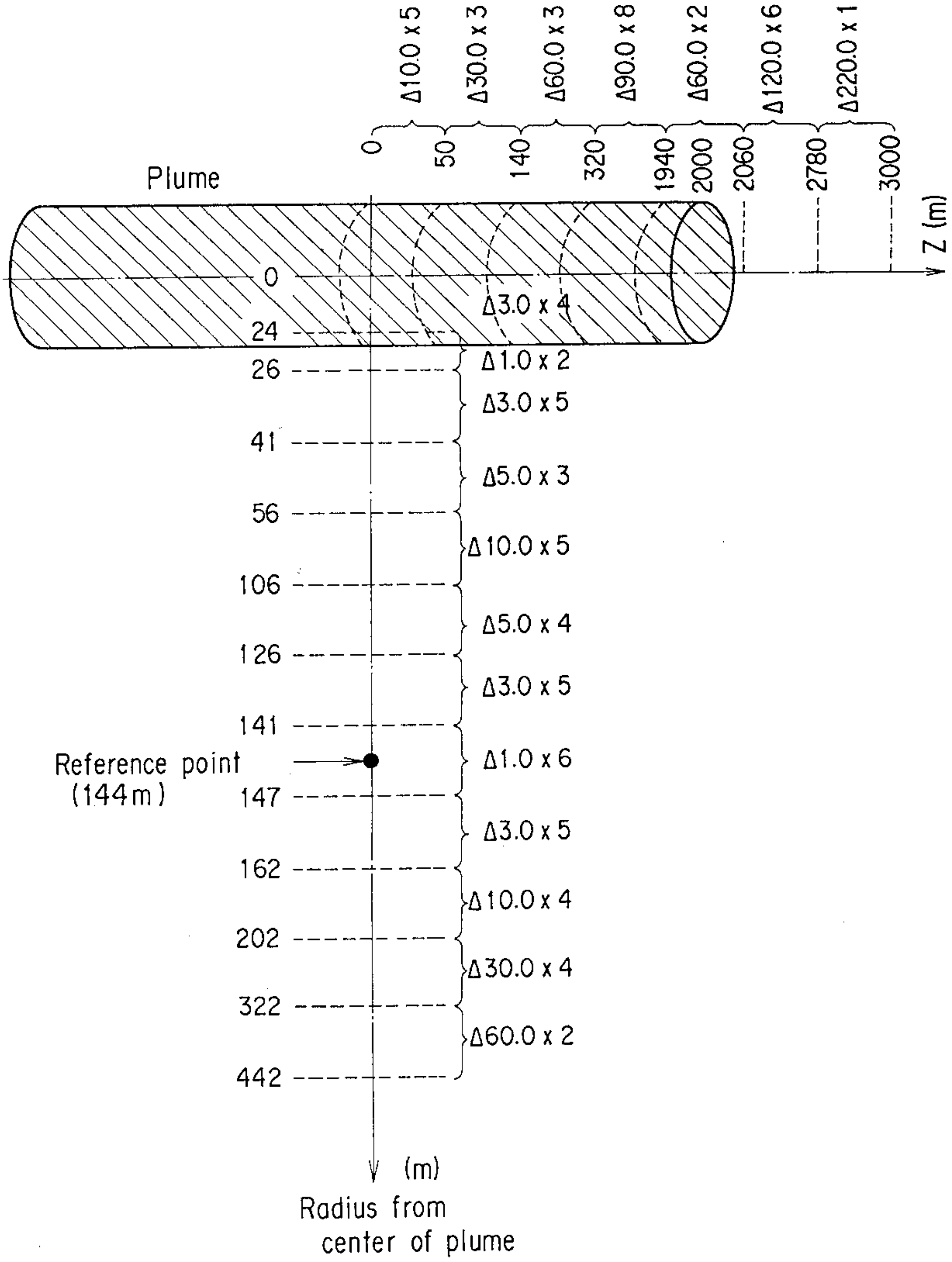

Fig., 3 Spatial mesh structure in two dimensional transport calculation.

