RADIOLOGICAL IMPACT OF A NATIONAL REPOSITORY FOR RADIOACTIVE WASTE:THE ITALIAN CASE

G. Petrangeli[1]*, A. Rogani*[2] *and E. Tabet*[3]

[1]University of Pisa, DIMNP, Via Diotisalvi,2, 56100 Pisa

[2]National Institute of Health, Viale Regina Elena, 299, 00161 Rome, Italy

[3]Formerly National Institute of Health, Viale Regina Elena, 299, 00161 Rome, Italy

A – EXTERNAL IMPACT EVENTS AND SOURCE TERMS

A1 – Radioactive Waste Repository

Type of repository

It is assumed that the disposal structure is similar to the French one in l'Aube or to the Spanish one in El Cabril. The waste are assumed to comply with the ANPA Technical Guide (T.G.) n. 26 and are, therefore, conditioned in a concrete matrix with compression strength of at least 50 Kg/cm^2 [1].

Reference impact

It is assumed that the reference impact produces a conical crater having an angle of 90^0 and a depth of 4 m. The cause of the impact is, moreover assumed to be undefined; it could be eventually identified, however, with a plane crash, with the launch of a projectile or with the blast of an internal or external explosive charge.

The 4 m deep crater has been chosen as it can be related with an explosive projectile of medium size (discussion at the Hannover Congress on the nuclear underground sites [2]). The volume of material expelled from the crater would then be of about 70 m^3 corresponding to a weight of about 140 tons.

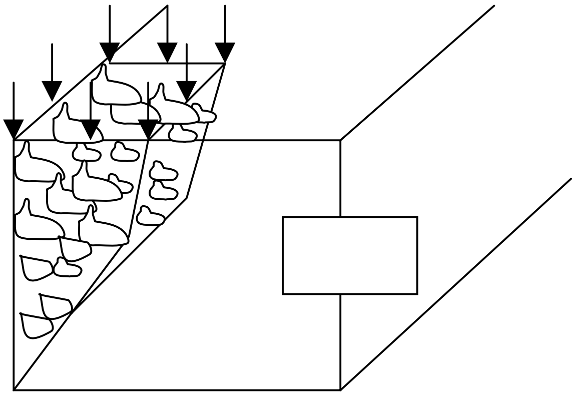


Fig. 1 Fragmentation of the impacted concrete block

These values can be compared with the effect of mining explosives and with the effect of a plane crash. The amount of rock (hard limestone rock) demolished in an open air mine is of the order of 7-10 tons of rock per Kg of explosive [3]. The 140 tons of rock considered above would then correspond (in ideal conditions) to about 20 Kg of explosive, an amount to be considered modest.

The effect of an aeroplane crash, then, may cause, according to usual assumptions, a load of bout 10 000 tons on a surface area of 7 m^2, orresponding to about 150 Kg/cm^2.

This load might cause the fall and the fragmentation of a column of structure, by assumption 10-15 m high,
with a volume of about 70 m3 (see Figure 1).

Fragmentation and dispersion of material

It is assumed that the material has been fragmented in blocks with diameter of 20-30 cm and that a layer 1-3 mm thick of each block is pulverised in fragments with dimension ranging from 1μ to 1-3 mm, with an uniform distribution in this interval :

Table 1

Average dimension of blocks[m]	1mm layer volume [m^3]	3 mm layer volume [m^3]
0.33	1.2	3.6
0.20	2.1	6.3

If an intermediate case among those shown in the table is chosen (volume equal to 2.5 m^3), a weight of finely fractured material of 5t is obtained, corresponding to a fraction of about 3% of the total. This percentage is not in contrast with the values estimated, e.g., for the Chernobyl accident [4].
It is reasonable to make the assumption, also on the basis of accident data, that the coarser part of the produced powder (from 10μ to 1 mm), having an overall weight approximately equal to the total one (99%), will be deposited over a radius of a few kilometres (2 Km are assumed) from the release point, with an average concentration

$$c\ [g/m^2] = 5x10^6 /(\pi \times 2000^2)= 0.4\ g/m^2$$

This evaluation cannot be regarded as conservative since the effect of wind is completely ignored; this effect will cause the angular distribution of the particulate to be non-uniform.
An estimate of the concentration of the deposited radioactivity can be made by assuming:

