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# RADIOCHEMICAL FACILITY HAZARD EVALUATION

E. D. ARNOLD
A. T. GRESKY
J. P. NICHOLS

## ABSTRACT

The methods, results, and conclusions of a quantitative evaluation of the hazards associated with maximum credible accidents in large ORNL radiochemical facilities are presented. Building containment criteria and types and effects of credible accidents that may occur in the facilities are summarized. Personnel dose and fallout equations based on building containment restrictions, behavior of gases and aerosols, and atmospheric dispersion are derived. The personnel dose and downwind contamination levels resulting from the maximum credible accidents in the facilities are reported.

**NOTICE** This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

## 1.0 INTRODUCTION

The 3019 evaporator explosion and other accidental releases of activity in the fall of 1959 precipitated a review of ORNL radiochemical facilities, the aim of which was to outline building changes that were required to confine the effects of the maximum credible accident to the involved facility. Such building changes were considered advisable to prevent jeopardizing laboratory personnel and other laboratory facilities in the event of such an accident. This review led to the establishment of building and ventilation design criteria, one requirement of which was that secondary building containment would be placed around all process cells which could otherwise leak significant activity directly to the environment in the event of an accident.

It has been the purpose of the study which I will describe to attempt to evaluate the hazards that are involved in radiochemical facilities which are being revised to meet the design criteria, in particular the effectiveness of secondary containment to prevent the impairment of other laboratory facilities in the event of an accident. Maximum radiation doses and fallout patterns have been evaluated for the maximum credible hazard in each of the facilities.

I plan to discuss some of the design criteria, types of credible accidents, methods of hazard evaluation, and some of the general results and conclusions. I also plan to stress the evaluation of large, predominantly wet chemistry facilities such as 3019, 3517, and 2527. I will also indicate how the methods of evaluation may be extended to dry operations in facilities such as the segmenting facility or glove box laboratories.

## 2.0 CONTAINMENT CRITERIA FOR A PROJECTED RADIOCHEMICAL FACILITY

A schematic diagram of a radiochemical facility which meets the minimum recommended design criteria is shown in Fig. 1. The diagram depicts a typical vessel in a process cell which is completely surrounded by a building. The cell, which constitutes primary containment, is capable of withstanding the blast effects of the maximum credible explosion without rupture and permits only a minimum leakage of radioactive material to the secondary containment shell, the building structure. Other criteria for the process vessels, cells, and buildings are as follows:

Process vessels are maintained at a vacuum of at least 2 in. w.g. during normal operation by a VOG system which passes through a local scrubber and filter system as well as plant treatment system before being exhausted at a stack.

A cell is maintained at a vacuum of at least 1 in. w.g. during normal operation. The cell ventilation exhaust capacity is at least equivalent to 1/10 of a cell volume per minute. The air intake to the cell is through a roughing filter and check valve. The cell exhaust passes to a cell ventilation manifold, roughing and absolute filters and from thence to the

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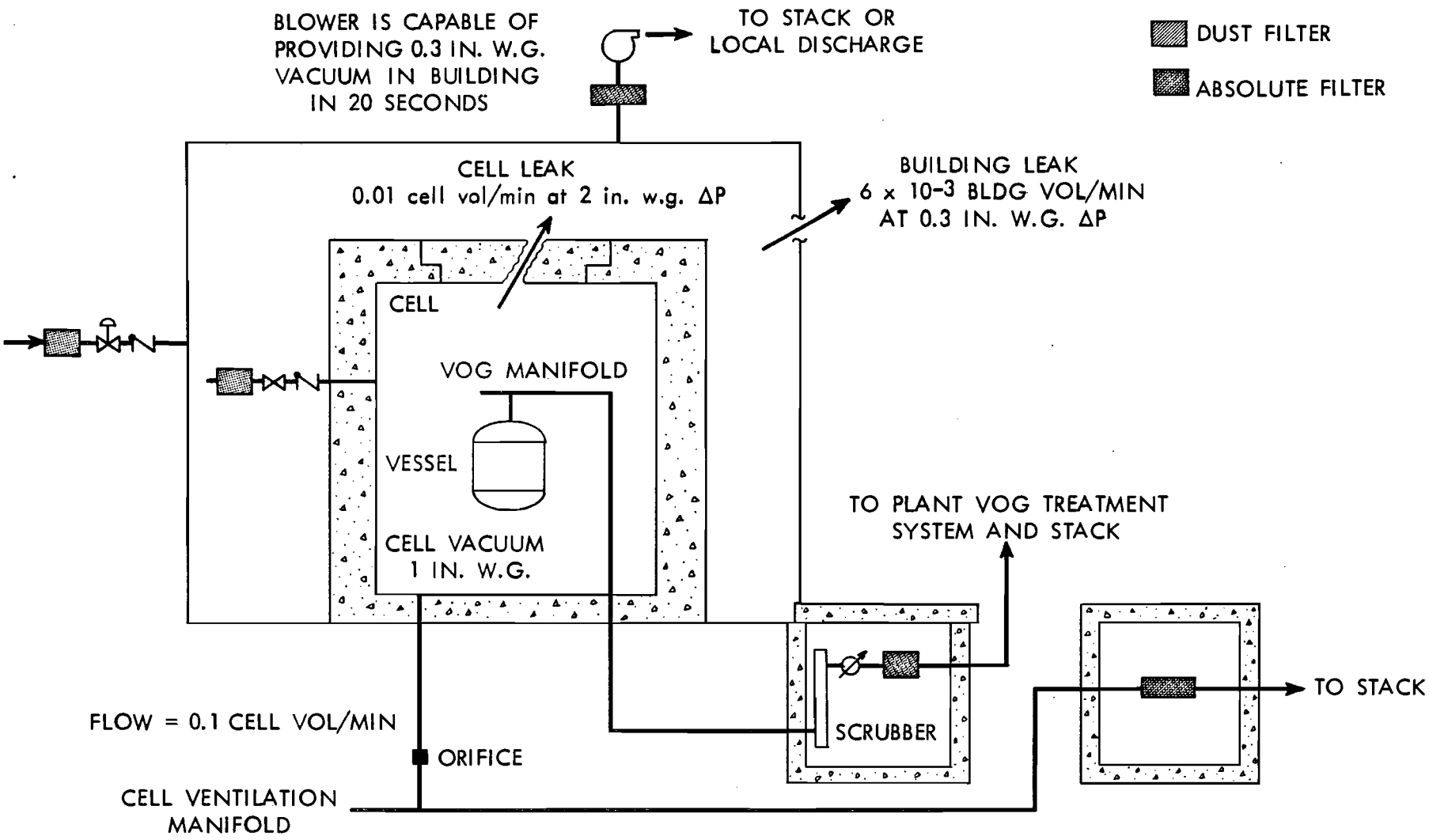


Fig. 1. Schematic diagram of minimum containment provisions for radiochemical facilities.

stack. The cell is sealed such that the leak rate is less than or equal to 1/100 of a cell volume per minute at 2 in. w.g. differential pressure.

The building is maintained at a few hundredths of an inch w.g. vacuum during normal operation. The intake is through duct filters and check valves. The exhaust is through roughing and absolute filters located at the roof of the building or at the stack. The cell ventilation blower must have sufficient capacity to evacuate the building to 0.3 in. w.g. vacuum in 20 seconds by closing the intake. The building is sealed such that a leak rate of no more than $6 \times 10^{-3}$ building volumes per minute will occur at a differential pressure of 0.3 in. w.g. This criterion is included to assure that the building vacuum will be capable of balancing a vacuum of 0.3 in. w.g. that could be created on the lee side of a building by a 30-mile-per-hour wind. It was assumed that winds of speeds greater than 30 miles per hour are sufficiently rare as to be incredible.

## 3.0 TYPES AND EFFECTS OF INVERSIVE ACCIDENTS

The most serious accidents that may credibly occur in large radiochemical facilities are chemical and nuclear explosions which rupture vessels that are filled with radioactive process solutions. Instrumentative and procedural safeguards greatly minimize the possibility of such an accident but there remains a finite probability of occurrence. It is our current belief that a radiochemical facility can be designed in such a manner that the maximum credible explosion would generate not more than 100 cu ft of gas and would have blast effects less than that of 3 lbs of TNT. Three pounds of TNT liberates approximately 5700 Btu of energy, generates approximately 100 cu ft of hot gases, and creates a shock wave which has a pressure of approximately 800 lbs per sq ft and an energy of approximately 230 ft lbs per sq ft at a distance of 15 ft. Thick concrete cells of the type used in ORNL radiochemical facilities can withstand such explosive effects without rupture.

To control the magnitude of credible chemical explosions within the reference TNT detonation, we have found it reasonable to limit the maximum quantity of reactants. A typical restriction was to limit the free volume of conceptual dissolvers in which hydrogen is formed such that no more than approximately 10 cu ft of hydrogen-air mixture could be formed. Such a mixture if it were to detonate would produce approximately 100 cu ft of hot gas and slightly less energetic shock waves than the referenced TNT detonation. In another restriction separation equipment was designed to prevent the accidental release of significant quantities of organic materials into vessels where they could conceivably be boiled with nitric acid to form greater than a few pounds of an explosive compound.

Experience and calculations indicate three factors which are pertinent to the maximum nuclear explosion: (1) The most powerful burst will probably be the initial burst. (2) The maximum initial burst will probably be limited by gas generation and thermal expansion to the order of $10^{12}$ fissions per cc (approximately $10^{18}$ fissions for vessels of approximately 1000-liter capacity such as are considered in the evaluation). (3) It is not incredible that such a burst could rupture a vessel. If the nuclear reaction is not shut down in the initial

burst by rupture of the vessel, it is probable that the vessel would not be ruptured at all and the reaction would recur with $10^{19}$-$10^{20}$ or more fissions until the solution was boiled down or the fissile material forcibly ejected. This type of nuclear accident would have less serious consequences than a burst that ruptured a vessel and scatters a highly radioactive process solution. A nuclear burst of $10^{18}$ fissions releases approximately 30,000 Btu of energy, 4 cu ft of radiolytic gas, and not more than 100 cu ft of steam. You may realize that only approximately 3,000 Btu's are required to form 100 cu ft of steam, but if this much steam were formed it would constitute an extremely efficient shutdown mechanism and limit the reaction to less than $10^{18}$ fissions. Also, since a nuclear burst in solution occurs in millisecond time rather than microsecond time as in TNT detonations, the shock waves will be less energetic than from the referenced TNT detonation.

The effects of the maximum chemical explosion would be that an aerosol of the radioactive material would be formed in the cell air and a small fraction would reach the environment through the vessel off-gas system, cell off-gas system, and through successive leaks from the cell and from the building. The maximum nuclear burst would disperse new gaseous fission products in addition to the aerosol, and operating personnel would receive direct prompt gamma and neutron radiation through the shield. I will describe these effects in reverse order.

The prompt gamma and neutron dose that would be received through a cell wall from a nuclear reaction of $10^{18}$ fissions is seen in Fig. 2. From these data one may conclude that in a typical radiochemical facility in which the concrete walls are 5 to 6 ft thick the direct radiation constitutes only a few mr and is not a significant hazard. It would not even be significant in a recurring type nuclear reaction, since personnel could be expected to evacuate the area of the shield before more than the order of $10^{18}$ fissions occur. The data also indicate that lethal doses of gamma and neutron radiation could be received when there is little or no concrete shielding; this suggests that the use of thick concrete cells should be considered even for those operations with fissile materials that are not inherently gamma radioactive.