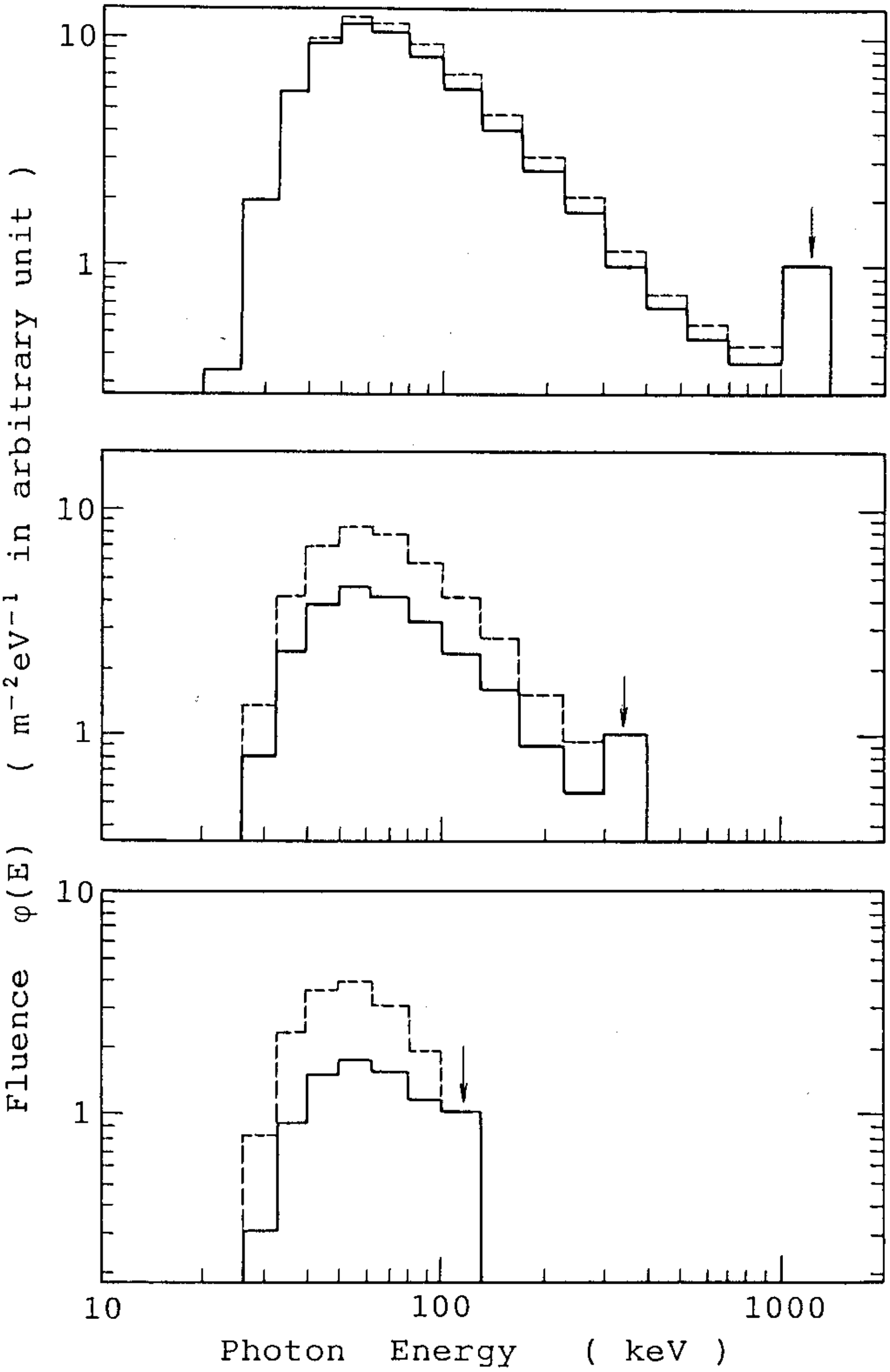

Fig. 4 γ-ray energy spectra at 1 m above the ground for monoenergetic γ-ray sources of submersion (solid line) and overhead plume (broken line) trailing horizontally with cylindrical shape of 120 m height and 50 m diameter. Source energy group is indicated by an arrow.

