Introduction

After the Chernobyl accident, in Italy, like in many other European countries, the challenge connected with the management of radiological emergencies involving a large territorial area has been carefully addressed.

In this country the radiological emergency planning is regulated by the Law Decree n. 241/2000, where the procedure for setting the emergency plan is established referring both to accidental events occurring in Italian nuclear installations and to other events which may involve the Italian territory. Following the specific indications of the Law, a National Emergency Plan of protective measures for radiological emergencies has been set up to cope with nuclear risks which require actions at national level. In 1987 the Italian Government decided the nuclear moratorium and, at present, the Italian nuclear power plants are not operational: therefore, the most relevant nuclear risk source identified in the National Plan is related to an accident occurring in a nuclear power plant near the Italian borders. However, risks related to severe accidents to other nuclear facilities present in Italy, such as provisional radioactive waste deposits or research centers, are not taken into account in the Plan. In this paper the hypothetical radiological impact of a severe external event in a spent fuel storage pool has been evaluated, as this event appears to be one of those with the most severe consequences.

Risk assessment of external events in nuclear facilities

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Summary. - After the Chernobyl accident, a National Emergency Plan of protective measures for radiological emergencies has been set up in Italy to cope with nuclear risks which require actions at national level. Since the Italian nuclear power plants are, at present, not operational, the most relevant nuclear risk source identified in the National Emergency Plan is related to an accident occurring in a nuclear power plant near the Italian borders. However, risks related to severe accidents to other nuclear facilities present in Italy, such as provisional radioactive waste deposits or research centers, are not taken into account in the Plan. In this paper the hypothetical radiological impact of a severe external event in a spent fuel storage pool has been evaluated, as this event appears to be one of those with the most severe consequences.

Key words: nuclear plant, radiological impact, radiological emergency.

Riassunto (Stima del rischio di eventi esterni in installazioni nucleari). - Dopo l’incidente di Chernobyl è stato elaborato in Italia un Piano Nazionale di Emergenza, per fronteggiare le emergenze radiologiche che richiedono interventi a livello nazionale. Poiché in Italia le centrali nucleari non sono più in esercizio, lo scenario di riferimento, identificato nel Piano, è un incidente ad una centrale nucleare vicino ai nostri confini. Tuttavia il Piano non prende in considerazione i rischi connessi con eventi severi ad altre installazioni nucleari, per esempio, i depositi di rifiuti radioattivi o i centri di ricerca. In questo lavoro si valuta la conseguenza sanitaria di un incidente severo provocato da cause esterne in una piscina di stoccaggio del combustibile irraggiato, poiché tale evento appare come uno dei più gravi tra quelli con rilevante impatto radiologico.

Parole chiave: impianto nucleare, impatto radiologico, emergenza radiologica.


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As for the four nuclear plants that were operational in Italy, in two of them the spent fuel elements have been removed from the site, while, for the remaining two, the fuel has been removed from the core and is still present (in part) in the fuel decay pool. Other nuclear facilities, such as temporary radioactive waste deposits or research centers, are also present in Italy. Unfortunately, not all of the radioactive material and the spent fuel elements are conditioned or stored in such a way to make unlikely the spread of radioactive contamination as a consequence of an accident.

Nuclear facilities are generally designed to withstand several external events as earthquakes, tornados and accidental crashes of small aircrafts. But the consequences of the crash of large fully fuelled aircrafts onto a nuclear power plant or other nuclear facilities are still a matter for analysis.

In this paper the radiological impact of this typology of events in some reference nuclear installations has been evaluated. The case of a severe accident in a spent fuel storage pool is worked out in some detail, as this event appears to be one of those with the most severe consequences.

The radiological evaluations have been carried out by means of the interactive algorithm RANA (Radiological Assessment of Nuclear Accidents), worked out to evaluate the space and time structure of the radiological consequences of an accident at a nuclear plant in Europe [2]. Last developments of the model allow dealing with an arbitrary source term, allowing for both deterministic (short distance) and stochastic effects evaluation. Along with the previous functions, a new set of tools allows the user to evaluate also the areas where doses (from several exposure pathways and to all age classes) exceed those at which the onset of deterministic effects begin, a variable that plays a major role in emergency planning.

