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FOAM DECONTAMINATION OF AIR CONTAINING RADIOACTIVE IODINE AND PARTICULATES FOLLOWING A NUCLEAR INCIDENT

S.H. Jury

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CHEMICAL TECHNOLOGY

FOAM DECONTAMINATION OF AIR CONTAINING RADIOACTIVE IODINE AND PARTICULATES FOLLOWING A NUCLEAR INCIDENT

S. H. Jury

OCTOBER 1966

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FOAM DECONTAMINATION OF AIR CONTAINING RADIOACTIVE IODINE AND PARTICULATES FOLLOWING A NUCLEAR INCIDENT

S. H. Jury

ABSTRACT

Foam suppression of radioactive iodine and particulates following a nuclear incident is briefly reviewed, emphasis being placed on methods of characterizing and categorizing the various contaminants.

It is proposed that volatile contaminants can be sorbed on the particulates and the latter, via Einsteinian diffusion, can act as vehicle for transport of radioactive contaminants to the surface of the bubble. In the light of this kinetic mechanism an investigation was made via a mathematical analysis of diffusion in bubbles in static foam and in foam beds subjected to elution. It was shown that in, the absence of chemical reagents to reduce the vapor pressure of radio-volatile components, the elution operation is a basic requirement to attain decontamination factors of 10^{-3} to 10^{-9} in the gas phase of the bubble. For mathematical convenience the decontamination factor is here defined as the ratio of final over initial concentration. Even if vapor pressure and back-diffusion of radio-volatile components is not a problem the bed must still be eluted to prevent re-dispersing the contaminants during the foam collapsing phase of the operation.

A number of other factors are discussed (involving the cost of the operation, equipment and its maintenance, the problem of uniform eluant feed distribution, velocity criteria, and dynamic decontamination factor via which one can exercise some control over back diffusion).

INTRODUCTION

Sometime ago it was proposed[2] that following a catastrophic nuclear incident the contaminants in the confining space could be removed by filling the space with a high expansion foam which via diffusion would act as a collector for the contaminants. The efficiency of such a single stage batch operation would of course

depend on the "back pressure" exerted by the contaminants collected. Tests indicated that the decontamination factor is not as good as one would expect based on the assumption that the contaminants exerted no back pressure. Other investigations (1) showed that during the course of an incident iodine could react with organic components which are present in pipe dope, paint, etc. to produce radio-volatiles capable of high back pressures.

Mathematical analysis of the suppression operation has been confined to the calculation of diffusion within single bubbles subjected to the batch operation and agreement between tests and calculation has been rather poor[1]. It has been suggested that these findings could be due to (a) the back pressure phenomenon which was not taken into account in the model, and/or (b) the method of analysis of gas phase concentration in the bubble. In the latter case it is conceivable that some of the contaminants were redispersed during the course of breaking the foam to allow access to the gas phase.

One point that seems to have been overlooked is that the magnified surface area of the finely dispersed aerosol should give rise to pronounced sorption of the radio-vapors by the aerosol. This matter will be considered in greater detail later in this report.

The purpose of this report is to (a) identify methods of characterizing contaminants, (b) evaluate and extend as required models and mathematical analysis of same that have been published to date, and (c) investigate a proposed foam suppression operation (complete with mathematical analysis) which is capable of decontamination factors in the range of 10^{-3} to 10^{-9}. Note that, as will become obvious later in this report, it is mathematically convenient to define the decontamination factor as the ratio of final to initial concentrations. This definition is reciprocally related to the one peculiar to the nuclear process technology.

METHODS OF CHARACTERIZING CONTAMINANTS

For chemical engineering purposes it is convenient to recognize that there are two classes of contaminants involved. Gas or vapors such as iodine, organic iodides, etc all exerting appreciable vapor pressure at environmental temperature belong to the one class whereas the aerosols of uranium oxide particulates and other solids of low vapor pressure suspended in air belong to the other. Here vapor pressure and particulate size as well as size distribution are methods of characterizing the contaminants.