Now I would like to describe some of the properties of gaseous fission products which are formed in a nuclear accident. We assume that all the known isotopes of bromine, iodine, xenon, and krypton would be released as they are formed in a nuclear accident. It was assumed that 99.9% of the bromine and iodine could be removed from the ventilation streams in a caustic scrubber. It was found that the isotopes with half lives in the order of 1 minute and the fission yields of a few per cent were controlling in the dose calculations. The maximum permissible concentrations of these isotopes are rather large, since by reason of their short life they constitute only external radiation hazards. They make up for their higher maximum permissible concentration, however, because of their much greater activity. It was of interest to know that if one assumes that iodine and bromine are not scrubbed out the resulting radiation hazard is just about equally divided among the four gaseous elements. Thus, even if the iodine and bromine are quantitatively removed by scrubbing the hazard is only reduced by about a factor of 2.

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FIG. 2.
THE PROMPT NEUTRON AND GAMMA DOSE AT THE OUTSIDE OF A NORMAL CONCRETE SHIELD FROM A NUCLEAR REACTION OF $10^{18}$ FISSIONS*

| CONCRETE SHIELD THICKNESS, FT | DOSE AT OUTSIDE OF SHIELD, rem | |
|---|---|---|
| | METAL NUCLEAR REACTION | NUCLEAR REACTION IN AQUEOUS SOLUTION |
| 1 | 88,000 | 5,200 |
| 3 | 317 | 23 |
| 4 | 17.0 | 1.9 |
| 5 | 0.960 | 0.14 |
| 6 | 0.059 | 0.012 |

*THE DOSE RATE MAY BE CALCULATED FOR ANY OTHER NUMBER OF FISSIONS THROUGH THE USE OF A DIRECT PROPORTION.

Now I will describe the effects of a dispersive accident that creates an aerosol. In addition to the dispersion of solution that could occur in a wet chemical facility, aerosols would also be generated in the maximum credible accident in the segmenting facility or glove box facility. Uranium and plutonium smoke from a fuel element fire would be the aerosol from a segmenting facility accident, and heavy element dust would be the aerosol from the maximum glove box accident. The physical properties of aerosols are such as to very effectively restrict the escape of radioactive particles through ventilation streams to the environment. This is seen commonly in practice, since through the use of appropriate de-entrainment mechanisms the condensate from the evaporation of the radioactive solution may be made to contain only $10^{-4}$ to $10^{-6}$ of the activity of the solution.

In order to evaluate the release of aerosols from a cell we must be able to ascribe removal efficiencies to filters and to cracks in cell walls. For superficial velocities less than approximately 0.15 ft per second it has been found that an aerosol formed by vigorous mixing of a solution with air is metastable and has a concentration in the order of 10 milligrams per cubic meter. This metastable concentration is approximately equivalent to fog, which has a concentration of approximately 10 mg/$M^3$ and a particle size of approximately 10 microns. For orientational purposes a 1-in.-per-hr rain with mass mean particle size of 3000 microns has a concentration of 1000 mg/$M^3$. We have consistently found the particle size distribution of the metastable aerosol to be approximately that shown in Fig. 3. Another piece of relevant information reported by Garner in Transactions of the Institution of Chemical Engineers is that the weight distribution of particles smaller than 10 to 20 microns will be fairly constant, even if there is gross entrainment of larger droplets. The knowledge that this distribution is fairly constant and constitutes approximately 10 mg/$M^3$ may be used to estimate the approximate concentration of particles smaller than a given size, even in an air stream which is very concentrated with liquid droplets. Practically, it is possible to assign efficiencies to an absolute filter and calculate the effluent concentration.

Using as much data as we could find, we conservatively assigned the following efficiencies to an absolute filter: 100% for particles greater than 5 microns, 99.95% for particles between 5 and 0.3 microns, 95% for particles between 0.3 and 0.1 microns, and 87% for particles less than 0.1 micron. The filter efficiency for particles smaller than 0.1 micron is based on data obtained by Leslie Silverman at the Harvard Air Cleaning Laboratory. Applying these efficiencies to the particle size distribution in Fig. 3, we obtained 0.14 mg/$M^3$ as the effluent concentration of liquid aerosol from absolute filters. We think that it is also appropriate to assume that the liquid particles in the aerosol have essentially the original solution composition. We also use the concentration of 0.14 milligrams per cubic meter as the filter effluent concentration of heavy element dust. This would indicate a conservatively high penetration of dust even if a large fraction is smaller than 0.1 micron, since it has been observed that heavy element dust exists in relatively stable air at concentrations only in the order of 0.1 to 1 milligrams per cubic meter. It must be assumed that filters are only 87% efficient in removing smoke, since smoke particles are predominantly in the range 0.05-0.1 microns.

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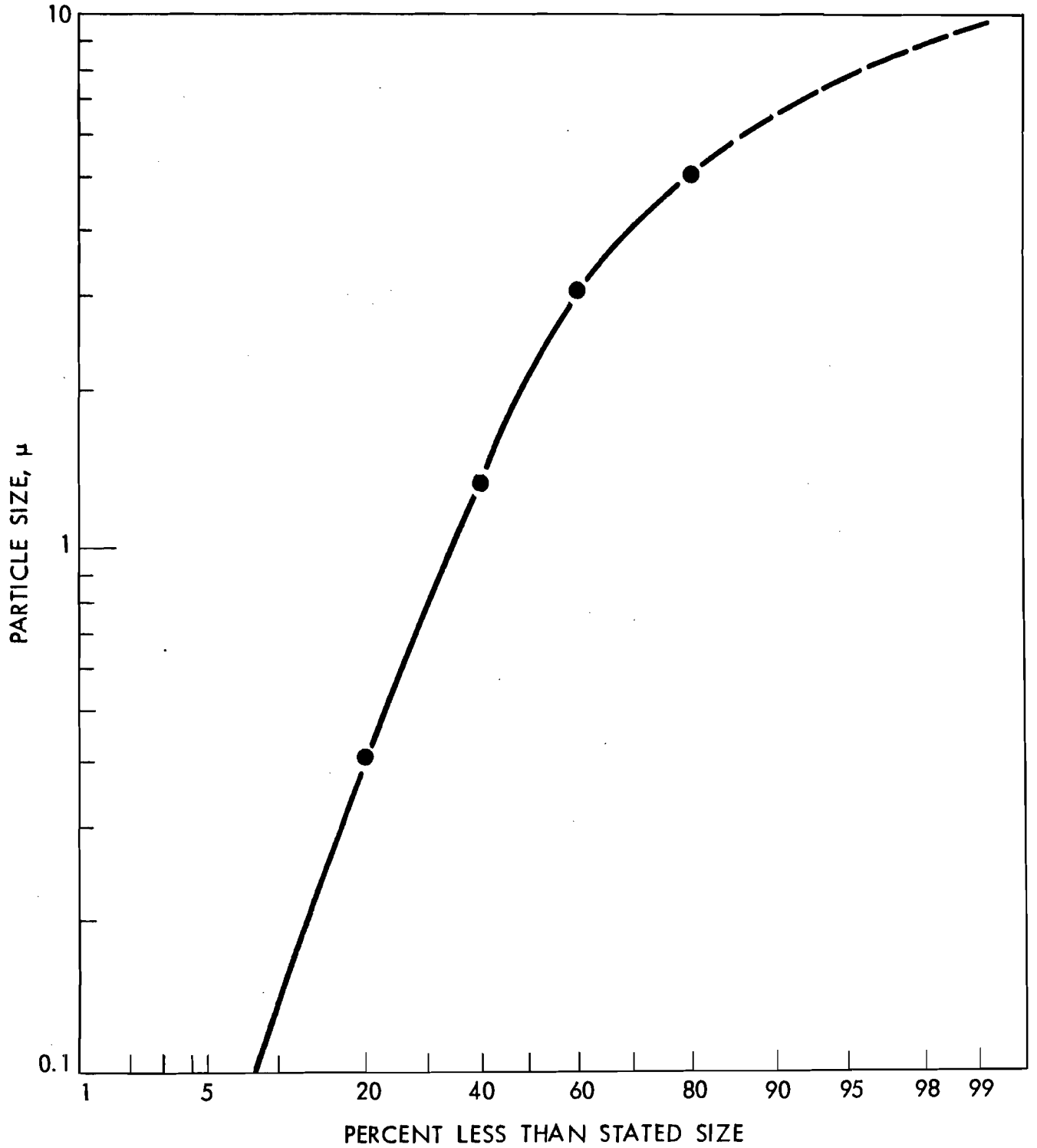


Fig. 3. The particle size distribution of a stable aerosol which has encountered several changes of direction in a pipeline.

Now I will describe methods of evaluation of the concentration of aerosols in air which leaks from a cell. In a typical cell the design leak rate is equivalent to a flow of 100 cfm through a 5-in. orifice. Cell cracks will not simulate a single orifice but will consist of many small tortuous paths through 5 ft of concrete. The evaporator de-entrainment studies by Walsh and Schlea at SRP indicate that a single right angle impingement of characteristics that we think are indicative of cell cracks will conservatively reduce any liquid aerosol concentration to 10 mg/$M^3$. Fine heavy element dust would be reduced to the order of 1 milligram per cubic meter and the concentration of smoke and leaked air would probably be no more than approximately 100 milligrams per cubic meter.

Now that I have described some of the effects of credible accidents I would like to briefly summarize the methods of evaluation of personnel dose and fallout.

## 4.0 METHODS OF EVALUATION

The downwind radiation dose that would be received from the release of radioactive material from a stack or elevated source during unchanging weather conditions may be expressed as the product of the curies released, atmospheric dilution factor, and appropriate conversion factors divided by the $MPC_a$. This relation is shown in Fig. 4. The $MPC_a$ of a radionuclide may be considered as that concentration of the radionuclide in air which will cause 100 mr of radiation dose in 40 hours of exposure. In the case of radionuclides which are predominantly internal radiation hazards, the bulk of the dose does not occur during the exposure period but is accumulated over a lifetime due to the presence of the radionuclude in the body. In the downwind exposure calculation we chose to use the so-called maximum average atmospheric dilution factor which is a measure of the maximum downwind ground concentration averaged over a period of the order of 1/2 hour and is an approximate measure of the maximum downwind ground concentration averaged over a several-minute period. We chose to evaluate the constant at a conservatively low wind speed of approximately 3 miles per hour, since this is the average ORNL wind speed and since it constitutes approximately the worst case. The plume rise of a stack causes the effective atmospheric dilution to be greater at significantly lower wind speeds and of course at very high wind speeds the dilution is significantly greater because of the extreme turbulence. We applied this concept to the calculation of the downwind internal and external dose arising from the gaseous fission products and from the aerosol; it implicitly assumes that the aerosol which escapes through an absolute filter is of such a small size that it behaves as a gas and is inhaled and exhaled as a gas. We think it is a fairly good approximation, since the aerosol particles which escape through an absolute filter are generally less than 0.1 micron in size and have negligible settling velocity.