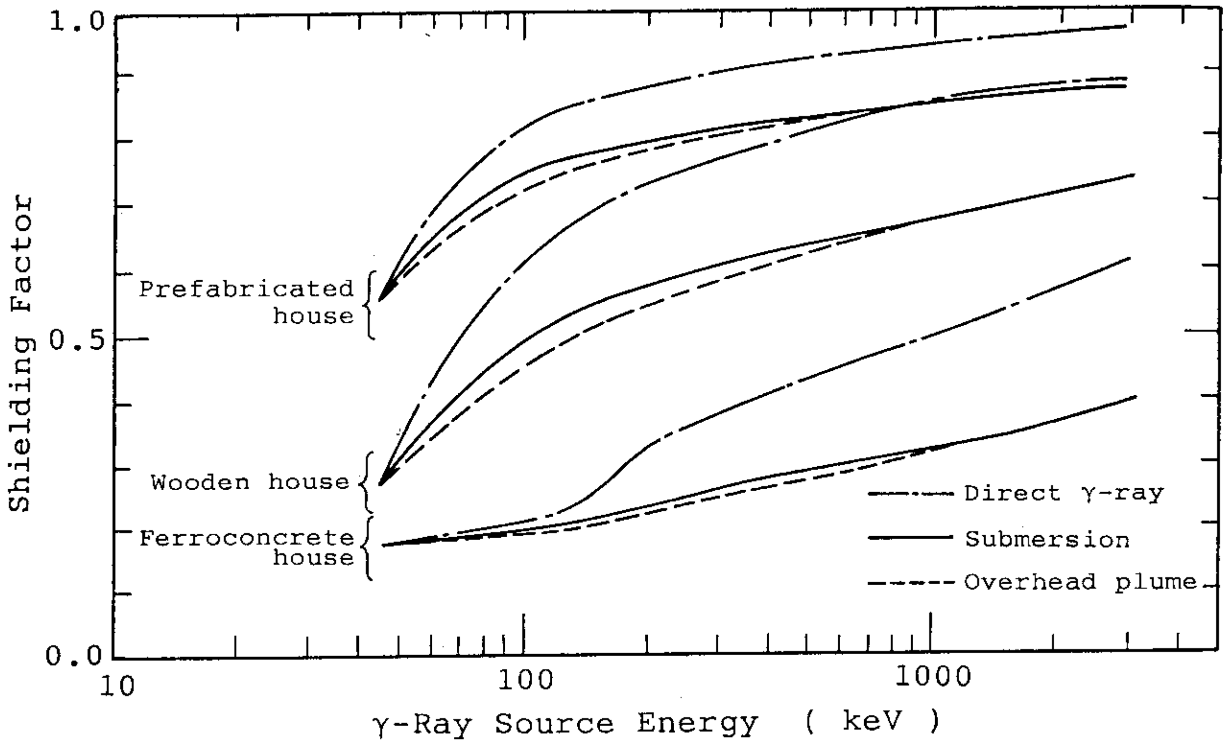

Fig. 5 Shielding factor of houses against two types of radioactive cloud containing monoenergetic γ-ray source. Also plotted are those against direct γ-rays.