Contaminants may also be characterized by their diffusivities. In the case of gases or vapors diffusing through air there has been much reported in the literature concerning measured values as well as methods for estimating diffusivities.

In the case of aerosols Einstein's formula for calculating diffusivity, i.e.

$$D = \frac{RTg_c}{6\pi\mu rN} \tag{1}$$

seems to be applicable. Here

D = diffusivity, $cm^2/sec \cdot molecule$

R = gas constant, g force·cm/g mole·°K (=75,000)

T = prevailing temperature, °K

g_c = 980 g mass·cm/g force·sec^2

μ = viscosity of carrier gas (air) at temperature T, g mass/cm·sec (0.0018 for air at 20°C)

r = particulate radius, cm

N = Number = $6.06 \cdot 10^{23}$ molecules/g mole

For smoke particles of 10 micron diameter in air at 20°C

$$D = 2.1 \cdot 10^{-8}\ cm^2/sec$$

whereas for iodine gas molecules

$$D = 0.1\ cm^2/sec$$

A compound such as methyl iodide is characterized by a high vapor pressure whereas the vapor pressure of uranium oxide would be comparatively small at 20°C. Methyl iodide is soluble in water at the low concentrations involved in a critical incident. Based on Raoult's Law one would expect that

$$p = XP_o \tag{2}$$

where

p = partial pressure of methyl iodide in the vapor phase at temperature T, psia

P_o = vapor pressure of pure methyl iodide at temperature T, psia

X = mole fraction of methyl iodide dissolved in aqueous solution

If

P = total pressure of the gas-vapor phase over the aqueous solution, psia

then

$$\frac{p}{P} = \frac{P_o}{P} X \tag{3}$$

where

$\frac{p}{P}$ = mole fraction of methyl iodide in the gas-vapor phase

$\frac{P_o}{P}$ = slope of the linear relation (Eq. 3) relating p/P and X

The partial pressure, p, is also called the "back pressure." The larger P_o for a given X the larger the back pressure and the more difficult the reduction of p from a chemical engineering viewpoint.

KINETIC MECHANISMS OF MASS TRANSFER IN SINGLE BUBBLES

At the instant of formation of a bubble in a foam operation one would anticipate circulation of the gas phase within the bubble.

However after the bubble is formed this circulation probably subsides and any mass transfer in the gas phase after this time takes place in the radial direction and is due to molecular or Brownian diffusion both of which follow Ficks Law. There also exists the possibility of adsorption by the aerosol of the vapor component in the gas phase. With this model in mind one can proceed to describe the model mathematically.

The aerosol-vapor sorption equilibrium may be represented by the linear isotherm

$$C_{va} = K\, C_{vg} \tag{4}$$

where

C_{va} = vapor concentration on aerosol, lbs vapor/lb aerosol

K = sorption isotherm proportionality constant, ft^3/lb

C_{vg} = vapor concentration in the gas phase, lb/ft^3

The vapor material balance for an incremental spherical shell of the gas phase is

$$\text{Rate of Accumulation} = \Sigma \text{ inflow} - \Sigma \text{ outflow} \tag{5}$$

Thus

$$\frac{\partial\, C_{vg} 4\pi r^2 \Delta r + C_{va} C_{ag} 4\pi r^2 \Delta r}{\partial t} = + D_v 4\pi (r+\frac{\Delta r}{2})^2 \frac{\partial\, C_{vg} + \frac{\partial C_{vg}}{\partial r} \frac{\Delta r}{2}}{\partial r}$$

$$- D_v 4\pi (r-\frac{\Delta r}{2})^2 \frac{\partial\, C_{vg} - \frac{\partial C_{vg}}{\partial r} \frac{\Delta r}{2}}{\partial r}$$

