NUREG-1081

Post-Accident Gas Generation from Radiolysis of Organic Materials

U.S. Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

James Wing

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Post-Accident Gas Generation from Radiolysis of Organic Materials

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ABSTRACT

This report presents a methodology for estimating the gas generation rates resulting from radiolysis of organic materials in paints and electrical cable insulation inside a nuclear reactor containment building under design basis accident conditions. The methodology was based on absorption of the radiation energies from the post-accident fission products and the assumed gas yields of the irradiated materials. A sample calculation was made using conservative assumptions, plant-specific data of a nuclear power plant, and a radiation source term which took into account the time-dependent release and physico-chemical behavior of the fission products.

EXECUTIVE SUMMARY

This document presents a methodology for estimating the gas generation rates from radiolysis of organic materials inside the reactor containment building of a nuclear power plant under the design basis accident conditions.

Section 1 consists of brief discussions on the purposes of estimating the gas generation rates, the design basis accident conditions, the major sources of gases, the amounts and chemical compositions of the organic materials, and the assumed gas yields from radiolysis of the organic materials.

Section 2 describes the sources of ionizing radiation energies from the post-accident fission products, the attenuation of the radiation energies, and the energy fluxes incident on the surfaces of the organic materials.

Section 3 summarizes the radiation energies that are available for absorption by the organic materials.

Section 4 describes the absorption of radiation energies by the organic materials.

Section 5 is a collection of equations for estimating the gas generation rates.

Section 6 presents a sample calculation using the specific data of a nuclear power plant, and a discussion on the results of the calculation.

Section 7 discusses the assumptions, simplifications, and uncertainties in the methodology and sample calculation, and includes a conclusion.

Section 8 identifies the symbols used in this report.

Section 9 lists the references quoted in this work.

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POST-ACCIDENT GAS GENERATION FROM RADIOLYSIS OF ORGANIC MATERIALS

1.0 INTRODUCTION

Following a postulated accident in a nuclear power plant, such as a loss of the primary coolant, combustible gases can be generated inside the reactor containment building as a result of the processes listed below (references 2 and 7):

(1) Reaction of zirconium in the reactor fuel cladding with the reactor coolant;

(2) Radiolysis of the post-accident emergency cooling solutions;

(3) Corrosion of metals by the post-accident emergency cooling and containment spray solutions; and

(4) Radiolytic decomposition of organic materials.

The Chemical Engineering Branch of the Office of Nuclear Reactor Regulation has the primary review responsibility to estimate the quantity of combustible gases that can be produced from organic materials and protective coatings (paints) inside a containment building under design basis accident (DBA) conditions, in accordance with Section 6.1.2, "Protective Coating Systems (Paints) - Organic Materials," of the Standard Review Plan (reference 2). This report summarizes a procedure for the estimation of gas generation rates from radiolysis of the organic materials.

1.1 Design Basis Accident Conditions

The environmental conditions, under which organic materials and paints can decompose following a design basis accident, include the ionizing radiation

dose, temperature, pressure, and humidity inside the containment building. In those plants which provide post-accident containment spray capability, the chemical composition of the spray solution is also a factor. A set of post-accident environmental conditions is defined in NUREG-0588, revision 1 (reference 1), for qualification of safety-related electrical equipment, paints, protective coatings, and electrical cables. The ANSI standard N101.2-1972 (reference 6) specifies a corresponding set of experimental conditions for testing protective coating systems to be used in light water nuclear reactor containment facilities.

1.2 Sources of Combustible Gases

The major sources of materials that can generate significant amounts of combustible gases are the organic compounds in electrical cable insulation and zinc and organic ingredients in dried paints that are exposed to the containment atmosphere. Other decomposable materials found inside the containment building of a typical nuclear power plant may include lubricants, sealants, snubber fluids, charcoal, adhesives, pump motor oils, paper products, and fibers. These materials are not expected to produce significant quantities of combustible gases because (1) their amounts are usually small compared with cable insulation and paints; (2) they are isolated from the containment atmosphere; and/or (3) they do not decompose readily under the design basis accident environmental conditions.

The amount and chemical composition of electrical cable insulation materials, found inside a containment building, vary from plant to plant. A survey of a few randomly selected nuclear power plants shows that the total estimated weight of the cable insulation materials range from 16,600 to 190,000 pounds (7,530 to 86,200 kilograms). The chemical ingredients may be chlorosulfonated polyethylene, ethylene propylene, fluoropolymer, silicone rubber, polyvinyl chloride, or neoprene. The electrical cables, if safety related, should be environmentally qualified in accordance with the recommendations of NUREG-0588 (reference 1), and the insulation materials in the cables so qualified should withstand the design basis accident conditions. However, under the influence

of post-accident ionizing radiation, the organic ingredients in the cable insulation are susceptible to decomposition to produce hydrogen gas and low-molecular weight hydrocarbons (reference 8).

Protective coatings (paints) cover the interior surfaces of a containment building and surfaces of equipment inside the containment proper. The amount and chemical composition of the dried paints vary from plant to plant. A survey of a few randomly selected nuclear power plants shows that the total surface areas of paints inside containments range from 1.8×10^4 to 5×10^5 square feet (1.7×10^3 to 4.6×10^4 square meters), with thicknesses of 3 to 30 mils (7.6×10^{-3} to 7.6×10^{-2} centimeters). Typical chemical ingredients may be zinc, ethyl silicate, epoxy polyamide, and epoxy phenolics. Tables 1 and 2 list the protective coating systems commonly used in nuclear facilities for painting steel and concrete surfaces, respectively (reference 11).

Under the design basis accident conditions, the zinc in the paints can react with water and steam to generate hydrogen gas (references 13 and 14). The organic ingredients in the dried paints are susceptible to decomposition by ionizing radiation to produce hydrogen and other gases (reference 8). In this report, we are concerned only with the radiation decomposition of organic materials.

The amount of paints on the equipment inside a containment building is usually small compared with those applied on the interior walls and structures of the containment. The locations of these equipment are difficult to specify for our calculations. For simplicity in our calculations, we will assume that all the known paints inside the containment are coated on the interior walls of the containment building.

1.3 Radiolysis of Organic Materials

Production of hydrogen gas and low-molecular weight hydrocarbons from various organic compounds by ionizing radiation has been experimentally studied. The yield of a given radiolytic product is usually expressed by the G value, in units of number of molecules generated per 100 electron volts (eV) of radiation energy absorbed by the material. Table 3 lists the G values of a number of

Table 1. Generic Coating Systems Presently Used in Nuclear Facilities on Steel (from reference 11).

System 1	Prime - Ethyl Silicate Inorganic Zinc Finish - None
System 2	Prime - Ethyl Silicate Inorganic Zinc Finish - Epoxy Polyamide
System 3	Prime - Ethyl Silicate Inorganic Zinc Finish - Epoxy Phenolic
System 4	Prime - Single Package Inorganic Zinc Finish - None
System 5	Prime - Epoxy Polyamide Finish - Epoxy Polyamide
System 6	Prime - Epoxy Phenolic Finish - Epoxy Phenolic

Table 2. Generic Coating Systems Presently Used in Nuclear Facilities on Concrete (from reference 11).