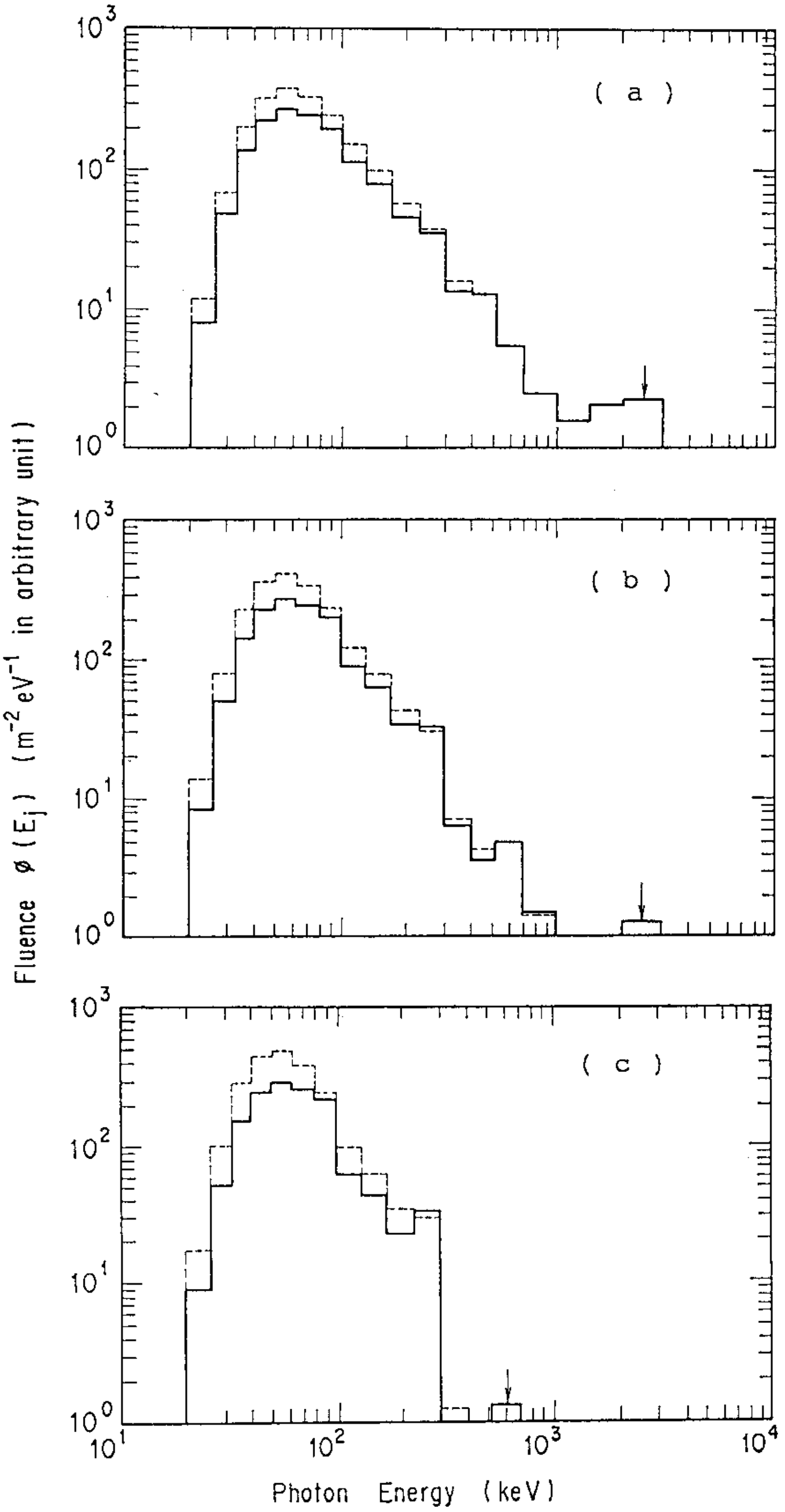

Fig. 6 γ-ray energy spectra at 1 m above the ground for submersion (solid line) and overhead plume (broken line) at (a) 0.05, (b) 3.0, (c) 20, (d) 125 and (e) 800 hours after rector shutdown. The spectra are normalized at the energy group indicated by an arrow.

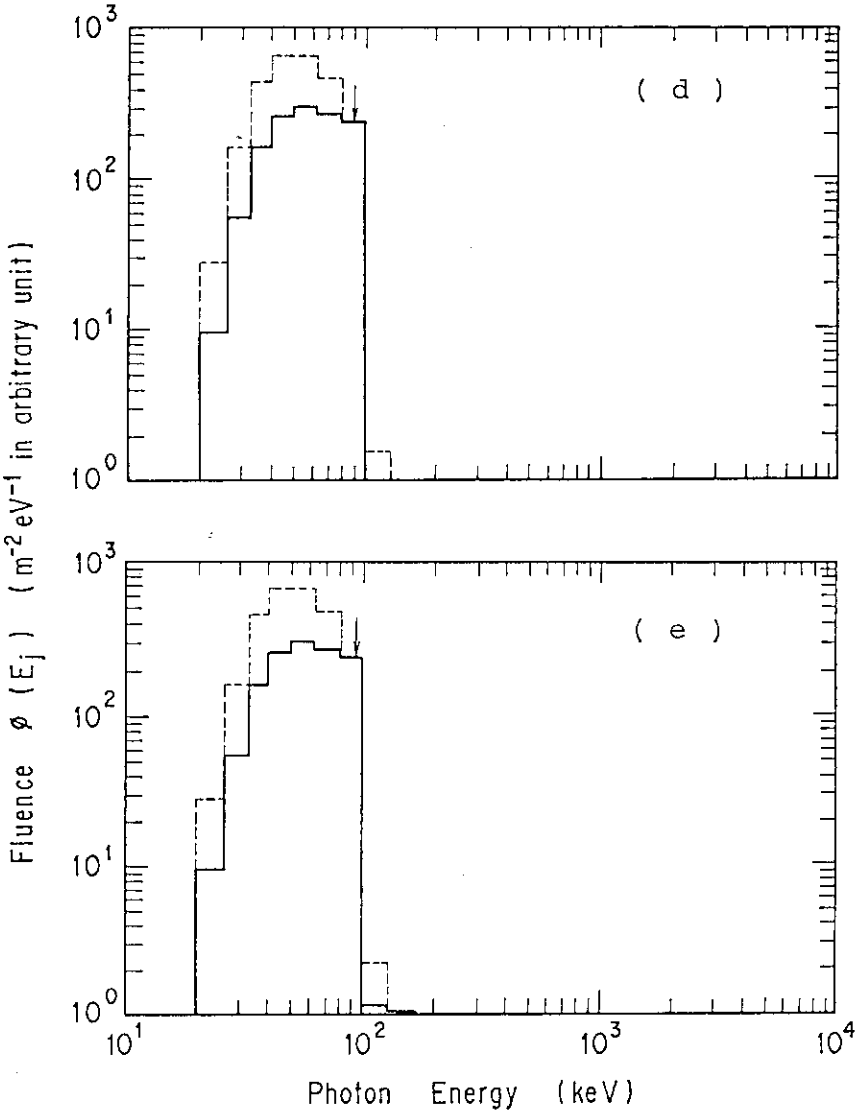

Fig. 6 (Continued)