The downwind dose resulting from the release of gaseous fission products or aerosol through the vessel off-gas system is calculated using the relations given in Fig. 5. In calculating the effects of the gaseous fission products it is assumed that a sustained or single burst of $10^{18}$ fissions occurs in the vessel and that the gaseous fission products continuously leave the vessel and are entrained as they are formed. For each gaseous radionuclide the maximum

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FIG. 4.
GROUND DOSE FROM RELEASE OF RADIOACTIVE MATERIAL FROM A STACK

$$\text{DOSE, rem} = \frac{(c)\ (k)\ (0.1)\ (1.44)}{(MPC)\ (1.44 \times 10^5)} = \frac{c\ 10^{-6}\ k}{MPC}$$

WHERE:

c = QUANTITY OF MATERIAL RELEASED, CURIES

$MPC_a$ = CONCENTRATION OF RADIONUCLIDE IN AIR WHICH GIVES 0.1 rem OF RADIATION DOSE FOR 40 HOURS OF EXPOSURE

k = MAXIMUM AVERAGE ATMOSPHERIC DILUTION FACTOR, $\frac{sec}{M^3}$

$$= \frac{2}{(\pi)(e)(\text{WIND SPEED, M/sec})(\text{HEIGHT OF RELEASE, M})^2}$$

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FIG. 5.
RELEASE FROM VESSEL OFF-GAS SYSTEM

A GASEOUS FISSION PRODUCTS (FROM $10^{18}$ FISSIONS)

$$d_{iv} = \left[ \frac{Q_i^o \; e^{-\lambda_i t_D}}{X_i} \right] \frac{10^{-6} k}{MPC_i}$$

WHERE: $X_i$ = DECONTAMINATION FACTOR FOR i

$t_D$ = DECAY TIME ENROUTE TO STACK, SEC

$Q_i^o$ = CURIES FORMED IN $10^{18}$ FISSIONS

$$= \frac{(10^{18})(\text{FISSION YIELD})(\text{DECAY CONSTANT})}{3.7 \times 10^{10}}$$

B AEROSOL

$$D_v = \left[ (A_v)(m)(0.14 \text{ mg/M}^3)(4.77 \times 10^{-4})(3.6 \times 10^3) \right] \frac{10^{-6} k}{MPC}$$

WHERE: $A_v$ = VOG FLOW RATE, cfm

m = CONCENTRATION OF ACTIVITY IN SOLUTION, CURIES/mg

downwind dose is calculated using the equation at the top of Fig. 5, which takes into consideration decay of the radionuclude in transit to the stack and the decontamination factor for the radionuclide in the vessel off-gas treatment system. In general, it was assumed that the decontamination factor for xenon and krypton gases is 1 and that the iodine and bromine isotopes are decontaminated by a factor of 1000 in the caustic scrubber. The aerosol release is calculated assuming that aerosol is continuously generated in the vessel for a 1-hr period following the accident and is continuously entrained in the air which is normally flowing through the vessel off-gas manifold. It is assumed that the filter effluent contains a concentration of 0.14 milligrams per cubic meter of air which has the original solution composition of radioactive material.

The equations for evaluation of the cell ventilation system release are given in Fig. 6. It is assumed that a burst of $10^{18}$ fission occurs which ruptures the process vessel and scatters its contents throughout the cell, terminating the reaction. It also assumes that the gaseous fission products are evenly distributed in the cell and remain mixed. The downwind dose from individual gaseous fission products is calculated taking into consideration decay in the cell and in transit to the stack and decontamination of individual gaseous radionuclides in the treatment system. The downwind aerosol dose is calculated assuming that aerosol is entrained in a volume of air equivalent to one cell volume which passes through the exhaust at the bottom of the cell to the cell ventilation manifold. If one wished to take into account additional generation of aerosol which might occur in the cell ventilation manifold, one would multiply the aerosol downwind dose by the ratio of the air flow rate at the filter to the cell purge rate.

The effect of a release to the secondary containment shell may be calculated using the equations in Fig. 7. The volume of cell air which leaks to the secondary containment cell is calculated knowing the cell leak rate at 2 in. of water differential pressure and assuming turbulent flow during the 1-second period in which the cell is pressurized. A pseudo dose to personnel in the secondary containment shell may be calculated by assuming that the leaked cell air is uniformly distributed in the volume of the secondary cell and personnel are exposed to this air for 2 minutes before evacuation. The concentration of aerosol in the leaked air is calculated considering impingement which occurs in the tortuous path through the cell wall and the gaseous fission product concentration is that concentration obtained by dispersing all of the gaseous fission products in the volume of the cell.

The release of activity from the secondary containment shell is by two mechanisms; the normal ventilation flow through the absolute filter and the building leakage which occurs if there is a significant wind to create a lee vacuum on the building. The downwind ground concentration for individual gaseous fission products and the aerosol is calculated using the equations in Fig. 8. The downwind dose is the sum of the dose which occurs from the leak from the building during the 20-second period which is required to evacuate the building to 0.3 in. w.g. vacuum and the release through the building ventilation system. For the gaseous fission products appropriate corrections are made for decay inside the building and in transit through the building ventilation system.

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FIG. 6.
RELEASE FROM CELL VENTILATION SYSTEM

A GASEOUS FISSION PRODUCTS

$$d_{ic} = \left[ \frac{R\ Q_i^o\ e^{-\lambda_i t_D}}{(R + \lambda_i)\ X_i} \right] \frac{10^{-6}\ k}{mpc}$$

WHERE: R = CELL REMOVAL CONSTANT, CELL VOLUMES/SEC

B AEROSOL

$$D_c = \left[ \frac{V_c\ 0.14\ m}{35.3} \right] \frac{10^{-6}\ k}{mpc}$$

WHERE: $V_c$ = CELL VOLUME, CU. FT.

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FIG. 7.
RELEASE TO SECONDARY CONTAINMENT SHELL

$$\text{LEAK VOLUME} = \frac{\left(10^{-2}\ \frac{\text{CELL VOLUME}}{\text{MIN}}\right)}{60} \left[\frac{\frac{1}{2}\left(407\ \frac{V_{EX}}{V_c} - 1\right)}{2}\right]^{1/2}$$

WHERE $V_{EX}$ = EXPLOSION VOLUME = 100 CU. FT.

THE PSEUDO DOSE BEFORE EVACUATION OF THE SECONDARY CONTAINMENT SHELL IS:

A GASEOUS FISSION PRODUCTS

$$d_{i(2\ \text{MIN})} = Q_i^{o}\left[\left(\frac{10^{-2}}{60}\right)\left(\frac{10150}{V_c} - 0.25\right)^{1/2}\left(\frac{1 - e^{-120\,\lambda_i}}{\lambda_i}\right)\right]\frac{(35.3)(10^{-6})}{V_B(MPC_i)}$$

WHERE: $V_B$ = SECONDARY CONTAINMENT SHELL VOLUME

B AEROSOL

$$D_{(2\ \text{MIN})} = \left[(10^{mg}/M^3)(m)\left(\frac{10^{-2}\ V_c}{60}\right)\left(\frac{10150}{V_c} - 0.25\right)\right]^{1/2}\frac{120\ (10^{-6})}{V_B(MPC)}$$

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Fig. 8.
RELEASE FROM SECONDARY CONTAINMENT SHELL

A GASEOUS FISSION PRODUCTS

$$d_{id} = Q_i^{o}\left[\left(\frac{10^{-2}}{60}\right)\left(\frac{10150}{V_c} - 0.25\right)^{1/2}\frac{(10^{-6})}{(MPC)_i}\right]\left[\frac{R_L k_L\left(1-e^{-(R_L+\lambda_i)20}\right)}{(R_L+\lambda_i)} + \frac{R_B k_B e^{-\lambda_i t_D}}{(R_B+\lambda_i)}\right]$$

WHERE: $R_L$ = LEAK RATE CONSTANT, SEC. CONT. VOLS/SEC
$R_B$ = VENTILATION RATE CONSTANT, SEC. CONT. VOLS/SEC
$k_L$ = ATMOSPHERIC DILUTION FACTOR FOR LEAK, SEC/$M^3$
$k_B$ = ATMOSPHERIC DILUTION FACTOR FOR BUILDING VENTILATION, SEC/$M^3$

B AEROSOL

$$D_d = \left[(10)(m)\left(\frac{10^{-2}}{60}\right)\left(\frac{10150}{V_c} - 0.25\right)^{1/2}\frac{(V_c)(10^{-6})}{(35.3)(MPC)}\right]\left[k_L\frac{(6\times 10^{-3})(20)}{60} + k_B\left(\frac{0.14}{10}\right)\right]$$

In addition to the dose calculations, we calculated the downwind ground contamination that will occur from fallout of the radioactive particulate matter using equations given in AECU-3066 and the nomograms in ORO-176. The particle sizes of the particulate materials released from the secondary containment shell leak was assumed to be approximately 10 microns and the particle size released through the filter ventilation system was assumed commensurate with the filter efficiencies. The results were expressed as the distance downwind from the source to which the ground is contaminated to the hazard and required decontamination level. The hazardous level for beta-gamma contamination was considered to be that concentration in curies per square meter which would give a reading of 2-1/2 mr per hr above ground as determined by a GM survey meter with an open window. For alpha materials the hazardous ground concentration in curies per square meter was considered to be the arithmetic product of 250,000 times the MPC air for 40 hr of exposure.

## 5.0 RESULTS AND CONCLUSIONS

The results of the evaluation may best be illustrated with the aid of an example. In Fig. 9 are shown the effects of the maximum credible accidents in Bldg. 3019. The two maximum credible accidents in this facility were considered to be a chemical explosion that shattered a waste evaporator containing 6,000,000 curies of mixed long-cooled fission products and a nuclear explosion in the plutonium storage tank that contains 60 kg of plutonium solution at 100 g/liter. It is seen that the maximum downwind dose from the aerosol release from either accident is just a few mrem. The aerosol personnel dose before evacuation of the secondary containment shell for the two accidents is 14 and 31 mrem, respectively. In the nuclear explosion the gaseous fission product dose is 220 mrem from the vessel off-gas release and 150 mrem from the cell off-gas release. The dose that would occur before evacuation of a secondary containment shell is 180 mrem. The ground dose from the building release is not shown, since it was less than 1 mrem, and the ground would not be contaminated downwind from the release point.

The only facility in which truly hazardous conditions were found to exist following the maximum credible accident was in the alpha isolation laboratory where the primary containment is glove boxes and secondary containment is the building. The maximum credible accident here would be an accident that ruptures the glove box that contains 30 grams of fine americium oxide powder. This accident could cause a lethal radiation dose to glove box operators and require that the ground be decontaminated for 45 meters downwind. If the glove box is considered a vessel, and the laboratory is separately ventilated from the building in order to constitute primary containment, a lethal dose would still be received by operators within the laboratory but the ground would only require decontamination for a distance of 8 meters downwind from the release point.

We are continuing to perform calculations and are planning experimental work to verify assumptions and indicate areas of undue conservatism. Detailed simultaneous flow equations have been written for the ventilation systems of several of the facilities and

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FIG. 9.
RESULTS OF HAZARD EVALUATION FOR BUILDING 3019

| EFFECT | TYPE OF ACCIDENT | | |
|---|---|---|---|
| | CHEMICAL EXPLOSION* | NUCLEAR EXPLOSION** | |
| | AEROSOL | GASEOUS FP's | AEROSOL |
| MAXIMUM DOSE FROM VOG RELEASE, rem | $1.9 \times 10^{-3}$ | $2.2 \times 10^{-1}$ | $4.3 \times 10^{-3}$ |
| MAXIMUM DOSE FROM COG RELEASE, REM | $1.5 \times 10^{-3}$ | $1.5 \times 10^{-1}$ | $3.5 \times 10^{-3}$ |
| TWO-MINUTE DOSE TO PERSONNEL IN SECONDARY CONTAINMENT ZONE, rem | $1.4 \times 10^{-2}$ | $1.8 \times 10^{-1}$ | $3.1 \times 10^{-2}$ |
| DISTANCE DOWNWIND FROM BUILDING TO WHICH GROUND IS CONTAMINATED TO HAZARD LEVEL | 0 | 0 | |

*SHATTERS 1AW WASTE EVAPORATOR CONTAINING A SOLUTION OF $6 \times 10^6$ CURIES OF MIXED SIX-MONTH-COOLED FISSION PRODUCTS

**$10^{18}$ FISSIONS WHICH SHATTERS Pu STORAGE TANK CONTAINING 60 kg (4500 CURIES) OF Pu AT 100 g/LITER

these equations are being solved on analog computers to give cell pressure transients for various cell perturbations. The 3019 system analysis has been completed; significant results were that indeed for a 100-cu-ft instantaneous gas input to the cell the positive pressure in the cell was dissipated in approximately 1 sec; 200 cu ft of gas could be dissipated in approximately 1-1/2 sec. The cell pressure transient for various ramp impulses were also determined. These results will be described in more detail in the forthcoming ORNL report.