$$+ D_a 4\pi (r+\frac{\Delta r}{2})^2 \frac{\partial\, C_{ag} + \frac{\partial C_{ag}}{\partial r} \frac{\Delta r}{2}}{\partial r} \left(C_{va} + \frac{\partial C_{va}}{\partial r} \frac{\Delta r}{2} \right)$$

$$- D_a 4\pi (r-\frac{\Delta r}{2})^2 \frac{\partial\, C_{ag} - \frac{\partial C_{ag}}{\partial r} \frac{\Delta r}{2}}{\partial r} \left(C_{va} - \frac{\partial C_{va}}{\partial r} \frac{\Delta r}{2} \right) \tag{6}$$

which can be rearranged to read

$$\frac{\partial(C_{vg} + C_{va}\, C_{ag})}{\partial t} = D_v\left(\frac{\partial^2 C_{vg}}{\partial r^2} + \frac{2}{r}\frac{\partial C_{vg}}{\partial r}\right)$$

$$+ D_a\left(\frac{\partial^2 C_{ag}}{\partial r^2} C_{va} + \frac{2}{r}\frac{\partial C_{ag}}{\partial r} C_{va} + \frac{\partial C_{ag}}{\partial r}\frac{\partial C_{va}}{\partial r}\right) \qquad (7)$$

where

C_{ag} = aerosol concentration in gas phase, lb/ft^3

r = radial position, ft

t = time, sec

D_a = aerosol diffusivity through gas phase, ft^2/sec

D_v = vapor diffusivity through gas phase, ft^2/sec

If K = 0 then our last differential equation reduces to

$$\frac{\partial C_{vg}}{\partial t} = D_v\left(\frac{\partial^2 C_{vg}}{\partial r^2} + \frac{2}{r}\frac{\partial C_{vg}}{\partial r}\right) \qquad (8)$$

The aerosol material balance for an incremental spherical shell of the gas phase is derived by methods similar to those preceding and simplifies to

$$\frac{\partial C_{ag}}{\partial t} = D_a\left(\frac{\partial^2 C_{ag}}{\partial r^2} + \frac{2}{r}\frac{\partial C_{ag}}{\partial r}\right) \qquad (9)$$

This equation as well as Equation 8 has the same form as the classical equation for molecular diffusion in a spherical geometry.

Equation 8 is idealized in the sense that K = 0 implies that adsorption of vapor from the gas phase on to the surface of the solid aerosol particles suspended in the gas phase. Actually K could be very large if the oxidation of uranium is an activation process which produces a highly porous aerosol particle. The non-idealized Equation 7 may be simplified by using Equation 9 to eliminate some of the terms in r so that Equation 7 becomes

$$\frac{\partial C_{vg}}{\partial t} + C_{ag}\frac{\partial C_{va}}{\partial t} = D_v\left(\frac{\partial^2 C_{vg}}{\partial r^2} + \frac{2}{r}\frac{\partial C_{vg}}{\partial r}\right) + D_a\frac{\partial C_{ag}}{\partial r}\frac{\partial C_{va}}{\partial r} \qquad (10)$$

The sorption isotherm Equation 4 may be used to eliminate C_{va} to show that

$$\left(1 + C_{ag}K\right) \frac{\partial C_{vg}}{\partial t} = D_v \left(\frac{\partial^2 C_{vg}}{\partial r^2} + \frac{2}{r} \frac{\partial C_{vg}}{\partial r}\right) + D_a K \frac{\partial C_{ag}}{\partial r} \frac{\partial C_{vg}}{\partial r} \tag{11}$$

When we used Equation 9 to simplify Equation 7 to produce Equation 11 we in effect eliminated from Equation 7 and consequently Equation 11 the accumulation of vapor in the increment which comes about by virtue of its adsorption on and being carried by the aerosol particulates into and through the increment. If in an incident the amount of aerosol released is many times greater than the amount of radio-vapor and if K has any reasonable value or sorption is irreversible then all terms in Equation 11 reduce essentially to zero because C_{vg} becomes infinitesimally small. In this case diffusion of vapor and aerosol are governed by Equation 9. This then is the equation that will be solved in subsequent consideration of diffusion.