System 1	Surfacer - Regular Build Epoxy Polyamide (Solvent) Finish - Epoxy Polyamide (Solvent)
System 2	Surfacer - High Build Epoxy Polyamide (Solvent) Finish - Epoxy Polyamide (Solvent)
System 3	Surfacer - High Build (Three Pack) Epoxy Polyamide (Solvent) Finish - Epoxy Polyamide (Solvent)
System 4	Surfacer - Regular Build Epoxy Phenolic (Solvent) Finish - Epoxy Phenolic (Solvent)
System 5	Surfacer - Regular Build Epoxy Polyamide (Water Based) Finish - Epoxy Polyamide (Water Based)

Table 3. Gas Yields from Irradiated Plastics and Elastomers (from reference 8)

Material	Gas evolved Molecules/100 eV[a]
Polyethylene	3.1
Polystyrene	0.08
Poly (α-methylstyrene)	0.08
Natural rubber	0.3
Styrene-butadiene rubber	0.15
Styrene-butadiene plastic	~0.08
Polyisobutylene rubber	0.8
Polyamide - nylon	1.1
Aniline-formaldehyde polymer	~0.08
Melamine-formaldehyde polymer (cellulosic filler)	0.45
Urea-formaldehyde polymer (cellulosic filler)	0.8
Nitrile-butadiene rubber	0.15
Casein plastic	0.15
Poly (methyl methacrylate)	1.5
Poly (ethylene terephthalate)	0.15
Allyl diglycol carbonate	1.9
Polyesters (general)	0.08 to 1.9
Cellulose acetate polymer	0.8
Cellulose acetate-butyrate polymer	1.2
Cellulose propionate polymer	1.5
Cellulose nitrate polymer	4.6
Ethyl cellulose polymer	1.5
Phenolic plastic (no filler)	0.1
Phenolic plastic (cellulose filler)	0.8
Phenolic plastic (mineral filler)	<0.08
Silicone elastomer	0.9
Ethyl acrylate rubber	1.2
Chloroprene rubber	0.15
Poly (vinyl formal)	~4.3
Triallyl cyanurate polymer	~0.08
Polysulfide rubber	0.23

[a]Energy absorbed by the polyme[illegible]g any filler.

organic compounds (reference 8). Knowing the exact chemical composition of the organic ingredients in the dried paints and cable insulation materials, we can select the proper G values to calculate the gas generation from radiolysis of these materials.

If the G value is unavailable for a given chemical compound, we may assume a value corresponding to the substance that is chemically similar to the compound in question. For example, Tables 1 and 2 indicate that the organic coatings used in nuclear facilities are mainly epoxy polyamide and phenolic. The G value for polyamide (nylon) is 1.1. The G values for phenolic plastics range from <0.08 to 0.8, depending on the fillers. We may use the value of 1.1 for organic paints if we do not know their chemical compositions.

Electrical cable insulation materials have been modeled in reference 4 as having an outer layer of Hypalon (chemical formula $C_{85}H_{157}Cl_{13}SO_2$) and an inner layer of ethylene propylene rubber. The G value for Hypalon may be taken as 0.15 (as for chloroprene rubber) and that for ethylene propylene rubber may be taken as 0.8 (as for polyisobutylene rubber). These G values may be converted into gram-moles per million electron volt (g-mole/MeV). For organic paints

$$G_p = \frac{1.1 \text{ molecules}}{100 \text{ eV}} \times \frac{\text{g-mole}}{6.02 \times 10^{23} \text{ molecules}} \times \frac{10^6 \text{ eV}}{\text{MeV}}$$

$$= 1.83 \times 10^{-20} \text{ g-mole/MeV} \qquad \text{(Equation 1-1)}$$

For Hypalon

$$G_H = \frac{0.15 \text{ molecules}}{100 \text{ eV}}$$

$$= 2.49 \times 10^{-21} \text{ g-mole/MeV} \qquad \text{(Equation 1-2)}$$

For ethylene propylene rubber

$$G_E = \frac{0.8 \text{ molecules}}{100 \text{ eV}}$$

$$= 1.33 \times 10^{-20} \text{ g-mole/MeV} \qquad \text{(Equation 1-3)}$$

For conservatism, we assume that all the gases that will be generated from the radiolysis of paints and cable insulation are combustible and will be released instantaneously into the containment atmosphere.

2.0 SOURCES OF IONIZING RADIATION

The principal sources of ionizing radiation following a design basis accident are the beta and gamma radiations emitted by the fission products that are released from the nuclear fuel elements into the containment proper. The release of fission products into the containment atmosphere has been assumed to be instantaneous (reference 1). But a realistic model assumed that the fission products were released to the containment atmosphere at various rates according to their physico-chemical behaviors (reference 4).

Some of the fission products in the containment atmosphere will remain airborne. The others may be deposited (plated out) on the interior surfaces of the containment walls and on the surfaces of equipment and internal structures of the containment building. Some of the airborne fission products will be removed by either the post-accident containment spray system or the pressure suppression pool water in a boiling water reactor. The containment spray solution may wash down some of the plateout fission products. The spray solution will drain to the containment sump. Re-circulation of the sump solution may re-introduce the previously removed fission products back to the containment space and walls.

The distribution of the fission products in the containment atmosphere, interior surfaces, and sump water will depend upon the physical and chemical behavior of each fission product. Attempts have been made to partition the fission products into airborne, plateout, and waterborne fractions (references 1 and 3). Such a partition would be difficult to model because the post-accident containment spray and re-circulation change the distribution of the fission products in a dynamic manner. In addition, regardless how the fission products are distributed, the paints and electrical cables will be exposed to the radiation from the fission products in all the three fractions, although each fraction contributes to a different degree of irradiation.

We assume that the post-accident fission products will be released from the fuel elements in a timely fashion as modeled in references 4 and 5, and that the released fission products remain airborne and are uniformly distributed throughout the containment space. The gamma and beta radiation from these fission products will be attenuated by the containment air before reaching the surfaces of the paints and electrical cables. In the following section, we will discuss the gamma and beta radiation energy fluxes incident on the surfaces of the paints and cables. In Sections 3 and 4, we will discuss the absorption of the incident radiation by the paint body and cable insulation materials to produce gases.