In conclusion, by considering the proposed containment in ORNL radiochemical processing buildings and imposing conservative values of physical limitations which we know to exist, we have been able to show to our own satisfaction that the effect of what we considered to be the maximum credible accident in each of the facilities, with the exception of the alpha isolation laboratory, results in acceptable personnel exposure and negligible downwind ground contamination. The results indicate that it would probably be sufficiently safe to locate large private industry radiochemical plants in areas of high population density if ORNL-type containment criteria are used. The results also point up a need for further study aimed at eliminating the possibility of dispersive accidents in glove box laboratories.

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# APPENDIX I

## SUPPLEMENTARY DATA AND RESULTS

This section contains tables and figures of additional data and results which were accumulated in the hazard evaluation study.

Table 1 lists a complete set of the standards and assumptions that were used in estimating the release of activity from radiochemical facilities.

Table 2 lists properties of gaseous fission products which are formed in a nuclear excursion.

Table 3 lists the maximum radioactive content of radiochemical facilities in the Chemical Technology Division.

Table 4 lists properties of building ventilation systems.

Figure 10 presents data on the liquid aerosol concentration as a function of air velocity.

Table 5 is a summary of the radiological and fallout hazards associated with Chemical Technology Division facilities.

Table 1. Standards and Assumptions Used in Estimating Radiolytic Gas Leak Hazards

Design Standards

Cell volume exhaust capacity = $10^{-1}$ cell volume/minute (all Chemical Technology facilities meet or exceed this value).

Cell volume leak rate = $10^{-2}$ cell volume/minute at 2 in. w.g. pressure differential. (Chemical Technology facilities do not meet this specification at present but proposed changes in structure, coatings, etc., will alter the cells to reach this specification.)

Building leak rate = $6 \times 10^{-3}$ building volume/minute. (Change in building tightness, ventilation air locks for personnel access, and automatically instrumented or administrative controls on doors will require the air leakage in existing facilities to meet this specification.)

Cell vacuum, initial = 1 in. of water. (Most facilities can meet or exceed this value--the higher the initial vacuum, the lower the overpressure following an explosion.)

Duration of cell pressurization = 1 second. (All cell exhaust systems have a large reserve capacity at relatively high pressures so that an excess volume of 100 cu ft of gas generated by an explosion can be removed in approximately 1 second.)

Backflow gas from cell is filtered by Dust-stop filters, or an equivalent tortuous path through holes or crevices. Backflow preventers, designed to operate in less than 1 second or less of positive flow, will be installed.

Building vacuum-emergency $\geq$ 0.3 in. of water. The emergency building ventilation system will have enough reserve capacity to pump the secondary containment zone down to a vacuum of 0.3 in. of water if the leak-tightness specification is met provided (1) the air supply system is shut down and (2) in certain buildings auxiliary filtered exhausters are started.

Caustic scrubber (local) removes 99.9% of $I_2$ and $Br_2$.

Filter removes 99.95% of particles 0.3 microns in size.

Aerosols penetrating filters will contain 0.14 mg/$M^3$ total suspended solids of same radioactive material composition as original solution.

(Continued)

Table 1, Continued

Assumptions

All $I_2$, Kr, Xe, and $Br_2$ escapes to VOG system.

Particles of same composition as bulk solution are carried to VOG system at a concentration of 10 mg/$M^3$ with a mean particle size of 3 μ.

For radioactive material in dry state: metastable suspension density of 10 mg/$M^3$; average particle size of 1 μ.

MPC for mixed fission products = $6.6 \times 10^{-9}$ μc/cc.

All other MPC values were obtained from NBS Handbook 69.

Specification for maximum permissible ground contamination, constituting hazards to personnel, were set as follows:

(1) β, γ = a reading of 2.5 mr/hr above ground as determined by a GM survey meter with open window.

(2) α = $2.5 \times 10^5$ $MPC_{(air,\ 40h)}$, with units of curies/$M^2$.

Specification for maximum permissible ground contamination constituting levels which should be decontaminated were set as follows:

(1) β, γ = a reading of 0.25 mr/hr, i.e., 0.1 hazard level, and

(2) α = $1.25 \times 10^4$ $MPC_{(air,\ 40H)}$, i.e., 0.05 hazard level.

For release of gases from primary to secondary containment areas, the cell or dry-box composition (of the metastable suspension of particulates and volatile fission products) is used as the source gas composition.

In cases where secondary containment zone is compartmentalized (so that the entire secondary containment volume is not available for burst dilution, as would be the case in 3508), the worst case of the smallest secondary volume is used.

In the 3026 case, it was assumed that approximately 69 kg of uranium was completely burned; 13% of the content would escape through the filter as smoke, having a mean

(Continued)

Table 1, Continued

particulate radius of 0.1 μ; $10^{-2}$% was assumed to burn during the 1 second while the cell was pressurized; 1% of the total activity (suspended in the air of the cell) would escape into the secondary containment during the pressurization period.

Building leaks for 20 seconds before emergency vacuum is reached. (Most building ventilation systems can function and pump down to design vacuum in 20 seconds or less.)

Building leaks for one hour if emergency system fails. (A maximum average wind velocity of 32 mph has been recorded at ORNL for a duration of one hour.)

Building evacuation time - 2 minutes. (This period appears reasonable as a result of evacuation tests.)

In estimating the exposure received by personnel within a building, it was assumed that the activity leaving the cell was instantly and uniformly diluted with the air contained in the building. (This assumption is admittedly erroneous, since it would be possible for the leak to occur either (1) far away from any personnel; or (2) directly in path of nearby personnel, in which cases the actual doses could be either much lower or much higher than those calculated.)

Wind velocity during building leak = 30 mph. (This wind velocity only occurs 0.03% of the time.)

Wind velocities for fallout deposition calculations = 15 mph.

Wind velocities for fallout overlays were 15 and 5 mph. (There appears to be some discrepancy here but the size of a building leak is directly proportional to the wind velocity while the total integrated dose and fallout is inversely proportional to the wind velocity. A high wind velocity was used to calculate the total quantity leaving while the lower wind velocities were used to show what would happen if that quantity was released during more normal conditions.)

Height of release from building = 10 meters

$n = 0.33$ (atmospheric stability parameter)

$C_y = C_z = 0.15$ (atmospheric diffusion constants)

Table 2. Properties of Gaseous Fission Products Which Are Formed in a Nuclear Reaction

| Radionuclide | Half-life | $(mpc)_i$ c/M$^3$ | $\gamma_i$ % | $\lambda_i$ sec$^{-1}$ | Quantity Formed in $10^{18}$ Fissions, curies |
|---|---|---|---|---|---|
| $Br^{84}$ | 30m | $10^{-6}$ | 1.1 | $3.85 \times 10^{-4}$ | 115 |
| $Br^{85}$ | 3.0m | $3 \times 10^{-6}$ | 1.5 | $3.85 \times 10^{-3}$ | 1,560 |
| $Br^{87}$ | 55.6s | $5 \times 10^{-7}$ | 2.7 | $1.25 \times 10^{-2}$ | 9,100 |
| $Br^{88}$ | 15.5s | $10^{-6}$ | 2.9 | $4.47 \times 10^{-2}$ | 35,000 |
| $Kr^{87}$ | 78m | $10^{-6}$ | 2.7 | $1.48 \times 10^{-4}$ | 108 |
| $Kr^{88}$ | 2.8h | $10^{-6}$ | 3.7 | $6.95 \times 10^{-5}$ | 70 |
| $Kr^{89}$ | 3.18m | $10^{-6}$ | 4.6 | $3.63 \times 10^{-3}$ | 4,500 |
| $Kr^{90}$ | 33s | $10^{-6}$ | 5.2 | $2.1 \times 10^{-2}$ | 30,000 |
| $Xe^{135m}$ | 15.6m | $4 \times 10^{-6}$ | 1.8 | $7.4 \times 10^{-4}$ | 360 |
| $Xe^{137}$ | 3.9m | $10^{-6}$ | 5.9 | $2.96 \times 10^{-3}$ | 4,700 |
| $Xe^{138}$ | 17m | $10^{-6}$ | 5.5 | $6.79 \times 10^{-4}$ | 1,000 |
| $Xe^{139}$ | 41s | $10^{-6}$ | 4.7 | $1.67 \times 10^{-2}$ | 22,000 |
| $Xe^{140}$ | 16s | $10^{-6}$ | 3.7 | $4.33 \times 10^{-2}$ | 43,000 |
| $I^{131}$ | 8.05d | $9 \times 10^{-9}$ | 2.9 | $9.96 \times 10^{-7}$ | 0.78 |
| $I^{132}$ | 2.4d | $2 \times 10^{-7}$ | 4.4 | $8.02 \times 10^{-5}$ | 93 |
| $I^{133}$ | 20.8h | $3 \times 10^{-8}$ | 6.5 | $9.25 \times 10^{-6}$ | 16 |
| $I^{134}$ | 52.5m | $5 \times 10^{-7}$ | 7.6 | $2.20 \times 10^{-4}$ | 410 |
| $I^{135}$ | 6.68h | $10^{-7}$ | 5.9 | $2.89 \times 10^{-5}$ | 45 |
| $I^{136}$ | 86s | $10^{-6}$ | 3.1 | $8.06 \times 10^{-3}$ | 1,140 |
| $I^{137}$ | 22s | $10^{-5}$ | 4.9 | $3.15 \times 10^{-2}$ | 40,000 |

Gaseous fission products which were found to have a negligible effect on the dose from the gas cloud because of long half-life of the radionuclides or its parent, low fission yield, high mpc, or exceedingly short half-life are: $Br^{82}$, $Br^{83}$, $Br^{89}$, $Kr^{83m}$, $Kr^{85m}$, $Kr^{85}$, $Kr^{91}$, $Kr^{92}$, $Xe^{131m2}$, $Xe^{133m}$, $Xe^{133}$, $I^{129}$, $I^{138}$, $I^{139}$.

Table 3. Maximum Radioactive Content of Process Buildings

| Bldg. | Material | Inventory in Building | Releasable Inventory in Most Likely Vessel: Quantity | Releasable Inventory in Most Likely Vessel: Concentration, curies/mg | Remarks |
|---|---|---|---|---|---|
| 3019 SX | $Kr^{85}$, curies | ~200 | | | In metal, could only be released over relatively long period. |
| | Mixed FP's, curies | $6 \times 10^6$ | $6 \times 10^6$ | $1.1 \times 10^{-2}$ | Could be released by an explosion. |
| | $I^{131}$, curies | ~1 | ~1 | - | Negligible. Could be released by an explosion. |
| | Alphas, curies | - | - | - | Negligible. Could be released by an explosion. |
| | $Pu^{239}$ (15% $Pu^{240}$) | 60 kg | 60 kg<br>4500 curies | $0.75 \times 10^{-5}$ | Could be released by criticality accident or $H_2$-$O_2$ explosion. |
| | Mixed FP's, curies | Neg. | Neg. | - | Negligible. Could be released by criticality accident or $H_2$-$O_2$ explosion. |
| 3019 Vol. | $Kr^{85}$, curies | 100 | 100 | | Could be released by rupture. These would not be released in the credible nuclear accident. |
| | Mixed FP's, curies | $5 \times 10^4$ | ~0 | | Not releasable - molten salt. These would not be released in the credible nuclear accident. |
| | $I^{131}$, curies | ~0 | ~0 | | Not releasable - molten salt. These would not be released in the credible nuclear accident. |
| | Pu, curies | 0.6 | | | Not releasable - molten salt. These would not be released in the credible nuclear accident. |
| 3505 | Mixed FP's, curies | 250 | 20 | $5 \times 10^{-9}$ | Could be released in explosion. |
| | Pu | < 1 g | | | Could be released in explosion. |
| | $U^{238}$, kg | 1500 | 1280 | $1.1 \times 10^{-10}$ | Could be released in explosion. |

(Continued)

