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STUDY ON COLLECTION EFFICIENCY OF FISSION PRODUCTS BY SPRAY : EXPERIMENTAL DEVICE AND MODELLING

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ABSTRACT

Consequences of an hypothetical overheating reactor accident in nuclear power plants can be limited by spraying cold water drops into containment building. The spray reduces the pressure and the temperature levels by condensation of steam and leads to the washout of fission products (aerosols and gaseous iodine). The present study includes a large program devoted to the evaluation of realistic washout rates.

An experimental device (named CARAIDAS) was designed and built in order to determine the collection efficiency of aerosols and iodine absorption by drops with representative conditions of post-accident atmosphere. This experimental device is presented in the paper and more particularly :
- the experimental enclosure in which representative thermodynamic conditions can be achieved,
- the monosized drops generator, the drops diameter measurement and the drops collector,
- the cesium iodide aerosols generator and the aerosols measurements

Modelling of steam condensation on drops, aerosols collection and iodine absorption are described. First experimental and code results on drops and aerosols behaviour are compared.

NOMENCLATURE :

C	: concentration	$(mol.m^{-3})$
Cp	: calorific capacity	$(J.kg^{-1}.K^{-1})$
C_{th}	: heat accomodation coefficient	(-)
Cu	: Cunningham correction coefficient	(-)
d	: diameter	(m)
Dif	: diffusion coefficient	$(m.s^{-1})$
dm	: drop mass increase	(kg)
E	: collection efficiency	(-)
h	: heat transfer coefficient	$(W.m^{-2}.K^{-1})$
H_v	: enthalpy of water vaporization	$(J.mol^{-1})$
k	: mass transfer coefficient	$(m.s^{-2})$
L	: free path of gaseous molecules	(m)
m	: mass	(kg)
M	: molar mass	$(kg.mol^{-1})$

N	: mass flux density	($mol.m^{-2}.s^{-1}$)
P	: pressure	(Pa)
Psat	: saturation vapor pressure	(Pa)
q	: heat flux density	($W.m^{-2}$)
T	: temperature	(K)
v	: drop velocity	($m.s^{-1}$)
λ	: thermal conductivity	($W.m^{-1}.K^{-1}$)
ρ	: density	($kg.m^{-3}$)
μ	: dynamic viscosity	(Pa.s)

Dimensionless numbers :

Knusend number :	$Kn = \frac{2L}{d_p}$	(-)
Nusselt number :	$Nu = \frac{h.d_d}{\lambda}$	(-)
Prandtl number :	$Pr = \frac{Cp.\mu}{\lambda}$	(-)
Reynolds number :	$Re = \frac{\rho_g.v.d_d}{\mu_g}$	(-)
Schmidt number :	$Sc = \frac{\mu}{\rho.Dif}$	(-)
Sherwood number :	$Sh = \frac{k.d_d}{Dif}$	(-)
Stokes number :	$Stk = \frac{d_p^2.\rho_p.v}{9.\mu_g.d_d}$	(-)

Subscripts :

d	: drop
g	: gaseous
i	: gas-drop interface
I	: iodine
p	: particle
pot	: potential
vis	: viscous
w	: water
diffu	: brownian diffusion
difph	: diffusiophoresis
imp	: impaction
int	: interception
therph	: thermophoresis
tot	: total

I. INTRODUCTION

Consequences of an hypothetical overheating reactor accident in a nuclear power plant can be limited by spraying cold water drops into the containment building. The spray reduces the pressure and the temperature levels inside the containment building by steam condensation on drops. With this thermalhydraulic function, spray leads to the washout of fission products (aerosols and iodine) emitted in the reactor building atmosphere. Today, this spray system is taken into account in different safety codes, using washout rates which have been determined during global experiments. These washout rates provide conservative assumptions. This present study integrates into a large program devoted to the evaluation of more realistic washout rates. First, we develop an experimental device and a modelling in order to determine aerosols collection efficiencies and iodine absorption in severe accident representative conditions.

II. EXPERIMENTAL DEVICE

In order to comply with experimental device design requirements[1], different devices have been developped, tested and set up on CARAIDAS (figure 1) :
- experimental enclosure in which representative thermodynamic conditions could be achieved,
- the monosized drops generator, the drops diameter measurements and the drops collector,
- the cesium iodide aerosols generator, concentration and size distribution measurements.

II.1. Experimental enclosure

Experimental enclosure is a five meters high cylinder with an inner diameter of 0.6 meter. The vessel is heated up by circulating a thermofluid through the double-wall unit. This system is split into three sections to ensure uniform temperatures overall the vessel height. The vessel has 8 windows (100 mm diameter) and several penetrations (50 mm diameter) for instrumentation purposes.
The thermofluid circuit comprises :
- a pump with a flow rate of 12 m^3/h,
- an electric heater (40 kW) using a PID regulation can heat up the thermofluid at a maximum of 160°C. The temperature in the main pipe is monitored by two sensors (Pt100, class A),
- the thermofluid repartition into the three sections is ensured by one valve and one flow meter for each section.

Homogeneous thermodynamic working conditions are obtained by using an air-steam circulation with:
- a varying flow rate fan (0 to 50 m^3/h),
- an electric heater (5 kW), using a PID regulation, can heat up air-steam mixture with a temperature range between 20 to 160°C ; the temperature is monitored by two Pt100 sensors (class A),
- an absolute pressure PID regulation in the range of 1 to 8 bars is carried out by using two valves (one for pressurized air alimentation and one for release),

The steam saturation rate in the vessel is also controlled by a PID regulator. Steam is produced by an electric generator and injected using a valve controlled by the regulator. Steam saturation rate range is between a few per cent and 95 %. Highest saturation limit is 95 % to avoid condensation particularly on windows.

This air-steam circulation ensures a good mixture in the vessel. When nominal working conditions (P, T, S) are reached, air-steam circulation is stopped and then the vessel is isolated by two valves. Several sensors are installed on the vessel to check air-steam mixture homogeneity :
- five gas temperature sensors (Pt100, class A),
- three inner vessel wall sensors (Pt100, class A),

- one pressure transducer (0-10 bars),
- three steam saturation ratio measurements by dew point measurement,
- one steam partial pressure measurement by sampling some gas and condensation by cooling.

All of these experimental data are displayed and saved by using a PC supervisor.

II.2. Drops devices

Drops generator is above the experimental enclosure because this device must be at ambient temperature and this, whatever enclosure temperature. In order to produce monosized drops, the generator (figure 2) is based on a break-up process of a jet into drops by applying a periodic disturbance. This principle of generation induces a one drop diameter spacing. This small drops spacing is not large enough to avoid drops coalescence, so an electrostatic sorting out drops is set up. A stream of uniformly charged drops is shaped by applying a potential difference between a ring electrode and the feeding tube. When a negative impulsion is applied to the ring electrode, an uncharged drop is produced. The deflection plates placed downstream, which are under electrical potential difference, create an electric field. Charged drops passing through this electrical field are deflected and collected. Uncharged drops are not deflected and they are injected in the experimental enclosure. The rate of injection of uncharged drops is variable from 1 to 1/1000. This device is able to produce monosized water drops with a diameter between 100 and 500 μm. Drops injection temperature is measured by a Pt100 sensor on the feeding tube. Drops injection temperature can be set between 20°C to 80°C by a small electric heater.

After injection in the vessel, drops diameter is modified by steam condensation or evaporation as function of thermodynamic conditions. So, three drops diameter measurements are forecast for three falling drops heights: z=0, z=2.51 and z=4.39 meters. These measurements are based on drops shadows axial transmittance. A stroboscopic incoherent light source is placed in front of linear camera (CCD). When a drop comes in front of the CCD camera, analogic signals from photodiodes are obtained and then numerized. Numerical drop shadow is processing in order to calculate the real drop diameter.

At the end of the fall, drops must be collected to measure aerosols mass in drops, so a drops collector ensures three functions :

- drops collection,
- dynamic containment of drops collection surface,
- sample output.