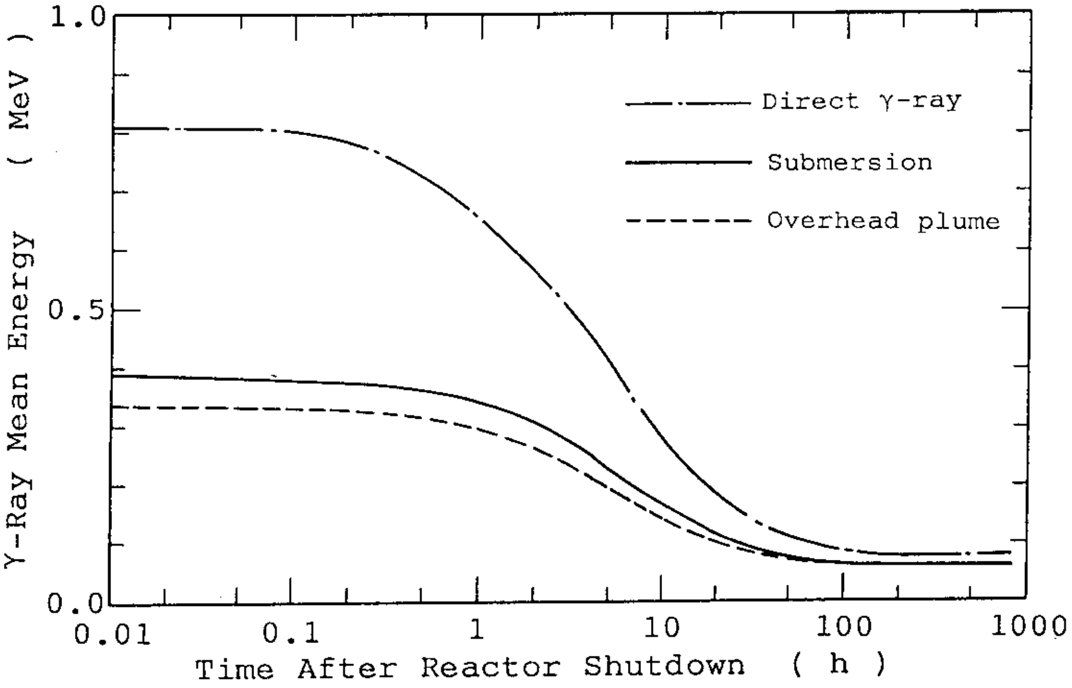

Fig. 7 γ-ray mean energy at 1 m above the ground due to radioactive cloud as a function of time after reactor shutdown.

