



Release of Radionuclides Following Severe Accident in Interim Storage Facility: Source Term Determination

Sonia Morandi, Mario Mariani

Dipartimento di Ingegneria Nucleare, Politecnico di Milano
Milan, Italy
sonia.morandi@polimi.it, mario.mariani@polimi.it,

Roberto Covini

Joint Research Centre, European Commission
Ispra, Italy
roberto.covini@cec.eu.int

Francesca Giacobbo

Dipartimento di Ingegneria Nucleare, Politecnico di Milano
Milan, Italy
francesca.giacobbo@polimi.it

ABSTRACT

Among the severe accidents that can cause the release of radionuclides from an interim storage facility, with a consequent relevant radiological impact on the population, there is the impact of an aircraft on the facility.

In this work, a safety assessment analysis for the case of an aircraft crash into an interim storage facility is tackled. To this aim a methodology, based upon DOE, IAEA and NUREG standard procedures and upon conservative yet realistic hypothesis, has been developed in order to evaluate the total radioactivity, “source term”, released to the biosphere in consequence of the impact, without recurring to the use of complicated numerical codes.

The procedure consists in the identification of the accidental scenarios, in the evaluation of the consequent damage to the building structures and to the waste packages and in the determination of the total release of radionuclides through the building-atmosphere interface.

The methodology here developed has been applied to the case of an aircraft crash into an interim storage facility currently under design. Results show that in case of perforation followed by a fire incident the total released activity would be greater of some orders of magnitude with respect to the case of mere perforation.

1 INTRODUCTION

The nuclear power activities, together with the non-energy nuclear activities in the industrial and medical fields, have led to a production of a non-negligible amount of radioactive waste. Considerably larger quantities of radioactive waste will be produced in the decommissioning of nuclear plants. The waste thus far produced is currently stored at its site of origin inside interim storage facilities, waiting to be transferred to final disposal facilities. Interim storage facilities must be designed so as to guarantee isolation of the radionuclides from the biosphere. To this aim safety assessment analysis must take into account those

accidental scenarios that could cause the release of radionuclides to the biosphere. The impact of an aircraft on the facility is one of the severe accidents that can have a relevant radiological impact on the population.

In this work, a real case study concerning the safety of an interim storage facility currently under design is considered. The total radioactivity released from the facility in case of impact with an aircraft, in the following referred as ‘source term’, is evaluated on the basis of DOE, IAEA and NUREG standard procedures [1,2,3] and upon conservative yet realistic hypothesis. In order to identify the possible accidental scenarios, the developed procedure takes into account the following aspects: i) the structural characteristics of the interim storage facility, ii) the characteristics of the impacting object and iii) the characteristics of the impact event.

The paper is organized as follows. The second Section illustrates the methodology adopted for the evaluation of the source term. The third Section describes the case study. The fourth Section describes the application of the methodology to the case study and reports the results. Some remarks on the proposed approach and future developments conclude the paper.

2 METHODOLOGY

The methodology here adopted for the evaluation of the total activity released in case of an aircraft crash into an interim storage facility, source term, consists in the following steps: 1) identification of the accidental scenarios, 2) evaluation of the structural damage, 3) evaluation of the mechanical damage of the waste packages, 4) source term determination.

2.1 Identification of the accidental scenarios

The categories of aircraft that could hit the facility under consideration are selected on the basis of the kind of airports located near the interim storage facility. Taking into account the aerodynamic and technical characteristics of the selected aircrafts the most probable accidental scenarios are identified.

2.2 Evaluation of the Structural Damage

The structural damage to the facility due to the impact with an aircraft is evaluated by means of the DOE procedure ‘Accidental analysis for aircraft crash into hazardous facilities’ [1].

According to the DOE procedure the structure of the facility may undergo two local damages: i) *scabbing*, which signifies the peeling off of material from the back face of the target or ii) *perforation*, which means that the aircraft fully penetrates the target or passes through the target involving the waste inside the facility. Among these mechanical damages only the latter one can be responsible of a release of radionuclides to the biosphere, thus the following analysis is focused on perforation events.