Drops are collected on fiberglass filters, 80 mm diameter, 1.55 mm thickness and temperature proof under 200°C. These filters can soak up water drops volume (a few milliliters). The collected aerosols mass by drops during fall is dissolved in 10 ml of distilled water and measured by fluorimetric method. Aerosols sedimentation on collection surface is avoided by a dynamic containment : clean air is blown throught collection filter and get back by a circular aspiration on the top of the dynamic containment device not to modify aerosols concentration in the experimental vessel. Extraction of several samples during test is been able by a pressure thruster which shifts drops collector from experimental vessel to the SAS where it can be brought out and put a new drops collector in place.

II.3. Aerosols devices

Aerosols generation is based on mechanical spraying by rotative disk, of cesium iodide solution tagged by soda fluorescein. Rotational device is an air turbine because high rotation speed is needful

(3000 rounds per second). Rotation speed is set by air pressure inlet the turbine and monitored by an electromagnetic indicator. Spraying disk (8 mm diameter) is fed up with cesium iodide solution with steady state flow rate. Sprayed droplets diameter which is function of rotation speed and solution flow rate, is about 20 μm. After evaporation, dry aerosols diameter is function of cesium iodide concentration :

$$d_p = d_{droplet}\left(\frac{[ICs]_{solution}}{\rho_{ICs}}\right)^{1/3} \qquad \text{eq.1}$$

With this specific generator, it is possible to produce aerosols with temperature (20-160°C) and pressure (1-7 bars). Aerosols diameter range is between 0.5 and 5 μm with a geometric standard deviation lower than 1.7 and aerosols mass flow rate is roughly 0.1 g/h.

Four aerosols samples are set up on experimental enclosure to check homogeneity of concentration and particles size distribution. Aerosols concentrations are measured on fiberglass filters of 25 mm diameter. Each sample is going on one or two minutes with a 1 l/min flow rate. The filtered aerosols mass is measured by fluorimetric method.

Particles size distribution measurements are given by inertial impactor in vessel pressure and temperature conditions. Aerosols are discriminated among eight size ranges corresponding to aerodynamic diameters from 0.35 to 7.5 μm. Data processing is performed by a classical log-probability graph. This method gives aerosols mass median diameter and geometric standard deviation.

This experimental device allows to measure experimental drops diameter evolution and collected aerosols mass by drops as function of different experimental conditions representative of severe accident scenarios. At the same time we develop a modelling of this experimental device.

III. Modelling

Drops characteristics (temperature, size, iodine and particles concentration) are modified during the fall. Three phenomena of transfer between the gas and the monosized drops are to be modelled :

- heat and steam transfer,
- gaseous iodine transfer,
- particles collection.

Steam condensation, iodine absorption and particles collection are coupled together because some of collection mechanisms depend on steam condensation flow rate.
The basic assumption of these following models is that water drops are supposed independant.

III.1. Steam and heat transfer

Steam and heat transfer from the gaseous phase to the liquid one is modelled by the double film theory (figure 3). Steam mass transfer is located in the gaseous film and heat transfer takes place through the whole double film. Beyond this double film, temperatures and concentrations are supposed steady.

The steam flow rate is the following one : $N_w = k_{g,w} \times \left(\frac{P_w}{RT_g} - \frac{Psat(T_i)}{RT_i}\right)$ eq.2

where $k_{g,w}$ is the ratio between the diffusion coefficient of steam in air and the thickness of the gaseous film. This transfer coefficient is computed thanks to a correlation given by BEARD and PRUPPACHER[2]: $Sh_{g,w} = 1.61 + 0.718 \times Re_d^{1/2} \times Sc_{g,w}^{1/3}$

The heat flow rate through the gaseous film is :

$$q = \underbrace{h_g \times (T_g - T_i)}_{\text{convective exchanges}} + \underbrace{N_w \times H_v}_{\text{condensation contribution}}$$

h_g is also computed by a correlation (BEARD and PRUPPACHER[2]) :

$$Nu_{g,w} = 2 + 0.69 \times Re_d^{1/2} \times Pr_g^{1/3}$$

This flow rate q is equal to the one of the drop side : $q = h_d \times (T_i - T_d)$

h_d is computed by HENDOU's correlations[3].

Finally:
$$\underbrace{h_g \times (T_g - T_i)}_{\text{convective exchanges}} + \underbrace{N_w \times H_v}_{\text{condensation contribution}} = h_d \times (T_i - T_d) \qquad \text{eq.3}$$

So coupling equation eq.2 and equation eq.3, T_i and N_W are determined by a numerical method (Newton-Raphson). The knowledge of the steam flow rate and of the convective exchanges value allows to compute the drops growth during a lapse of time called dt :

$$d_d(t+dt) = \left(d_d^3(t) + \frac{6 \times d_d^2(t) \times dt \times N_w \times H_v}{\rho_d} \right)^{1/3}$$

Then drop heating is computed using the heat balance on the drop between t and t+dt :

$$m \times Cp_d \times dT_d = h_g \times (T_g - T_i) \times \pi \times d_d^2 \times dt + dm \times H_v$$

$$\text{with:} \quad dm = \frac{\pi \times d_d^2 \times dt \times N_w \times H_v}{\rho_d}$$

So :
$$T_d(t+dt) = T_d(t) + \frac{h_g \times (T_g - T_i) \times \pi \times d_d^2 \times dt + dm \times H_v}{m \times Cp_d}$$

III.2. Iodine transfer

The energetic iodine flow rate contribution is disregarded. Iodine transfer from the gaseous phase to the liquid one is firstable controlled by diffusion through the gaseous film, since by the thermodynamic equilibrium between the both phases which depends on the temperature at the interface, and at least by chemical reactions which take place into the drops.

At low steam flow rates, iodine transfer through the gaseous film is estimated as :

$$N_I = k_{g,I} \times (C_{g,I} - C_{gi,I})$$

This flow is equal to the one through the liquid film : $N_I = k_{d,I} \times (C_{di,I} - C_{d,I})$

Finally :
$$k_{g,I} \times (C_{g,I} - C_{gi,I}) = k_{d,I} \times (C_{di,I} - C_{d,I}) \qquad \text{eq.4}$$

The unknown values are C_{gi} and C_{di}. They are linked by the thermodynamic equilibrium at the interface and by chemical reactions. Hydrolysis of molecular iodine and HOI dissociation are only considered. The other reactions are slow regarding to the fall time of drops (few seconds in CARAIDAS).

- gas-liquid equilibrium : $I_{2,gas} \leftrightarrow I_{2,liq}$ $$Ki = \frac{[I_{2\,liq}]}{[I_{2\,gas}]} \quad \text{eq.5}$$

- iodine hydrolysis : $I_{2,liq} + H_2O \leftrightarrow HOI + I^- + H^+$ $$K_1 = \frac{[HOI] \times [I^-] \times [H^+]}{[I_{2,liq}]} \quad \text{eq.6}$$

- hypoiodous acid dissociation : $HOI \leftrightarrow OI^- + H^+$ $$K_2 = \frac{[OI^-] \times [H^+]}{[HOI]} \quad \text{eq.7}$$

The concentration in protons is supposed to be a constant value. The reaction equilibrium constants are given by GAUVAIN and FILIPPI[4].