### Reference event

After a nuclear plant has been permanently shutdown and the fuel has been stored in the storage pool, the accident scenarios of the operating plants are no longer applicable. The remaining source of risk is associated with events that involve the spent fuel in the pool. Various studies [3, 4] have shown that the consequences of events that cause a complete drainage of the fuel pool are relevant.

In this paper the impact of an aircraft on a spent fuel storage pool, with the consequent fire due to the combustion of (10 tons of) the aircraft fuel, has been taken as reference event. The considerable amount of available thermal energy is evaluated to induce:

- the draining of the spent fuel pool (with a water volume of ~ 10³ m³);
- the failure of a notable fraction of the stored spent fuel elements.

Considerations similar to those of NUREG-6451[4] suggest, for the damaged fuel elements, the release fractions shown in Table 1 and compared with those of the most severe BWR accident [5] and with the release fractions in the Chernobyl event [6]. As can be seen from this table, the dimension of the reference release corresponds to that of a very severe accident of an operating nuclear power plant, as described in ref. [5], when iodine and caesium isotopes are considered.

It is assumed that ~ 10³ fuel elements (supposed to come from a BWR plant) had been stored in the pool since ~15 years and that, from energy balance considerations, the failure of about 10% of elements occurs. A more accurate evaluation of the fraction of damaged fuel would require a modelling of the heat

<table>
<thead>
<tr>
<th>Nuclides group</th>
<th>Release fraction</th>
<th>BWR 1 accident</th>
<th>Chernobyl accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble gases</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Iodine</td>
<td>1</td>
<td>4 · 10⁻¹</td>
<td>5 · 10⁻¹ - 6 · 10⁻¹</td>
</tr>
<tr>
<td>Caesium</td>
<td>1</td>
<td>4 · 10⁻¹</td>
<td>2 · 10⁻¹ - 4 · 10⁻¹</td>
</tr>
<tr>
<td>Tellurium</td>
<td>2 · 10⁻²</td>
<td>7 · 10⁻¹</td>
<td>2.5 · 10⁻¹ - 6 · 10⁻¹</td>
</tr>
<tr>
<td>Strontium</td>
<td>2 · 10⁻³</td>
<td>5 · 10⁻²</td>
<td>4 · 10⁻² - 6 · 10⁻²</td>
</tr>
<tr>
<td>Ruthenium</td>
<td>2 · 10⁻⁵</td>
<td>5 · 10⁻¹</td>
<td>&gt; 3.5 · 10⁻²</td>
</tr>
<tr>
<td>Lantanides</td>
<td>6 · 10⁻⁶</td>
<td>5 · 10⁻³</td>
<td>3.5 · 10⁻²</td>
</tr>
</tbody>
</table>

### Table 2. Source term for the reference event

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Released activity/ TBq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr-90</td>
<td>7.0 · 10</td>
</tr>
<tr>
<td>Cs-134</td>
<td>3.2 · 10²</td>
</tr>
<tr>
<td>Cs-137</td>
<td>5.0 · 10⁴</td>
</tr>
<tr>
<td>Pu-238</td>
<td>8.8 · 10⁻³</td>
</tr>
<tr>
<td>Pu-239</td>
<td>1.5 · 10⁻³</td>
</tr>
<tr>
<td>Pu-240</td>
<td>2.4 · 10⁻³</td>
</tr>
<tr>
<td>Pu-241</td>
<td>2.5 · 10⁻¹</td>
</tr>
<tr>
<td>Cm-242</td>
<td>2.1 · 10⁶</td>
</tr>
<tr>
<td>Cm-244</td>
<td>3.6 · 10⁻³</td>
</tr>
</tbody>
</table>
transfer process to the fuel elements, which is beyond the aim of this paper. (*)

For more detailed considerations about the phenomenology of fuel heating and related effects (such as the heat production from the cladding-air or steam exothermic reaction) we refer to ref. [4].

Among the nuclides embedded in the fuel elements only caesium 134, caesium 137, strontium 90 and some attinides need basically to be considered, as the other relevant isotopes are fully decayed or play now a minor role. Table 2 shows the activities released of the considered radionuclides.