2.1 Energy Fluxes Incident on Paint Surfaces

The fraction of the initial gamma radiation energy flux, ϕ_o, remaining after passing through a distance x (cm) in air is

$$\frac{\phi_\gamma}{\phi_o} = e^{-\mu_\gamma x} \qquad \text{(Equation 2-1)}$$

where ϕ_γ is the gamma radiation energy flux after passing through a distance of x and μ_γ is the linear absorption coefficient, in unit of 1/cm, for gamma radiation in air. Let E_γ represent the total gamma radiation energy release rate from the post-accident fission products in a containment space V. The change in ϕ_γ through a distance of dx is

$$d\phi_\gamma = \frac{E_\gamma}{V} e^{-\mu_\gamma x} dx \qquad \text{(Equation 2-2)}$$

We may approximate the containment space by a sphere with a radius of r (cm). The gamma radiation energy flux incident on the paint surface, $\phi_{\gamma,p}$, after travelling through an average distance of r in the air is

$$\phi_{\gamma,p} = \int_o^r \frac{E_\gamma}{V} e^{-\mu_\gamma x} dx \qquad \text{(Equation 2-3)}$$

$$= \frac{E_\gamma}{V} \frac{(1 - e^{-\mu_\gamma r})}{\mu_\gamma} \qquad \text{(Equation 2-4)}$$

Similarly, for beta radiation, the energy flux, $\phi_{\beta,p}$, incident on the paint surface is

$$\phi_{\beta,p} = \frac{E_\beta}{V} \frac{(1 - e^{-\mu_\beta r})}{\mu_\beta} \qquad \text{(Equation 2-5)}$$

where E_β is the total energy release rate from beta radiation of the post-accident fission products in the containment space, and μ_β is the linear absorption coefficient for beta radiation in air.

The average gamma radiation energy of post-accident fission products is 1.0 MeV (reference 5). The mass absorption coefficient μ_γ/ρ_a, where ρ_a is the density of air, for 1.0 MeV gamma radiation energy in air is 0.0636 cm^2/g (reference 10). The density of moist air may be taken as 0.000588 g/cm^3 at 100°C and one atmosphere (reference 12). So, $\mu_\gamma = 3.74 \times 10^{-5}/cm$, and Equation 2-4 becomes

$$\phi_{\gamma,p} = \frac{E_\gamma}{V} \frac{(1 - e^{-0.0000374r})}{0.0000374} \text{ (MeV/cm}^2\text{-sec)} \qquad \text{(Equation 2-6)}$$

For beta radiation, the ratio μ_β/ρ is experimentally found to be nearly independent of the atomic weight of the absorber whose density is ρ, and can be expressed by the following empirical formula (reference 9):

$$\frac{\mu_\beta}{\rho} = \frac{17}{E_m^{1.14}} \qquad \text{(Equation 2-7)}$$

where E_m is the maximum energy of beta radiation in MeV. The maximum energy of beta radiation from post-accident fission products is 0.55 MeV (reference 5). By substitution, we have

$$\frac{\mu_\beta}{\rho} = 33.6 \qquad \text{(Equation 2-8)}$$

and $\mu_\beta = 0.0198/cm$

Equation 2-5 becomes

$$\phi_{\beta,p} = \frac{E_\beta}{V} \frac{(1 - e^{-0.0198r})}{0.0198} \cong \frac{E_{\beta(MeV/cm^2\text{-}sec)}}{0.0198V} \qquad \text{(Equation 2-9)}$$

The approximation in Equation 2-9 is a result of the relatively large values of r (in the order of 2000 cm) and μ_β.

In the above discussions, we ignore radiation shieldings in the paths of the airborne gamma and beta radiations by equipment and internal structures inside the containment.

2.2 Energy Fluxes Incident on Cable Surfaces

It would be difficult to describe the exact locations of the uncovered (not shielded by metal conduits) electrical cables inside a containment building of a nuclear power plant. For our calculations, we simply assume that the cables are located midway between the center and the walls of the containment proper, so that the uncovered electrical cables are exposed to radiation from all sides, whereas the paints on the walls are exposed to radiation from only the side facing the containment atmosphere. The average distance travelled by the radiation of the airborne fission products is approximately r, the same as for the paints. Thus, the gamma radiation energy flux, $\phi_{\gamma,c}$, incident on the cable surfaces is

$$\phi_{\gamma,c} = \frac{E_\gamma}{V} \frac{(1 - e^{-\mu_\gamma r})}{\mu_\gamma} \qquad \text{(Equation 2-10)}$$

$$= \frac{E_\gamma}{V} \frac{(1 - e^{-0.0000374r})}{0.0000374} \left(\frac{MeV}{cm^2\text{-}sec}\right) \qquad \text{(Equation 2-11)}$$

Since beta particles have short ranges, we must consider self-shielding of the cables. Electrical cables are usually arranged in bundles on cable trays. We assume that the cables will receive only half the beta radiation. This reduction in beta radiation exposure is allowed because of localized shielding by other cables and by the cable trays (reference 1). Thus, the beta radiation energy flux, $\phi_{\beta,c}$, incident on the cable surfaces is

$$\phi_{\beta,c} = \frac{E_\beta \left(1 - e^{-\mu_\beta r}\right)}{2V \mu_\beta} \qquad \text{(Equation 2-12)}$$

$$\cong \frac{E_\beta}{0.0396V} \left(\frac{MeV}{cm^2\text{-}sec}\right) \qquad \text{(Equation 2-13)}$$

3.0 ENERGIES AVAILABLE FOR ABSORPTION

In the previous sections, we discussed the energy fluxes incident on the surfaces of the paints and electrical cables. The energy that will be available for absorption by an absorber, is the product of the incident energy flux times the area intercepted by the surface of the absorber.

The gamma and beta radiation energy release rates, $F_{\gamma,p}$ and $F_{\beta,p}$, respectively, that are available for absorption by the paints with a total surface area of S_p (cm^2) are

$$F_{\gamma,p} = \phi_{\gamma,p} S_p = \frac{E_\gamma S_p}{V \mu_\gamma} \left(1 - e^{-\mu_\gamma r}\right) \qquad \text{(Equation 3-1)}$$

$$= \frac{E_\gamma S_p}{V} \frac{\left(1 - e^{-0.0000374r}\right)}{0.0000374} \text{ (MeV/sec)} \qquad \text{(Equation 3-2)}$$

$$F_{\beta,p} = \phi_{\beta,p} S_p = \frac{E_\beta S_p}{V \mu_\beta} \left(1 - e^{-\mu_\beta r}\right) \qquad \text{(Equation 3-3)}$$

$$\cong \frac{E_\beta S_p}{0.0198V} \text{(MeV/sec)} \qquad \text{(Equation 3-4)}$$

The gamma and beta radiation energy release rates $F_{\gamma,c}$ and $F_{\beta,c}$, respectively, that are available for absorption by the electrical cables with a total surface area of S_c (cm^2) are

$$F_{\gamma,c} = \phi_{\gamma,c} S_c = \frac{E_\gamma S_c}{V \mu_\gamma} \left(1 - e^{-\mu_\gamma r}\right) \qquad \text{(Equation 3-5)}$$

$$= \frac{E_\gamma S_c}{V} \frac{\left(1 - e^{-0.0000374r}\right)}{0.0000374} \text{ (MeV/sec)} \qquad \text{(Equation 3-6)}$$

$$F_{\beta,c} = \phi_{\beta,c} S_c = \frac{E_\beta S_c}{2 V \mu_\beta} (1 - e^{-\mu_\beta r}) \qquad \text{(Equation 3-7)}$$

$$\cong \frac{E_\beta S_c}{0.0396V} (\text{MeV/sec}) \qquad \text{(Equation 3-8)}$$

4.0 ABSORPTION OF RADIATION ENERGIES

We will discuss the absorption of radiation energies by the organic materials in paints and electrical cable insulation in the following separate sections.

