RELEASE FRACTION OF PWR AFTER SEVERE ACCIDENTS

MOUSTAFA AZIZ and El- MESSAIRY

National Center for Nuclear Safety and Radiation Protection

P. O. Box 7551 , Cairo , Egypt

ABSTRACT

The aerosol dynamics equation is solved in a closed system to simulate the release of aerosol from containment to the outside atmosphere in the case of containment failure , the factors that affect the release fraction is studied . It is found that early failure time and higher pressure increase the release fraction, also the release is affected by the break area and the aerosol particle size.

INTRODUCTION

The fission fragments and gases are emitted after sever accidents resulting in core meltdown and core concrete interactions , these aerosols are transported and fill the reactor containment . With increasing the pressure above pressure design bases , a failure of containment may occur and subsequently these aerosols will release into the external environment leading to a source term of radioactivity that affect the safety of workers and public. The amount of aerosol which escape to the environment can be described by the release fraction which is defined as the total aerosol released divided by the initial aerosol in the containment. The factors that affect the release fraction are studied , these factors are containment pressure , failure time , break area and the size of aerosol particle .

Containment failure mode includes early failure and late failure.Early failure is defined as failure prior to or shortly after the core debris penetrates the reactor vessel,several accidents can lead to early failure like direct containment heating,steam explosions and hydrogen burning while gradual overpressurization results in late failure(1,2,3) .

The present study describes the physical and mathematical model, numerical method and input data , results and discussions , and finally the derived conclusions are presented.

PHYSICAL AND MATHEMATICAL MODEL

The radionuclides behaviour inside the containment can be described by the aerosol dynamic equation which is given by [3,4,5]

$$\frac{\partial n(v,t)}{\partial t} = \frac{1}{2}\int_0^v K(u, v-u)\, n(u,t)\, n(v-u,t)\, du - n(v,t)\int_0^\infty K(u,v)\, n(u,t)\, du - R(v,t)\, n(v,t) - \alpha(v,t)\, n(v,t) \qquad (1)$$

where

$n(v,t)dv$ = number of aerosol particles which have volume in the range between v and v+dv at time t per unit volume .

$K(u,v)$ = the coagulation kernel . ($cm^3\ s^{-1}$)

$R(v,t)$ = removal rate for particles of volume v at time t on the floor and walls due to diffusion and sedimentation. (s^{-1})

$\alpha(v,t)$ = leakage rate for transport of aerosol from the containment to the atmosphere. (s^{-1})

1- Coagulation Processes

The particles coagulate due to both Brownian and gravitational motion . For particles in the continuum regime the coagulation kernel is given by [4,6]

$$K(u,v) = 4\pi (D_1 + D_2)(a_1 + a_2)\, \epsilon_B + \pi\, (a_1 + a_2)^2\, |\, U_{s1} - U_{s2}\, |\, \epsilon_G \qquad (2)$$

Where:-

a_1 , a_2 particle radii of volume u,v respectively .

D_1 , D_2 diffusion coefficients for particles of radii a_1 , a_2

U_{s1} ,U_{s2} are Stokes terminal velocities for particles 1 and 2

ϵ_B Brownian collision efficiency which takes into account the effect of Van der Waals forces and viscous interaction.

ϵ_G gravitational collision efficiency , the detailed calculation of both ϵ_B and ϵ_G can be found in[4,7]

The first term on the right hand side is due to Brownian motion and the second term is due to gravitational settling.

2- Removal Processes

The particles are removed from the system due to gravitational settling and Brownian deposition at a rate given by [4,5,6]

$$R(v,t) = \left[\frac{A_G}{V} U_s + \frac{A_B}{V} \frac{D(v)}{\delta} \right] f_c \qquad (3)$$

where : R(v,t) are functions of the particle size, which is itself varying with time . A_G , A_B the area available for gravitational settling and Brownian deposition respectively, D(v) the diffusion coefficient for particle of volume v, V containment volume .