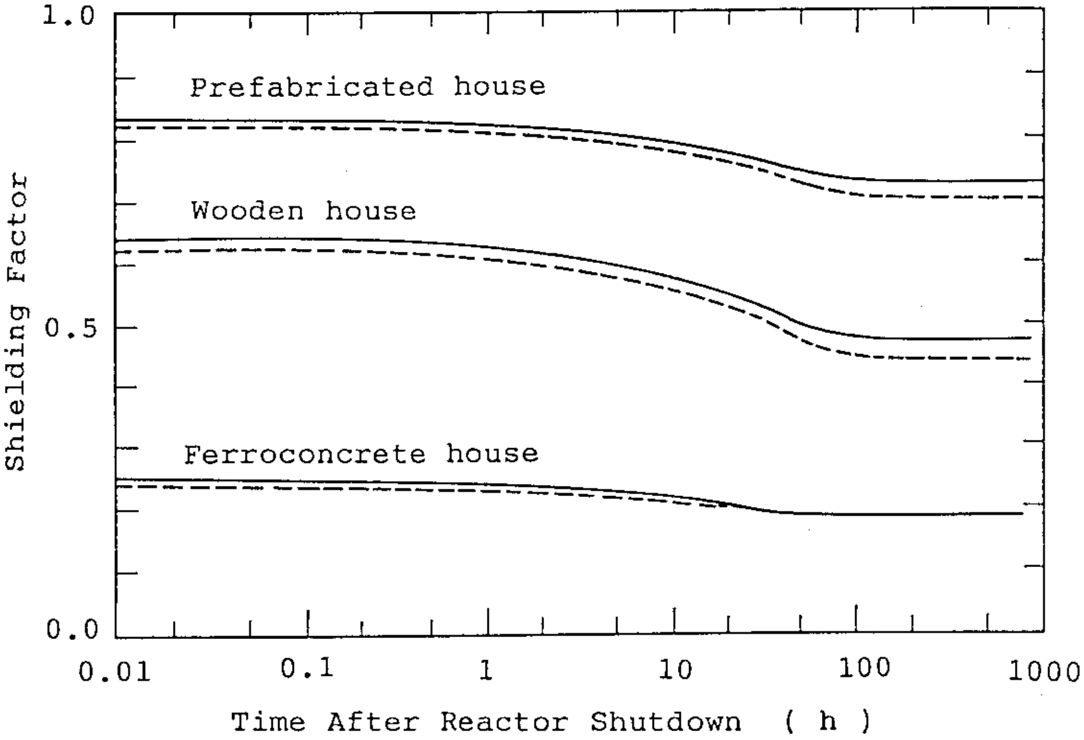

Fig. 8 Shielding factor of houses against noble gas cloud as a function of time after reactor shutdown. Solid and broken lines represent the factors for submersion and overhead plume, respectively.

