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TO: T. L. Gershun*

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SUBJECT:

RAINOUT CONTAINMENT

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I STATEMENT OF PROBLEM

Evaluate the potential efficiency of a sprinkler system as an air-borne fission product containment mechanism.

II. SUMMARY OF RESULTS AND RECOMMENDATIONS

A rainout system for the removal of an airborne cloud of fission products was found to be worthy of detailed consideration only under restricted circumstances. The primary inadequacies and objections to a rainout system are listed below:

1. Particles with radii less than 1 micron are not removed by rain, thus the major portion of the fission products contained in a cloud resulting from combustion or meltdown are unaffected by a rainout system.
2. Particles with radii greater than ~5 microns will probably settle out without the added impetus of a rainout system.

Therefore, the rainout concept is limited to particulates with

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radii between 1 and 6 microns.

3. The maximum obtainable reduction for a typical dust bearing cloud with reasonable expenditures of water is less than a factor of 10.
4. The most efficient removal is for a confined cloud, e.g., within the reactor building.
5. An outdoor rainout system is limited by building leakage rates, wind velocities, and the degree of saturation of the air with water vapor.
6. The droplet sizes corresponding to efficient removal of dusts is inefficient for the removal of vapor and vice versa.
Thus one may not efficiently remove both particulates and iodine vapor.

The rainout containment system does have the following attribute:
It is theoretically possible to remove 99.9% of the iodine vapor from a vapor cloud with a total water expenditure of 0.2 mm. The above efficiency is based on uniform water droplets of 50 micron radii and is only applicable from a practical standpoint to a confined cloud and rainout system.

It seems feasible to substitute some sort of dust or powder for water as the vehicle for the rainout of iodine. The above system could be used in conjunction with a filtration system which would simultaneously remove the dust or powder with the adsorbed iodine and also the radioactive particulates.

III. METHODS USED

A. Theoretical Considerations

1. Washout of Particles

The washout of aerosols by rain is described by the following equation:⁽¹⁾

$$\Delta(r,s) = \pi S^2 N(s) V(s) E(r,s) \quad (1)$$

where:

$\Delta(r,s)$ = proportion of a monodisperse aerosol of radius
r removed per second by raindrops of radius
S, sec.⁻¹

S = radius of raindrop, cm

$N(s)$ = the raindrop density drops/cm³

$V(s)$ = terminal velocity of raindrop, cm/sec

$E(r,s)$ = collection efficiency⁽²⁾

The rate of rainfall is given by

$$R = N(s) V(s) \frac{4}{3} \pi S^3 \quad (2)$$

Where R is the rate of rainfall per second and the other terms were previously defined. Substitution of $N(s)$ from Equation (2) into Equation (1) yields the following equation:

$$\Delta(r,s) = 3 R E(r,s) / 4 S \quad (3)$$

It should be noted that ordinary rain is composed of a droplet size distribution dependent on the rate of rainfall.⁽⁵⁾ However, for the purposes of this study, it is assumed that the sprinkling system would provide drops of uniform size. The collection efficiency, $E(r,s)$ of raindrops of various sizes for different particle sizes appears in

Table I in the appendix as taken from Reference 2. These values were used to obtain the removal constant, $\Lambda(r,s)$ for a rain rate of 1 mm/hr. The results are plotted in Figures 1 and 2 with raindrop size and particle size as parameters respectively.

The collection efficiency for particles with radii less than ~ 1 micron is essentially zero for raindrops of any size. (2,4) The critical radius of water droplets below which no collection occurs for a given particle size is presented in Reference 2 and appears in Table II in the Appendix. The physical interpretation of the phenomena of zero collection efficiency is that the particle has insufficient momentum to reach the droplet through the boundary layer of still air before it is swept around the particle by the air-flow stream lines. In addition, the particles in the submicron range are too large to diffuse to any extent across the boundary layer of still air during the time they are in the proximity of the droplet. The latter phenomena, however, becomes the primary means of removal for molecular size particles such as gases.

Figure 3 is a plot of the value of $\Lambda(\max)$ and the value of the droplet size at which $\Lambda(\max)$ occurs as a function of particle size. The plot is useful in obtaining an estimate of the maximum removal constant, Λ , for small particle size.

