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NOTE TO: Distribution

FROM: Themis P. Speis, Director  
Division of Safety Technology  
Office of Nuclear Reactor Regulation

SUBJECT: NRC/IDCOR MEETING ON OUTSTANDING TECHNICAL ISSUES FOR  
SEVERE ACCIDENTS

An NRC/IDCOR meeting is scheduled for March 26 on outstanding technical issues. A copy of the meeting notice is enclosed. A list of the outstanding issues together with a brief description of each issue has been prepared by G. Marino. A copy of G. Marino's writeup is also enclosed. This will serve as background information for the meeting. The meeting will be a working meeting with fewer attendees than we have had at previous IDCOR meetings.

The lead responsibility of preparing for the meeting and representing NRC at the meeting on the various issues has been assigned to individuals as indicated on the margin of the second enclosure. Please review the issue you are responsible for and in preparation for the IDCOR meeting attend an NRC staff meeting in the MNBB room 6110 on Tuesday, March 19, from 9:00 A.M. to 4:00 P.M. The purpose of the meeting is to discuss: (1) the approach to be taken for the resolution of the issues at the IDCOR meeting; (2) NRC's position on each of the issues; (3) proposed resolution of the issues, and (4) the detailed agenda of the March 26 IDCOR Meeting.

A handwritten signature of Themis P. Speis is located above his name and title.

Themis P. Speis, Director  
Division of Safety Technology  
Office of Nuclear Reactor Regulation

Enclosures:

1. Meeting Notice
2. List of Outstanding Issues

cc: D. Ross  
J. Knight  
O. Bassett  
F. Gillespie  
G. Arlotto  
D. Muller  
R. Houston  
B. Sheron  
L. Hulman  
G. Burdick

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## AEROSOL DEPLETION IN LEAKAGE PATHS

TRAP-MET models aerosol depletion in unidirectional flows by the expression (TRAPMET Users' Manual, NUREG/CR-0632) ~~by~~ using a fictitious depletion velocity,  $V_d$ .

$$V_d = \left( \frac{N_0}{N} - 1 \right) \frac{a V_g}{2L} \quad (1.)$$

Here  $V_g$  is the average gas velocity,  $a$  and  $L$  the radius and length of the duct, and  $N_0$  and  $N$  the aerosol density (mass of aerosol per gas volume) at the beginning and end of the flow. The use of a depletion velocity takes precedent from atmospheric fallout models, but is fictitious in that it is a single linear parameter intended to model a variety of processes not necessarily of a linear nature.

The quantity in brackets in equation (1.) is just the fraction depleted from the aerosol ( $\frac{N_0}{N}$  is a "DF"), ( $V_g/L$ ) is the mean residence time of gas in the duct, such that  $\frac{a V_g}{L}$  is the deposition velocity needed to completely deplete the aerosol within the duct. The constant, 2, can be considered either as a deposition and reentrainment equilibrium constant, or as an estimate that gas in the boundary layer ~~travels~~ travels at only half the velocity of the majority of the gas near the duct center. This approximate expression is most likely adequate when  $\frac{V_d}{V_g}$  is smaller than  $a/L$ .

Stokes' law for the gravity settling of spherical particles of diameter  $D$ , material density  $\rho$ , in a gas of viscosity  $\eta$  is

$$V_d = \frac{\rho g D^2}{18 \eta} \quad (2)$$

The viscosity of air at STP is  $180 \mu\text{poise}$ , or  $18 \mu\text{pascal-seconds}$ , while that of hot gases or steam is several times larger. The density of aerosols of interest is from 3 to  $10 \text{ tonnes/m}^3$ , and  $g$  is  $9.8 \text{ m/sec}^2$ . For a general figure then

$$V_d \approx \frac{(9.8)(5 \times 10^3 \text{ kg/m}^3) D^2}{(18)(20)(10^{-6})} = 1.4 \times 10^8 D^2 \quad (3)$$

Gas velocities of interest range from several meters/sec for containment pressure leakage through small, long holes limited to viscous flow, to several hundred meters/sec for Bernoulli flow from high pressure volumes within containment.  $V_d$ , then, is  $\sim 10^4 \text{ m/sec}$  for  $1 \mu\text{m}$  particles and larger fraction of a m/sec for  $100 \mu\text{m}$  particles.