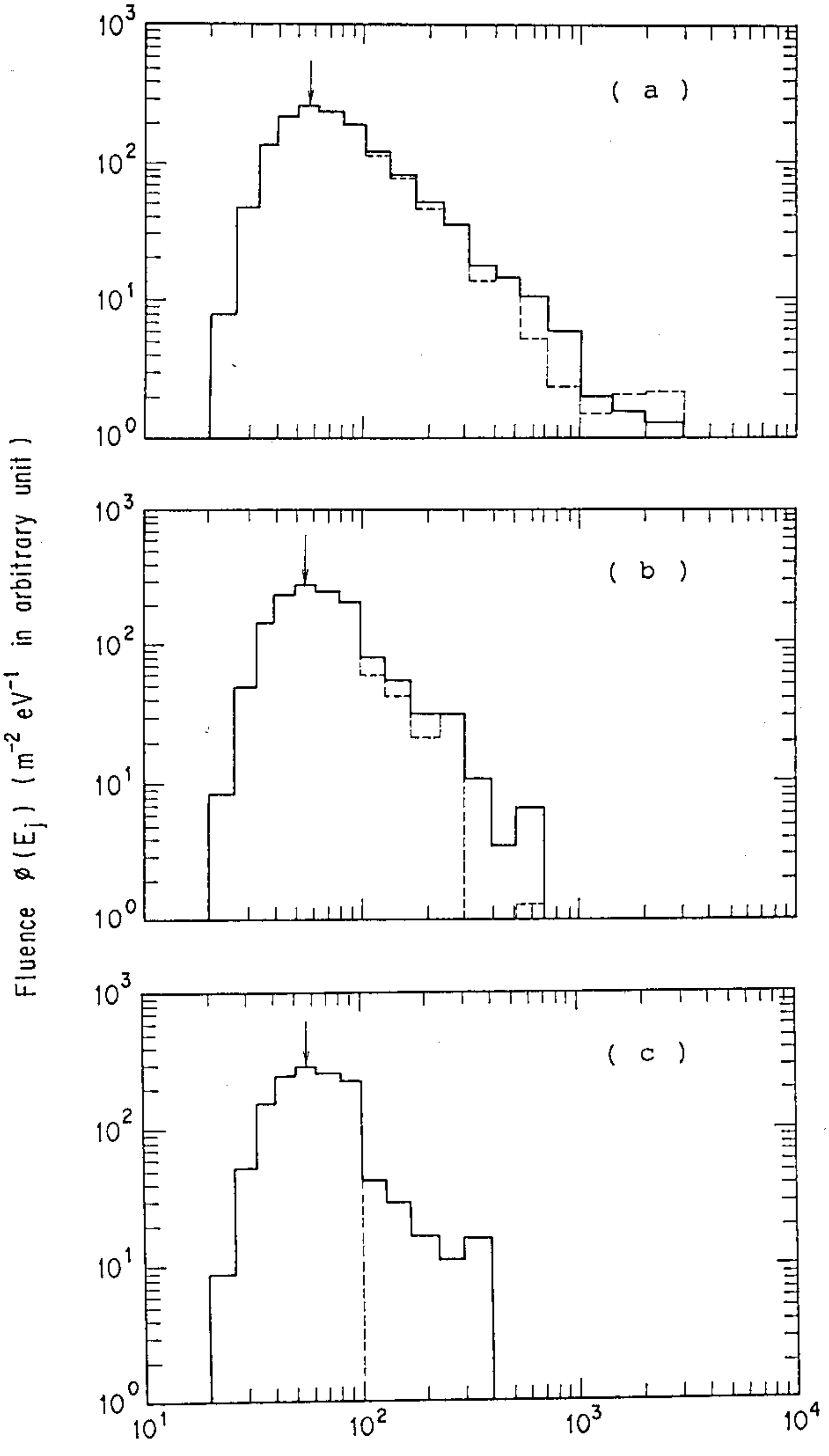

Fig. 9 Comparison of energy spectra between due to noble gas submersion (broken line) and iodine-mixed one (solid line) at (a) 0.05, (b) 20 and (c) 800 hours after rector shutdown. The spectra are adjusted at the energy group indicated by an arrow.

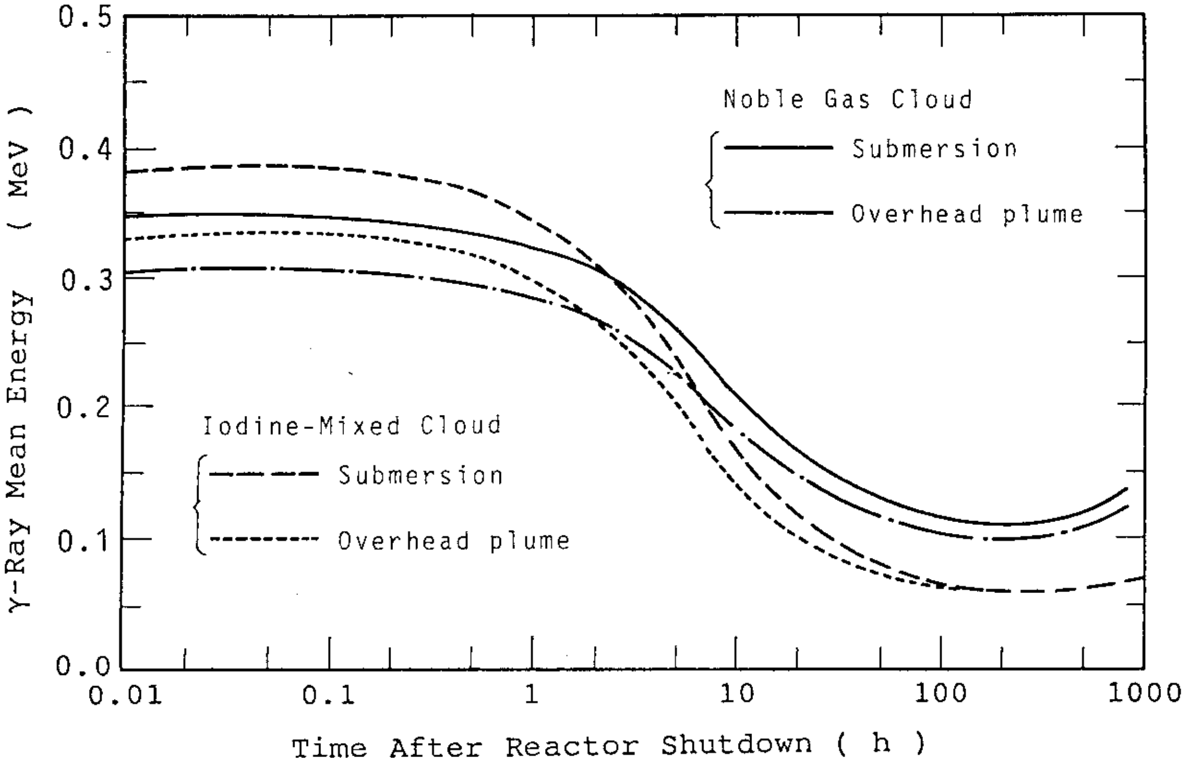

Fig. 10 Comparison of γ-ray mean energies between due to noble gas cloud and to iodine-mixed one as a function of time after reactor shutdown.