2. Washout of Vapor

The washout of a vapor by rain is described by the following equation: ⁽¹⁾

$$\Lambda(s) = 2\pi N(s) D [2.0 + 0.60 Re^{1/2} Sc^{1/3}] \quad (4)$$

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where: $\Delta(s)$ = proportion of the vapor removed per second by a drop of radius S , sec^{-1}

D = the molecular diffusion constant of the vapor in air; $0.085 \text{ cm}^2/\text{sec}$ for iodine.⁽¹⁾

ν = the kinematic viscosity of air; $0.147 \text{ cm}^2/\text{sec}$ @ 15°C

Re = the Reynolds number for flow around the droplet,

Sc = the Schmidt number,

The value of $N(s)$ from Equation 2 was substituted into Equation (4) and the resulting equation follows:

$$\Delta(s) = \frac{1.5RD}{S^2 \nu(s)} \left[2.0 + 0.60 Re^{1/2} Sc^{1/3} \right] \quad (5)$$

The removal constant, $\Delta(s)$, for iodine vapor was obtained for several droplet sizes and is plotted in Figure 4. A comparison of the removal constants for iodine vapor and particulates of varying size is given in Figure 5 as a function of water droplet radius.

It can be seen from Figures 4 and 5 that very high efficiencies are obtained for the removal of iodine vapor with water droplet radii below ~ 100 microns. The increased efficiency, for a given rain rate, is a result of the increased droplet density, $N(s)$ and the resulting increase in droplet surface area.

Equation (4) as used to obtain the removal constant, Δ , is directly applicable to obtain the evaporation of water droplets in air with the substitution of the diffusion constant, D , for water vapor in air. In fact, Equation (4) was derived for the case of evaporation of water droplets in air.⁽¹⁾ The diffusion constant for water vapor in air is $0.256 \text{ cm}^2/\text{sec}$ ⁽⁶⁾ compared to $0.085 \text{ cm}^2/\text{sec}$ ⁽¹⁾ for iodine vapor. Thus,

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the evaporation rate in dry air will be ~ 3 times greater than the deposition of iodine vapor on the droplet. Consequently, there will be no removal of the iodine vapor in dry air. The reported removal constants as plotted in Figure 4 are strictly applicable in air saturated with water vapor such as one would find during a rain shower.

The removal constants as presented in Figure 4 are based on uniform droplet size with no agglomeration. It is evident that one will not be able to obtain the idealized condition of uniform droplet size.

As stated previously, this study does not take cognizance of that phenomenon; it follows that the results are somewhat optimistic, i.e. the removal constants are too large, since agglomeration undoubtedly occurs to some extent.

3. Depletion of Cloud

The removal of the particles or vapors from the cloud is given by the following differential equation:

$$\frac{dC}{dt} = -C\Lambda \quad (6)$$

where:

C = the concentration of the particles or vapors

$\frac{dC}{dt}$ = the rate of removal of particles or vapors

Λ = the removal constant as obtained above, sec^{-1}

t = the time elapse, sec

Thus the fraction of the particles or vapors remaining in the cloud

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is given by:

$$C/C_0 = e^{-\Delta t} \quad (7)$$

where C_0 and C are the original and final concentrations in the cloud assuming no dispersion of the cloud.

It is evident upon examination of Equations (3), (5), and (7) that the proportion of the particles or vapors remaining in the cloud is independent of the rain rate - assuming that the droplet size remains constant with rain rate - and is solely dependent on the total water throughout per unit area. Thus one may quickly deduce that the optimum washout with the minimum water expenditure will occur before the cloud has had a chance to disperse. From a practical standpoint, this condition is met by having the washout occur inside a containment shell or confining building.

B. Investigation of Washout by a Sprinkler System

1. Particle Size Distribution

Typical particle size distribution for fumes resulting from combustion and dusts caused by an accident of an undescribed nature were found in Wash-740,⁽³⁾ and are given below.

<u>Particle Size</u>	Diameter (μ)	<u>Distribution</u>	
		% by number	% by weight
Group having 1.0 μ mass median diameter	0.5	95	40
	1.5	5	60
Group having 7.0 μ mass median diameter	1.5	15	1
	3.5	60	16
	7.0	23	45
	15.0	2	38

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It was stated in Reference 3 that the most likely release would be in combination with combustion thus resulting in a small particle size distribution characterized by a fume. The type of accident which would release products having a particle size typical of dusts was not given, but it was merely postulated that an accident which would result in such a distribution could not be ruled out.

A series of meltdowns of irradiated fuel elements revealed that 50-90% of the activity was associated with particles having a size less than 1 micron mass median diameter.⁽⁷⁾ Thus one might conclude that meltdown or combustion of fuel elements or other radioactive species will lead to a fume with a distribution similar to that given in the above table for a mass median diameter of 1 micron. The typical dust as given in the above table will not generally be associated with an accident involving meltdown or combustion, but might be a consideration in an accident involving an explosion.