- that the total amount of released radioactive material is composed of Cs 137 ;
- that the equivalent value of Cs 137 is equal to the value indicated in T.G.26 as the limit for conditioned, Category II, waste (3.7 MBq/g)

The total radioactivity in the released particulate is then:

$$R = 5x10^6 \times 3.7 \times 10^{-6}\ [TBq] \sim 20\ TBq$$

With this assumption, the concentration on the ground is:

$$C = 0.4 \times 3.7 \times 10^6\ Bq/m^2 \sim 1500\ KBq/m^2$$

The finest fraction of particles (from 1 to 10 μ), with an overall weight of about 50 Kg and a total radioactivity of 0.2 TBq, can be supposed to be dispersed by diffusion and deposition.

Alternative source term

A different approach to the previously considered accident can be pursued, along the following lines:
a – to assume an applied force of 5000 tons for the reference aircraft impact, [as it was adopted in Italy for power plants, instead of the 10000 tons adopted in the previous evaluation];
b – to allow for the dynamical character of the load applied by the impacting aircraft on the concrete: this would imply an increment in the limit load as allowed by the applicable regulations (e.g. American Concrete Institute ACI 349);
c – to evaluate the depth of the fractured material as a consequence of the impact by the penetration formulas adopted for nuclear plant evaluations, such as the NDRC formula
(see Appendix I for more details)

d- to add to the aircraft impact the fire of the transported fuel; this consideration could influence the dispersion of the released particulate. In particular, the coarse fraction could be transported and deposited farther than the assumed 2 km.

Taking into account the previous assumptions, the volume of fractured material would result of the order of 12 m^3 instead of the 70 m^3 assumed above; the coarse fraction of the release could be of the order of 860 kg instead of 5 ton while the fine fraction would turn out to be equal to 8.6 kg (instead of 50 kg).

The uncertainty in the evaluation of the effect of the fire is rather high. Some indications could be, again, obtained from the observation of the behaviour of the Chernobyl release.
In that case [4], the large [>20 μ] particles were deposited within a radius of 5 km from the plant : the same assumption could be made also in this case since the sequence of events is here similar to the Chernobyl one : an explosion followed by a fire.
With these assumptions, the following distribution of released material is obtained:

- coarse fraction [>20 μ] : weight = 860 kg
- ground concentration =0.011 g/m^2, corresponding to 41 kBq / m^2

fine fraction : weight = 17.2 kg,

This would be dispersed also under the influence of the buoyancy effect of the fire. In the case of Chernobyl the thermal elevation of the plume caused by the fire was of the order of 1000 m [4] and this figure could be assumed to be valid also for our case[a] .
The usual thermal-elevation formulas can be used to perform a further evaluation of the height to which the radioactive release will be brought by the flame. The Stümke formula, as an example [b] [6] would indicate a plume rise of the order of more than 1000 m.

The uncertainty of this evaluation is, however high, since both the wind velocity field and the atmospheric turbulence have a strong influence on the phenomenon.

It has to be noted that the presence of a fuel fire should not significantly increase the amount of radioactive particulate released; indeed, the duration of the fire is short and, on the other side, the radioactive waste packages are made of "fire resistant" and "non flame propagating" materials [1]

A2 - TEMPORARY SPENT FUEL STORAGE

Characteristics of the cask

The cask complies with the international requirements for fuel transportation and therefore it resists to fall, punching, submersion. Moreover the cask will be designed against aircraft fall and consequent fire. The cask considered has two independent leak tight lids, each one equipped with metallic seals and designed against the above listed events. It is assumed that the cask contains 50 fuel elements of the Caorso type and that the maximum temperature of the cladding is 200 ^{o}C. The interior of the cask is normally kept at negative pressure and in an inert atmosphere.