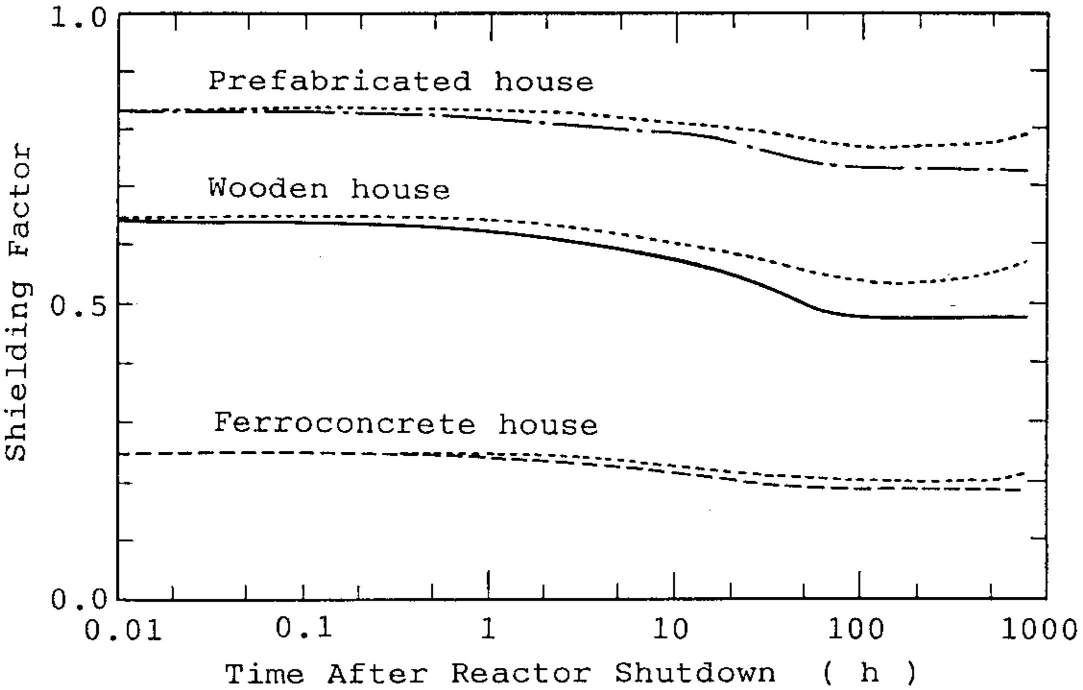

Fig. 11 Shielding factor of houses against noble gas submersion as a function of time after reactor shutdown. Also plotted with broken lines are those against submersion mixed with radioiodines by 25 % of core inventory.

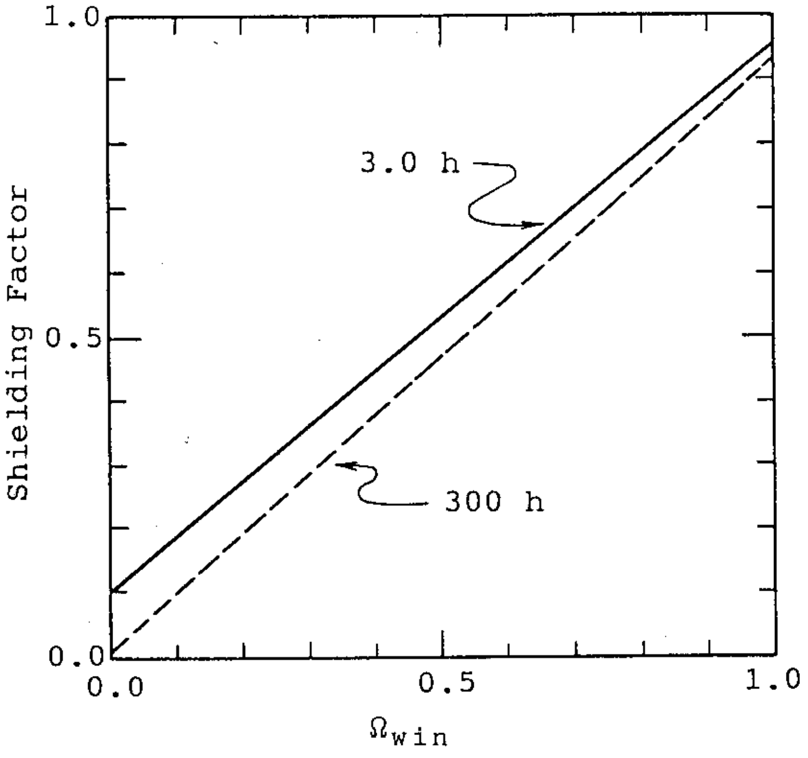

Fig. 12 Shielding factor of ferroconcrete house against noble gas submersion at 3 and 300 hours after reactor shutdown as a function of solid angle subtented by window.