δ= diffusion boundary layer thickness .

f_c = Cunnigham correction factor , which enables Stokes drag to be used for large value of Knudsen number. U_s = Stokes terminal velocity $(=\rho_p d^2{}_p g/18\mu)$. g = gravitational constant , μ gas viscosity, ρ_p ,d_p density and diameter of aerosol particles.

3- Release term

The failure is described by break area A_o with diameter D_o through which the gases with mass flow rate W(t) leave the containment. The release continues until the pressure P(t) inside the containment will become equal to the atmospheric pressure P_o ; at this time the release stop.

Applying the continuity and energy equations with the following assumptions[7,8] :-

(a) validity of ideal gas laws.

(b perfect gas undergoes an adiabatic expansion through the break. (c) neglecting the friction between the gas and the walls.

(d) temperature is kept constant during the release.

(e) $A_o/A_c << 1$ (for small break , A_c containment area)

Therefore the pressure rate and mass flow rate is given by :

$$\frac{dP}{dt} = - \frac{A_o}{V}\sqrt{2RT}\, \psi\left(\frac{P_o}{P}\right) . P \qquad (4)$$

Where ψ is given by

$$\psi\left(\frac{P_o}{P}\right) = \sqrt{\left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{P_o}{P}\right)^{\frac{2}{\gamma}} - \left(\frac{P_o}{P}\right)^{\left(1+\frac{1}{\gamma}\right)}\right]} \ , if \ \left(\frac{P_o}{P}\right) \geq X_{crit}.$$

$$\psi\left(\frac{P_o}{P}\right) = \psi_{max.} = \sqrt{\frac{\gamma}{2}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \ , if \ \left(\frac{P_o}{P}\right) \leq X_{crit}.$$

and

$$W(t) = A_o\sqrt{(2mP)} \cdot \psi\left(\frac{P_o}{P}\right) \tag{5}$$

The coupling coefficient $\alpha(v,t)$

$$\alpha(v,t) = \frac{W(t)}{M(t)} \tag{6}$$

where

$$X_{crit.} = \left[\frac{2}{\gamma+1}\right]^{\frac{\gamma}{\gamma-1}}$$

P containment pressure , P_o atmospheric pressure. V containment volume , m(t) is the gas density . M(t) the mass of gas in the containment = m(t).V , R = gas constant , γ the ratio of isobaric to isocoric heat capacity(=1.4), W(t) mass of gas release to the environment through the break in the containment wall.

NUMERICAL METHODS AND INPUT DATA

The method of sectional representation(9,10,11) is used to solve the aerosol dynamics equation by dividing the particle size range into I (I=40) sections and dealing only with one integral quantity for each section ,then the resulting system of ordinary differential equations is solved by Runge-Kutta method .

In the case of containment failure equations 5,6 and 7 are solved simultaneously with equation 1 to calculate the coupling coefficient and pressure at every time step.As the containment pressure reaches atmospheric pressure the leakage term in equation (1) is neglected.

The particle diameter range from 0.1 μm to 100 μm is considered with lognormal initial distributions which are given by

$$n(v,0)=\frac{N_o}{\sqrt{2\pi\sigma}}\cdot\frac{1}{v}\cdot\exp[-\frac{1}{2\sigma}\ln^2(\frac{v}{v_o})] \qquad (7)$$

and the initial aerosol volume is given by

$$V(0) = \int_{v_{min}}^{v_{max}} n(v,0)\,v dv \qquad (8)$$

where ; N_o , v_o , σ are total initial number of particles per unit volume of the containment, initial average volume of particles , and standard deviation .

v_{min} and v_{max} are the minimum and maximum particle volume respectively. The containment dimensions are 50 m hight , 50 m diameter (table 1).

Two aerosol systems are considered to test the effect of aerosol particle size on the release fraction , the first have mean initial diameter 1 μm with total initial volume $V(0)=0.86327*10^{-4}$ cm^3 per unit volume of the containment, the second system have mean initial diameter 0.5 μm with total initial volume $V(0)=0.107907*10^{-4}$ cm^3 per unit volume of the containment.