4.1 Absorption of Gamma and Beta Radiation by Paints

The fraction of the incident gamma radiation transmitted after passing through a distance of y in an absorber is $e^{-\sigma_\gamma y}$, where σ_γ is the linear absorption coefficient, in unit of 1/cm, of the absorber for gamma radiation. The fraction of the incident gamma radiation absorbed by the paint body as the absorber, $A_{\gamma,p}$, with a thickness of y_p is

$$A_{\gamma,p} = (1-e^{-\sigma_{\gamma,p} y_p}) \qquad \text{(Equation 4-1)}$$

where $\sigma_{\gamma,p}$ is the linear absorption coefficient for gamma radiation in paints. The major ingredient in organic paints is carbon. The average energy of gamma radiation in post-accident fission products is 1.0 MeV (reference 5). The mass absorption coefficient, $\sigma_{\nu,p}/\rho_p$, where ρ_p is the density of paints, for carbon is 0.0637 cm^2/g (reference 10). The average density of dried paint films may be taken as 1.6 g/cm^3 and the average thickness of paint films may be taken as 0.0813 cm (reference 14). The absorption of the incident gamma radiation by the paint films to produce gases is

$$A_{\gamma,p} = (1 - e^{-0.0637 \times 1.6 \times 0.0813}) = 0.00825 \qquad \text{(Equation 4-2)}$$

For beta radiation, the absorption by paint films is

$$A_{\beta,p} = (1-e^{-\sigma_{\beta,p} y_p}) \qquad \text{(Equation 4-3)}$$

where $\sigma_{\beta,p}$ is the linear absorption coefficient for beta radiation in paints. Using Equation 2-8, $\sigma_{\beta,p}/\rho_p = 33.6$, Equation 4-3 becomes

$$A_{\beta,p} = (1 - e^{-33.6 \times 1.6 \times 0.0813}) = 0.987 \qquad \text{(Equation 4-4)}$$

4.2 Absorption of Gamma and Beta Radiation by Cable Insulation Materials

Electrical cables are modeled in Figure 1 (from reference 4) as having (1) an outer jacket of Hypalon with a density ρ_H of 1.55 g/cm³ and a thickness y_H of 0.183 cm, (2) an inner layer of ethylene propylene rubber (EPR) with a density ρ_E of 1.27 g/cm³ and a thickness y_E of 0.218 cm, and (3) a core of copper wire with a diameter of 1.458 cm.

The major ingredient in Hypalon and EPR is carbon. From reference 10, $\sigma_{\gamma,H}/\rho_H = \sigma_{\gamma,E}/\rho_E = 0.0637$ cm²/g and from Equation 2-8, $\sigma_{\beta,H}/\rho_H = \sigma_{\beta,E}/\rho_E = 33.6$, where $\sigma_{\gamma,H}$ and $\sigma_{\gamma,E}$ are the linear absorption coefficients for gamma radiation in Hypalon and EPR, respectively, and $\sigma_{\beta,H}$ and $\sigma_{\beta,E}$ are the linear absorption coefficients for beta radiation in Hypalon and EPR, respectively.

The absorption of the incident gamma radiation energy by the Hypalon layer is

$$A_{\gamma,H} = (1-e^{-\sigma_{\gamma,H} y_H}) \qquad \text{(Equation 4-5)}$$

$$= (1 - e^{-0.0637 \times 1.55 \times 0.183}) = 0.0179 \qquad \text{(Equation 4-6)}$$

The absorption of the incident gamma radiation energy by the EPR layer is

$$A_{\gamma,E} = (1 - e^{-\sigma_{\gamma,E} y_E}) e^{-\sigma_{\gamma,H} y_H} \qquad \text{(Equation 4-7)}$$

$$= (1 - e^{-0.0637 \times 1.27 \times 0.218}) e^{-0.0637 \times 1.55 \times 0.183}$$

$$= 0.0172 \qquad \text{(Equation 4-8)}$$

The factor $e^{-\sigma_{\gamma,H} y_H}$ in Equation 4-7 gives the fraction of the incident gamma radiation remaining after passing through, i.e., not being absorbed by, the Hypalon layer.

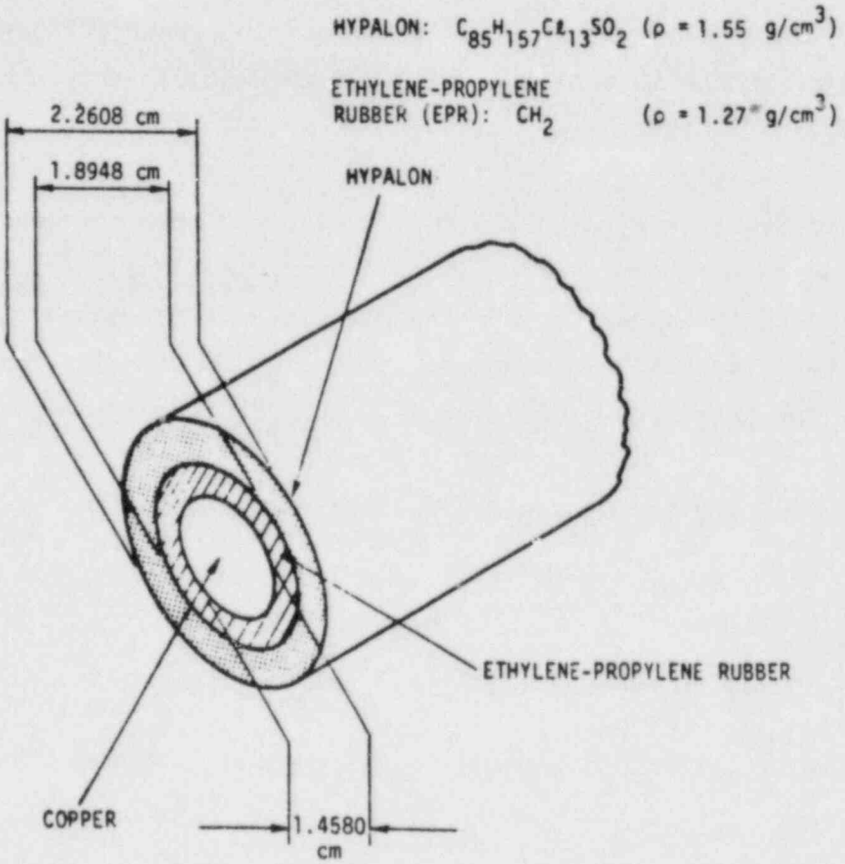

Figure 1. Model of Electrical Cables (from reference 4).