Reference impact

It is assumed, as in A1, that the cause of the impact is undefined: it could be likely identified, however, either with a plane crash, or with the launch of a projectile or with the blast of an internal or external explosive charge. The effect of an aeroplane crash may cause, according to usual assumptions, a load of about 10 000 tons on a surface area of 7 m^2, corresponding to about 150 Kg/cm^2.
Notwithstanding the strength characteristics of the cask and of its leak tight seals against impact and other conceivable external loads, it is assumed that, in the accident considered, both seals will be damaged, allowing a certain communication between internal and external atmosphere and a gas flow dependent on the pressure difference between inside and outside. Immediately after the deterioration of the seals, the external air will flow to the inside of the cask because of the internal under-pressure. Subsequently, as a consequence of the lowering of external atmospheric pressure, part of the gas contained inside the cask might escape to the outside. If it is assumed that the variation of the atmospheric pressure in one day is ~10 mbar, the percentage of the internal atmosphere flown to the outside will be in the same period of time 10/1000 = 1 %. It is assumed here that after one day, countermeasures have been taken for stopping the release.

Amount of significant fission products in the internal atmosphere of the cask and external release in one day

Only Caesium 137 (and 134), Strontium 90 and Krypton 85 are here considered ; indeed, the other isotopes normally taken into account in explorative evaluations like this one are either completely decayed after at least 15 years since the removal of the fuel from the reactor (as Xenon and Iodine), or are not volatile enough to be released at relatively low temperature and through narrow and tortuous leak paths (e.g., imperfections in the metallic seals). Krypton 85, moreover, can be neglected in most cases. It is here assumed that, due to the assumed long decay time, the fuel elements do not generate a significant amount of heat.

It can be also assumed that the amount of the fission products in the gap between fuel and cladding be the same which was there when the fuel was discharged from the reactor. Indeed, the phenomenon of diffusion from the fuel to the gap is governed by a diffusion coefficient $D'_{Cs}{}^{c}$ which depends on the temperature in °K according to an Arrhenius type law [7], [8].

The ratio between the diffusion coefficient at the average operating temperature of the fuel (roughly 1300 °K) and at the fuel temperature after shutdown and during the storage (typically 500 °K) is practically infinite. The inventory of radioactive isotopes in the gap is, then, practically equal to that at the discharge from the reactor. Therefore, for the Caorso reactor (860 Mwe) and on the basis of the data on the content of fission products of a 1000 Mwe :

In all the fuel (560 elements), after 15 years decay:

Kr 85 : ~6.5×10^{3} TBq
Cs 137: ~ 1.1×10^{5} TBq
Sr 90 : ~ 0.9×10^{5} TBq

In the gap of 50 elements, assuming the percentage in the gap itself equal to1%:

Kr 85: ~ 6 TBq
Cs 137: ~ 100 TBq
Sr 90: ~ 80 TBq

Assuming, moreover, that the fuel rods leaking as a consequence of the event be those of 5 elements, corresponding to 10% of the total (therefore, equal to ten times the percentage of fissured rods normally assumed in safety analyses for the normal operation of a reactor), values available for release equal to one tenth of those indicated above are obtained.

For the case here examined, the effect of gas pressure within each fuel rod is considered to be negligible; this item, however, could be sometimes significant and should therefore evaluated for each specific case under study.

The external release in one day will be, for the considerations made above on the consequence of the variation of the atmospheric pressure, equal to one hundredth of the available activity values:

Kr 85 : $6 \ 10^{-3}$ TBq

Cs-137: 0.1 TBq

Sr 90: 0.08 TBq

The release has to be assumed at ground level in cases where no accompanying fuel failure is postulated and up to hundreds of meters height in the case where a fire is supposed to occur.

A fire of short duration (less than one hour) as the one involved in a plane crash or a fire with intervention of fire brigades could have a limited influence on the amount of the release since the thermal time constant of the cask wall (more than 30 cm of steel or cast iron) should be higher than the fire duration: in these conditions, the increase in the internal cask pressure caused by the fire could be high enough to change the amount (but not the order of magnitude) of the previously described release assumptions. A simple thermal analysis shows, indeed, that a conservative estimate of the internal pressure increase caused by the fire in half an hour could be of the order of 30 millibar (namely a factor of three over the above described assumptions). In conclusion, the release in case of fire could be of the order of three times the one assumed above, in a time frame less than one hour. The two releases should not be combined.