It is apparent that if  $\frac{a}{L}$  is less than  $\frac{V_d}{V_g}$ , gravity settling alone will quickly plug the duct. It is also apparent that hygroscopic aerosols will settle quickly in moist gases, since  $D^2$  will increase more rapidly than  $\rho$  will decrease. At Windscale (or more correctly, in southern England downwind),  $V_d$  was of the order of  $10^{-3} \text{ m/sec}$  and  $V_g$  was  $\sim 1 \text{ m/sec}$ . In real duct flows, gas pressure drops and direction changes are more important than gravity settling, which is why impactors work in aerosol measurements.

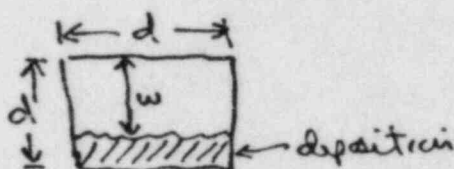
In the Morewitz plugging model, the total aerosol mass leaked prior to plugging of the duct,  $M_p$ ,

is related to the <sup>initial</sup> diameter of the duct,  $d$ , by.

$$m_p = K d^3 \quad (4.)$$

Here  $K$  is a heuristic constant that is generally found to be of the order of 10 to 20 times the material ~~of~~ density of the aerosol particles,  $K$  having the dimensions of density. The data supporting Morewitz's model is nothing short of remarkable in agreeing with the exponent of  $d$ , with  $K$  varying only modestly and being generally lower for moist gases and hygroscopic particles.

We may follow the sort of simple model used in TRAP-MELT, but, for convenience, view the duct as initially square in cross-section, filling only by gravity settling.



Using TRAP-MELT variables, the mass flux of aerosol going into the leak at any time is just  $N_0 v_g w d$ .  $1/v_g$  is the mean residence time inside, and  $v_d/v_g w$  is the fraction lost inside by deposition. Here we use the  $v_d/v_g \ll 1$  approximation. The product of the mass flux into and the fraction depleted within the leak,  $N_0 d v_d$ , is then the rate of mass deposition on the floor of the duct. Under these approximations,

$$\frac{dw}{dt} = -\frac{N_0}{\rho} v_d \quad (5.)$$



where  $\rho$  is the density of the deposit. The solution of (5.) is

$$w = d - \frac{N_0 v_d t}{\rho}, \quad (6.)$$

with  $t=0$  at the start of flow of aerosol of constant density  $N_0$ . The rate of passage of aerosol mass out the far end of the duct,  $\frac{dM_p}{dt}$ , is given by the difference between the influx and deposition, or.

$$\frac{dM_p}{dt} = N_0 d (v_g w - v_d L) \quad (7.)$$

The time at which plugging occurs, i.e.  $w=0$ ,  $t=t_p$ , can be gotten from (6.)

$$t_p = \frac{\rho d}{N_0 v_d} \quad (8.)$$

Combining (6.) and (7) yields an expression for the momentum relation.

$$M_p = N_0 d \int_0^{t_p} \left( v_g d - \frac{v_g v_d N_0 t}{\rho} - v_d L \right) dt \quad (9.)$$

The solution of (9.) is

$$M_p = \frac{v_g \rho}{2 v_d} d^3 - \rho d^2 L \quad (10.)$$

4/2/84

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Since  $v_g/v_d \gg 1$ , and rapid plugging is ~~para~~ expected if  $L \gg d$ , the first term must dominate, in which case the constant in (4.) is:

$$K \approx \frac{v_g \rho}{2 v_d} \quad (11.)$$

The question naturally ~~arises~~ arises as to why  $K$  does not vary markedly. Note, however, that for gravity settling,  $v_d \propto \rho/\eta$ , and, if the flow is limited by gas viscosity,  $v_g \propto 1/\eta$ . Hence, for all intents and purposes, we can predict

$$K \approx \frac{K'}{D^2} \quad (12.)$$

The Mercury data actually looks good by our simple model as long as the various aerosols in the many experiments all had  $D \approx 10 \mu\text{m}$ .