Similarly, the absorptions of the incident beta radiation energy by Hypalon and EPR are, respectively

$$A_{\beta,H} = (1 - e^{-\sigma_{\beta,H} y_H}) \quad \text{(Equation 4-9)}$$

$$= (1 - e^{-33.6 \times 1.55 \times 0.183}) \simeq 1.0 \quad \text{(Equation 4-10)}$$

$$A_{\beta,E} = (1 - e^{-\sigma_{\beta,E} y_E})\, e^{-\sigma_{\beta',H} y_H} \quad \text{(Equation 4-11)}$$

$$= (1 - e^{-33.6 \times 1.27 \times 0.218})\, e^{-33.6 \times 1.55 \times 0.183}$$

$$= 7.26 \times 10^{-5} \quad \text{(Equation 4-12)}$$

The result in Equation 4-12 suggests that we may neglect the radiolysis of EPR by beta radiation.

5.0 GAS GENERATION RATES FROM RADIOLYSIS OF ORGANIC MATERIALS

The gas generation rate, R, from the radiation decomposition of an absorber is the product of $G\phi SA$, where G is the radiolysis yield, ϕ is the incident energy flux, S is the surface area of the absorber, and A is the absorption of the available radiation energy. The unit for R depends on the units we choose for G and ϕ.

Combining Equations 2-4, 2-6, 3-1, 3-2, 4-1, and 4-2, we obtain the gas generation rate, $R_{\gamma,p}$ for gamma radiation decomposition of paints with a total surface area S_p:

$$R_{\gamma,p} = G_p\, \phi_{\gamma,p}\, S_p\, A_{\gamma,p} \quad \text{(Equation 5-1)}$$

$$= \frac{G_p\, E_\gamma\, S_p}{V\, \mu_\gamma} (1 - e^{-\mu_\gamma r})\ (1 - e^{-\sigma_{\gamma,p} y_p}) \quad \text{(Equation 5-2)}$$

$$= 221 \frac{G_p E_\gamma S_p}{V} (1 - e^{-0.0000374r}) \qquad \text{(Equation 5-3)}$$

Combining Equations 2-5, 2-9, 3-3, 3-4, 4-3, and 4-4, we obtain the gas generation rate, $R_{\beta,p}$, for beta radiation decomposition of paints:

$$R_{\beta,p} = G_p \phi_{\beta,p} S_p A_{\beta,p} \qquad \text{(Equation 5-4)}$$

$$= \frac{G_p E_\beta S_p}{V \mu_\beta} (1 - e^{-\mu_\beta r}) (1 - e^{-\sigma_{\beta,p} y_p}) \qquad \text{(Equation 5-5)}$$

$$= 49.8 \frac{G_p E_\beta S_p}{V} \qquad \text{(Equation 5-6)}$$

Combining Equations 2-10, 2-11, 3-5, 3-6, 4-5, and 4-6, we obtain the gas generation rate, $R_{\gamma,H}$, for gamma radiation decomposition of Hypalon with a total surface area of S_c:

$$R_{\gamma,H} = G_H \phi_{\gamma,c} S_c A_{\beta,H} \qquad \text{(Equation 5-7)}$$

$$= \frac{G_H E_\gamma S_c}{V \mu_\gamma} (1 - e^{-\mu_\gamma r}) (1 - e^{-\sigma_{\gamma,H} y_H}) \qquad \text{(Equation 5-8)}$$

$$= 479 \frac{G_H E_\gamma S_c}{V} (1 - e^{-0.0000374r}) \qquad \text{(Equation 5-9)}$$

Combining Equations 2-12, 2-13, 3-7, 3-8, 4-9, and 4-10, we obtain the gas generation rate, $R_{\beta,H}$, for beta radiation decomposition of Hypalon:

$$R_{\beta,H} = G_H \phi_{\beta,c} S_c A_{\beta,H} \qquad \text{(Equation 5-10)}$$

$$= \frac{G_H E_\beta S_c}{2 V \mu_\beta} (1 - e^{-\mu_\beta r}) (1 - e^{-\sigma_{\beta,H} y_H}) \qquad \text{(Equation 5-11)}$$

$$= 25.3 \frac{G_H E_\beta S_c}{V} \qquad \text{(Equation 5-12)}$$

Combining Equations 2-10, 2-11, 3-5, 3-6, 4-7, and 4-8, we obtain the gas generation rate, $R_{\gamma,E}$, for gamma radiation decomposition of ethylene propylene rubber with a total outer surface area of S_E:

$$R_{\gamma,E} = G_E \phi_{\gamma,c} S_E A_{\gamma,E} \qquad \text{(Equation 5-13)}$$

$$= \frac{G_E E_\gamma S_E}{V \mu_\gamma} (1 - e^{-\mu_\gamma r}) (1 - e^{-\sigma_{\gamma,E} y_E}) e^{-\sigma_{\gamma,H} y_H} \qquad \text{(Equation 5-14)}$$

$$= 460 \frac{G_E E_\gamma S_E}{V} (1 - e^{-0.0000374r}) \qquad \text{(Equation 5-15)}$$

Combining Equations 2-12, 2-13, 3-7, 3-8, 4-11, and 4-12, we obtain the gas generation rate, $R_{\beta,E}$, for beta radiation decomposition of ethylene propylene rubber:

$$R_{\beta,E} = G_E \phi_{\beta,c} S_E A_{\beta,E} \qquad \text{(Equation 5-16)}$$

$$= \frac{G_E E_\beta S_E}{2V \mu_\beta} (1 - e^{-\mu_\beta r}) (1 - e^{-\sigma_{\beta,E} y_E}) e^{-\sigma_{\beta,H} y_H} \qquad \text{(Equation 5-17)}$$

$$= 1.83 \times 10^{-3} \frac{G_E E_\beta S_E}{V} \qquad \text{(Equation 5-18)}$$

5.1 Total Gas Generation Rate

The total gas generation rate, R, from radiolysis of the organic materials in paints and cable insulation is simply the sum of the rates from gamma and beta radiation decomposition of the paints, Hypalon and ethylene propylene rubber. Combining Equations, 5-3, 5-6, 5-9, 5-12, 5-15, and 5-18, we obtain

$$R = R_{\beta,p} + R_{\beta,p} + R_{\gamma,H} + R_{\beta,H} + R_{\gamma,E} + R_{\beta,E} \qquad \text{(Equation 5-19)}$$

$$= 221 \frac{G_p E_\gamma S_p}{V} (1 - e^{-0.0000374r})$$

$$+ 49.8 \frac{G_p E_\beta S_p}{V}$$

$$+ 479 \frac{G_H E_\gamma S_c}{V} (1 - e^{-0.0000374r})$$

$$+ 25.3 \frac{G_H E_\beta S_c}{V}$$

$$+ 460 \frac{G_E E_\gamma S_E}{V} (1 - e^{-0.0000374r})$$

$$+ 1.83 \times 10^{-3} \frac{G_E E_\beta S_E}{V} \qquad \text{(Equation 5-20)}$$

6.0 SAMPLE CALCULATIONS

For the sample calculations, we use the plant parameters of a boiling water reactor plant which has a large amount of electrical cable insulation materials inside the containment. The specific parameters and other pertinent data are:

Net free volume of containment, $V = 1.64 \times 10^6$ ft^3 $= 4.64 \times 10^{10}$ cm^3
(including the drywell and wetwell)