B – RADIOLOGICAL CONSEQUENCES OF THE FUEL CASK ACCIDENT

In the previous paragraphs we have seen a few plausible mechanisms that could lead to significant releases from a radioactive waste deposit or from a fuel cask.
In this chapter we shall evaluate the radiological consequences of a reference accident , limiting ourselves to the case of the release from a fuel cask. It can be shown, indeed, that the size of its potential contamination is substantially larger than that produced by an equivalent accident to a waste deposit.
In order to get an appreciation of the risk of a fuel cask accident we shall select a “worst case” event in which all the volatile nuclides are supposed to be released to the atmosphere for an amount equal to 5×10^{-2} of their content in the fuel [9].
This applies to the following groups:

Xe-Kr; I-Br; Cs-Rb; Te-Sb; Sr-Ba.

Less volatile elements as Ruthenium and the attinides are not supposed to be available for release into the atmosphere, in the accident scenario previously described.
According to that scenario a significant thermal energy release could be expected from the burning of the (7 tons of) plane fuel. This, in turn, will transfer to the ascending plume ~ 4 $\times 10^{7}$ cal/s, from which a substantial thermal elevation of the plume (of the order of several hundreds of metres) has to be expected. We note that at short distances from the damaged cask the worst case scenario would, instead, require ignoring the thermal elevation of the plume (as will be shown later).
The evaluation of cloud propagation and of the radiological consequences of the release , shown in tab. 2 , has been carried out by means of the algorithm RANA (Radiological Analysis of Nuclear Accidents) [10] , with the following assumptions (inter alia):

Table 2 : Some of the significant releases /PBq for the reference accident

Strontium-90	3.5 10^{-1}
Caesium-134	6.3 10^{-3}
Caesium-137	4.4 10^{-1}

1. Plume propagation is described by a mixed Pasquill-“wedge” model;
2. Standard effects, such as, for example, finite cloud corrections, or plume depletion due to ground deposition or radioactive decay, are accounted for;

- Neutral D Paquill-Gifford diffusion category has been conventionally chosen;
- Thermal buoyancy, as implied by the combustion of 7 tons of kerosene, is taken into account;
- Dry deposition is assumed to occur along the cloud path.

Different choices, such as allowing for wet deposition or a different diffusion category, are fully compatible, however, with the chosen algorithm, although are not presented here for the sake of shortness (the case of a zero elevation release will be briefly sketched).
Fig 2 shows Caesium 137 ground deposition as a function of the distance, along the plume axis, from the damaged fuel cask. A strong buoyancy may be clearly inferred from the shape of the curve.

Tabs 3, 4 and fig. 3 show the behaviour of inhalation, ground and total (inhalation + cloud + ground) doses, respectively, for the reference group of the children due the nuclides that were shown above (Cs 134, Cs 137 and Sr 90).