Equations eq.5 and eq.6 allow to express $C_{di,I}$ (which is : $[HOI]+[OI^-]+[I^-]+[I_{2,liq}]$) as a function of $C_{gi,I}$:

$$C_{d_i,I} = Ki \times C_{g_i,I} + 2 \times \frac{\sqrt{K_1 \times \left(K_2 + [H^+]\right) \times Ki \times C_{g_i,I} \times 1000}}{[H^+]}$$

This expression is used in the place of C_{di} in equation eq.4. Solving equation eq.4 provides C_{di} and so N_I. At least, the updated concentration in iodine into the drop is computed :

$$C_{d,I}(t+dt) = C_{d,I}(t) + \frac{\pi \times d_d^2(t) \times dt \times N_I}{\left(\frac{\pi \times d_d^3(t)}{6}\right)}$$

III.3. Particles collection

Aerosols collection models are completly different than those for iodine absorption. They are based on semi-empirical correlations to calculate collection efficiencies for different mechanisms. Collection efficiency is defined as the ratio of aerosol mass collected by a drop and the aerosols mass in swept out volume. Five mechanisms of particles collection are listed :
- impaction
- interception
- diffusiophoresis
- thermophoresis
- brownian diffusion

Mechanical effects

- *impaction* : drops fall induces fluid flow variations. High inertia particles turn off flow lines around the drop and then are collected on the drop. The efficiency of this mechanism increases with drop velocity and particle mass. POWERS and BURSON[5] suggest :

$$E_{imp} = \frac{E_{vis,imp} + \dfrac{Re_d\, E_{pot,imp}}{60}}{1 + \dfrac{Re_d}{60}}$$

if $Stk \leq 0.0833$ then $\quad E_{pot,imp} = 0$

if $0.0833 \leq Stk \leq 0.2$ then $\quad E_{pot,imp} = 8.57\left(\dfrac{Stk}{Stk + 0.5}\right)^2 (Stk - 0.0833)$

if $Stk \geq 0.2$ then $\quad E_{pot,imp} = \left(\dfrac{Stk}{Stk + 0.5}\right)^2$

if $Stk \leq 1.214$ then $\quad E_{visc,imp} = 0$

if $Stk \geq 1.214$ then $\quad E_{visc,imp} = \left(1 + \dfrac{0.75 \ln(2\,Stk)}{Stk - 1.214}\right)^{-2}$

- *interception*: this mechanism is only based on a geometric effect. If a particle on a flow line meet the drop, it is collected. POWERS and BURSON[5] propose :

$$E_{int} = \frac{E_{vis,int} + \dfrac{Re_d\, E_{pot,int}}{60}}{1 + \dfrac{Re_d}{60}}$$

with $\quad E_{visc,int} = \left(1 + \dfrac{d_p}{d_d}\right)^2 \left[1 - \dfrac{1.5}{1 + \dfrac{d_p}{d_d}} + 0.5\left(1 + \dfrac{d_p}{d_d}\right)^3\right]$

and $\quad E_{pot,int} = 3\dfrac{d_p}{d_d}$

Phoretic effects : the temperature gradient and the steam flow around drops respectively induce thermophoresis and diffusiophoresis.

- *diffusiophoresis* : steam condensation on cold water drops induces a steam flow towards drops. This flow drags along particles. WALDMANN and SCHMITT[6] suggest a formula corrected by the ventilation coefficient of PRUPPACHER[7]:

$$E_{difph} = 4.f_v \frac{\sqrt{M_w}}{x_w\sqrt{M_w} + x_a\sqrt{M_a}} \frac{Dif_w}{V \times d_d} \ln\left(\frac{P - Psat(T_i)}{P - P_w}\right)$$

if $Sc_{g,w}^{1/3}.Re_d^{1/2} < 1.4$ then $$f_v = 2.\left(1 + 0.108\left(Sc_{g,w}^{1/3}\ Re_d^{1/2}\right)^2\right)$$

if $Sc_{g,w}^{1/3}.Re_d^{1/2} \geq 1.4$ then $$f_v = 2.\left(0.78 + 0.308\left(Sc_{g,w}^{1/3}\ Re_d^{1/2}\right)\right)$$

- *thermophoresis* : it occurs when particles set in a temperature gradient. Impacts of gas on the warm side are more important than on the cold side of the particle. As a result, this difference creates a force which drags along particles towards cold drops.

$$E_{therph} = \frac{4\,C_{th}\,\mu_g\,f_h\left(T_g - T_d\right)}{C_g\,T_g\,V.d_d}$$

C_{th} is the dimensionless coefficient of TALBOT[8] and f_h is the heat ventilation coefficient of PRUPPACHER[7]:

$$C_{th} = \frac{2 \times 1.147\left(\frac{\lambda_g}{\lambda_p} + 2.2\,Kn\right)Cu}{\left(1 + 3 \times 1.146\,Kn\right) \times \left(1 + 2\frac{\lambda_g}{\lambda_p} + 2 \times 2.2\,Kn\right)}$$

if $Pr_g^{1/3}.Re_d^{1/2} < 1.4$ then $$f_h = 2.\left(1 + 0.108\left(Pr_g^{1/3}\ Re_d^{1/2}\right)^2\right)$$

if $Pr_g^{1/3}.Re_d^{1/2} \geq 1.4$ then $$f_h = 2.\left(0.78 + 0.308\left(Pr_g^{1/3}\ Re_d^{1/2}\right)\right)$$

At least, we describe brownian diffusion collection by modelling efficiency as PRUPPACHER[7] suggests :

if $Re_d < 1$ then $$E_{diffu} = \frac{4 \times Dif_p \times 2\left(1 + 0.5\,Re_d^{1/2}\ Sc_p^{1/3}\right)}{V.d_d}$$

if $Re_d \geq 1$ then $$E_{diffu} = \frac{4 \times Dif_p \times 2\left(1 + 0.3\,Re_d^{1/2}\ Sc_p^{1/3}\right)}{V.d_d}$$

The total efficiency is supposed to be the sum of the five elementary efficiencies :

$$E_{tot} = \sum_{i=1}^{5} E_i(d_p)$$

The emitted particles are polydisperse. The efficiency is computed for each particle size class. So, for the whole distribution :

$$E = \sum_{d_p\,min}^{d_p\,max} E_{tot}(d_p) \times f(d_p) \times \log(\Delta d_p)$$

The collected particles mass during a lapse dt is :

$$M_p(dt) = \sum_{d_p\,min}^{d_p\,max} E_{tot}(d_p) \times f(d_p) \times \log(\Delta d_p) \times \frac{\pi\, d_d^2(t)}{4} \times v \times dt \times C_p$$

Finally, the mass collected during the drop fall is :

$$Mp = \sum_{t=0}^{t_{fall}} \left(\sum_{d_p\,min}^{d_p\,max} E(d_p) \times f(d_p) \times \log(\Delta d_p) \times \frac{\pi\, d_d^2(t)}{4} \times v \right) dt \times C_p$$

IV CODE RESULTS

From the modelling of the different phenomena involving in the washout of fission products by spraying water drops, the drops and particles behaviours in CARAIDAS are estimated.

IV.1. Drops behaviour

The different evolutions of drops diameter and drops temperature as function of falling height are plotted on the figures 4, 5 and 6. The thermodynamic conditions of gas are steady during the drop fall: 5 bars pressure, 140°C temperature and several steam saturation rates. The initial diameters are 100, 300, and 500 μm.

At the drop fall beginning, the steam flow rate and the heat flow rate induce growth and heating of drops. When the steam saturation rate is equal to 1, this condensation phenomenon occurs on a varying height (3, 20 and 60 centimeters) according to the initial diameter (100, 300 and 500 μm). When the steam saturation decreases, the condensation height also decreases. After, the diameter and temperature of the drops are steady if $S=1$. On the other hand, evaporation phenomenon appears if $S<1$: there is an equilibrium between the heat flow brought to the drop by convective exchanges and the heat flow lost by the drop because of evaporation. Thus, drop temperature is steady but the diameter decreases. We consider that the drop completely disappears when its diameter is smaller than five micrometers.

All these computations show that thermodynamic equilibrium between the drops and the gaseous mixture is quickly reached when the steam saturation rate is equal to 1. On the other hand, when the gas is not saturated ($S<1$), the temperature speedly becomes steady whereas there is no balanced size.

IV.2. Aerosols behaviour

The modelling of drops behaviour coupled with the correlations providing particles elementary collection efficiencies allows to compute the average efficiency on a 5 meters fall. Different experimental conditions and particles diameters are tested for 100 μm diameter drops :

- figure 7 : In this case of atmospheric conditions ($P=1$ bar and $T=20$°C) with $S=1$, phoretic effects are negligible. Impaction and interception are the main mechanisms for the largest aerosols. For the smallest ones, brownian diffusion collection is the main mechanism. As a result, the average total efficiency is minimal (10^{-3}) for the aerosols which the diameter is around 0.5 μm.

- figure 8 : For these conditions, characteristic of spray scenarios (5 bars, 140°C and S=1), phoretic effects are not any more negligible. Thermophoresis is always the minority effect whatever the particles diameter. Diffusiophoresis efficiency which does not depend on particles diameter is slightly higher than the other ones when the total efficiency is minimal. Impaction, interception and diffusion mechanisms efficiencies do not vary a lot as function of thermodynamic conditions.