SOLUTION OF THE DIFFUSION EQUATION

The limiting conditions on Equation 9 are

$$C_{ag}(o,r) = C_o = \text{constant}; \quad 0 \leq r < R \tag{12}$$

$$C_{ag}(t,r) = 0; \quad t > 0 \tag{13}$$

$$\left(\frac{\partial C_{ag}}{\partial r}\right)_{r=o} = 0; \quad \text{all } t \tag{14}$$

where

R = radius of bubble, ft

and these must be considered in the solution of Equation 9.

If we define

$$U(r,t) = r\, C_{ag}(r,t) \tag{15}$$

then

$$\frac{\partial U}{\partial t} = D_a \frac{\partial^2 U}{\partial r_2} \tag{16}$$

and

$$U(o,r) = rC_o \tag{17}$$

$$U(t,R) = 0 \tag{18}$$

$$U(t,o) = 0 \tag{19}$$

If the Laplace transform of U with respect to t is defined as

$$S_t U = p \int_o^\infty e^{-pt} U(r,t)dt = g(p,r) \tag{20}$$

then

$$\frac{d^2g}{dr^2} - \frac{p}{D_a}(g-rC_o) = 0 \tag{21}$$

If we define

$$h = g-rC_o \tag{22}$$

then

$$\frac{d^2h}{dr^2} - \frac{p}{D_a} h = 0 \tag{23}$$

or

$$g-rC_o = A \sinh\sqrt{\frac{p}{D_a}}\, r + B \cosh\sqrt{\frac{p}{D_a}}\, r \tag{24}$$

When r=0 Equation 24 must reduce to zero and then

$$B = 0$$

Also when r=R

$$-RC_o = A \sinh\sqrt{\frac{p}{D_a}}\, R \tag{25}$$

or

$$g-rC_o = -RC_o \frac{\sinh\sqrt{\frac{p}{D_a}}\, r}{\sinh\sqrt{\frac{p}{D_a}}\, R} \tag{26}$$

and

$$\frac{C_{ag}}{C_o} = 1 - \frac{R}{r} \mathcal{L}_t^{-1} \frac{\sinh \sqrt{\frac{p}{D_a}}\, r}{\sinh \sqrt{\frac{p}{D_a}}\, R}$$

$$= 2 \frac{R}{r} \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\sin n \pi \frac{r}{R}}{n\pi} e^{-\frac{n^2\pi^2}{R^2} D_a t} \tag{27}$$

This is the expression for calculating at any time t the concentration at any point in the gas phase of the bubble.

An average gas phase concentration in the bubble may be defined as

$$Q = \frac{\int_o^R C_{ag} 4\pi r^2 dr}{4/3\pi R^3} \tag{28}$$

Substituting for C_{ag} using Equation 27 one finds that

$$\frac{Q}{Q_o} = 6 \sum_{n=1}^{\infty} \frac{e^{\frac{-n^2\pi^2}{R^2} D_a t}}{n^2\pi^2} \tag{29}$$

which is the same result as the one determined by Yoder and Silverman[2]. Here $\frac{Q}{Q_o}$ is the decontamination factor. The latter authors pointed out that Equation 29 applies to a vapor (which exerts no back pressure) as well as to an aerosol if one changes the diffusivity value accordingly. In view of previous discussion we may now add that the same solution also applies to diffusion of an aerosol which has a vapor adsorbed on and/or in it. In this latter case it is implied that the vapor sorbed on the aerosol particle is not preferentially displaced by water or surface active agent when the aerosol particle enters the liquid phase. If it is displaced then of course the desorbed vapor would be free to exert its back pressure and diffuse back into the gas phase of the bubble thus increasing the radioactivity of the gas phase (unless there was present in the aqueous liquor a reagent that would at least convert to a nonvolatile form the radioactive part of the volatile compound).