2. Meteorological and Geometrical Considerations

It was shown in section A-3 that the optimum washout with a minimum expenditure of water is obtained for a confined cloud. This condition can be obtained inside a building or outside with weather conditions such that: there is no wind, the rate of evaporation of the water droplet is small compared to the rate of diffusion of the iodine to the droplet, the rate of expansion of the cloud by diffusion is insignificant in comparison to the area covered by the sprinkling system, and the time required to remove the desired portion of the cloud.

For the purposes of this evaluation study it is also postulated that

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the radioactive cloud is being released as a point source within the sprinkling system.

A discussion on the effects of non-ideal conditions on a sprinkling system located on the outside of the building will be found in section C-2 below.

3. Washout of a Typical Fume

It was previously shown on Figure 1 that particles with diameters less than 2 microns will not be removed by water droplets. Thus the particulates in a typical fume cannot be removed by a sprinkling system. However, during a meltdown or combustion of a fuel element a significant portion of the total fission product release will be radioactive iodine. The proportion of iodine released in relationship to the other radioactive products will depend on the history of the element. Experience with fission product releases has proven that iodine is in many cases the major biological hazard (e.g. the Windscale incident). With this in mind, it was decided to investigate the removal rate for the iodine in a fume despite the fact that the particulate matter will not be removed. The conditions for the release are the ideal conditions as outlined in section B-2 above. The proportion of iodine remaining in a cloud as a function of total water throughput is presented in Figure 6 with water droplet size as a parameter. It must be remembered that the proportions of iodine removed is independent of rain rate under stagnant cloud conditions. It can be seen from the curves of Figure 6 that theoretically 99.9% of the iodine can be removed with a throughput of only 0.2 of a mm

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of water with a water droplet size of 50 microns. In general, up to water droplet size of 150 to 200 microns the efficiency is very good and the system would be practical provided the theoretically determined removal constants are obtainable and the stipulated conditions are met. With this potential performance it is possible that such a removal system would be warranted within a building where the washout of iodine is of major importance. The compatibility problem between water and the reactor components could be relieved by the use of other purging agents. One need not use water since any particle or droplet that will settle in a fashion similar to water (see Figure 7) will yield the same theoretical removal constant for a given particle or droplet size.

4. Washout of a Typical Dust

The washout of the typical dust is of less practical interest than the washout of the iodine and the fume for two reasons: (1) It is not formed to any extent in combustion or meltdown of a fuel element which are the more frequently postulated accidents. (2) The particle size distribution is such that it will probably settle sufficiently rapidly without a washout mechanism being employed. (See Figure 8) The proportion of radioactive cloud of a typical dust remaining as a function of total water throughput is presented in Figure 9 based on a maximum removal efficiency for the 3.5 micron diameter particle ($s = 1600$ microns - see Figure 5). Figure 10 is the same as Figure 9 except the removal rate is optimized for the 7 micron diameter particle ($s = 200$ microns - see Figure 5). The proportion of the original

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iodine remaining in the cloud is included in the curves.

It will be seen upon examination of Figures 6, 9, and 10 that the overall removal efficiency for the dust is much less than that obtainable for iodine vapor. Examination of Figure 4 and Table 2 reveals that a 50 micron water droplet will not remove particles with radii below 4 microns and that the efficiency for particles with radii less than 6 microns is very low. The settling velocity of a 5 micron particle is approximately 1.5 ft/min. (See Figure 8). Thus one might readily conclude that the water droplet size (50 microns) required for maximum removal efficiency for the iodine will essentially be ineffective for the dust particles of interest (i.e. those with radii greater than 2 micron and less than 5 micron). It is also evident that the droplet size necessary for efficient removal of the dust is inefficient for removal of the iodine. Thus one can conclude that the rainout system will not efficiently remove both the iodine and the typical dust.

C. Discussion

1. Sprinkling System Located Inside of a Containment Structure

The geometrical and meteorological conditions as postulated in section B-2 above are applicable to a sprinkling system located within a confining building. Thus, it is theoretically possible to remove 99.9% of the iodine vapor from a cloud with a total water expenditure of approximately 0.2 mm.

The sprinkling system is not effective for the removal of particulates with diameters less than 2 microns such as might be found in a typical fume formed from combustion or meltdown of a fuel element.

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The sprinkling system is a wasteful expenditure for the removal of particulates with diameters more than ~ 12 microns. Particles of this or greater size have terminal velocities such that they will probably settle out within the building without the additional impetus of a rainout system.

It seems feasible, therefore, to use a sprinkling system within a building to remove the iodine vapor provided one can find a suitable rainout vehicle such that is compatible with components and materials within the building and is not too expensive. It is possible that one might be able to use some sort of dust or powder as a vehicle for the rainout of the iodine vapor in conjunction with a filtration system which would simultaneously remove the dust or powder with the adsorbed iodine and also the radioactive particulates.