- figure 9 : The conditions are the same than ones of figure 8 excepted the initial drop temperature which is 80°C in this case. These values square with a scenario of recirculation. Despite lower values, diffusiophoresis efficiency is always the higher effect when the total efficiency is minimal. The decrease is due to the lower difference between gas and drops temperatures at the top of the vessel. The steam flow rate is lower so phoretic effects decrease.

Similary calculations are plotted on figures 10, 11 and 12 for 500 μm diameter drops. For ambient conditions (figure 10), phoretic effects are also negligible. The minimal efficiency (10^{-3}) resulting from impaction, interception and brownian diffusion mechanisms, is placed for aerosols which the size is lower than 0.1 μm.
In conditions characteric of spray scenarios (figure 11 and figure 12), diffusiophoresis is the main effect for aerosols which the diameter is lower than 1 μm. Thus, the minimal efficiency reached 10^{-2} thanks to the phoretic effects.

The previous curves represent the average efficiencies on a five meters fall. But these efficiencies change a lot as function of falling height because of the evolution of the steam flow rate and the temperature gradients around drops.
On figure 13 and figure 14, all the efficiencies and drops temperature are plotted for two particles diameters : 0.1 and 5 μm. We clearly observe that the phoretic effects are very important at the beginning of the fall but stop when temperature becomes steady.
Mechanical effects, do not depend a lot on temperature, are almost steady during the fall. The slight variations are only due to the changing drop size and to the drop velocity evolution. The temperature equilibrium is quickly reached so the efficiencies steady values are close to the average values dropped on figure 11.

V. EXPERIMENTAL RESULTS

Acquisition of experimental results on the device CARAIDAS allows to qualify the modelling of the different phenomena involved in the fission products washout by spray.
We only present the first experimental results. At the moment, an important campaign of tests is going on.

The three falling height drops diameter measurements and drop behaviour modelling are plotted on the figures 15, 16, 17 and 18 for different experimental conditions. Each experimental drops diameter is the average value of about fifty experimental points. Because of the slight decrease of diameter in some tests, the average values are accompanied with a confidence interval. If n is the number of experimental measurements, x_i a measurement i and x_a the average value on the measurements, we obtain :

the estimated standard deviation: $$s=\sqrt{\frac{\sum_{n=1}^{n}(x_i-x_a)^2}{n-1}}$$

the confidence interval on x_a: $i = 2 \times \frac{2\,s}{\sqrt{n}}$

(there are ninetyfive chances in a hundred that x_a is included in this interval)

Any confidence interval is drawn because it is very small (a few micrometers) in relation to the drops diameter decrease. So we can conclude that experimental measurement decreases are significant.
There is a good agreement between calculations and experiments whatever thermodynamic conditions (figure 15, 16, 17 and 18). Even when the drop evaporates a lot (dry warm air on figure 18), the divergences between the code and the experimental data are low.
More experimental results, with condensation thermodynamic conditions, will be getting but we can expected a good agreement also.

VI. CONCLUSION

The experimental device CARAIDAS is operational for aerosols experiments, so particles collection efficiencies as function of different working conditions representative of severe accident will be determined. Experimental aerosols tests are going on. In the same time, we have developped a model. Experimental collection efficiencies and code results will be used in order to propose qualified collection efficiencies correlations. At the end of this program more realistic washout rates could be computed as function of accident scenarios. Iodine experimental tests will be done after aerosols tests.

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figure 1: Experimental device scheme