Length of radiation path in containment air, $r = 2.23 \times 10^3$ cm

Total surface area of paints, $S_p = 90{,}200$ ft^2 $= 8.38 \times 10^7$ cm^2

Total weight of cable insulation materials $= 1.90 \times 10^5$ Lbs
$= 8.62 \times 10^7$ g

Weighted average density of cable insulation materials (reference 4) = 1.40 g/cm^3

Outside diameter of cables (reference 4) =2.261 cm

Diameter of ethylene propylene rubber (reference 4) = 1.895 cm

Diameter of copper wire (reference 4) = 1.458 cm

Volume of cable insulation materials = $\frac{8.62 \times 10^{} \text{ g}}{1.40 \text{ g/cm}^3}$

$$= L \left[\pi \left(\frac{2.261}{2}\right)^2 - \pi \left(\frac{1.458}{2}\right)^2\right]$$

Total length of electrical cables, $L = 2.63 \times 10^7$ cm

Total surface area of electrical cables, $S_c = 2.63 \times 10^7 \times 2.261\pi$
$= 1.87 \times 10^8$ cm^2

Total surface area of ethylene propylene rubber, $S_E = 1.57 \times 10^8$ cm^2

Gas generation yield from radiolysis of paints, $G_p = 1.83 \times 10^{-20}$ g-mole/MeV (Equation 1-1)

Gas generation yield from radiolysis of Hypalon, $G_H = 2.49 \times 10^{-21}$ g-mole/MeV (Equation 1-2)

Gas generation yield from radiolysis of EPR, $G_E = 1.33 \times 10^{-20}$ g-mole/MeV (Equation 1-3)

Rated power level of the nuclear reactor, $P = 3.995 \times 10^9$ watts

Reference 5 provides the total gamma and beta radiation energy release rates per unit power, in MeV/sec-watt, as a function of time after an accident. Using the above data and Equation 5-20, we can calculate the rates of gas generation as a function of time after an accident. Using the symbols $\dot{E}_\gamma$ and $\dot{E}_\beta$ for the total energy release rates of gamma and beta radiation, respectively, per unit power, and P for the rated power level, the total gas generation rate becomes

$$R = R_{\gamma,p} + R_{\beta,p} + R_{\gamma,H} + R_{\beta,H} + R_{\gamma,E} + R_{\beta,E} \qquad \text{(Equation 6-1)}$$

where, from Equations 5-3, 5-6, 5-9, 5-12, 5-15 and 5-18,

$$R_{\gamma,p} = 221\ G_p\ \dot{E}_\gamma\ S_p\ \frac{P}{V}\ (1 - e^{-0.0000374r}) \qquad \text{(Equation 6-2)}$$

$$R_{\beta,p} = 49.8\ G_p\ \dot{E}_\beta\ S_p\ \frac{P}{V} \qquad \text{(Equation 6-3)}$$

$$R_{\gamma,H} = 479\ G_H\ \dot{E}_\gamma\ S_c\ \frac{P}{V}\ (1 - e^{-0.0000374r}) \qquad \text{(Equation 6-4)}$$

$$R_{\beta,H} = 25.3\ G_H\ \dot{E}_\beta\ S_c\ \frac{P}{V} \qquad \text{(Equation 6-5)}$$

$$R_{\gamma,E} = 460\ G_E\ \dot{E}_\gamma\ S_E\ \frac{P}{V}\ (1 - e^{-0.0000374r}) \qquad \text{(Equation 6-6)}$$

$$R_{\beta,E} = 1.83 \times 10^{-3}\ G_E\ \dot{E}_\beta\ S_E\ \frac{P}{V} \qquad \text{(Equation 6-7)}$$

By substitution and neglecting the radiolysis of ethylene propylene rubber by beta radiation, we have

$$R_{\gamma,p} = 221 \times 1.83 \times 10^{-20} \times \dot{E}_\gamma \times 8.38 \times 10^{-7} \times \frac{3.995 \times 10^9}{4.64 \times 10^{10}}\ (1 - e^{-0.0000374 \times 2230})$$

$$= 2.33 \times 10^{-12}\ \dot{E}_\gamma \text{ g-mole/sec} \qquad \text{(Equation 6-8)}$$

$$R_{\beta,p} = 49.8 \times 1.83 \times 10^{-20} \times \dot{E}_\beta \times 8.38 \times 10^{7} \times \frac{3.995 \times 10^9}{4.64 \times 10^{10}}$$

$$= 6.58 \times 10^{-12}\ \dot{E}_\beta \text{ g-mole/sec} \qquad \text{(Equation 6-9)}$$

$$R_{\gamma,H} = 479 \times 2.49 \times 10^{-21} \times \dot{E}_\gamma \times 1.87 \times 10^{8} \times \frac{3.995 \times 10^9}{4.64 \times 10^{10}}\ (1 - e^{-0.0000374 \times 2230})$$

$$= 1.54 \times 10^{-12}\ \dot{E}_\gamma \text{ g-mole/sec} \qquad \text{(Equation 6-10)}$$

$$R_{\beta,H} = 25.3 \times 2.49 \times 10^{-21}\ \dot{E}_{\beta}\ 1.87 \times 10^{8} \times \frac{3.995 \times 10^{9}}{4.64 \times 10^{10}}$$

$$= 1.01 \times 10^{-12}\ \dot{E}_{\beta}\ \text{g-mole/sec} \qquad \text{(Equation 6-11)}$$

$$R_{\gamma,E} = 460 \times 1.33 \times 10^{-20} \times \dot{E}_{\gamma} \times 1.57 \times 10^{8} \times \frac{3.995 \times 10^{9}}{4.64 \times 10^{10}} \left(1 - e^{-0.0000374 \times 2230}\right)$$

$$= 6.62 \times 10^{-12}\ \dot{E}_{\gamma}\ \text{g-mole/sec} \qquad \text{(Equation 6-12)}$$

We can simplify the calculations by combining Equations 6-8, 6-10, and 6-12 to give the gas generation rate from gamma radiolysis, R_{γ}.

$$R_{\gamma} = R_{\gamma,p} + R_{\gamma,H} + R_{\gamma,E}$$
$$= 1.05 \times 10^{-11}\ \dot{E}_{\gamma}\ \text{g-mole/sec} \qquad \text{(Equation 6-13)}$$

Similarly, combining Equations 6-9 and 6-11 will give the gas generation rate from beta radiolysis, R_{β}.

$$R_{\beta} = R_{\beta,p} + R_{\beta,H}$$
$$= 7.59 \times 10^{-12}\ \dot{E}_{\beta}\ \text{g-mole/sec} \qquad \text{(Equation 6-14)}$$

6.1 Results and Discussion

Equations 6-8 through 6-12 indicate that the ethylene propylene rubber is the dominant contributor to gas generation by gamma radiolysis and the paints are the dominant contributors by beta radiolysis for this particular plant. It is necessary, therefore, to consider both the electrical cable insulation materials and paints in the safety evaluation of organic materials in accordance with Section 6.1.2 of the Standard Review Plan (reference 2).