Table 3, Continued

| Bldg. | Material | Inventory in Building | Releasable Inventory in Most Likely Vessel: Quantity | Releasable Inventory in Most Likely Vessel: Concentration, curies/mg | Remarks |
|---|---|---|---|---|---|
| 2527 | $Kr^{85}$, curies | 1930 | 190 | | Release to cell ventilation system in 2 min by explosion. |
| | Mixed FP's, curies | $1.7 \times 10^6$ | $1.7 \times 10^6$ | $6.8 \times 10^{-3}$ | Could be released by nuclear accident. |
| | $I^{131}$, curies | 0.092 | 0.092 | | Not controlling. |
| | Alpha-emitters, curies | - | | - | Not controlling. |
| 3508 CTD | $Am^{241}$, g | 175 | 30 | | Could be released to secondary containment shell by fire as 1 μ powder of $AmO_2$. |
| | $U^{233}$, g | 250 | 250 | $1 \times 10^{-6}$ | Solution could be released by explosion. |
| 4507 | Mixed FP's, curies | 1190 | 1190 | $1 \times 10^{-4}$ | Could possibly be released by an explosion. |
| | Th, g | 10,800 | 10,800 | | |
| | U, g | 317 | 317 | | |
| 3026 | $Kr^{85}$, curies | 35 | 35 | | In metal, criticality not credible; could possibly be released in a uranium fire. |
| | Mixed FP's, curies | 3800 | 3800 | | |
| | $U^{238}$, kg | 67 | 67 | | |
| | $U^{235}$, kg | 1.84 | 1.84 | | |
| | Pu, kg | 0.04 | 0.04 | | |
| 3508 Anal. | Pu, g | - | 50 | $0.75 \times 10^{-5}$ | Solution could be released by explosion. |

Table 4 Properties of Ventilation Systems Revised Copy

| | Bldg. 3019, SX | Bldg 3019, Volatility | Bldg. 3505 | Bldg. 2527 | Bldg. 3026 | Bldg. 3508 | Bldg. 4507 |
|---|---|---|---|---|---|---|---|
| **VOO System** | | | | | | | |
| Flow, cfm | 300 | - | 180 | 50 | - | - | < 10 |
| Local scrubber | x | - | | | - | - | |
| Local absolute filters | x | - | x | x | - | - | |
| 3039 VOO treatment system | x | - | x | x | - | - | x |
| Decay time, sec | 150 | - | 136 | 150 | - | - | 30 |
| Stack dilution factor, sec/$M^3$ | $1.6 \times 10^{-5}$ | - | $1.6 \times 10^{-5}$ | $1.6 \times 10^{-5}$ | - | - | $1.6 \times 10^{-5}$ |
| **COG System** | Cells 3, 4, 5 / Cells 6 and 7 | Cell 1 / Cell 2 | Large Cell / Small Cell | Cells 1 and 2 | Cell A | CT Glove Boxes / Anal. Glove Boxes | Cells 1, 2, 3, 4 |
| Cell volume, cu ft | 10,000 / 20,000 | 5600 / 10,000 | 6260 / 2160 | 15,000 | 3750 | 16 / 16 | 660 |
| Cell flow, cfm | 1150 / 2300 | 700 / 2300 | | 1500 | 500 | 5.0 / 5.0 | 100 |
| Flow at filters, cfm | 11,750 | 11,750 | 4500 | 3000 | 500 | 100 / 100 | 15,000 |
| Local scrubber | | x | | | | | |
| Inlet roughing filter system | x | x | x | | | | |
| Inlet absolute filter system | | | | x | x | x / x | x |
| Exhaust absolute filter system | x | x | x | x | x | x / x | x |
| Decay time, sec | 30 | 30 | 60 | 20 | 15 | 27 | 50 |
| Stack | 3020 | 3020 | 3039 | local | 3039 | 3039 / Roof | 3039 |
| Stack dilution factor, sec/$M^3$ | $2.3 \times 10^{-5}$ | $2.3 \times 10^{-5}$ | $1.6 \times 10^{-5}$ | $10^{-4}$ | $1.6 \times 10^{-5}$ | $1.6 \times 10^{-5}$ / $10^{-3}$ | $1.6 \times 10^{-5}$ |
| **Secondary Containment System** | | | | | | | Compartment A / B / C |
| Volume, cu ft | 210,000 | 210,000 | 76,800 | 380,000 | 21,500 | 5280 | 18,000 / 18,000 / 18,000 |
| Flow, cfm | 0.3 in. w.g. in 20 sec | 0.3 in. w.g. in 20 sec | | 30,000 | 5,000 | 880 | 3,000 / 3,000 / 3,000 |
| Emergency system | x | x | | | | | |
| Continuous system | | | | x | x | x | x |
| Inlet roughing filter system | x | x | | x | x | | x |
| Exhaust absolute filter system | x | x | No Filters | x | x | x | x |
| Discharge at top of building | | | x | x | | x | x |
| Emergency discharge to 3039 stack | 3020 | 3020 | | | 3039 | | 3039 |
| Exhaust dilution factor, sec/$M^3$ | $2.3 \times 10^{-5}$ | $2.3 \times 10^{-5}$ | $\sim 1.7 \times 10^{-3}$ | $1.7 \times 10^{-3}$ | $1.6 \times 10^{-5}$ | $1.7 \times 10^{-3}$ | $1.6 \times 10^{-5}$ |

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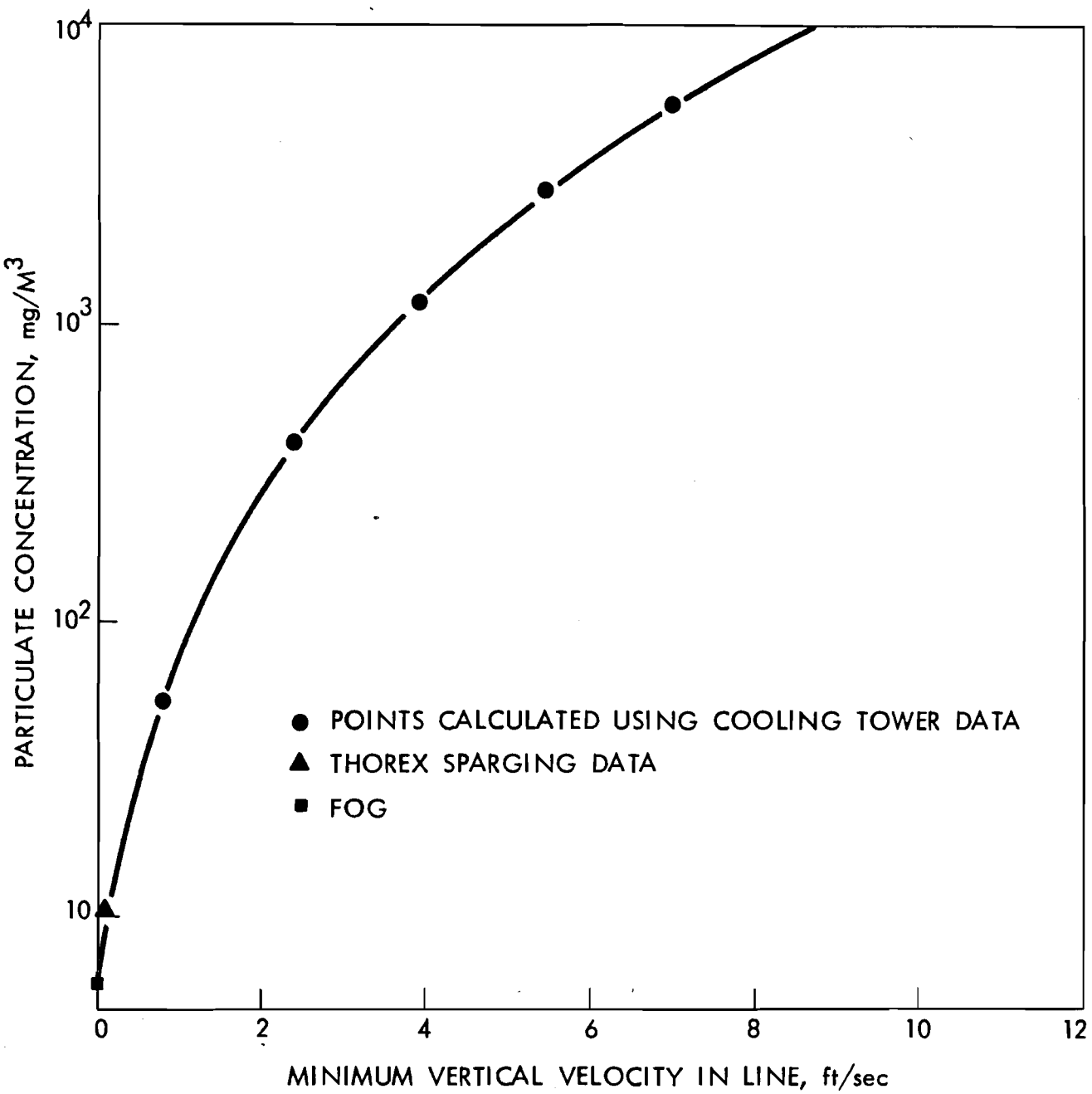



Fig. 10. The effect of minimum superficial velocity in an off-gas line on the concentration of liquid solution particles resulting from very vigorous mixing of a solution with air. (solution density = 1 g/cc)

**Table 5 Summary of Radiological and Fallout Hazards from Credible Accidents in Facilities of the Chemical Technology Division**

(Conditions of assumed credible accidents are given in Table 3; properties of ventilation systems given in Table 4)