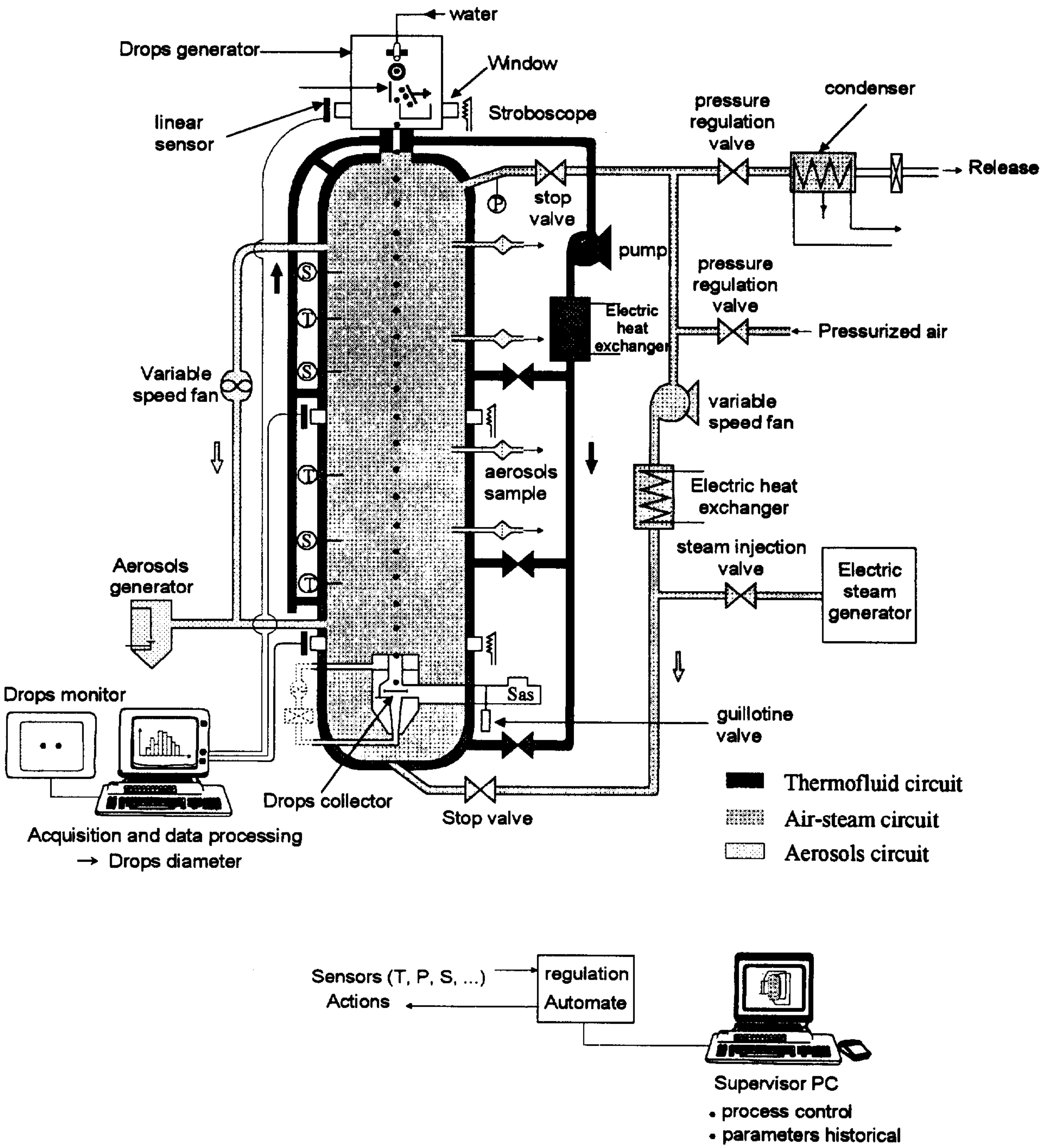


Figure 2 : Electrostatic sorting out drops generator

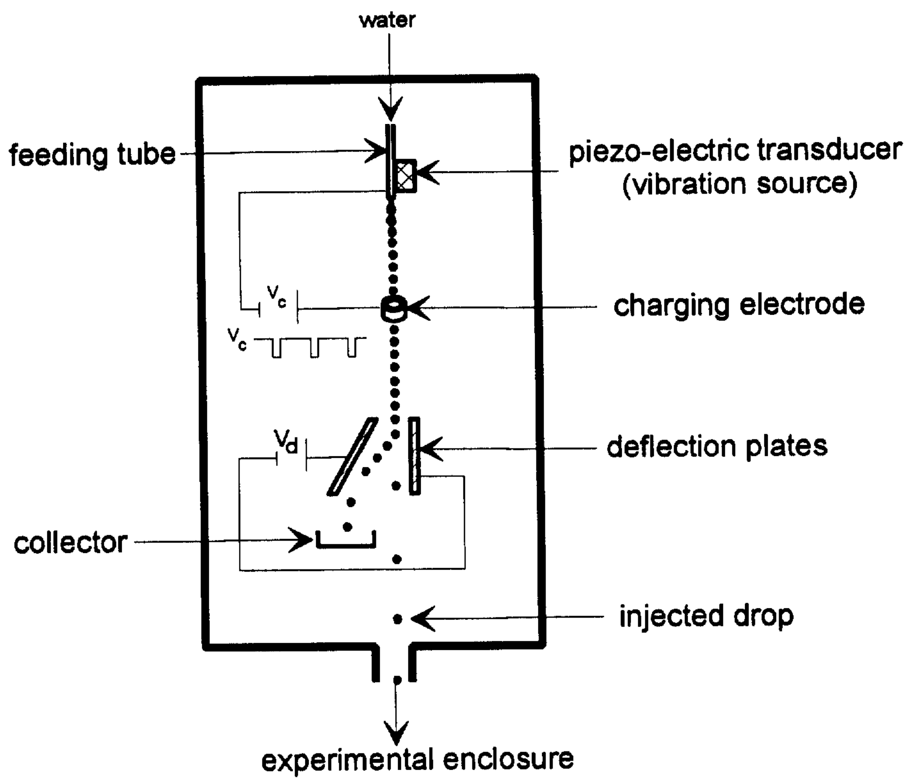


Figure 3: Double-film theory scheme

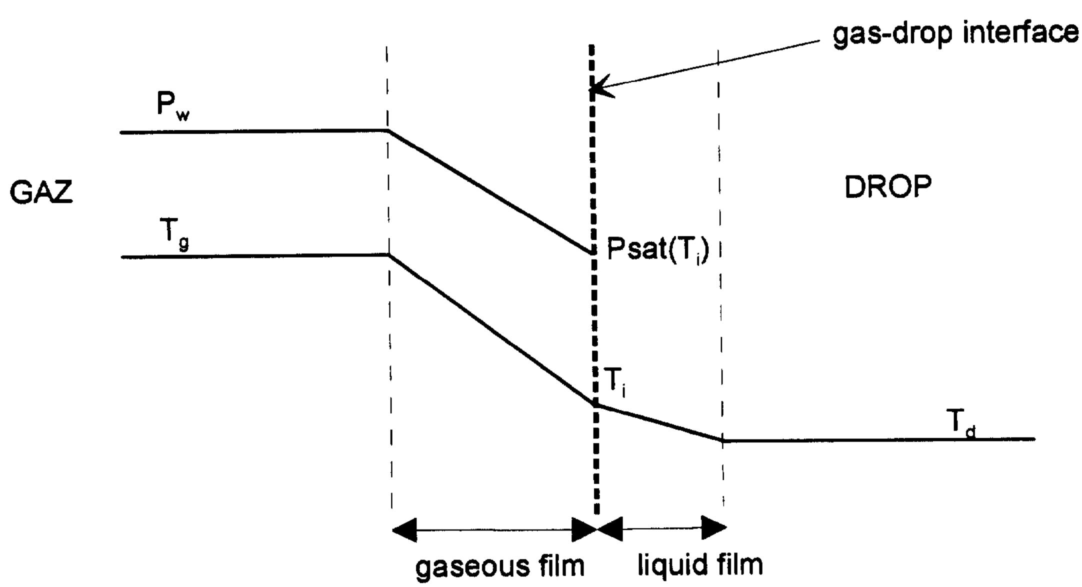


Fig. 4a: Drop diameter versus falling height - Initial drop diameter : 100 µm

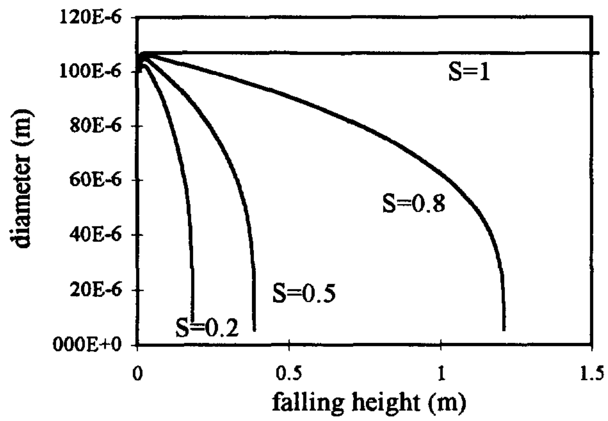


Fig. 4b: Drop temperature versus falling height - Initial drop diameter : 100 µm

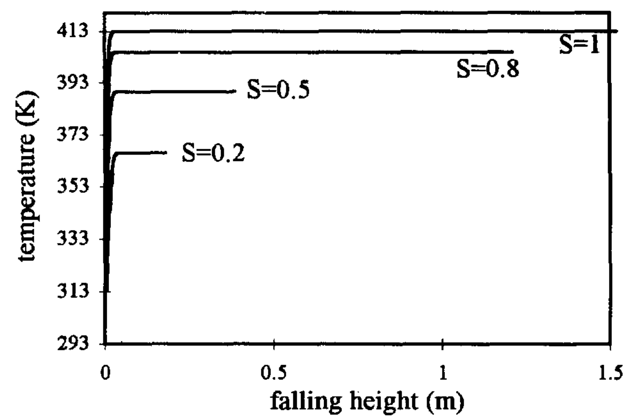


Fig. 5a: Drop diameter versus falling height - Initial drop diameter : 300 µm

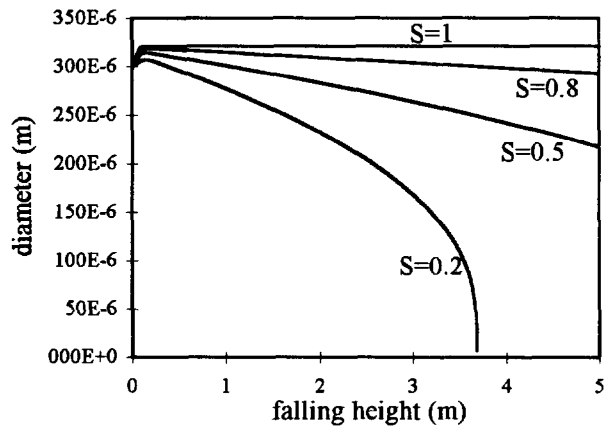


Fig. 5b: Drop temperature versus falling height - Initial drop diameter : 300 µm

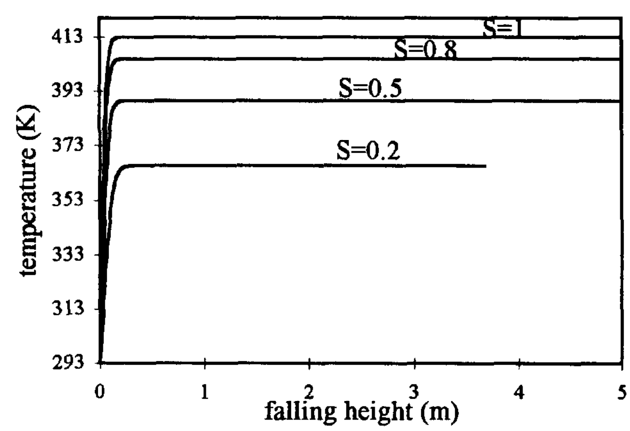


Fig. 6a: Drop diameter versus falling height - Initial drop diameter : 500 µm

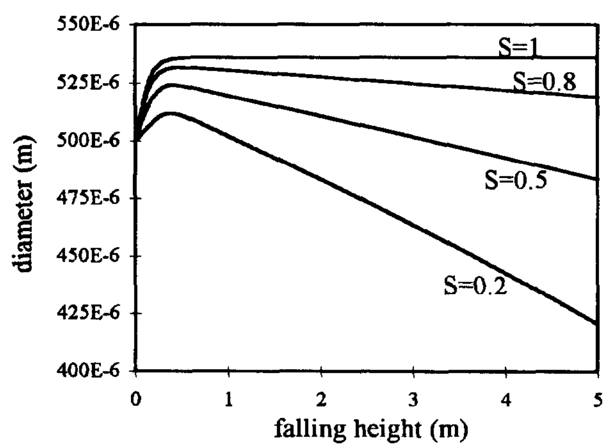