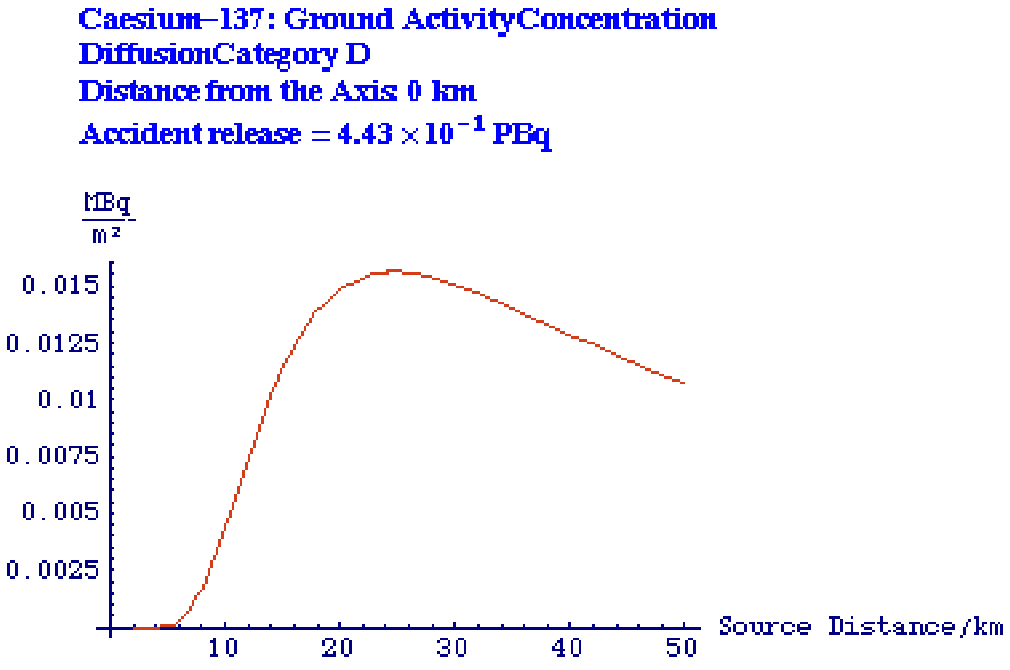


Fig 2. Caesium-137 ground deposition as a function of the distance from the source, for the reference release (computer output).

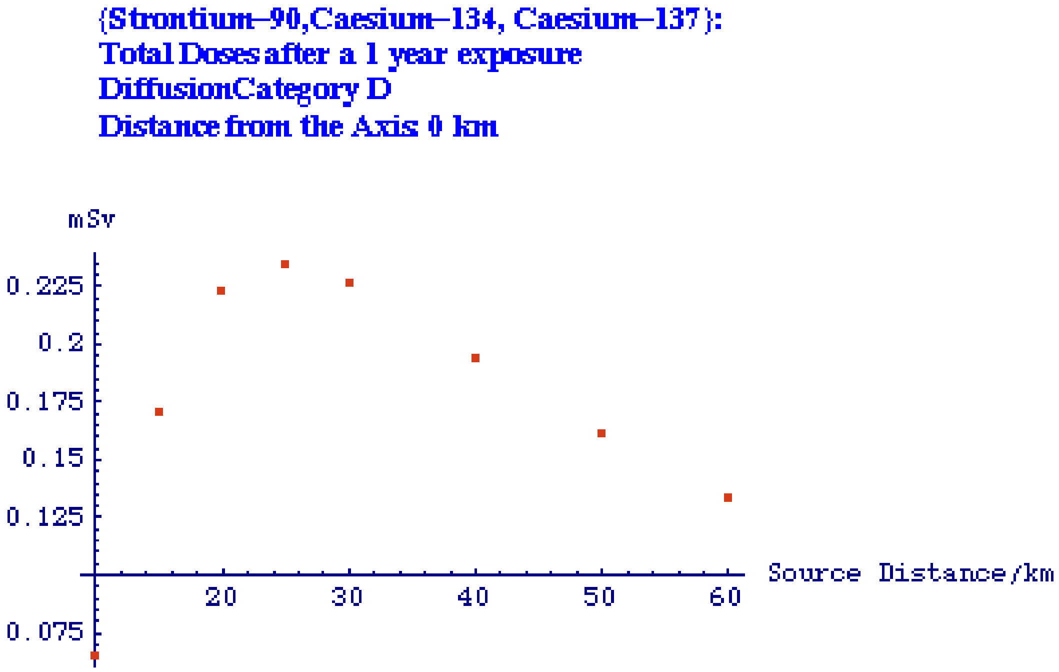
Table 3 Inhalation dose [mSv] to the children at various distances [km] from the source.

10	$2.8\ 10^{-2}$
15	$7.3\ 10^{-2}$
20	$9.5\ 10^{-2}$
25	$1.0\ 10^{-1}$
30	$9.6\ 10^{-2}$
40	$8.2\ 10^{-2}$
50	$6.8\ 10^{-2}$
60	$5.7\ 10^{-2}$

Table 4 . Ground dose [mSv] for the reference accident, after a 1 year exposure.
(Distances from the source are in km)

10	$3.7\ \ 10^{-2}$
15	$9.8\ \ 10^{-2}$
20	$1.3\ 10^{-1}$
25	$1.3\ 10^{-1}$
30	$1.3\ 10^{-1}$
40	$1.1\ 10^{-1}$
50	$9.2\ 10^{-2}$
60	$7.7\ 10^{-2}$

Fig. 3 Total dose to the children at various distances from the damaged fuel cask.