2.2.1 Perforation

The following empirical Eq. (1) is adopted for the determination of the perforation thickness, T_{p_r} [m] defined as the panel thickness that is just large enough to allow an aircraft to pass through the panel without any exit velocity [1]:

$$T_{p_r} = 0.0029 \left(\frac{U}{v_i} \right)^{0.25} \left(\frac{W \cdot v_i^2}{D \cdot f_c} \right)^{0.5} \quad (1)$$

Where U is a reference velocity assumed equal to 60.96 m/sec; v_i is the aircraft impact velocity [m/sec]; W is the aircraft weight [kg]; D is the effective aircraft diameter [m]; f_c is the ultimate compressive strength of concrete [Pa].

According to the above expression it can be assumed conservatively that perforation takes place if the wall thickness, t , is lower than $1.2 \cdot T_p$ for a non-deformable aircraft and lower than $0.84 \cdot T_p$ for a deformable aircraft [1].

2.3 Evaluation of the mechanical damage of the waste packages

The mechanical damage of the waste packages is evaluated on the basis of a series of conservative considerations regarding the kinetic energy of the aircraft and the energy released in the impact.

The kinetic energy of an aircraft penetrating the facility is partially dissipated in the perforation of the structure of the civil building and partially dissipated in the impact with the waste packages. On the basis of the thickness of the panel it is possible to obtain from Eq. (1) the initial velocity of an aircraft which passes through the panel without any exit velocity and consequently an estimation of the kinetic energy dissipated by the aircraft in the perforation. An estimation of the energy dissipated in the impact with the waste packages during the path of the aircraft inside the building, once perforated the panel, can be obtained by subtracting the estimated energy dissipated in the perforation from the kinetic energy of the aircraft before the impact.

The energy released to the waste packages impacted by the aircraft is estimated assuming, under conservative hypothesis, that the most part of levels of packages positioned along the path of the aircraft is involved in the impact and that the energy released to each level of impacted packages is the same.

The mechanical damage of the waste packages can be evaluated comparing the energy released to each waste package by the impact, obtained by the above procedure, with the energy capable of damaging a waste package, usually estimated as the energy released in the impact with the ground in consequence of a fall from a height of 9.2 m [3,4].

2.4 Source Term determination

The amount of radioactivity released by an aircraft crash into the facility is evaluated by summing the fractions of radioactivity released due to the mechanical damage, R_{md} , and to burning of the waste packages, R_f .

2.4.1 Radioactivity released due to mechanical damage of the waste package

The evaluation of the fraction of radioactivity released to the environment from the facility in consequence of mechanical damage of the waste packages is typically estimated by the following five-component linear equation for each radionuclide contained in the waste packages [5]:

$$R_{md} = MAR \cdot DR \cdot ARF \cdot RF \cdot LPF \quad (2)$$

where R_{md} is the radioactivity [Bq] released by mechanical damage of the waste packages; MAR (Material At Risk) is the amount of radionuclides [Bq] available to be acted on by a given physical stress expressed in terms of activity; DR (Damage Ratio) is the fraction [-] of the MAR actually impacted; ARF (Airborne Release Fraction) represents the fraction [-] of the radionuclide suspended in air as an aerosol and thus available for transport; RF

(Respirable Fraction) is the fraction [-] of airborne radionuclides that can be inhaled into the human respiratory system; *LPF* (Leakpath Factor) is the fraction [-] of the radionuclides in the aerosol transported along multiple leakpaths through the building-atmosphere interface.

For the case of mechanical damage due to fall of solid waste that undergo brittle fracture (i.e. waste immobilized in concrete), the product (*ARF·RF*) can be calculated by the following equation, [5]:

$$ARF \cdot RF = A \cdot P \cdot g \cdot h \quad (3)$$

where *A* is an empirical coefficient assumed equal to $2 \cdot 10^{-11}$ cm s²/g, *P* is the density of the solid waste [g/cm³], *g* is the gravitational acceleration [cm/s²] and *h* is the fall height [cm].

For solid waste that experiences predominantly plastic deformation (i.e. waste not immobilized in concrete), the product (*ARF·RF*) is assumed equal to $1 \cdot 10^{-4}$ [5].

The Eq. (3) adopted for the evaluation of the product (*ARF·RF*) can be used as well in the case of solid waste packages that undergo brittle fracture when impacted or crushed by an aircraft. To this aim it is assumed conservatively that the fall height, *h*, is equal to

$$h = h_1 + h_2 \quad (4)$$

where *h*₁ is the real elevation of the waste package and *h*₂ is obtained according to the following expression

$$mgh_2 = E_i \quad (5)$$

where *E*_{*i*} is the total energy released to the waste package by the impact with the aircraft, *m* is the mass of the solid waste packages and *g* is the gravitational acceleration. By so doing the energy released to a waste package by the impact is assumed equal to the energy released to a waste package falling from a height of *h*₂.