Fig. 6b: Drop temperature versus falling height - Initial drop diameter : 500 µm

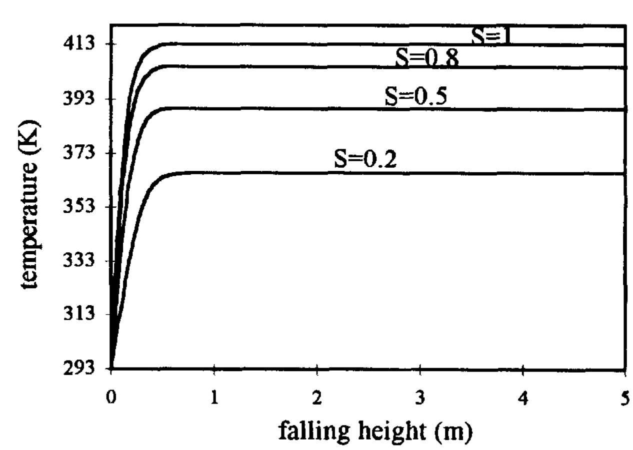


Figure 7: Collection efficiency versus aerosol diameter
P = 1 bar, Tdrop = Tgas = 20 °C, S = 1, Ddrop = 100 µm

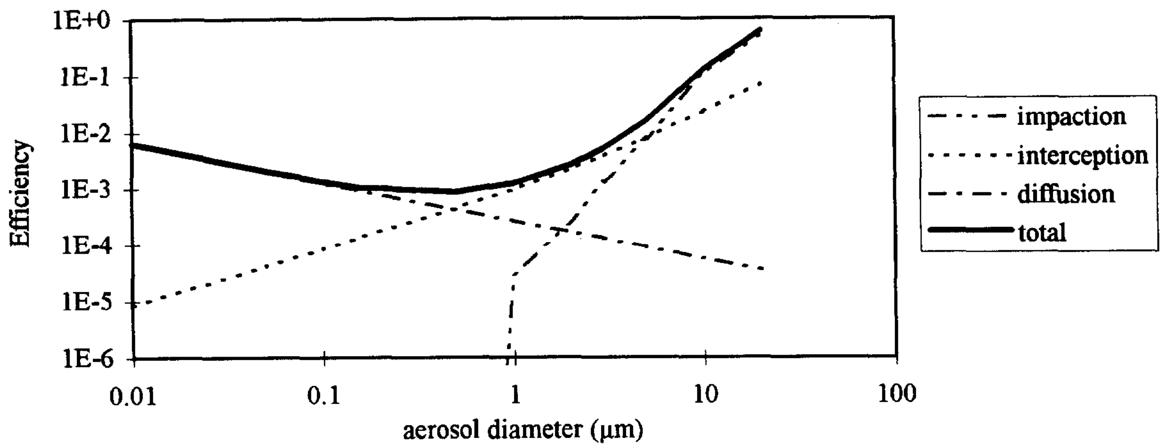


Figure 8: Collection efficiency versus aerosol diameter
P = 1 bar, Tgas = 140 °C, Tdrop = 20 °C, S = 1, Ddrop = 100 µm

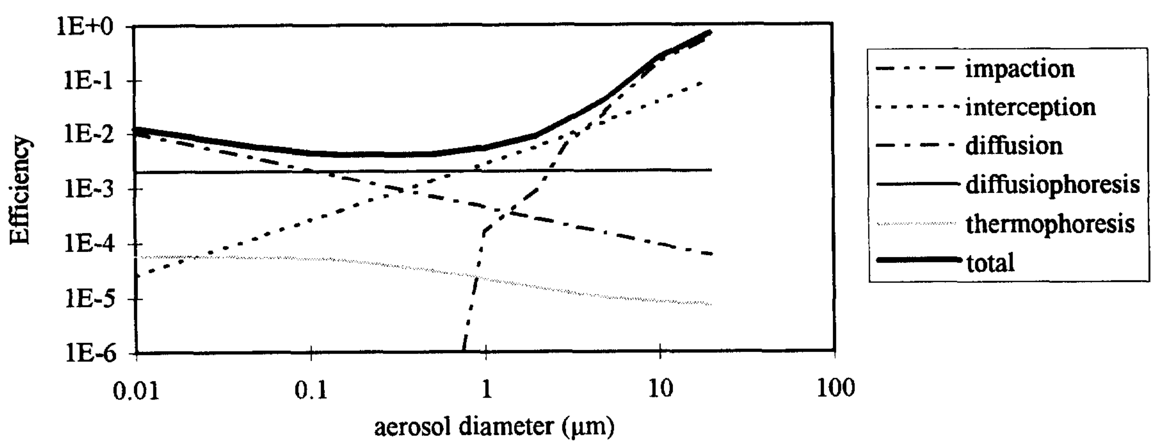


Figure 9: Collection efficiency versus aerosol diameter
P = 5 bars, Tgas = 140 °C, Tdrop = 80 °C, S = 1, Ddrop = 100 µm

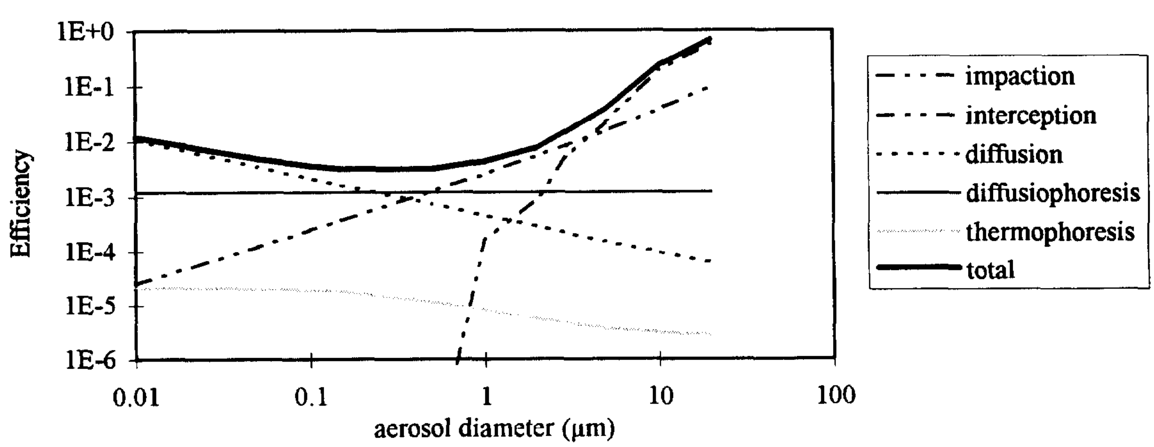


Figure 10: Collection efficiency versus aerosol diameter
P = 1 bar, Tdrop = Tgas = 20 °C, S = 1, Ddrop = 500 μm

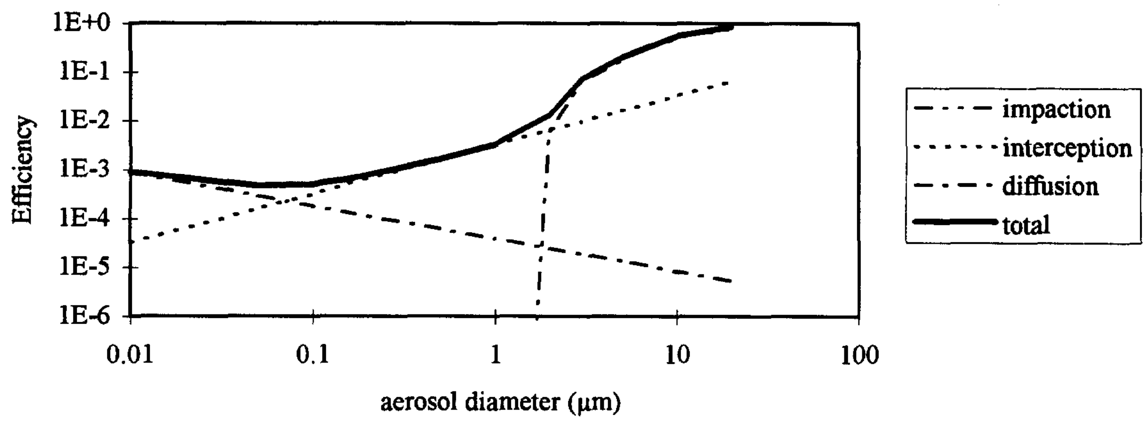


Figure 11: Collection efficiency versus aerosol diameter
P = 5 bars, Tgas = 140 °C, Tdrop = 20 °C, S = 1, Ddrop =500 μm