Finally, fig. 4 gives Caesium 137 ground contamination contour lines at those distances from the source where contamination attains its largest values. As it could be expected, the strong thermal elevation of the plume, while increasing the distances reached by the release, allows a rather effective dilution to take place. From fig. 3 it can be seen that the total doses are such that no countermeasure would be required. More significant doses would require the release of a substantial fraction of the whole fuel cask inventory: this seems hard to be reconciled with the design specifications of the considered casks.

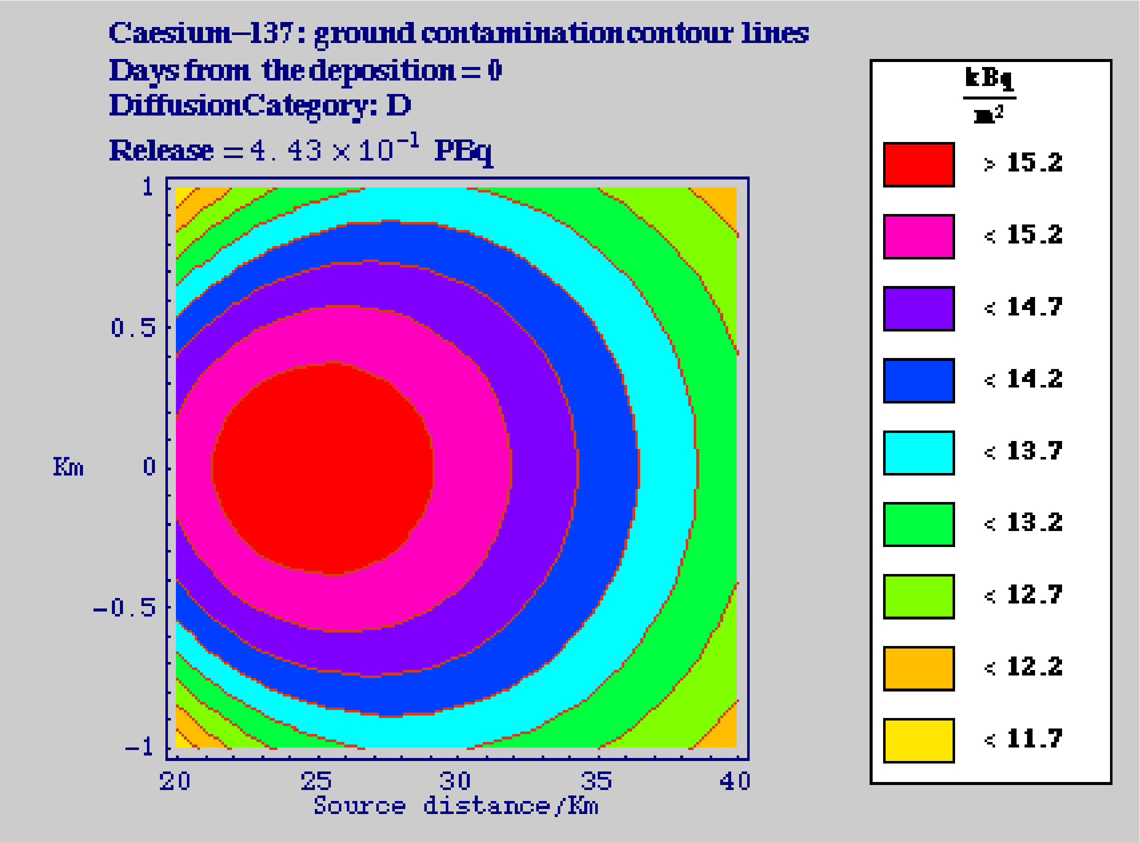
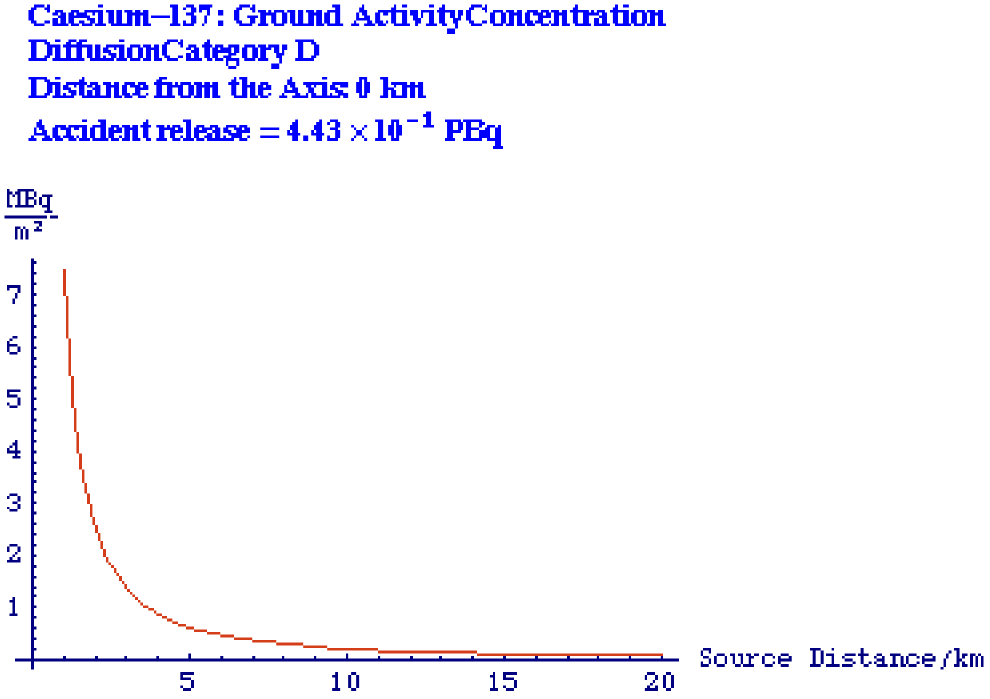