2.4.2 Radioactivity released due to the burning of the waste packages

The evaluation of the fraction of radioactivity released to the environment from the facility in the case of a fire incident which involves the waste packages, *R*_{*f*} [Bq], is obtained by the following four-component linear equation [6]:

$$R_f = A_0 \cdot F_w \cdot F_r \cdot F_a \quad (6)$$

where *A*₀ is the amount of radionuclides contained in the packages involved in the fire incident [Bq], *F*_{*w*} is the fraction [-] of waste involved in the fire incident, *F*_{*r*} is the fraction [-] of material leaked from packages and suspended in air, *F*_{*a*} is the fraction [-] of aerosol released outside the facility. *F*_{*r*} is calculated according to the following equation [6]:

$$F_r = 0.1 \cdot 20^{(i-3)} \quad (7)$$

where *i* is the index of inflammability which is influenced by the physical and chemical properties of the waste and ranges between 0 and 3 for undamaged packages and between 1 and 3 for damaged packages.

3 CASE STUDY

The evaluation of the total radioactivity released, source term, in case of an aircraft crash into an interim storage facility currently under design is here tackled on the basis of the developed methodology. In the following, the structural characteristics of the interim storage facility together with the characteristics of the waste packages and their positioning inside the facility are reported.

3.1 Interim Storage Facility

According to the current design, the facility will be a civil building made of reinforced concrete, 18 m high with a plan of 72x56 m² divided into two rooms, with outside main wall thickness of 0.3 m and roof thickness of 0.25 m, surrounded by banks and buildings which act as biological shield for the population of the neighbourhood (Figure 1). The facility is designed as to reduce to the minimum the probability of fire incidents and the conditioned waste is stored in metal and concrete containers fire-resistant up to 30 minutes (REI 30).

The waste packages will be disposed taking advantage from the fact that external packages containing LLW will thus protect the inner ones containing HLW (Figure 1). Pallets containing waste packages will be stacked in six levels, 25x7 per level, in each room of the interim storage facility building. In order to consider the worst case in terms of safety assessment in the following analysis the facility is assumed to be partially filled in such a way that shielding action of the packages is at its minimum (Figure 1).

The pallets, which may contain from 1 to 6 packages, have the following dimensions (LxWxH): 2.8x1.9x1.4 m and 2.8x1.9x2.2 m.

3.2 Radioactive Waste

The interim storage facility is supposed to contain a volume of about 10⁴ m³ of 2nd and 3rd category waste [7] (referable to LLW/HLW [8]) conditioned respectively into bitumen and concrete matrices with a total activity of 3.38 10¹¹ Bq of α radiation and 6.64 10¹⁴ Bq of β and γ radiation.

4 APPLICATION OF THE METHODOLOGY TO THE CASE STUDY

4.1 Identification of the accidental scenarios

On the basis of the airports located near the interim storage facility, two categories of aircraft that could hit the facility have been selected: single engined aircraft and helicopter. The aircraft selected for each category and their principal characteristics (maximum values of mass, diameter and velocity) of the aircrafts here considered are reported in Table 1.

Table 1: Technical characteristics of the aircrafts selected

Aircraft category		Mass [kg]	Diameter [m]	Velocity [m/s]
Single engined aircraft	Aermacchi M290 TP RediGO	1900	1.4	97.6
	Piper Seneca V	1999	1.5	105,0
	Piper Turbo Arrow	1315	1.9	91.7
Helicopter	Agusta A109 POWER	3000	1.6	79.2
	Agusta AB412	5398	2.3	62.8
	Agusta EH101	14600	5.7	77.8
	Agusta A129	5100	1.6	77.2

The scenarios considered, on the basis of the aerodynamic and technical characteristics of the selected aircrafts, are reported in Table 2. In particular, for what concerns the impact of an aircraft on the wall of the facility it is assumed that the aircraft hit the wall with an inclination of about 50 degree with respect to the ground due to the presence of a bank surrounding the facility (Figure 1). As for a crash into the roof, it has been assumed conservatively that the aircraft hit the roof perpendicularly (i.e. with an inclination of about 90 degree with respect to the ground) right in the weakest point of structure of the roof, i.e. the centre of the vault (Figure 1). Furthermore it has been considered that the fuel present in the tanks of the aircraft could generate a fire incident which, independently of the amount of fuel, would involve a number of packages greater than those damaged by the mere impact. In particular, it has been assumed conservatively that the number of damaged packages in case of fire incident due to an impact on the wall or on roof are respectively 232 and 624.