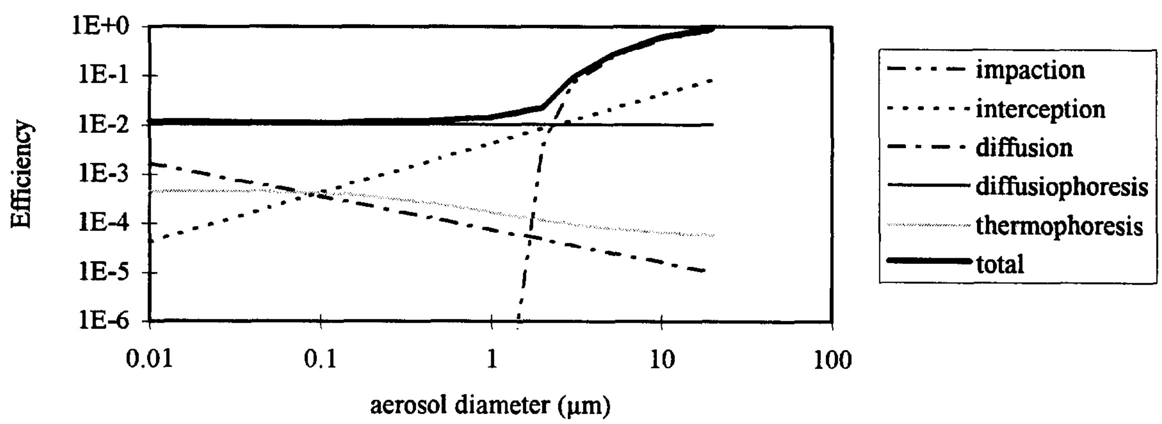


Figure 12: Collection efficiency versus aerosol diameter
P = 5 bars, Tgas = 140 °C, Tdrop = 80 °C, S = 1, Ddrop = 500 μm

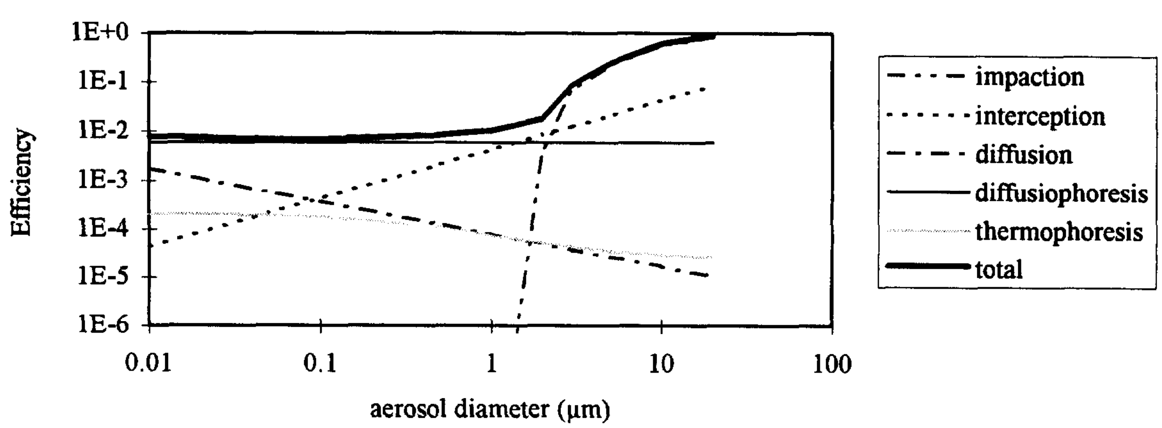


Figure 13: Elementary efficiency versus falling height
P = 5 bars, Tgas = 140 °C, Tdrop = 20 °C, S = 1
Ddrop = 500 µm, Daerosol = 0.1 µm

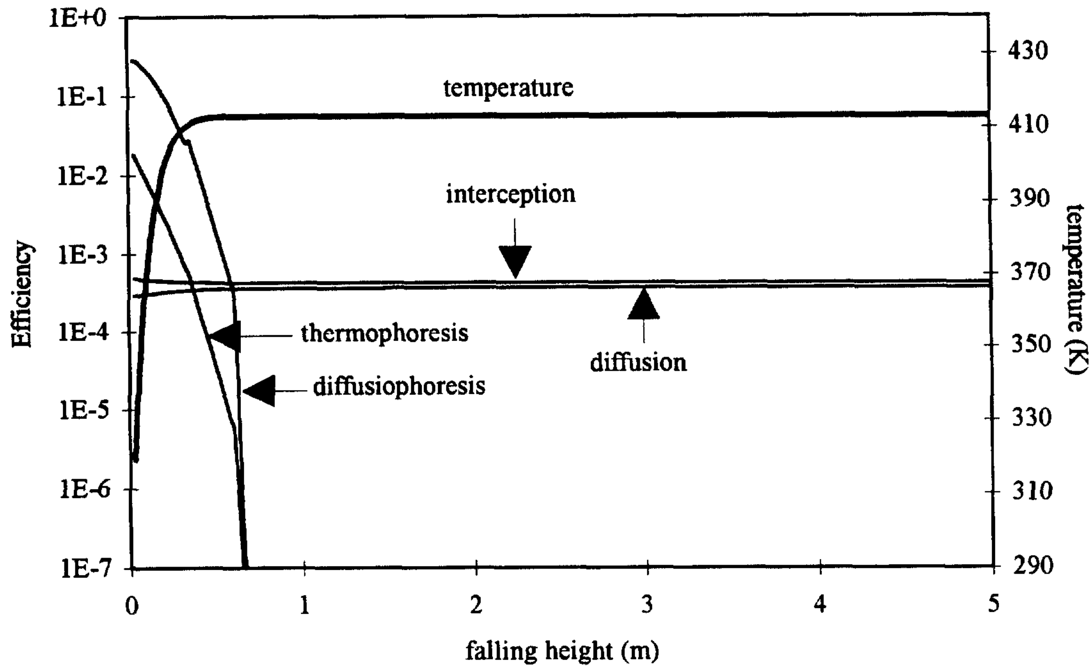
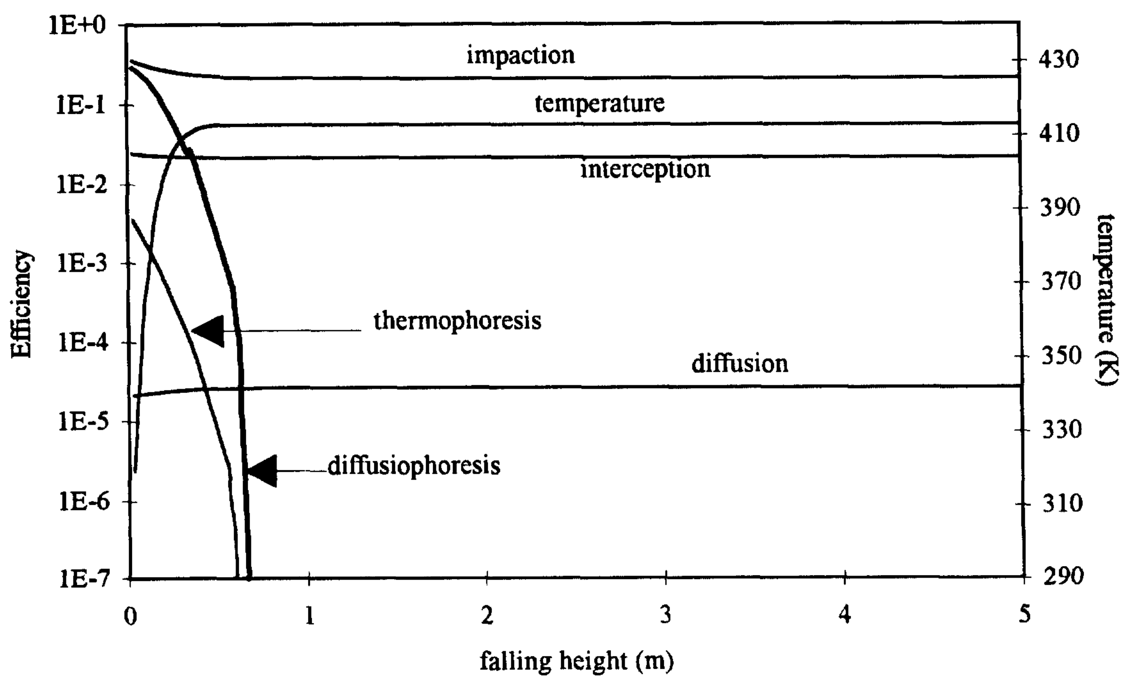