The instantanuous release rate is given by

$$f(t)=\int_{v_{min}}^{v_{max}} \alpha(v,t)\, v\, n(v,t)\, dv \qquad (9)$$

and the total release fraction is given by

$$F(t) = \frac{1}{V(o)} \int_{t_o}^{t} \int_{v_{min}}^{v_{max}} \alpha(v,t)\, v\, n(v,t)\, dv\, dt \qquad (10)$$

The removal fraction is given by

$$R(t) = \frac{1}{V(o)} \int_{0}^{t} \int_{v_{min}}^{v_{max}} R(v,t)\, v\, n(v,t)\, dv\, dt \qquad (11)$$

Table (1) aerosol data (ref. 7)

aerosol density	1000 kg/m^3
initial distribution	Lognormal with standard deviation σ=1 and $d_o(0)$=1 μm or 0.5 μm
No. of sections	40 sections
Containment temperature	373 K
gas density	0.9449 kg m^{-3}
initial number N(0)	10^{14} particles $/m^3$

RESULTS AND DISCISSIONS

Fig. 1 shows the variation of pressure with time after containment failure for initial containment pressure 0.5 MPa with three different break area of diameter 1 m , 0.5 m , and 0.25 m. It is found that as the break area increases the containment depressurize faster .

Fig. 2 shows the relation of the instantanuous release with time after containment failure for initial containment pressure

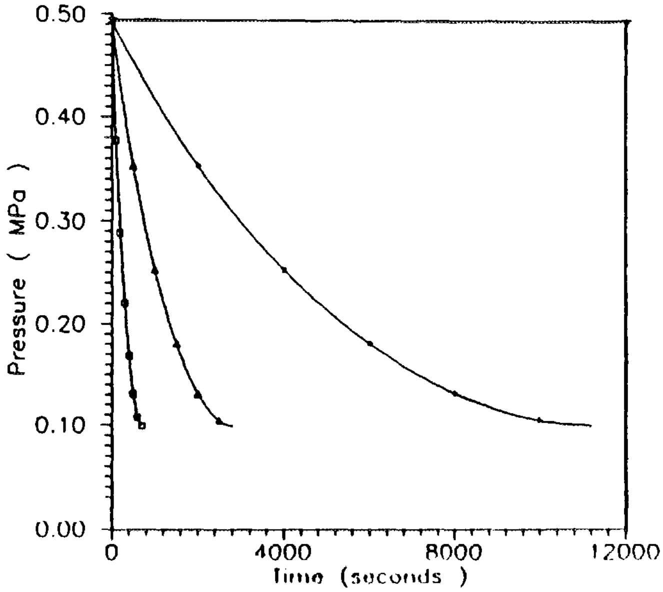

Fig. 1 the pressure after containment failure versus time for three break area , □ for 1 m diameter, ▵ for 0.5 m diameter and * for 0.25 m diameter

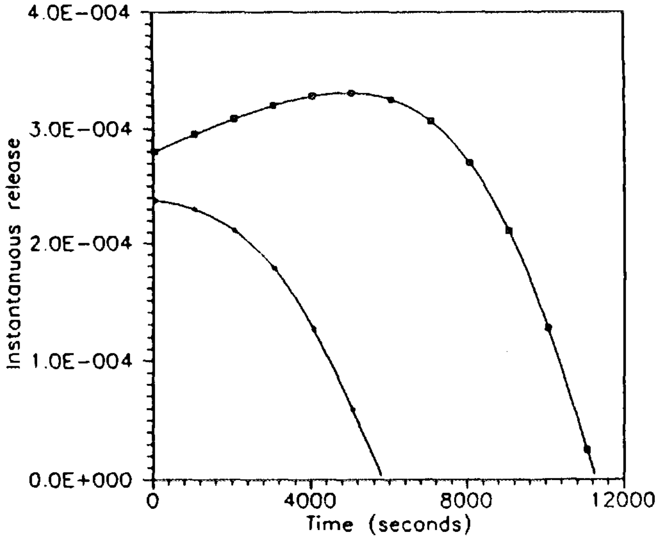

Fig. 2 the instantanuous release rate versus time for two initial containment pressure 0.5 MPa(□) and 0.2 MPa(*)