Sodium thiosulphate has in the case of iodine been used to convert it to the nonvolatile sodium iodide[2].

APPLICATION OF THEORETICAL RESULTS PERTAINING TO INDIVIDUAL BUBBLES

The exponents in the exponential of Equation 29 may be written

$$\tau_n = \frac{R^2}{n^2 \pi^2 D_a} \tag{30}$$

where the τ_n are the time constants of the exponential decay terms. The ratio of successive time constants in the series is

$$\frac{\tau_n}{\tau_{n+1}} = \frac{(n+1)^2}{n^2}$$

So that for n=1

$$\frac{\tau_1}{\tau_2} = 4$$

and for n=2

$$\frac{\tau_2}{\tau_3} = \frac{9}{4} = 2.25$$

and for n=3

$$\frac{\tau_3}{\tau_4} = \frac{16}{9} = 1.78$$

and finally

$$\lim_{n \to \infty} \frac{\tau_n}{\tau_{n+1}} = 1$$

Thus after $t=\tau_1$ all subsequent exponentials have decayed to negligible proportions and

$$\frac{Q}{Q_o} = \frac{6}{\pi^2} e^{\frac{-t}{\tau_1}} \tag{31}$$

or

$$2.303 \log \frac{Q}{Q_o} = 2.303 \log \frac{6}{\pi^2} - \frac{t}{\tau_1} \tag{32}$$

For a decontamination factor

$$\frac{Q}{Q_o} = 10^{-9}$$

we find that

$$\frac{t}{\tau_1} = -9 \cdot 2.303 + 2.303 \log \frac{6}{\pi^2}$$

$$\frac{t}{\tau_1} = 2.303\ [8.782]$$

$$= 20.2$$

If

$D_a = 2.1 \cdot 10^{-8}$ cm^2/sec (10 micron diameter aerosol)

$R = 2.5$ cm (See reference 2)

then

$$\tau_1 \equiv \frac{(2.5)^2}{\pi^2\ 2.1 \cdot 10^{-8} \cdot 3600 \cdot 24} = 347 \text{ days}$$

and

$$t = \frac{20.2 \cdot 3 \cdot 10^7}{3600 \cdot 24} = 7000 \text{ days}$$

For a 0.05 micron particle[2]

$$D_a = 4.2 \cdot 10^{-6} \text{ cm}^2/\text{sec}$$

and τ_1 and t are 200 times smaller than for a 10 micron aerosol particle or

$$\tau_1 = 1.73 \text{ days}$$

$$t = 35 \text{ days}$$

For a decontamination factor of 10^{-3} the t would be reduced roughly by a factor of 3.

It is obvious from the foregoing calculations that one should use a very small bubble size if foam suppression is to be really effective in a short time and this is probably the reason foam suppression decontamination factors have not been too impressive

in past investigations[2]. To produce the small bubbles the fan used by previous investigators would probably have to be replaced with a turbo-compressor and sintered metal dispersion or sparging tubes submerged in a tank of aqueous surfactant.

FOAM SUPPRESSION AND THE PERCOLATION OPERATION

If one envisions the gas bubbles as playing the role of a granule and the foam as being the counterpart of a dense bed then one can orient his thoughts along the lines of the percolation operations, i.e. sorption, heat recuperation, ion exchange, for the purpose of analysis of a proposed foam clean-up operation prior to breaking of the foam. The latter seems to be desirable if one wishes to insure against redispersing of radioactive particles during foam breaking. In the case of back pressure phenomena the clean-up operation is a must. Clean-up in the case at hand would involve trickling fresh non-aerated aqueous surfactant down through the bed of foam to displace from the bed the interstitial liquid into which the radioactive components have and are diffusing.

If one considers an incremental height of bed ΔZ and writes the two material balances, one for the interstitial liquid and one for the gas phase, he finds that the liquid phase bed equation is

$$\frac{\partial C_L}{\partial t} = - v_L \frac{\partial C_L}{\partial Z} - \frac{\bar{R}}{\alpha} \tag{33}$$

and that for the gas phase bed equation is

$$\frac{\partial Q}{\partial t} = \frac{\bar{R}}{1-\alpha} \tag{34}$$

where

C_L = bulk liquid concentration, lb/ft^3 liq.