Equations 6-13 and 6-14 suggest that, if the gamma and beta radiations of fission products release energy at comparable rates, then gamma radiolysis of the organic materials would produce higher gas generation rates than beta radiolysis. Table 4 is a tabulation of the calculated gas generation rates, in gram-moles per second, from radiation decomposition of the organic materials, as a function of time after a postulated accident. The results show that, at a given time after an accident, gamma radiolysis indeed produces a higher rate of gas generation than beta radiolysis in most cases. The total energy release rate from gamma radiation of the post-accident fission products is in many cases higher than that from beta radiation at a given time. The predominant gas production rates come from gamma radiolysis of the EPR layer, as Equation 6-12 indicates, even though the EPR layer is shielded by the Hypalon.

The total gas generation rates (last column in Table 4) increase rapidly with time after the postulated accident, reach a peak at 2000 seconds, and gradually fall thereafter. These changes in gas generation rates follow directly the rise and fall of the total energy release rates of the fission products as a function of time after the accident (second and third columns).

7.0 SUMMARY OF ASSUMPTIONS

In the development of the present methodology, we have made the following major assumptions:

(1) We ignored the diffusion rates of the gases in the absorbers. All the gases produced from the radiolysis of organic materials were assumed to diffuse instantaneously into the containment building atmosphere. This assumption is conservative, since a finite diffusion rate will reduce the gas generation rate.

(2) We ignored the synergetic effects of temperature, humidity, oxygen in air, and chemical additives in the post-accident containment spray solutions on the radiolytic yields. No precise information is presently available about these effects. The G values given in Table 3 were for approximately room temperature and in a limited supply of oxygen or in vacuum (reference 8).

Table 4. Gas Generation Rates From Radioloysis of Organic Materials in a Typical Nuclear Power Plant

Time after accident (seconds)	$\dot{E}_\gamma$ (MeV/sec-Watt)	$\dot{E}_\beta$ (MeV/sec-Watt)	R_γ (g-mole/sec)	R_β (g-mole/sec)	R (g-mole/sec)
5.00E1*	3.45E7	3.61E7	3.62E-4	2.74E-4	6.4E-4
6.00E1	6.68E7	6.93E7	7.01E-4	5.26E-4	1.2E-3
1.00E2	1.95E8	1.94E8	2.05E-3	1.47E-3	3.5E-3
2.00E2	1.09E10	7.57E9	1.14E-1	5.75E-2	1.7E-1
5.00E2	1.37E10	8.51E9	1.44E-1	6.46E-2	2.1E-1
1.00E3	1.84E10	1.05E10	1.93E-1	7.97E-2	2.7E-1
2.00E3	3.26E10	1.79E10	3.42E-1	1.36E-1	4.8E-1
3.60E3	2.67E10	1.36E10	2.80E-1	1.03E-1	3.8E-1
5.40E3	2.47E10	1.18E10	2.59E-1	8.96E-2	3.5E-1
1.00E4	2.06E10	9.31E9	2.16E-1	7.07E-2	2.9E-1
2.00E4	1.65E10	7.19E9	1.73E-1	5.46E-2	2.3E-1
4.32E4	1.33E10	5.50E9	1.40E-1	4.17E-2	1.8E-1
5.00E4	1.27E10	5.22E9	1.33E-1	3.96E-2	1.7E-1
8.64E4	1.07E10	4.27E9	1.12E-1	3.24E-2	1.4E-1
1.00E5	1.01E10	4.02E9	1.06E-1	3.05E-2	1.4E-1
2.00E5	7.37E9	2.92E9	7.74E-2	2.22E-2	1.0E-1
3.46E5	5.07E9	2.11E9	5.32E-2	1.60E-2	6.9E-2
5.00E5	3.57E9	1.60E9	3.75E-2	1.21E-2	5.0E-2
8.64E5	1.84E9	9.94E8	1.93E-2	7.54E-3	2.7E-2
1.00E6	1.51E9	8.74E8	1.59E-2	6.63E-3	2.3E-2
2.00E6	6.73E8	5.30E8	7.07E-3	4.02E-3	1.1E-2
2.59E6	5.31E8	4.62E8	5.58E-3	3.51E-3	9.1E-3
5.00E6	2.96E8	3.45E8	3.11E-3	2.62E-3	5.7E-3
5.18E6	2.87E8	3.39E8	3.01E-3	2.57E-3	5.6E-3
1.00E7	1.63E8	2.58E8	1.71E-3	1.96E-3	3.7E-3
1.30E7	1.34E8	2.31E8	1.41E-3	1.75E-3	3.2E-3
2.00E7	1.06E8	1.91E8	1.11E-3	1.45E-3	2.6E-3
3.16E7	9.33E7	1.55E8	9.80E-4	1.18E-3	2.2E-3

*5.00E1 = $5.00 \times 10^1 = 50.0$

(3) We ignored radiation shielding, except the self-shielding of the electrical cables and shielding of the cable trays for beta radiation (Section 2.2). This assumption is conservative, because radiation shielding will reduce the radiation energy flux available for absorption to produce gases.

In the numerical substitutions, we have made the following simplifications:

(1) We used a constant temperature of 100°C and a constant pressure of 76 cm Hg for the post-accident containment air to estimate the air density in the computation of μ_γ and μ_β (Section 2.1). Following a postulated accident such as a loss of the nuclear reactor primary coolant, the containment air temperature rises rapidly to about 300°F (149°C) or 340°F (171°C), depending upon the nuclear reactor type, and, after about one day, it falls gradually to approximately 160°F (71°C) (references 1 and 6). Similarly, the containment atmospheric pressure rapidly rises to 41 or 57 pounds per square inch guage (288 or 371 cm Hg), depending upon the nuclear reactor type, and, about a day later, it gradually falls to 16 pounds per square inch guage (159 cm Hg) or below (reference 6). Air density decreases with increasing temperatures and decreasing pressures. The use of a constant temperature and pressure of 100°C and 76 cm Hg, respectively, in this work was a compromise between a short exposure at higher temperatures and pressures, and a much longer exposure at lower temperatures and one atmospheric pressure. A low air density will give smaller values of μ_γ and μ_β, which in turn will bring about less attenuation of the radiation energy fluxes (Equations 2-4 through 2-13) and, thus, result in greater gas generation rates than a high air density. This simplification, therefore, is conservative.

(2) We used an average thickness of 0.0813 cm (32 mils) for the paint films (Section 4.1), the thickest among the organic coating systems recommended in reference 14. A thick paint film will absorb more radiation energy (Equations 4-1 through 4-4) and, thus, produce higher gas generation rates than a thin one of an equal density. So, this simplification is conservative.

(3) We used an average density of 1.6 g/cm^3 for the paint films (Section 4.1). This value is higher than the densities of nylon, epoxy, and polyamide (reference 15). A high-density paint will absorb more radiation energy (Equations 4-1 through 4-4), and, thus, produce higher gas generation rates than a low-density paint of an equal thickness. This simplification is, therefore, conservative.

The largest uncertainty in the application of the present methodology probably is the selection of the G values (Section 1.3), since we do not have the true G values for the paints and the electrical cable insulation materials. Even if we know the exact chemical composition of the organic materials, the G values given in Table 3 are only approximate, especially those for rubbers (reference 8). Other sources of error include the radiation source term, uniform thickness of the paint films, uniform size and composition of the electrical cables, and spherical shape of the containment space.