| | Bldg. 3019, Solvent Extraction | | | | Bldg. 3019, Volatility | | Bldg. 3505 | | Bldg. 2527 | | Bldg. 4507 | | Bldg. 3026, Cell A | | | Bldg. 3508, Dry Boxes | | Bldg. 3508, Dry Boxes[a] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cells 3, 4, or 5 | | Cells 6 and 7 | | Krypton | | Mixed fp's | | | | | | | | | | | | |
| | Mixed fp's | $Pu^{239}$ | Mixed fp's | $Pu^{239}$ | Large Cell | Small Cell | Large Cell | Small Cell | Mixed fp's | Kr | Mixed fp's | $Pu^{239}$ | Mixed fp's | $Pu^{239}$ | Kr | $U^{233}$ | $Am^{241}$ | $U^{233}$ | $Am^{241}$ |
| Total amount vaporized or suspended, curies | 3.1x10 | $2.1\times10^{-2}$ | 6.3x10 | $4.2\times10^{-2}$ | $1.0\times10^{2}$ | $1.0\times10^{2}$ | $9.0\times10^{-6}$ | $3.1\times10^{-6}$ | 2.9x10 | $1.9\times10^{2}$ | $5.7\times10^{-1}$ | $7.7\times10^{-5}$ | $3.8\times10^{3}$ | 2.45 | 3.5x10 | - | - | - | - |
| Deposition, curies/$m^3$ | $1.1\times10^{-1}$ | $7.5\times10^{-5}$ | $1.1\times10^{-1}$ | $7.5\times10^{-5}$ | - | - | $5.0\times10^{-8}$ | $5.0\times10^{-8}$ | $6.8\times10^{-2}$ | $4.4\times10^{-1}$ | $3.0\times10^{-2}$ | $4.0\times10^{-6}$ | - | - | - | - | - | - | - |
| Total amount released through VOG system, curies | $8\times10^{-1}$ | $5.4\times10^{-3}$ | $8\times10^{-1}$ | $5.4\times10^{-3}$ | - | - | $2.2\times10^{-7}$ | $2.2\times10^{-7}$ | $8.2\times10^{-2}$ | $1.9\times10^{2}$ | $7.2\times10^{-3}$ | $9.7\times10^{-7}$ | - | - | - | - | - | $6.4\times10^{-9}$ | $1.73\times10^{-4}$ |
| Max dose from VOG aerosol release, rem | $1.9\times10^{-3}$ | $4.3\times10^{-3}$ | $1.9\times10^{-3}$ | $4.3\times10^{-3}$ | - | - | $<10^{-6}$ | $<10^{-6}$ | $2.0\times10^{-4}$ | $3.0\times10^{-3}$ | $1.7\times10^{-5}$ | $1.5\times10^{-5}$ | - | - | - | - | - | $<10^{-6}$ | $4.6\times10^{-4}$ |
| From VOG gaseous fp's from criticality incident, rem | - | $2.2\times10^{-1}$ | - | - | - | - | - | - | $1.5\times10^{-1}$ | - | $6.1\times10^{-1}$ | $6.1\times10^{-1}$ | - | - | - | - | - | - | - |
| Distance downwind of dose, m | 1760 | 1760 | 1760 | 1760 | - | - | 1760 | 1760 | 580 | 580 | 1760 | 1760 | - | - | - | - | - | 150 | 150 |
| Total amount released through COG system, curies | $4.3\times10^{-1}$ | $3.0\times10^{-3}$ | $8.6\times10^{-1}$ | $6.0\times10^{-3}$ | $1.0\times10^{2}$ | $1.0\times10^{2}$ | $1.2\times10^{-6}$ | $4.1\times10^{-7}$ | $4.1\times10^{-1}$ | $1.9\times10^{2}$ | $7.8\times10^{-3}$ | $1.1\times10^{-6}$ | $3.4\times10^{2}$ | $2.2\times10^{-1}$ | - | $6.4\times10^{-8}$ | $1.73\times10^{-3}$ | - | - |
| Max. dose from COG aerosol release, rem | $1.5\times10^{-3}$ | $3.5\times10^{-3}$ | $3.0\times10^{-3}$ | $7.0\times10^{-3}$ | $2.3\times10^{-3}$ | $2.3\times10^{-3}$ | $<10^{-6}$ | $<10^{-6}$ | $6.2\times10^{-3}$ | $1.9\times10^{-2}$ | $1.9\times10^{-5}$ | $1.7\times10^{-5}$ | $8.2\times10^{-1}$ | 1.77 | $5.6\times10^{-4}$ | $<10^{-6}$ | $4.6\times10^{-3}$ | - | - |
| From COG gaseous fp's from criticality incident, rem | - | $1.5\times10^{-1}$ | | | $9.7\times10^{-2}$ | - | - | - | $6.5\times10^{-1}$ | - | $1.7\times10^{-1}$ | $1.7\times10^{-1}$ | - | - | - | - | - | - | - |
| Distance downwind of dose, m | 1760 | 1760 | 1760 | 1760 | 1760 | 1760 | 1760 | 1760 | 580 | 580 | 1760 | 1760 | 1760 | 1760 | 1760 | 150 | 150 | - | - |
| Total amount released into bldg. or secondary containment, curies | $4.5\times10^{-3}$ | $3.1\times10^{-6}$ | $5.3\times10^{-3}$ | $3.6\times10^{-6}$ | $1.25\times10^{-2}$ | $1.25\times10^{-2}$ | $1.76\times10^{-9}$ | $6.1\times10^{-10}$ | $3.2\times10^{-3}$ | $2.1\times10^{-2}$ | $3.6\times10^{-4}$ | $4.9\times10^{-8}$ | $3.8\times10^{-3}$ | $2.45\times10^{-6}$ | $3.5\times10^{-5}$ | $1.5\times10^{-3}$ | 4.0 | $4.5\times10^{-5}$ | $1.2\times10^{-1}$ |
| Concentration, curies/$m^3$ | $7.5\times10^{-7}$ | $5.2\times10^{-10}$ | $8.8\times10^{-7}$ | $6.0\times10^{-10}$ | $2.1\times10^{-6}$ | $2.1\times10^{-6}$ | $8.1\times10^{-13}$ | $2.8\times10^{-13}$ | $3.0\times10^{-7}$ | $1.9\times10^{-6}$ | $6.9\times10^{-7}$ | $9.3\times10^{-11}$ | $6.2\times10^{-6}$ | $4.0\times10^{-9}$ | $5.7\times10^{-8}$ | $1.0\times10^{-5}$ | $2.7\times10^{-2}$ | $3.0\times10^{-7}$ | $8.1\times10^{-4}$ |
| 2-min dose to bldg. personnel from aerosol release, rem | $1.4\times10^{-2}$ | $3.1\times10^{-2}$ | $1.4\times10^{-2}$ | $3.6\times10^{-2}$ | $2.5\times10^{-5}$ | $2.5\times10^{-5}$ | $<10^{-6}$ | $<10^{-6}$ | $5.3\times10^{-3}$ | $2.1\times10^{-5}$ | $1.2\times10^{-2}$ | $1.1\times10^{-2}$ | $1.1\times10^{-1}$ | $2.4\times10^{-1}$ | $1.0\times10^{-2}$ | 1.0x10 | $5.4\times10^{5}$ | $3.6\times10^{-2}$ | $2.0\times10^{3}$ |
| From gaseous fp's in criticality release, rem | - | $1.8\times10^{-1}$ | - | - | $1.4\times10^{-1}$ | - | - | - | $7.5\times10^{-2}$ | - | 1.1x10 | 1.1x10 | - | - | - | - | - | - | - |
| Total amount leaking from bldg. assuming ventilation system works, curies | $7.5\times10^{-5}$ | $4.8\times10^{-8}$ | $8.6\times10^{-5}$ | $5.8\times10^{-8}$ | - | - | $2.7\times10^{-11}$ | $1.7\times10^{-11}$ | $5.0\times10^{-5}$ | - | $5.7\times10^{-6}$ | $7.7\times10^{-10}$ | $6.0\times10^{-5}$ | $3.27\times10^{-7}$ | - | $2.4\times10^{-5}$ | $6.5\times10^{-2}$ | $6.3\times10^{-7}$ | $1.7\times10^{-3}$ |
| Max downwind dose,+ rem | $<10^{-6}$ | $1.0\times10^{-6}$ | $<10^{-6}$ | $1.2\times10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $1.2\times10^{-5}$ | - | $<10^{-6}$ | $2.7\times10^{-8}$ | $<10^{-6}$ | $6.8\times10^{-6}$ | $<10^{-6}$ | $3.8\times10^{-4}$ | 1.87 | $1.0\times10^{-5}$ | $5.0\times10^{-2}$ |
| Distance downwind of dose, m | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Ground fallout at 20 m, curies/$m^2$ | $2.8\times10^{-10}$ | $1.8\times10^{-13}$ | $3.2\times10^{-10}$ | $2.1\times10^{-13}$ | - | - | $1.0\times10^{-16}$ | $6.2\times10^{-17}$ | $1.8\times10^{-10}$ | - | $2.1\times10^{-11}$ | $2.8\times10^{-15}$ | $1.8\times10^{-9}$ | $1.2\times10^{-12}$ | - | $9.5\times10^{-11}$ | $2.4\times10^{-7}$ | $2.5\times10^{-12}$ | $6.3\times10^{-9}$ |
| Distance downwind to which ground contaminated to hazardous level, m | 0 | 0 | 0 | 0 | - | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 6 | 0 | 0 |
| Ground must be decontaminated, m | 0 | 0 | 0 | 0 | - | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | - | 0 | 45 | 0 | 8 |
| Total amount leaking from bldg. assuming ventilation system fails, curies | $1.75\times10^{-3}$ | $1.2\times10^{-6}$ | $2\times10^{-3}$ | $1.35\times10^{-6}$ | - | - | $6.6\times10^{-10}$ | $4.1\times10^{-10}$ | $1.22\times10^{-3}$ | - | $1.5\times10^{-4}$ | $2.0\times10^{-8}$ | $1.87\times10^{-3}$ | $7.64\times10^{-6}$ | - | $6.0\times10^{-5}$ | 1.53 | $7.5\times10^{-6}$ | $1.9\times10^{-2}$ |
| Max. downwind dose,+ rem | $4.3\times10^{-5}$ | $9.8\times10^{-4}$ | $5.0\times10^{-5}$ | $1.1\times10^{-3}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $<10^{-6}$ | $4.2\times10^{-5}$ | - | $3.5\times10^{-6}$ | $3.1\times10^{-6}$ | $4.5\times10^{-5}$ | $6.2\times10^{-3}$ | $<10^{-6}$ | $8.6\times10^{-4}$ | $4.3\times10$ | $1.1\times10^{-4}$ | $5.4\times10^{-1}$ |
| Distance of dose, m | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Ground fallout at 20 m, curies/$m^2$ | $6.4\times10^{-9}$ | $4.4\times10^{-12}$ | $7.3\times10^{-9}$ | $4.9\times10^{-12}$ | - | - | $2.4\times10^{-15}$ | $1.5\times10^{-15}$ | $4.5\times10^{-9}$ | - | $5.1\times10^{-10}$ | $6.9\times10^{-14}$ | $6.8\times10^{-9}$ | $2.8\times10^{-11}$ | - | $2.2\times10^{-10}$ | $5.6\times10^{-6}$ | $2.7\times10^{-11}$ | $6.9\times10^{-8}$ |
| Distance downwind to which ground is contaminated to hazardous level, m | 0 | 0 | 0 | 0 | - | - | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | - | 0 | 46 | 0 | 5 |
| Ground must be decontaminated, m | 0 | 0 | 0 | 0 | - | - | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | - | 0 | 250 | 0 | 24 |
| Total amount released* through stack, curies | 1.23 | $8.4\times10^{-3}$ | 1.66 | $1.14\times10^{-2}$ | - | - | $1.5\times10^{-6}$ | $6.3\times10^{-7}$ | $5.2\times10^{-1}$ | $1.9\times10^{2}$ | $1.5\times10^{-2}$ | $2.0\times10^{-6}$ | $3.4\times10^{2}$ | $2.2\times10^{-1}$ | - | - | - | - | - |
| Ground at 1500 m, curies/$m^2$ | $3.2\times10^{-10}$ | $2.2\times10^{-12}$ | $4.3\times10^{-10}$ | $3.0\times10^{-12}$ | - | - | $3.9\times10^{-16}$ | $2.4\times10^{-16}$ | $5.6\times10^{-10}$ | - | $3.9\times10^{-12}$ | $5.3\times10^{-16}$ | $8.8\times10^{-8}$ | $5.7\times10^{-11}$ | - | - | - | - | - |
| Distance downwind to which ground is contaminated to hazardous level, m | 0 | 0 | 0 | 0 | - | - | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | - | - | - | - | - |
| Ground must be decontaminated, m | 0 | 0 | 0 | 0 | - | - | 0 | 0 | 0 | - | 0 | 0 | 0 | 0 | - | - | - | - | - |
| Prompt neutron and gamma dose during criticality incident, rem | | 1.9 | - | | 1.9 | - | - | - | $1.2\times10^{-2}$ | - | $4.0\times10^{-2}$ | - | - | - | - | - | - | - | - |

*See items 3 through 8 for dose calculations.

[a]Considers dry-box as vessel, room as cell, corridor as secondary containment; also considers 15 sec dose instead of 2-min dose (assumes operator can adjust mask in 15 sec) and that suspension contains 0.3 mg of $Am_2O_3/m^2$ instead of 10 mg/$m^3$, as assumed in other cases. (0.3 mg/$m^3$ is the mean of the range of data for $UO_3$ suspensions.)

Maximum allowable dose in any single incident is 3.0 rem. Maximum allowable fallout (See Table / ).

+In all cases release of gaseous fission products following a criticality incident, the dose is <1 mr.