Table 2: Accidental scenarios

Aircraft category	Aircraft crash into the wall	Aircraft crash into the roof	Fire incident due to the crash
Single engine aircraft	X	X	X
Helicopter		X	X

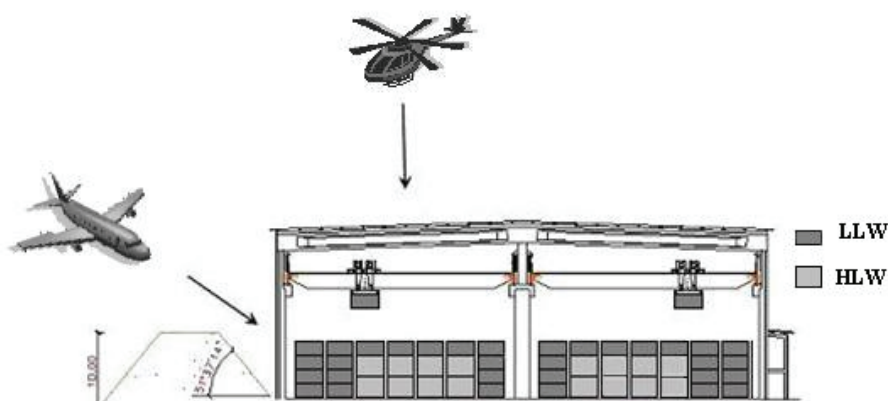


Figure 1: Disposition of the packages inside the facility and accidental scenarios of an aircraft crash into the wall or into the roof.

4.2 Evaluation of the structural damage

Table 3 reports the perforation thicknesses that have been evaluated for each of the selected aircrafts on the basis of Eq. (1) using data reported in Table 1 and assuming f_c , the ultimate compressive strength, equal to 38 MPa for the roof and 35 MPa for the wall. Comparing the thicknesses of the wall (0.30 m) and the roof (0.25 m) of the facility with the estimated perforation thicknesses it is easy to identify those accidental scenarios which cause perforation (reported in grey in Table 3).

Table 3: Perforation Thicknesses

Aircraft Category		Perforation Thickness [m]	
		Wall	Roof
Single engine aircraft	Aermacchi M290 TP RediGO	0.33	0.44
	Piper Seneca V	0.34	0.46
	Piper Turbo Arrow	0.22	0.30
Helicopter	Agusta A109 POWER	-	0.44
	Agusta AB412	-	0.41
	Agusta EH101	-	0.51
	Agusta A129	-	0.56

4.3 Evaluation of the mechanical damage of the waste packages

Data regarding damage of the waste packages for those accidental scenarios which give rise to perforation (Table 3), obtained on the basis of the methodology described in Section 2.3, are reported in Table 4.

Table 4: Mechanical damage: number of damaged waste packages

Aircraft Category		Number of damaged waste packages	
		Impact on the wall	Impact on the roof
Single engine aircraft	Aermacchi M290 TP RediGO	12	16
	Piper Seneca V	24	16
	Piper Turbo Arrow	-	8
Helicopter	Agusta A109 POWER	-	12
	Agusta AB412	-	12
	Agusta EH101	-	18
	Agusta A129	-	12

4.4 Source term determination

The amount of radioactivity released by an aircraft crash into the facility is evaluated by summing the fractions of radioactivity released due to the mechanical damage, R_{md} , and to the burning of the waste packages, R_f . The above quantities, reported in Table 5, have been evaluated according to the procedure described in Section 2.4, assuming for the density of the solid waste, P , the value of 2 g/cm^3 and assuming conservatively DR , LPF , F_w and F_a equal to 1. The values of F_r , have been assumed on the basis of the type of matrix [6], equal to $1.25 \cdot 10^{-5}$ and 0.1 for undamaged packages of waste respectively conditioned in concrete or bitumen and F_r equal to $2.5 \cdot 10^{-4}$ and 1 for damaged packages of waste conditioned respectively into concrete or bitumen. Results show that in case of perforation without fire incident the aircrafts which give rise the most dangerous impact are Agusta EH101 in case of impact into the roof and Piper Seneca V in case of impact into the wall. As for the case of perforation followed by a fire incident the total released activity would be greater of some orders of magnitude with respect to the case of mere perforation for all the aircrafts of Table 5.