Q = average gas phase concentration, lb/ft^3 gas

Z = distance down bed from top, ft

$\bar{R}$ = mass transfer rate between gas and liquid phases, $lb/(sec \cdot ft^3 \text{ bed})$

α = bed void fraction, ft^3/liquid/ft^3 of bed

$v_L = \frac{qL}{\alpha A}$ = interstitial liquid velocity, ft/sec

A = cross area of bed, ft^2

q_L = liquid volumetric flowrate through bed, ft^3/sec

If we eliminate $\bar{R}$ between Equations 33 and 34 then

$$v_L \frac{\partial C_L}{\partial Z} + \frac{\partial C_L}{\partial t} + \frac{1-\alpha}{\alpha} \frac{\partial Q}{\partial t} = 0 \qquad (35)$$

Normally it is this Equation 35 that would be solved in conjuncion with the rate Equation 29.

The problem in the present case can be solved somewhat more directly and completely if it is recognized that two basic time periods are involved. The first occurs immediately following start up and up to time Z_L/v_L where

Z_L = total bed height, ft

The second period involves operations beyond time Z_L/v_L.

During the first period and at time t the effluent concentration $C_L(Z_L,t)$ is that of liquid that was at a point Z_L-Z at time equal zero and during the time period $\frac{Z_L-Z}{v_L}$ has been in contact with the gas phase. Thus during this period the effluent concentration is

$$C_L(Z_L,t) = -\frac{1-\alpha}{\alpha} \int_o^t \frac{\partial Q}{\partial t} \, dt; \quad t \leq \frac{Z_L}{v_L}$$

$$= -\frac{1-\alpha}{\alpha} [Q(t) - Q(o)] \qquad (36)$$

During the second time period the liquid leaving the bed at time t is liquid that started into the bed at a time $\frac{Z_L}{v_L}$ earlier. Thus

$$C_L(Z_L,t) = -\frac{1-\alpha}{\alpha} \int_{t-Z_L/v_L}^t \frac{\partial Q}{\partial t} \, dt; \quad t \geq \frac{Z_L}{v_L} =$$

$$= -\frac{1-\alpha}{\alpha}\left[Q(t) - Q\left(t - \frac{Z_L}{v_L}\right)\right] \tag{37}$$

It will, of course, be noticed that at time Z_L/v_L both solution equations reduce to the same result as must be the case. The problem now remains to reduce Equations 36 and 37 to useful form.

In view of Equation 29, Equation 36 becomes

$$C_L(Z_L,t) = Q_o \frac{1-\alpha}{\alpha}\left(1 - 6\sum_{n=1}^{\infty} \frac{e^{-\frac{n^2\pi^2 Da}{R^2}t}}{n^2\pi^2}\right); \quad t \le \frac{Z_L}{v_L} \tag{38}$$

since

$$6\sum_{n=1}^{\infty}\frac{1}{n^2\pi^2} = 1$$

Also Equation 37 becomes

$$C_L(Z_L,t) = Q_o \frac{1-\alpha}{\alpha}\, 6\sum_{n=1}^{\infty}\frac{\left(e^{\frac{n^2\pi^2 Da}{R^2}\frac{Z_L}{v_L}} - 1\right)e^{-\frac{n^2\pi^2 Da}{R^2}t}}{n^2\pi^2}; \quad t \ge \frac{Z_L}{v_L} \tag{39}$$

These two equations may now be used to investigate the effluent concentration from the percolation operation.