Radiological impact of the accident

The cloud propagation and the radiological consequences of the reference event have been evaluated by means the RANA model with the following assumptions (inter alia):
- the release is assumed to last approximately half an hour. Standard effects, such as plume depletion due to ground deposition, radioactive decay or contribution of radioactive decay products, are accounted for;
- all the Pasquill-Gifford diffusion categories (together with their frequencies) have been considered;
- dry deposition is assumed to occur along the cloud path;
- the relevant exposure paths in the early emergency phase -external irradiation from the cloud, from ground deposition, and inhalation- are taken into account;
- the number of population exposed has been also evaluated, assuming a (local) mean population density equal to 100/km².

Figs 1 and 2 show, respectively, the time integral of Cs-137 concentration in air versus the distance from the release point and the structure of Cs-137 ground contamination for the most probable Pasquill-Gifford diffusion category D and a wind speed equal to 7 m/s.

Deterministic effects

For emergency planning purposes the absorbed doses (to bone marrow), as a function of distances from the sources, have been evaluated for all the atmospheric diffusion categories.

Table 3 shows the distances within which the absorbed doses of Cs-137 exceed the values of occurrence of deterministic effects for acute exposure of the organ [7] (the exposure is assumed to occur within 2 days). In this table the number of individuals affected by the release is also reported. We note that weather diffusion conditions play an important role in the assessment of the radiological consequences of the event considered.

Stochastic effects

The total effective dose (inhalation + cloud + ground deposition after 7 days from the reference event) has been evaluated for the most significant radionuclide (Cs-137); the values are referred to children (7-12 years). Fig. 3 shows the total effective dose versus the distance from the release point for Pasquill-Gifford category D and in the worst case-category F-.
Emergency management

After a nuclear accident involving the environmental dispersion of radioactive material, it could be necessary to introduce countermeasures to reduce exposure of individuals of population.

In the early phase (that is within a few days from the release) the exposure of the public can be relatively high due to inhalation of radioactive materials in the plume and external irradiation from the plume and from ground deposited activity. In this phase the urgent protective actions are sheltering, evacuation and administration of stable iodine.

Various international bodies have recommended a set of numerical values to be used as Intervention Levels of dose for each protective action [7-9]. Because of different nature of deterministic and stochastic effects, two approaches are needed.

Regarding the deterministic effects, one of the radiological protection principles for intervention states that: “all possible efforts should be made to prevent serious deterministic health effects” [8]. Then actions to prevent these effects should be taken below the threshold of their occurrence. These effects are not likely to occur for absorbed doses to bone marrow less than 0.5 Gy [7]. Moreover, in planning nuclear emergency, the possibility of teratogenic effects due to doses greater than \( \approx 0.1 \text{ Gy} \) for acute exposure of the foetus should be taken into account, too.

Regarding the stochastic effects, Table 4 shows the Intervention Levels of dose, recommended by the International Commission of Radiological Protection [7]; the other numerical guidelines [8, 9] are very similar.

From Fig. 3 we note that, in the reference event here considered, the lower value of the range of dose Intervention Level for evacuation is exceeded up to \( \approx 7 \) km from the facility, while the higher value, is exceeded for distances \( \leq 1.5 \) km. In the worst case-category F- the higher value is exceeded for distances \( \leq 10 \) km.

Conclusions

An important role in determining dose pattern following the accident could be played by the plume buoyancy due to the heat transfer to the ascending
material. This effect could mitigate the consequences of the severe release here considered. The determination of the amount of the effect would require a detailed knowledge of the thermal energy transfer to the plume, which needs an *ad hoc* modelling.

In the considered reference event, the range of distances within which the absorbed doses exceed the values of deterministic effects occurrence is such that a realistic implementation of effective and timely emergency countermeasures seems be possible. Similar considerations apply, of course, to the analysis of stochastic effects, the results showing the importance of an accurate knowledge of weather conditions.

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### Table 4. - Intervention levels of dose for implementation of protective measures

<table>
<thead>
<tr>
<th>Protective measure</th>
<th>Effective dose/mSv</th>
<th>Equivalent dose/mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evacuation</td>
<td>50*-500**</td>
<td></td>
</tr>
<tr>
<td>Sheltering</td>
<td>5*-50**</td>
<td></td>
</tr>
<tr>
<td>Iodine prophylaxis</td>
<td>50*-500**</td>
<td></td>
</tr>
</tbody>
</table>

* Level of dose below which the introduction of the measure is not considered justified [7]. ** Level of dose at which the implementation of measure will almost always be justified [7].

### REFERENCES