0.5 MPa and 0.2 MPa and break diameter 0.25 m .It is appear that the release rate increases as the pressure increase . The peak at the begining related to the release rate proportional to W(t)/M(t) and we can easly show that M(t) decrease fastly than W(t).

Figs. 3 and 4 show the dependence of the suspended and removal fraction with time for different containment pressure and different failure time t_o with lognormal initial condition of 1 μm mean initial diameter .

It is deduced that the suspended particles always decreases due to two types of removal:

1- removal by gravitalional settling and Brownian diffusion on the internal surfaces of the containment , this takes place at all times.

2- sudden decrease at the time of failure , this continue over the release period only.

The total removal of aerosol on the internal surfaces of the containment alwayes increase due to gravitational settling and Brownian deposition.

Parameters affecting release fraction

The parameters that affect the release fraction are , containment pressure , failure time , break area and the aerosol particle size.

1- Containment pressure

Fig. 5 shows that the release increase as pressure increase untill the saturation at relatively higher pressure occurs . Typical values are shown at table 2 , changing the pressure from 0.15 MPa to 0.3 MPa increases the release fraction by a factor of 2.25 , while changing from 0.3 to 0.8 increase the

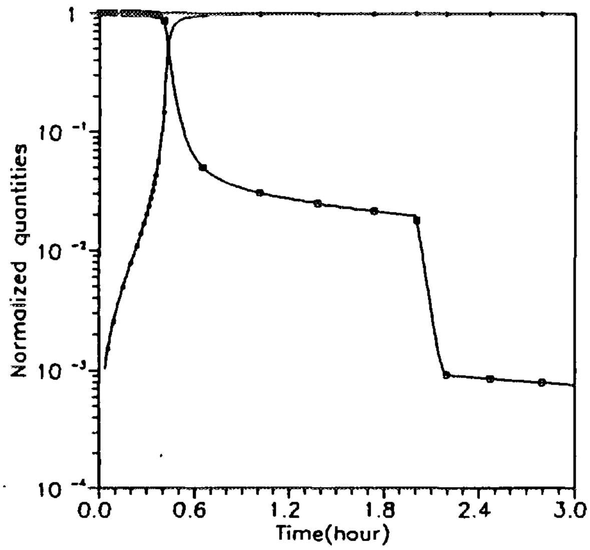

Fig.3 suspended (□)and removal ($_*$) fraction versus time , d_o (0) = 1 μm , P = 0.5 MPa and t_o = 2 hours and break diameter = 1 m.

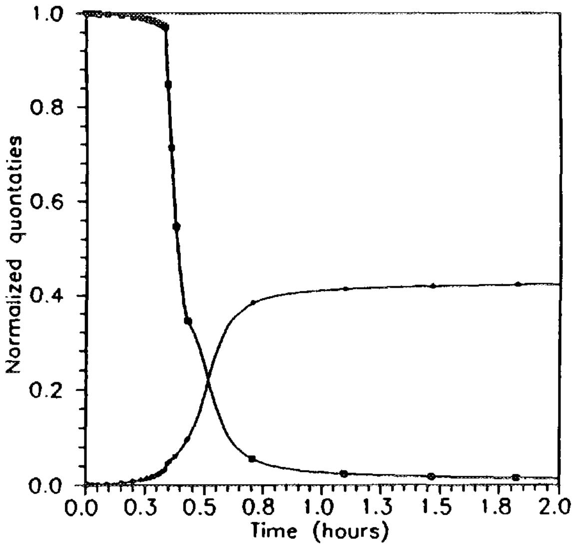

Fig.4 the suspended (□) , removal($_*$) fraction versus time , d_o (0) = 1 μm , P =0.2 MPa and t_o = 1200 second and break diameter = 1 m release by 1.2 only . Similiar results can be found for the third column at d_o = 0.5 μm.