2. Sprinkling System Located Outside of the Containment Structure

The idealized geometrical and meteorological condition as postulated in section B-2 are not in general available with an outdoor sprinkling system. The overall efficiency of the outside sprinkling system is much less than the inside system for the following reasons:

1. The cloud must leak from the building before it is contacted by the sprinkling system. For a postulated building leakage rate of 100% per day, it will require 2.3 days to leak 90% of the radioactive cloud from the building. Thus, the duration of sprinkling is controlled by the building leakage rates.

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2. The total water throughput per unit area of the cloud for a given decontamination factor will be the same as that needed for a confined cloud. To obtain a given throughput, one must establish a rain rate such that the desired water throughput will be obtained during the residence time of the cloud under the sprinkling system. Thus, the rain rate required is established by the area covered by the sprinkling system and the wind velocity. For a wind velocity of 3 mph (4.4 ft./sec) and a sprinkling system that extends 440 feet beyond the building, the desired water throughput must be obtained in 100 seconds and must be maintained until the cloud has leaked from the building.
3. In general the air will not be saturated with water vapor, thus the removal efficiency for iodine vapor may be drastically reduced due to evaporation of the water droplets. In fact, a situation could occur in which the water is evaporating with such rapidity that no iodine vapor would be removed.

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A P P E N D I C E S

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TABLE I

The collection efficiency E for drops of radius S falling through a cloud of smaller drops of radius r.

S (microns)	r(microns)							
	2	3	4	6	8	10	15	20
15	-	-	-	-	0.092	0.269	0.500	0.643
25	-	-	-	0.050	0.277	0.411	0.613	0.724
40	-	-	-	0.205	0.394	0.510	0.690	0.782
70	-	-	0.035	0.340	0.500	0.608	0.750	0.834
100	-	-	0.133	0.418	0.564	0.660	0.793	0.862
150	-	0.010	0.245	0.498	0.631	0.713	0.829	0.887
200	-	0.085	0.326	0.564	0.684	0.756	0.859	0.908
300	-	0.213	0.425	0.643	0.749	0.810	0.892	0.929
400	0.040	0.303	0.500	0.698	0.793	0.849	0.919	0.950
600	0.121	0.355	0.530	0.731	0.827	0.876	0.939	0.963
1000	0.140	0.358	0.535	0.738	0.834	0.886	0.944	0.966
1400	0.168	0.360	0.534	0.735	0.840	0.890	0.950	0.970
1800	0.117	0.288	0.456	0.680	0.800	0.865	0.935	0.965
2400	0.075	0.220	0.372	0.606	0.743	0.823	0.920	0.950
3000	0.050	0.170	0.306	0.546	0.690	0.785	0.900	0.940

TABLE II

Critical radii of falling drops below which no accretion occurs, for various cloud droplet radii r (radii in microns).

r	S _{crit}	r	S _{crit}
1.5	600	5	31
2	350	6	20
3	140	7	14
4	58

FIGURE 2

Δ as a Function of Droplet Radius with Particle
 Radius as a Parameter for a Rain Rate of 1 mm/hr.

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FIGURE 3
 Δ (max) and the Corresponding Water Droplet
Radius as a Function of Particle Radius
(Rain Rate = 1 mm/hr.)

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Δ max in Sec^{-1} (Rain Rate = 1 mm/hr.)

Radius of Water Droplets for Δ Max (microns)

Radius of Particle (microns)

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FIGURE 4
 Δ for Iodine Vapor as a Function
of Water Droplet Radius
(Rain Rate = 1 mm/hr)

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Δ in Sec^{-1} (Rain Rate = 1 mm/hr)

Radius of Droplets (microns)

FIGURE 5

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The Removal Constant Λ for Iodine Vapor and
Particulates of Radius r as a Function of Water Droplet Radius
(Rain Rate = 1 mm/hr.)

K&E SEMI-LOGARITHMIC 359-73L
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5 CYCLES X 300 DIVISIONS

Proportion of Iodine Remaining in Cloud (%)

S = radius of water droplet in microns

FIGURE 6
The Proportion of Iodine Remaining in a Cloud as a Function of Total Water Throughput with Water Droplet Radius as a Parameter

FIGURE 7

Terminal Velocity of Water Droplet
as a Function of Droplet Radius

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Terminal Velocity in Cm/sec

Radius of Droplets in microns

FIGURE 8

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Terminal Velocity of a Fission Particle
as a Function of Particle Radius ($\rho = 2.5$)

Terminal Velocity in cm/sec

Radius of Particle in Microns

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Proportion Remaining in the cloud (%)

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Proportion Remaining in the Cloud (%)