Fig. 4 Isoconcentration curves for Caesium-137 ground deposition (computer output)

If the plume elevation due to the thermal release is not taken into account, a rather different picture is obtained, as it could have been expected.

Fig. 5 shows Cs 137 contamination as a function of the distance, if the plume elevation is ignored. As it can be seen, the radioactive contamination is significant at short distances from the plant and doses much higher than those previously seen can be attained. Inhalation doses to the children at distances in the range 1-15 km may thus range from a few tens of mSv to 1 mSv, and total doses for a 1 year exposure approximately double these figures. This contamination configuration would then require some emergency countermeasures to be taken in the area on the border with the plant.

Fig.5 Cs-137 ground contamination for the reference accident, with no plume thermal elevation



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APPENDIX I

The NDRC formula:

$$x = \sqrt{4KNWd * \left(\frac{V_0}{1000d}\right)^{1.80}} \quad forx/d \leq 2.0$$

$$x = \sqrt{\{\ [\ KNWd * \left(\frac{V_0}{1000d}\right)\ ]^{.80} + d\ \}} forx/d \geq 2.0$$

where**:** x = penetration depth; K is a concrete penetrability factor which is a function of the concrete strength; K = 7 in our case; W, is the missile weight = 20000 kg; N is a missile form factor = 1 in our case; D is the impact area diameter = 2.6 m

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[a] In order to have an idea of the characteristics of the fire involved (presumably) in the reference plane crash, it has to be considered that the full fuel load charge of the aircraft can be assumed to be equal to 10 m^3, corresponding to roughly 7 tons. This amount of fuel, with a conservative assumption, can be considered to form a square pool with ten meters long sides. The burning velocity of a pool of cherosene [5] of this size is roughly 170 kg/m^2hr; the fuel would be completely burned out in about 25 minutes; the flame height should be equal to about twice its width, namely 20 meters.

[b]

$$\Delta h = 65 * \frac{d^{3/2}}{u} * \left(\frac{\Delta T}{T_s}\right)^{1/4}$$

where:

d, is the diameter of the efflux opening (in this case the pool width) [m]

u is the efflux velocity [m/s]

ΔT and T_s are the flame temperature elevation over the ambient one and the ambient temperature itself, respectively [^oK]

[c] $D'_{Cs}\ [s^{-1}] = 1.22 \exp(-72300/RT) \times 100^{Bu/28000}$

where:

- R= 1.987 cal/mole, °K
- T= temperature, °K
- Bu = fuel burnup, MWD/t