2- Failure time

Fig. 6 shows the release fraction versus failure time for two aerosol systems . It is noticed that the release decrease if the containment failure delays , because this gives more time for the deposition of particles on the internal surfaces of the containment.

3- Break area

Fig. 7 shows the release fraction versus break diameter in (m) . It is shown that large containment break should lead to larger release than the smaller one , and after certain size of hole the release fraction would reach its maximum and saturation value.

4- Aerosol size

To study the effect of aerosol particle size on the release fraction , the previous results are prepared from two aerosol systems the first have mean initial particle diameter 1 μm with total initial volume V(0)=0.86327 10^{-4} cm^3 per unit volume and the second system have 0.5 μm mean initial particle diameter with total initial volume V(0) =0.107907 10^{-4} cm^3 per unit volume. The first aerosol system is bigger 8 time in volume than the second.

Figs. 5 and 6 show that small aerosol sizes have higher release fraction than the larger one . This due to that the small particles live long time in the containment atmosphere, while large particles settle faster under the effect of gravitational field.

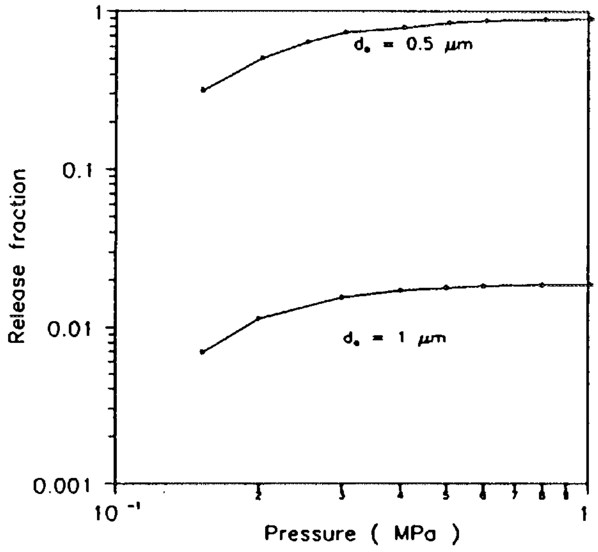

Fig. 5 the release fraction versus pressure for break diameter 1 m , failure time 2 hours , lognormal initial mean particle diameter 1 μm and 0.5 μm .

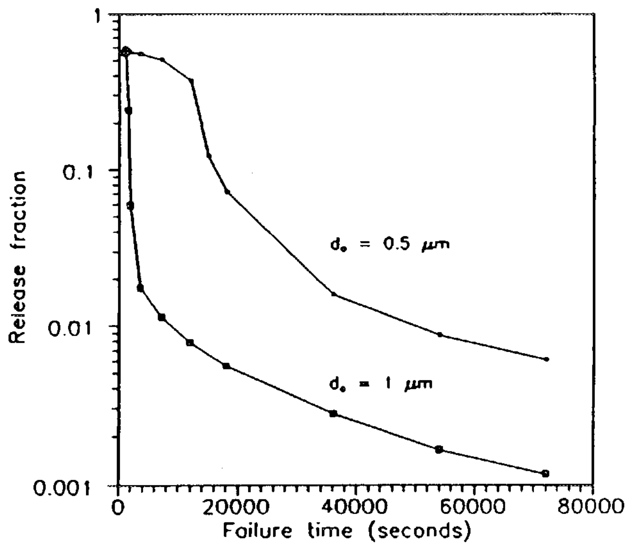

Fig. 6 the release fraction versus failure time for break diameter 1 m , pressure = 0.2 MPa , lognormal initial mean particle diameter 1 μm and 0.5 μm.