Equation 38 shows that the effluent concentration builds up from zero to a maximum concentration at time $\frac{Z_L}{v_L}$ as given by

$$\left[C_L\left(Z_L, \frac{Z_L}{v_L}\right)\right]_{MAX} = Q_o \frac{1-\alpha}{\alpha}\left[1 - 6\sum_{n=1}^{\infty}\frac{e^{-\frac{n^2\pi^2 Da}{R^2}\frac{Z_L}{v_L}}}{n^2\pi^2}\right] \tag{40}$$

Equation 39 on the other hand is equal to Equation 40 at time $\frac{Z_L}{v_L}$ and shows that for larger values of time, t, the effluent concentration decays toward zero from the maximum value specified by Equation 40.

Equation 40 itself has a maximum which for all practical purposes occurs by the time

$$\frac{Z_L}{v_L} \geq 10\,\tau_n \tag{41}$$

where still

$$\tau_n = \frac{R^2}{n^2\pi^2 Da}$$

Under these circumstances the maximum reaches its maximum value which from Equation 40 is

$$\left[C_L(Z_L,t)\right]_{\substack{MAX\\MAX}} = Q_o\,\frac{1-\alpha}{\alpha} \tag{42}$$

This is precisely the concentration the liquor in the bed would take on after

$$10\,\tau_n$$

if there was no flow through the bed, i.e.

$$v_L = 0$$

For all practical purposes reasonably high values of v_L should be used to reduce $(C_L)_{MAX}$ of Equation 40 and to reduce vapor counterdiffusion into the bubbles that would occur if C_L is allowed to build up and the vapor is displaced off the aerosol in the liquid phase and no other reagent is present to reduce the back pressure. The presence of the latter reagent is of course highly desirable to reduce subsequent waste-effluent disposal problems.

The difficulty with solving Equation 35 by classical means is that it leads only to solution Equation 39. The procedure is to define a new time, t^1, as

$$t^1 = t - \frac{Z}{v_L}$$

and then via Eulers theorem to write that

$$\left(\frac{\partial C_L}{\partial t}\right)_Z = \left(\frac{\partial C_L}{\partial t^1}\right)_Z \frac{\partial t^1}{\partial t} + \left(\frac{\partial C_L}{\partial Z}\right)_{t^1} \frac{\partial Z}{\partial t} = \left(\frac{\partial C_L}{\partial t^1}\right)_Z \tag{43}$$

and

$$\left(\frac{\partial C_L}{\partial Z}\right)_t = \left(\frac{\partial C_L}{\partial t^1}\right)_Z \frac{\partial t^1}{\partial Z} + \left(\frac{\partial C_L}{\partial Z}\right)_{t^1} \frac{\partial Z}{\partial Z} = -\frac{1}{v_L}\left(\frac{\partial C_L}{\partial t^1}\right)_Z + \left(\frac{\partial C_L}{\partial Z}\right)_{t^1} \tag{44}$$

and

$$\left(\frac{\partial Q}{\partial t}\right)_Z = \left(\frac{\partial Q}{\partial t^1}\right)_Z \frac{\partial t^1}{\partial t} + \left(\frac{\partial Q}{\partial Z}\right)_{t^1} \frac{\partial Z}{\partial t} = \left(\frac{\partial Q}{\partial t^1}\right)_Z \tag{45}$$

If we substitute for the corresponding derivatives in Equation 35 and integrate the result reduces to

$$C_L(Z_L, t^1) = -\frac{1-\alpha}{\alpha v_L} \int_0^{Z_L} \frac{\partial Q}{\partial t^1}\, dZ \tag{46}$$

This has the same solution (after substituting for the derivative and integrating) as expressed by Equation 39 but says nothing about the time period zero to Z_L/v_L.

APPLICATION OF THEORETICAL RESULTS PERTAINING TO THE ELUTION OF FOAM BED

If vapor back diffusion were not a problem the ideal way to elute a bed to confine the radioactivity to a minimum volume of eluant and yet to attain the desired decontamination factor is to postpone elution until the right hand side of Equation 29 reduces to the desired decontamination factor Q/Q_o as previously computed and then to elute for a time equal to Z_L/v_L (using a convenient value of v_L) before finally breaking the foam. In this case $C_L(Z_L, 0 \leq t \leq \frac{Z_L}{v_L})$ is essentially a square wave of length $\frac{Z_L}{v_L}$.