# APPENDIX II

## METEOROLOGY

The downwind ground concentration of gases that are released from an elevated source may be evaluated through the use of an atmospheric dilution factor, k.

$$k = \frac{\text{downwind ground concentration}}{\text{unit emission rate}} = \frac{c/M^3}{c/\text{sec}} = \frac{\text{sec}}{M^3}$$

c = curies

M = meter

This k can be used in the following types of equations:

$$\boxed{\text{Downwind concentration, fraction of } MPC_a = \frac{(q)\ (k)}{MPC_a}}$$

where q = release rate curies/sec

$MPC_a$ = maximum permissible concentration in air, taken from NBS-69

$$\boxed{\text{Downwind dose, rem} = \frac{(Q)\ (1.44)\left(k\,\frac{\text{sec}}{M^3}\right)}{10(MPC)_a\ (1.44 \times 10^5)} = \frac{10^{-6}\ Qk}{(MPC)_a}}$$

where Q = total curies released (over a period such that k is constant)

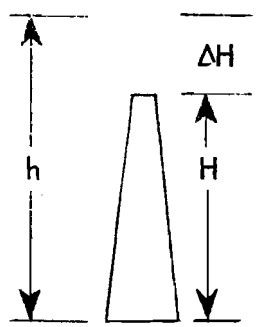
1.44 = factor to account for increased breathing rate during emergency conditions

$(MPC)_a$ = maximum permissible concentration for 40 hr of occupational exposure (the concentration that will cause 100 mr of dose in 40 hr exposure)

$1.44 \times 10^5$ = the number of seconds in 40 hr

It may be assumed that the downwind internal and external radiation hazard from an aerosol of mixed fission products sufficiently small in size to pass through an absolute filter may be evaluated through the use of the atmospheric dilution factor (i.e., it is assumed that aerosol behaves as a gas).

In order to evaluate k, it is necessary to calculate the effective height of the release point, taking the stack plume into consideration.




h = effective stack height, meters

H = actual stack height, meters

ΔH = plume rise, meters

d = diameter of stack, meters

$V_s$ = velocity in stack, M/sec

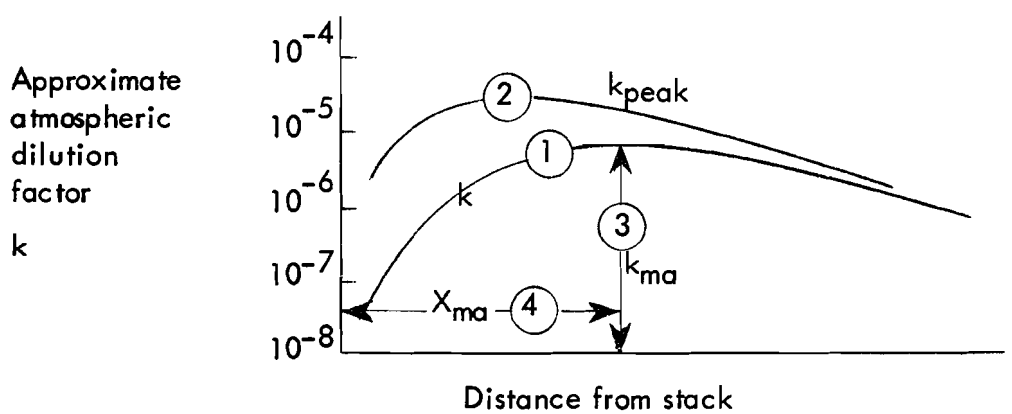
u = wind velocity, meters/sec

$T_s$ = stack gas temperature, °C

ΔT = stack gas temperature excess over ambient, °C

$$h = H + d\left(\frac{V_s}{u}\right)^{1.4}\left(1 + \frac{\Delta T}{T_s}\right)$$

k varies in the following manner with distance from a stack for a continuous stack emission:




Curve (1) depicts the average value of k as a function of distance from the stack for a given set of weather conditions.

$$k = \frac{2}{\pi C^2 u x^{2-n}} e^{-\left(\frac{h^2}{C^2 x^{2-n}}\right)}$$

C = diffusion constant (see AECU-3066, p. 114, or ORO-99)

n = stability parameter

Some approximate values of C and n are:

| Weather Condition | C | n |
|---|---|---|
| Large lapse | 0.18 | 0.20 |
| Small temperature gradient, neutral | 0.1 | 0.25 |
| Inversion | 0.06 | 0.33 |

$k_{peak}$ (2) is a measure of the peaks of the statistical fluctuation in ground concentration (it may be assumed that such peaks have short duration, ~1 sec, and large frequency, several times per hour).

$$k_{peak} = \frac{2}{\pi C^2 u x^{2-n}}$$

$k_{ma}$ (3) describes the maximum average ground concentration that will occur over a period of the order of 1 hour and the approximate maximum average concentration that will occur over shorter periods.

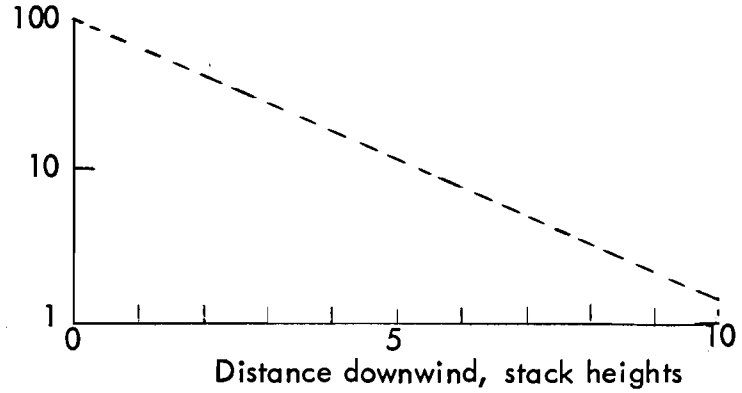
$$k_{ma} = \frac{2}{\pi e u h^2}$$

$X_{ma}$ (4) is the distance downwind from the stack, in meters, where the maximum average concentration will occur.

$$X_{ma} = \left(\frac{h^2}{C^2}\right)^{\frac{1}{2-n}}$$

For a given stack k is maximum (maximum ground concentration) at u = 1-3 mph due to the balance between u and h.

The peak to average concentration varies approximately in the following manner with distance from the stack:




Ground Deposition

A deposition constant, K, may be evaluated for ground deposition calculations.

$$K = \frac{w}{q} = \frac{\text{curies}/M^2 - \text{sec}}{\text{curies/sec}} = \frac{\text{curies}/M^2}{\text{curies}}$$

w = ground deposition rate

q = emission rate

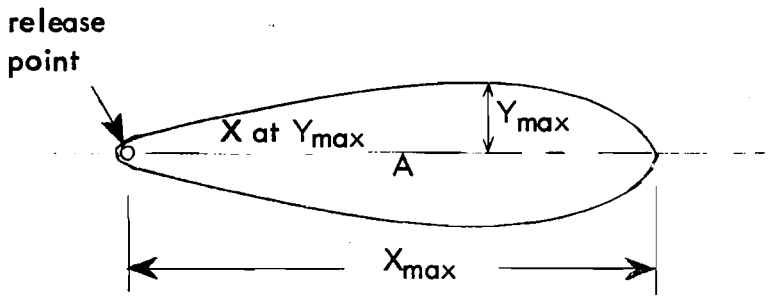
The maximum dry deposition of particles in the range of 1-100μ may be evaluated as a function of distance downwind, x, by

$$K_{\text{dry max}} = \frac{n}{2e\pi^{1/2}Cx^{2-(n/2)}}$$

The maximum rainout deposition of particles in the range of 1-100μ may be evaluated by

$$K_{\text{rain max}} = \frac{1}{e\pi^{1/2}Cx^{2-(n/2)}}$$

Isopeths of constant deposition during unchanging weather conditions have the following shape:




where $X_{max}$ = maximum downwind distance, M

$Y_{max}$ = maximum crosswind distance, M

X at $Y_{max}$ = downwind distance at maximum crosswind distance, M

A = enclosed area, $M^2$

The shape of the isopeth and enclosed area for a given set of weather conditions may be determined using the nomograms of ORO-176. The equation that describes the shape of the isopeth for a ground level release is

$$K = \frac{2V_g}{u\pi C_y C_z X^{2-n}} e^{-\left(\frac{4V_g X^{n/2}}{nu\pi^{1/2} C_z}\right)} e^{-\left(\frac{y^2}{C_y^2 X^{2-n}}\right)}$$

The previously undefined symbols are

$V_g$ = settling velocity of particles in still air, M/sec

y = distance crosswind from plume centerline, M

If the particles are released at an elevation, h, K from the previous equation is multiplied by an additional term, namely,

$$e^{-\left\{\frac{\left(h - \frac{XV_g}{u}\right)^2}{C_z^2 X^{2-n}}\right\}}$$

the particle settling velocity which will produce the maximum deposition a given distance, X, from the source is

$$V_g = \frac{nu\pi^{1/2}C_z X^{-n/2}}{4}$$

The shape of the deposition isopeth for a continuous ground level release during seasonal or annual periods in which weather conditions and wind directions and speeds change is expressed by the following equation using average values of u, C, and n

$$k_{Di} = \frac{16\ Fi\ V_g}{e\pi^{3/2}CuX^{\frac{4-n}{2}}}\ e^{-\left(\frac{4V_g X^{n/2}}{nu\pi^{1/2}C_z}\right)}$$

where

$k_{Di}$ = average deposition in $c/M^2$ per curie released for direction i along a 22.5° arc at distance X.

Fi = fractional frequency for wind blowing in direction i (direction is assumed to be in a section of 22.5°).

# APPENDIX III

## EFFECTS OF CHEMICAL, MECHANICAL, AND NUCLEAR EXPLOSIONS

An explosion is defined as the sudden production of a large quantity of usually hot gases from a smaller quantity of solid, liquid, or gas.

A detonation is a very rapid explosion that occurs in times of the order of 1-100 microseconds. It is characterized by brisance due to the energetic shock wave that is formed.

### III-1 Detonations

When a solid or a liquid detonates in air approximately half of the energy liberated from the reaction serves to heat up the air in the immediate vicinity of the explosive while the remaining half is carried through the air in the form of a shock wave. In a process cell the half of the energy which goes into heating up the cell air would cause little, if any, destruction. This heat, if instantaneously transferred to the cell air, could cause the pressure in the cell to rise several inches of water above atmospheric pressure; but this pressure would be relieved through the filtered cell ventilation system within a few seconds. The shock wave is very destructive, however, since it can cause shattering of the containment vessel, damage to other vessels from flying fragments or external pressure buckling, destruction of unit shielding, and escape of activity from the cell through doors or cell plugs which are blown open by the shock wave. Methods whereby the destructiveness of this type of shock wave may be evaluated are presented.

The methods presented here may be directly related to homogeneous gas detonations if the gas containment vessel is destroyed during the detonation. When $H_2$ with stoichiometric air to form water detonates at atmospheric pressure without rupturing the containment vessel, the equilibrium pressure after the explosion is in the order of 10 atm. and the maximum pressure in the shock wave at the container is in the order of 20-50 atm. If the containment vessel is shattered or torn open, the destructive effects are essentially those which would result if a solid or liquid detonation had occurred which caused an equivalent pressure at the vessel wall.

When an explosive is detonated in air, an initial shock wave spreads from the point of the detonation. At several explosive diameters this initial shock wave is swallowed up by an expanding hot gas cloud possessing a tremendous temperature and pressure and traveling with an initial radial velocity several times the speed of sound. The radial velocity and pressure of the hot gas cloud decrease rapidly as the volume of the hot gas cloud increases. When the pressure of the hot gas cloud decreases to near 1 atm., the radial expansion velocity will have decreased to near the speed of sound; at this time a secondary shock wave (hereafter to be referred to as the blast wave) will emerge from the hot gas cloud and spread from it.

The radial distance, $S_c$, where the hot gas cloud pressure will decrease to near 1 atm. and the blast wave will emerge from the cloud, has been measured and is practically constant on a weight basis for most explosives. These measurements may be empirically correlated for spherical explosive charges using the expression:

$$S_c = 3.0\, M^{1/3}$$

where M is the mass of the explosive expressed as equivalent pounds of TNT

$S_c$ = radial distance from center of cloud, ft

The blast wave, which emerges from the hot gas cloud and travels in the air away from the source, is characterized by a pressure wave and a rarefaction, or suction wave. The pressure part of the wave has an overpressure (pressure in excess of atmospheric) which is maximum at the front of the wave and progressively decreases with distance into the wave. The suction part of the wave, which follows the pressure part, has a differential negative pressure which is lower than the differential positive pressure of the pressure part of the wave. The pressure part of a blast wave is more destructive than the suction part of the wave, even though it is slightly less energetic, since it has the relatively greater pressure. In detonations of explosives approximately 50% of the total energy released appears in the blast wave with 20% of the total energy in the pressure part of the wave.