In view of the above assumptions, simplifications, and sources of error, we cannot assign uncertainties to the results of the sample calculation. However, on the basis of the conservative assumptions discussed above, the calculated gas generation rates contain elements of conservatism.

Finally, it may be noted that no precise information is presently available on the chemical composition of the gases evolved from radiolysis of the organic materials in paints and electrical cable insulation. Not all of these gases are necessarily combustible.

7.1 Conclusion

The methodology described in this report can be used to calculate the gas generation rates from radiolysis of organic materials. The sample calculation using the data from a nuclear power plant demonstrated an application of the methodology to the radiation decomposition of the organic materials in both the electrical cables and paints inside the reactor containment building under the design basis accident conditions.

8.0 SUMMARY OF SYMBOLS

A = absorption of radiation energy

$A_{\beta,E}$ = absorption of beta radiation energy by ethylene propylene rubber in electrical cables

$A_{\beta,H}$ = absorption of beta radiation energy by Hypalon in electrical cables

$A_{\beta,p}$ = absorption of beta radiation energy by paint films

$A_{\gamma,E}$ = absorption of gamma radiation energy by ethylene propylene rubber in electrical cables

$A_{\gamma,H}$ = absorption of gamma radiation energy by Hypalon in electrical cables

$A_{\gamma,p}$ = absorption of gamma radiation energy by paint films

E_{β} = total beta radiation energy release rate (million electron volts per second)

E_{γ} = total gamma radiation energy release rate (million electron volts per second)

E_{m} = maximum energy of beta radiation (million electron volts)

$\dot{E}_{\beta}$ = total beta radiation energy release rate per unit power (million electron volts per second-watt)

$\dot{E}_{\gamma}$ = total gamma radiation energy release rate per unit power (million electron volts per second-watt)

$F_{\beta,c}$ = beta radiation energy release rate available for absorption by electrical cables (million electron volts per second)

$F_{\beta,p}$ = beta radiation energy release rate available for absorption by paint films (million electron volts per second)

$F_{\gamma,c}$ = gamma radiation energy release rate available for absorption by electrical cables (million electron volts per second)

$F_{\gamma,p}$ = gamma radiation energy release rate available for absorption by paint films (million electron volts per second)

G = yield of radiolysis (molecules/100 electorn volts of radiation energy absorbed)

G_E = yield of gases from radiolysis of ethylene propylene rubber (molecules/100 electron volts of radiation energy absorbed)

G_H = yield of gases from radiolysis of Hypalon (molecules/100 electron volts of radiation energy absorbed)

G_p = yield of gas from radiolysis of paints (molecules/100 electron volts of radiation energy absorbed)

L = total length of electrical cables (centimeters)

P = rated power level of a nuclear reactor (watts)

R = total gas generation rate from radiolysis of organic materials (gram moles per second)

R_β = gas generation rates from beta radiolysis (gram moles per second)

R_γ = gas generation rate from gamma radiolysis (gram moles per second)

$R_{\beta,E}$ = gas generation rate from beta radiolysis of ethylene propylene rubber (gram moles per second)

$R_{\beta,H}$ = gas generation rate from beta radiolysis of Hypalon (gram moles per second)

$R_{\beta,p}$ = gas generation rate from beta radiolysis of paint films (gram moles per second)

$R_{\gamma,E}$ = gas generation rate from gamma radiolysis of ethylene propylene rubber (gram moles per second)

$R_{\gamma,H}$ = gas generation rate from gamma radiolysis of Hypalon (gram moles per second)

$R_{\gamma,p}$ = gas generation rate from gamma radiolysis of paint films (gram moles per second)

r = radius of a sphere (centimeters)

S = total surface area of an absorber (square centimeters)

S_c = total surface area of electrical cables (square centimeters)

S_E = total outer surface area of ethylene propylene rubber in electrical cables (square centimeters)

S_p = total surface area of paint films (square centimeters)

V = net free volume of a containment building (cubic centimeters)

χ = distance in air travelled by radiation of airborne fission products (centimeters)

y = average thickness of an absorber (centimeters)

y_E = thickness of ethylene propylene rubber in electrical cables (centimeters)

y_H = thickness of Hypalon in electrical cables (centimeters)

y_p = average thickness of paint films (centimeters)

μ_β = linear absorption coefficient for beta radiation in air (1/centimeter)

μ_γ = linear absorption coefficient for gamma radiation in air (1/centimeter)

ρ = density (grams per cubic centimeter)

ρ_a = density of air (grams per cubic centimeter)

ρ_E = density of ethylene propylene rubber (grams per cubic centimeter)

ρ_H = density of Hypalon (grams per cubic centimeter)

ρ_p = density of dried paint films (grams per cubic centimeter)

σ = linear absorption coefficient (1/centimeter)

σ_β = linear absorption coefficient for beta radiation (1/centimeter)

σ_γ = linear absorption coefficient for gamma radiation (1/centimeter)

$\sigma_{\beta,E}$ = linear absorption coefficient for beta radiation in ethylene propylene rubber (1/centimeter)

$\sigma_{\beta,H}$ = linear absorption coefficient for beta radiation in Hypalon (1/centimeter)

$\sigma_{\beta,p}$ = linear absorption coefficient for beta radiation in paint films (1/centimeter)

$\sigma_{\gamma,E}$ = linear absorption coefficient for gamma radiation in ethylene propylene rubber (1/centimeter)

$\sigma_{\gamma,H}$ = linear absorption coefficient for gamma radiation in Hypalon (1/centimeter)

$\sigma_{\gamma,p}$ = linear absorption coefficient for gamma radiation in paint films (1/centimeter)

ϕ = incident radiation energy flux (million electron volts per square centimeter - second)

ϕ_o = initial gamma radiation energy flux (million electron volts per square centimeter-second)

ϕ_β = beta radiation energy flux (million electron volts per square centimeter - second)

ϕ_γ = gamma radiation energy flux (million electron volts per square centimeter - second)

$\phi_{\beta,c}$ = beta radiation energy flux incident on electrical cable surfaces (million electron volts per square centimeter-second)

$\phi_{\beta,p}$ = beta radiation energy flux incident on paint surfaces (million electron volts per square centimeter-second)

$\phi_{\gamma,c}$ = gamma radiation energy flux incident on electrical cable surfaces (million electron volts per square centimeter-second)

$\phi_{\gamma,p}$ = gamma radiation energy flux incident on paint surfaces (million electron volts per square centimeter-second)

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This report presents a methodology for estimating the gas generation rates resulting from radiolysis of organic materials in paints and electrical cable insulation inside a nuclear reactor containment building under design basis accident conditions. The methodology was based on absorption of the radiation energies from the post-accident fission products and the assumed gas yields of the irradiated materials. A sample calculation was made using conservative assumptions, plant-specific data of a nuclear power plant, and a radiation source term which took into account the time-dependent release and physico-chemical behavior of the fission products.

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