Figure 14: Elementary efficiency versus falling height
P = 5 bars, Tgas = 140 °C, Tdrop = 20 °C, S = 1
Ddrop = 500 µm, Daerosol = 5 µm



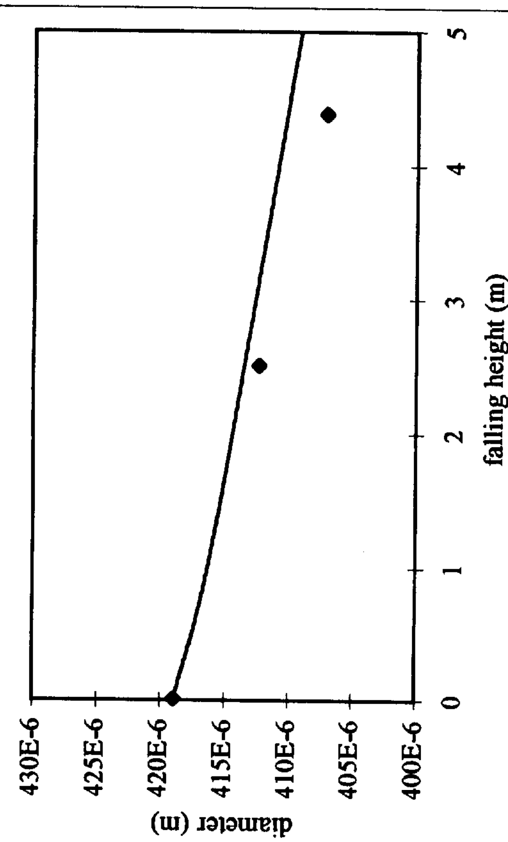


Figure 15: Drop diameter versus falling height
S = 32 %, P = 1 bar, Tgas = 21 °C, Tdrop = 20 °C

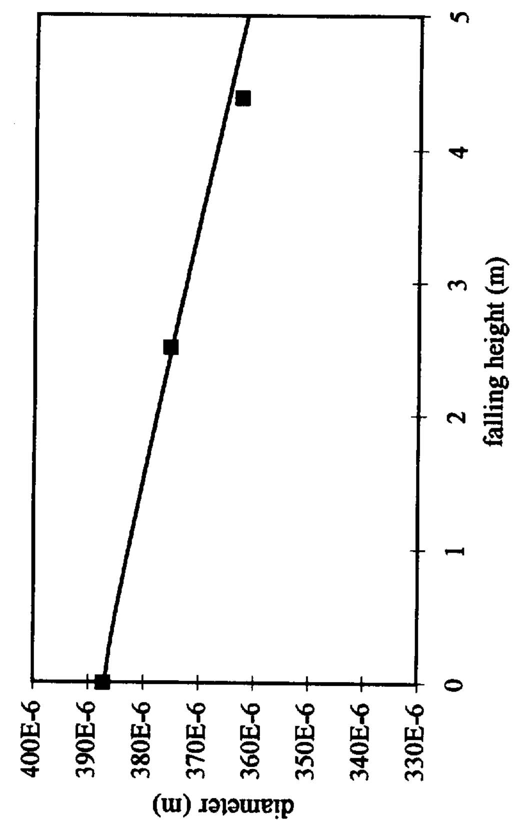


Figure 16: Drop diameter versus falling height
S = 12 %, P = 1 bar, Tgas = 47 °C, Tdrop = 20 °C

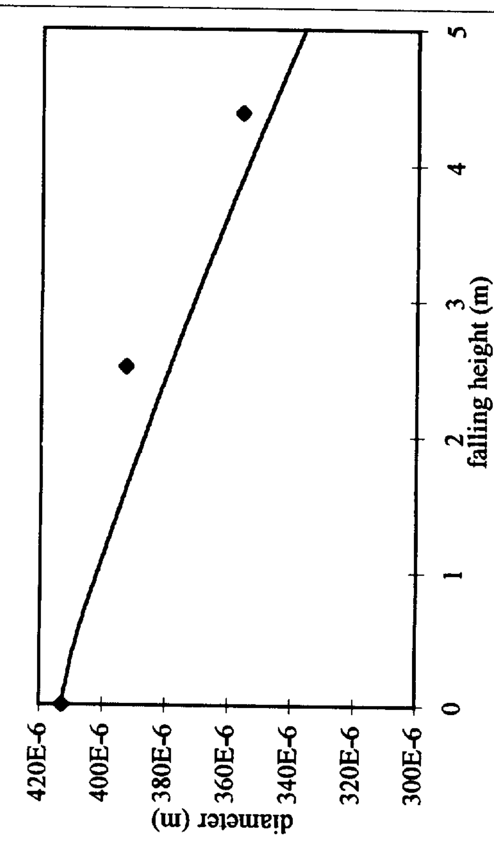


Figure 17: Drop diameter versus falling height
S = 1 %, P = 1 bar, Tgas = 105 °C, Tdrop = 30 °C

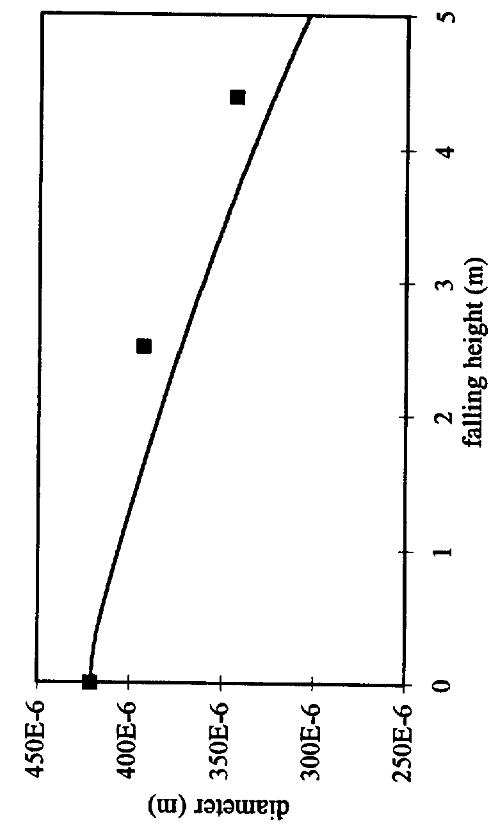


Figure 18: Drop diameter versus falling height
S = 1 %, P = 1 bar, Tgas = 146 °C, Tdrop = 30 °C

DISCUSSION

LEE: Are you aware that we requested the Phebus project at Cadarache to install a single drop aerosol experiment (instead of using a spray) during the test in the containment to assess current modeling of spray scrubbing of iodine?

DUCRET: I do not really know the answer because it is on another project.

LEE: Because the containment of Phebus is very small, if they are going to use a spray, the spray cone will practically cover everything in the containment. Therefore, if you look at the cross section (of the spray) versus the surface area and the volume (of the containment) it will be greatly distorted no matter what kind of spray is used, and the results will probably not be useful for validating the models for spray scrubbing of iodine. For this reason, we proposed to the CEA to use a single drop type experiment.