As the blast wave spreads from its source, its total area increases because of spherical divergence and the energy per unit area decreases. The energy per unit area in the pressure part of a blast wave as a function of distance from the source may be expressed approximately by:

$$\epsilon = \frac{E/5}{4\pi S^2}$$

for $S > S_c$

where $\epsilon$ = energy per unit area of wave front

S = distance from the center of the explosion

E = energy liberated in the explosion

Substituting for the constants, this equation may be rewritten for the energy per unit area in ft-lb/sq ft and radial distance in ft as:

$$\epsilon = \frac{1.09 \times 10^6 \text{ M}}{20\pi S^2} = \frac{1.74 \times 10^4 \text{ M}}{S^2} \qquad (\text{for } S > 3.0 \text{ M}^{1/3})$$

where: M is the mass of explosive expressed as lbs of TNT.

The calculation of the peak overpressure in a blast wave as a function of the distance from the source is somewhat more complicated than the energy calculation. The reason for this is that the contour of the pressure magnitude vs. distance from the wave front to any point in the wave curve changes with the radial distance from the source. A study of the shock waves from various explosives has revealed that the peak overpressure varies with distance from the source and mass of explosive in the following manner:

$$P = 7.23 \times 10^3 \frac{M^{1/3}}{S} - 1.04 \times 10^5 \frac{M^{2/3}}{S^2} + 1.24 \times 10^6 \frac{M}{S^3}$$

where: P = peak overpressure in wave, lb/sq ft

M = mass of explosive expressed as lbs of TNT

S = radial distance from the center of explosion, ft

This equation, which was determined experimentally, is applicable for distances close to the explosive as well as far away, since it yields the pressure of the hot gas cloud at distances less than $S_c$. The third term in the equation is predominant at small values of S, indicating that close to the source the peak pressure is directly proportional to the size of the explosion and inversely proportional to the third power of the distance; this corresponds approximately to uniform expansion of the hot gas cloud. At long range the initial term in the equation is predominant, indicating that the peak overpressure is decreasing linearly with distance and as the cube root of the size of the blast. Although the peak overpressure decreases linearly with distance, the wave pressure contour changes such that the wave becomes progressively less energetic with the inverse square of the distance from the source.

The destructiveness of a shock wave depends on the overpressure and the impulse (the product of the pressure and the time in which the pressure is exerted) of the wave. The author has chosen to use the energy behind a square foot of the wave front rather than the impulse as a damage criterion, since insufficient data are available to perform the integration necessary if the impulse criterion is used. A structure is always destroyed by the impulse it receives from or the energy absorbed from the blast wave. No amount of impulse or energy, however, will be effective in causing damage unless the pressure associated with it is above a critical value. Certain brittle structures, such as windows or concrete block walls, may be destroyed by such a small amount of energy that the peak overpressure can

often be considered as the sole damage criterion. The conditions of failure of such peak overpressure sensitive structures are shown in Table 4. Both the energy and overpressure are necessary to destroy large or ductile structures.

If the energy of a shock wave is significantly larger than that required to destroy a structure which might tend to contain the wave, the structure will be destroyed almost instantaneously and will not appreciably affect the characteristics of the wave. Thus, the peak overpressure and energy of a wave outside of a relatively thin walled vessel or a relatively weak building may be calculated approximately by assuming that the wave has traveled through free air without encountering any obstacles. If the energy of the shock wave is not sufficient to destroy the containment vessel, part of the energy of the wave will be absorbed by the vessel and part will be reflected. In the event that a shock wave is reflected from a structure with a completely rigid surface, the instantaneous overpressure at the time of reflection of the wave is approximately twice the overpressure of the incident wave and very little of the energy of the wave is absorbed in the structure. For most practical structures which might tend to contain a shock wave, however, it can be assumed that all of the energy in the shock wave is absorbed in the structure.

Several methods are available for attenuating shock waves which are traveling through air-filled tubes such as ventilation ducts. They are:

1. Provide compressible material to absorb energy from the shock wave. Sand is a suitable material for attenuating pressures of approximately $10^5$ atmospheres. Redwood is effective for pressures of the order of 100 psi. Cellular structures and crumpled metal may be designed to be effective for various wave pressures.

2. Expand the tube into a larger volume. The pressure of the wave will decrease approximately proportionally with the ratio of the areas.

3. Provide bends in the tube. A 90° bend will decrease the shock wave pressure approximately a factor of 2.

## III-2 Shockless Explosions

### Equilibrium Conditions

The adiabatic equilibrium pressure in a closed containment system can be calculated using the gas laws if heat of explosion, specific heats, and initial conditions are known.

### Transient Conditions

The transient pressure in a vented containment vessel may be evaluated by equating the accumulation of volume or pressure to the difference between input and output. The

Table 4. Conditions of Failure of Peak Overpressure - Sensitive Elements

| | Structural Element | Failure | Approximate Incident Blast Overpressure, lb/sq ft |
|---|---|---|---|
| 1. | Glass windows, large and small | Shattering, occasional frame failure | 70 - 150 |
| 2. | Corrugated asbestos siding | Shattering | 150 - 300 |
| 3. | Corrugated steel or aluminum paneling | Connection failure followed by buckling | 150 - 300 |
| 4. | Brick wall panel, 8-12 in. thick (not reinforced) | Shearing and flexure failure | 1000 - 1150 |
| 5. | Wood siding panels, standard house construction | Failure at main connections allowing a whole panel to be blown in | 70 - 150 |
| 6. | Concrete or cinder-block wall panels, 8-12 in thick (not reinforced) | Shattering of the wall | 300 - 450 |
| 7. | Pleated glass filters | Rupture | 40 - 80 |
| 8. | Three 1-in. laminations of annealed 4 x 4-ft plate glass | Possible fracture | 2500 |
| 9. | Three 1-in. laminations of tempered 4 x 4-ft plate glass | Possible fracture | 9000 |

input can be due to gas flow, input work, or heat. The output can usually be evaluated knowing the characteristics of the venting system. The equation usually has the following form:

$$\frac{dp}{dt} = F(t) - F'(p, t)$$

where: p = pressure

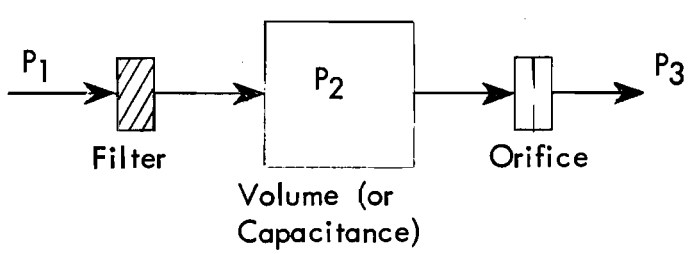
t = time

The following table lists some types of transient pressures that have been analyzed:

| | System | Reference |
|---|---|---|
| 1. | Input rate = 0 (sudden rise to peak pressure) | ORNL-3086 |
| 2. | Input rate = constant | ORNL-3086 |
| 3. | Input rate equivalent to constant heat release | ANL-5987 |
| 4. | Input rate equivalent to exponential heat release | LA-1441 |

Systems 1 and 2, which were evaluated by Perona, Dunn, and Johnson, are particularly applicable for evaluation of transient pressures within process cells following an explosion or rupture of a high pressure process line. A set of differential equations may be derived for a given cell ventilation system relating pressures, volumes, and resistances to flow. The equations for practical ventilation systems will usually be nonlinear so that solution on an analog computer may be expedient.

The method of derivation of the differential equations may be illustrated with reference to a schematic segment of a ventilating system:




The resistance to flow of the filter is given by Darcy's equation, which may be simplified for fixed filter thickness and fixed fluid viscosity to

$$Q = (P_1 - P_2)/R_F \qquad (1)$$

where: $Q$ = flow rate

$P_1 - P_2$ = pressure drop across filter

$R_F$ = resistance of filter

The resistance to flow of the orifice is given by

$$Q = (P_2 - P_3)^{1/2}/R_o \tag{2}$$

where: $P_2 - P_3$ = pressure drop across orifice

$R_o$ = resistance of orifice

In the case of unsteady flows, input - output = accumulation and

$$\frac{P_1 - P_2}{R_F} - \frac{(P_2 - P_3)^{1/2}}{R_o} = \frac{dN}{dt} = \frac{V}{RT}\frac{dP_2}{dt} \tag{3}$$

where: $N$ = number of moles of air in the capacitance

$t$ = time

$V$ = volume of capacitance

$R$ = gas constant

$T$ = temperature

It is usually appropriate to assume that no pressure drop occurs in duct work and that the ideal gas law is valid. Note that the steady state pressure relation is obtained on setting $dN/dt$ equal to zero. Proceeding in the same way, equations may be written for each capacitance in the ventilation system. Valves may be treated as orifices. Values for the resistance constants may be obtained from steady state data. Special items such as blowers and automatically controlled valves may also be taken into consideration knowing their time response to given pressure perturbations.

When pressure drop can change sign across an orifice or valve, the application of equation (2) can result in some difficulty because the sign change occurs within the square root radical and results in an imaginary number rather than changing the sign on Q. In these cases, where flow can occur in either direction, equation (2) should be replaced by:

$$Q = \frac{P_2 - P_3}{R_o} \left( \left| P_2 - P_3 \right| \right)^{-1/2} \tag{2'}$$

The square root circuitry using a servomultiplier achieves the results of equation (2').

Impulse perturbations may be introduced by instantaneously changing the pressure in the capacitance in question. Where the analog computer is used, this was done by changing the initial condition setting on the integrating amplifier in question to a value higher than the steady-state value before switching the computer to the "operate" position.

The introduction of a constant-rate air source to the capacitance in question is termed a "ramp perturbation." This is done by adding a constant to the differential equation describing the behavior of a capacitance. For example, the behavior of the schematic system during a ramp perturbation would be described by

$$\frac{dP_2}{dt} = \frac{RT}{R_F V} (P_1 - P_2) + K - \frac{RT}{R_o V} (P_2 - P_3)^{1/2} \tag{3}$$

in which K has the units in. $H_2O$/sec.

The total amount of gases leaked out of a cell during the period when it is above atmospheric pressure may be calculated from

$$L = \frac{1}{R_L} \int_o^t (P)^{1/2} \, dt \tag{4}$$

where: L = outleakage, $ft^3$

$R_L$ = resistance, (in. $H_2O)^{1/2}/(ft^3/sec)$

P = pressure relative to atmospheric, in. $H_2O$

and zero to t is the time in seconds during which P is larger than zero. $R_L$ can be calculated from equation (2) if the inleakage rate is known during steady-state operation.

## III-3 Nuclear Excursions

Current experience and calculations concerning the effects of accidentally-incurred nuclear excursions cause them to be thought of as a special case of a "shockless" explosion. Since such excursions as may be expected to occur in radiochemical processing facilities will have burst durations in the order of milliseconds, any shock waves that result will

generally be less destructive than the inherent gas pressure.

It is currently believed that the maximum burst from a homogeneous solution or water-moderated supercritical assembly will be equivalent to the order of $10^{12}$ fissions per cc of solution. In a 1000-liter vessel this burst would be equivalent to $10^{18}$ fissions, which releases 30,000 Btu of heat and 4 cu ft of radiolytic gas. The calculations by Heap indicate that a pressure of the order of 10 atmospheres or more could be developed within the excursion vessel and would probably cause it to rupture.

# APPENDIX IV

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