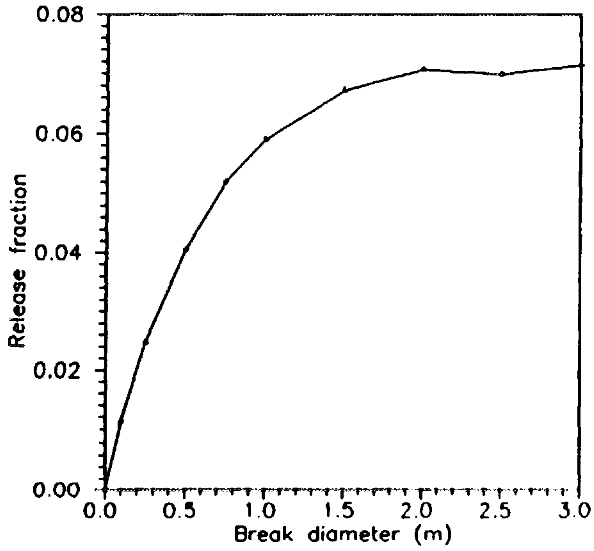

Fig. 7 the release fraction versus diameter of break area at initial pressure 0.2 MPa , failure time 1800 sec. lognormal initial mean particle diameter 1 μm .

Table 2 Release fraction at different pressures

Pressure (MPa)	release for $d_o(0)$ = 1 μm	release for $d_o(0)$ = 0.5 μm
0.15	0.688 E-2 *	0.317
0.3	0.155 E-1	0.73
0.8	0.186 E-1	0.885

* E-2 read 10^{-2}

CONCLUSION

1- The factors that affect the release fraction according to their importance are (a) failure time (b) containment pressure (c) break size (d) the size aerosol particles .

2- The release fraction deponds on the conditions of each accident it can be small value less than 0.001 or large values near from unity in worst conditions (higher pressure and early failure) like Chernobyl accident.

3- Larger values of the aerosol release fraction are observed for early containment failure than for later ones and higher containment pressure results in larger release fraction.

4- Small aerosol particles have greater chances to be released from the containment than larger ones.

5- The release can be minmized by designing the containment walls to withstand higher pressures and maintaining the inside atmosphere at lower pressure.

REFERENCES

(1)- B. De Boeck "review of Containment accidents" Nuc. Eng. and Design 145 , 279 (1993)

(2)-H. Jordan , P. M. Schumacher, J. A. Gieseke and K. W. Lee "Multiple Zone Aerosol Behavior Model" NUREG/CR -1294 , BMI-2042, 1980 , U. S. A.

(3)-D. R. Simpson,M. M. R. Williams and S. Simons "Modeling of an aerosol in Coupled Champers " Nuc. Sci. and Eng. 101 ,259 (1989)

(4)- A. M. Shahub and M. M. R. Williams . "The importance of Collision Efficiency in the Coagulation of Nuclear Aerosol Particles" Nucl. Tech. 86, 80(1989)

(5)- M. M. R. Wiliams and S. K. Loyalka "Aerosol Science , Theory and Practice" Pergamon Press , U. S. A , 1991

(6)- S. K. Friedlander "Smoke , Dust and Haze , Fundamentals of Aerosol Behavior" John Wiley & Sons , Inc 1977 , U. S. A.

(7)- Moustafa Aziz I. "PHD thesis" , Warsaw University of Technology 1994

(8)- Lewis "Nuclear Power Reactor Safety" , John Wiley , 1977

(9)- F. Gelbard , Y. Tambour , and J. H. seinfeld "Sectional Representations for Simulating Aerosol Dynamic" J. Colloid Interface Sci. 76, 541 (1980)

(10)-F. Gelbard and J. H. Seinfeld "Simulation of Multicomponent Aerosol Dynamics" J. Colloid Interface Sci. 78 , 485(1980)

(11)- F. Butuirat , M. Kielkiewicz and Moustafa I. "Method of sectional representation in aerosol dynamics "Kerntechnik, Oct. 1993