Table 5: Source term

	Impact on the Wall [Bq]				Impact on the Roof [Bq]			
	R_{md}	R_f	Total		R_{md}	R_f	Total	
			α	β, γ			α	β, γ
Aermacchi M290 TP RediGO	$6.2 \cdot 10^5$	$1.5 \cdot 10^{10}$	$9.3 \cdot 10^5$	$1.5 \cdot 10^{10}$	$1.9 \cdot 10^8$	$6.8 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.6 \cdot 10^{10}$
Piper Seneca V	$1.3 \cdot 10^6$	$2.2 \cdot 10^{10}$	$1.3 \cdot 10^6$	$2.2 \cdot 10^{10}$	$2.3 \cdot 10^8$	$6.8 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.7 \cdot 10^{10}$
Piper Turbo Arrow	-	-	-	-	$4.2 \cdot 10^5$	$6.8 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.6 \cdot 10^{10}$
Agusta A109 POWER	-	-	-	-	$1.0 \cdot 10^8$	$6.8 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.6 \cdot 10^{10}$
Agusta AB412	-	-	-	-	$1.1 \cdot 10^8$	$6.8 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.6 \cdot 10^{10}$
Agusta EH101	-	-	-	-	$7.3 \cdot 10^8$	$7.0 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.9 \cdot 10^{10}$
Agusta A129	-	-	-	-	$1.8 \cdot 10^8$	$6.8 \cdot 10^{10}$	$1.6 \cdot 10^9$	$6.6 \cdot 10^{10}$

5 CONCLUSIONS

Although ultimately destined for a final repository, the waste packages are temporarily located in interim storage facilities that must be designed so as to guarantee isolation of the radionuclides from the biosphere. Among the severe accidents that can have a relevant radiological impact on the population there is the impact of an aircraft on the facility.

In the present work, a case study concerning the safety of an interim storage facility under design has been considered. To this aim a simplified methodology, based upon the DOE, IAEA and NUREG standard procedures and upon conservative yet realistic hypothesis, has been developed in order to evaluate the total activity released to the biosphere in consequence of the impact.

The developed procedure provides a tool for obtaining, without recurring to the use of complicated numerical codes, a quick and conservative estimate of the source term useful in preliminary design and risk analysis of interim storage facilities and in nuclear emergency planning.

Future work will focus the evaluation of the dose to the population due to the spread in atmosphere of the radioactivity released in the impact. To this aim the diffusion of the airborne radionuclides in the environment will be simulated taking into account further data regarding the specific impact event such as the duration in time of the impact and the meteorological conditions at the moment of the impact together with site specific geographical, hydrographical, hydro-geological and environmental data.

REFERENCES

- [1] United States Department of Energy, Accident Analysis for Aircraft Crash into Hazardous Facilities. DOE-STD-3014-96, October 1996.
- [2] United States Department of Energy, Hazard Categorization and Accident Analysis Techniques for Compliance with Doe Order 5480.23, Nuclear Safety Analysis Report, DOE-STD-1027-92, December 1992.
- [3] IAEA, Regulations for the Safe Transport of Radioactive Materials, Safety Series No.6, Vienna, 1961.
- [4] IAEA, Regulations for the Safe Transport of Radioactive Materials. Notes on Certain Aspects of the Regulations, Safety Series No.7, Vienna, 1961.

- [5] United States Department of Energy, Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, DOE-Handbook 3010-94 Vol I, December 1994.
- [6] Draft Environmental Impact Statement on 10 CFR Part 61, Licensing Requirements for Land Disposal of Radioactive Waste, NUREG 0782 Vol. IV, Appendice G 1981.
- [7] ANPA, Gestione dei rifiuti radioattivi, Guida tecnica n. 26, 1987.
- [8] IAEA, Qualitative Acceptance Criteria for Radioactive Wastes to be disposed of in deep geological formations. IAEA Technical Document Series TECDOC-560, Vienna 1990.