If vapor back-diffusion is part of the problem then one must start elution at the earliest possible time recognizing that during

the operation Equations 29 and 38-40 govern the operation. Equation 29 governs in the sense that there is a desired aerosol decontamination factor (10^{-3} to 10^{-9}) to be attained as illustrated in Equation 32 and the computations that follow. This establishes the operating time, t_E, for elution. Equations 38-40 govern in the sense that they determine the operating value of v_L and consequently limit the extent of vapor back diffusion. If for example v_L were infinite then there would be no vapor back pressure.

Of Equations 38-40 the most stringent requirements are set by Equation 40 which for this reason we will use to define a dynamic decontamination factor thus

$$(DF)_{Dynamic} = \frac{\alpha}{1-\alpha} \frac{C_L(Z_L, \frac{Z_L}{v_L})MAX}{Q_o} = 1-6 \sum_{n=1}^{\infty} \frac{e^{-\frac{n^2\pi^2 Da}{R^2}\frac{Z_L}{v_L}}}{n^2\pi^2} \tag{47}$$

Now

$$\tau_1 = 1.73 \cdot 3600 \cdot 24 \text{ second}$$

whereas Z_L/v_L might be of the order of 100 seconds thus the exponential exponents early in the series are small and later terms are casualties of the n^2 appearing in the denominator of the summation. This makes Equation 47 as it stands an awkward job of evaluation. Since this is a case of small time, i.e. Z_L/v_L, one can use the initial value theorem in the frequency domain to derive a reasonable approximation to Equation 47.

The Laplace transform of Equation 47 is

$$S_t(DF)_{Dynamic} = 3 \frac{R\sqrt{\frac{p}{Da}} \cosh \sqrt{\frac{p}{Da}} R - \sinh \sqrt{\frac{p}{Da}} R}{\left(R \frac{p}{Da}\right)^2 \sinh \sqrt{\frac{p}{Da}} R} \tag{48}$$

By virtue of the reciprocity theorem one may write for large p, i.e. small time,

$$S_t(DF)_{Dynamic} \simeq \frac{3}{R\sqrt{\frac{p}{Da}}} \tag{49}$$

or

$$(DF)_{Dynamic} \simeq \frac{3\sqrt{Da}}{R}\, 2\sqrt{\frac{Z_L}{\pi v_L}}$$

or

$$(DF)_{Dynamic} \simeq 1.07\sqrt{\frac{\pi^2 Da}{R^2}\,\frac{Z_L}{v_L}} \tag{50}$$

If

$\tau_1 = 1.73 \cdot 3600 \cdot 24$ second
$Z_L = 50$ ft
$v_L = 0.5$ ft/sec

then

$$(DF)_{Dynamic} = 1.07\sqrt{\frac{100}{1.73 \cdot 3600 \cdot 24}} = 2.77 \cdot 10^{-2}$$

This is the worst case $(DF)_{Dynamic}$ for the conditions cited and is quite good when all is considered. At all other times than Z_L/v_L $(DF)_{Dynamic}$ will be smaller which is very favorable in combatting back diffusion of vapor constituents.

The total volume of eluant containing the contaminants is going to be appreciably greater than for the ideal case.

There is a practical limit on v_L. One cannot for example flow eluant down through the bed by gravity without satisfying the hydrodynamic relations governing such flow. There is also the problem of maintaining the bed of foam during the flow operation. This in itself would be serious enough as to force the use of chemical reagents that would resolve the back pressure problem in which case one would resort to the ideal type elution operation.

The greater the plan area over which the foam is spread the more expensive the equipment for evenly distributing liquid eluant feed over the top of the bed. This equipment has to be maintained in first class operating condition hopefully for many years of stand-by.

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