Note that TRAP-MET and Mercury part ways for long pipe runs. Applied to a 6" ID pipe 20 meters long, Mercury will pass tens of tonnes of material prior to plugging. For TRAP-MET with  $v_d \approx 10^{-3}$  meters/sec however, the pipe can be a 95% efficient particulate filter.

Fauske and Associates, Inc., (FAI) developed a heuristic aerosol correlation for IDCOR which, like Mercury's model, shows remarkably good fit to experiment. The FAI model is written as

$$\lambda = C_1 N^n, \quad A1 \quad (13.)$$

11/2/84

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for a first order depletion rate equation

$$\frac{dm}{dt} = -\lambda NV \quad (14.)$$

Here,  $m$  is the mass of aerosol particles and  $V$  the volume of gas in which they are dispersed, i.e.,  $N = m/V$ . The constants in (13.) are fit to be

$$C_1 = 0.022, n = 0.6 \text{ for } N > 6 \times 10^{-5} \text{ kg/m}^3$$

$$C_1 = 0.0016, n = 0.33 \text{ for } N < 6 \times 10^{-5} \text{ kg/m}^3$$

Defining the initial depletion rate ( $t=0$ ) as  $\lambda_0$

$$\lambda_0 = C_1 N_0^n \quad (15.)$$

and solving the combination of (13), (14) and (15.) yields

$$\frac{N_0}{N} = (\lambda_0 n t + 1)^{1/n} \quad (16.)$$

For steady-state flow with a constant  $N_0$  and  $N$ ,  $t$  will be the mean residence time  $\frac{L}{v_g}$ . For the more dense aerosols

$$\left(\frac{N_0}{N}\right)_{ss} = \left( \frac{(0.022)(0.6) L N_0^{0.6}}{v_g} + 1 \right)^{1/0.6}$$

$$1 = \left( \frac{1}{N^{0.6}} - \frac{0.0132 L}{v_g} \right) N_0^{0.6}$$

$$N^{-0.6} = N_0^{-0.6} + \frac{0.0132 L}{v_g}$$

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(17.)

For the less dense aerosol

$$N = N_0^{-0.33} + \frac{5.8 \times 10^{-1}}{v_g} \quad (18.)$$

All these FAI experiments are for "still" volumes of aerosol inside large containers. We can turn out a wide variety of solutions: Table entries are % transmission.

$L/v_g$  = seconds of mean residence time

$N_0$	<u>1.0 sec</u>	<u>10. sec</u>	<u>100. sec</u>
$10^{-1} \text{ Kg/m}^3$	99.5	94.1	62.0
$10^{-2}$	99.9	98.6	87.5
$10^{-3}$	100.	99.6	96.6
$10^{-4}$	100.	99.9	99.1
$10^{-5}$	100.	100.	99.6

It is apparent that the FAI model is applicable only to compact volumes depleted by agglomeration and fallout, and contains no factor to account for size distribution effects.

Of interest in restricted situations is the degree of dependence of deposition on size distribution. It is likely that long leak paths will greatly alter this distribution. Consider the average kinetic energy of Brownian motion at  $100^\circ \text{C}$ , at which average kinetic energy is  $5 \times 10^{-21} \text{ J/particle}$ .



Taking material density of the particle as  $5 \times 10^3 \text{ kg/m}^3$ , and spherical particles, thermal particle velocity  $v_T$  is

$$v_T = \frac{4.5 \times 10^{-12} \text{ m}^2/\text{sec}}{D}, \quad (19.)$$

while equation (3) gives gravitational settling velocity,  $v_d$ .

$D$	$v_T$	$v_d$
$0.1 \mu\text{m}$	$5 \times 10^{-5} \text{ m/s}$	$1.4 \times 10^{-9} \text{ m/s}$
$1.0 \mu\text{m}$	$5 \times 10^{-6}$	$1.4 \times 10^{-5}$
$10 \mu\text{m}$	$5 \times 10^{-7}$	$1.4 \times 10^{-3}$

Equations (3) and (19) say that  $v_T = v_d$  at  $0.9 \mu\text{m}$  particle diameter, at which diameter  $v_T + v_d \approx 5 \times 10^{-6} \text{ m/s}$ . Smaller particles will deplete by diffusion, larger by gravity, as dominant mechanisms. Obviously,  $v_d$  only depletes downward, while  $v_T$  depletes on all surfaces, so the real minimum is at a smaller ~~radius~~ particle diameter. Aerosol specialists generally put  $\sim 0.3 \mu\text{m}$  as the least depleted diameter. High surface-to-volume will deplete small particles, flow direction changes will deplete large particles.

The FAI expression depletes very dense ( $> 100 \text{ gms/m}^3$ ) aerosols at a prodigious rate. The next logical question is "what range or limits to aerosol mass densities exist?"

Consider a material having a normal boiling point,  $T_b$ . When it evaporates it takes a latent heat into the gas. If this latent heat,  $\Delta H_{\text{vap}}$ , is discharged against a solid surface, the vapor must deposit on that surface, while to form a condensation aerosol,  $\Delta H_{\text{vap}}$  must be given to the gas supporting the new-formed aerosol. AI

By Trouton's Rule

$$\Delta H_{\text{vap}} = (92 \text{ J/mole-Kelvin}) T_b \quad (20.)$$

If the vaporizing substance were a dissolved component rather than a pure phase, this rule could underestimate  $\Delta H_{\text{vap}}$ . Such would also be the case if vaporization occurred as a result of chemical reaction between the gas and the solid or liquid from which vapors were being formed. We may view (20.) as estimating a minimum  $\Delta H_{\text{vap}}$ .

To form a condensation aerosol,  $\Delta H_{\text{vap}}$  must be yielded to the gas phase; if it were given to a condensed phase then the vapor would deposit on that phase's surface rather than on an aerosol particle.

For most gases,  $C_p \approx 5/2 R$ , hence if a non-condensable gas is mixed with condensable vapor, being heated from  $T_g$  to  $T_b$ , the enthalpy accepted would be, for  $n_g$  ~~moles~~ moles of gas:

$$\Delta H_{\text{gas}} = \frac{5}{2} R n_g (T_b - T_g) \quad (21)$$

By ~~subtracting~~ <sup>combining</sup> (20) to (21), we would be stating that the gas accepts just enough energy to condense the vapor.

$$92 n_b T_b = \frac{5}{2} R n_g (T_b - T_g) \quad (22)$$

where (20) has been multiplied by  $n_b$ , the moles of vapor.

Using the ideal gas law, and ignoring the volume of aerosol:

$$\frac{n_b}{V} = \frac{5}{2} \frac{P}{92} \frac{(T_b - T_g)}{T_b^2} = 0.0272 \frac{P(T_b - T_g)}{T_b^2} \quad (23.)$$

Since our  $\Delta H_{vap}$  was a lower limit, reinforced by claiming it is the only source of heat to the gas,  $n_b/V$  in (23) is an upper limit. About the coldest  $T_g$  we could postulated would be 400 K (steam).

$T_b$	$\frac{(T_b - 400)}{T_b^2}$	$\therefore n_b/V$ at $P = 2 \times 10^5 \text{ Pa}$
500	$4 \times 10^{-4}$	2.2 $\text{moles/m}^3$
1000	$6 \times 10^{-4}$	3.3
1500	$4.89 \times 10^{-4}$	2.7
2000	$4 \times 10^{-4}$	2.2
2500	$3.36 \times 10^{-4}$	1.8

Which says that condensation aerosols can't get over a few hundred grams/ $\text{m}^3$ , in gas at  $T_b$  and 2 atmospheres. Interestingly, the maximum densities fall at about the boiling points of the control rod materials in PWR's and the tin in zircaloy. The FAI correlation, however, doesn't give such dense aerosols much ~~the~~ life time.

The aerosol densities in BMI-2104 look OK, though, since they fall within our permitted range by (23).