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Preliminary evaluation of an aircraft impact on a surface RWs disposal facility

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Sommario

The aim of this study is to evaluate the structural effects (global response)) induced by the impact of a civilian airplane into a near surface RWs repository, considered as a robust target (steel and reinforced concrete built structures).
According to the international safety and design guidelines and to the stress tests requirements for the security track, a military or civil aircraft impact (considered as a 'beyond design basis' event) into a nuclear facility like the disposal facility of El Cabril has been considered.
To perform reliable analysis of such a large-scale structure and determine the structural effects of the propagation of this types of impulsive loads (response of containment structure), a realistic but still feasible numerical model with suitable materials characteristics were used by means of which relevant physical phenomena are reflected.
The dynamic/ impulsive loads as well as the thermal load, due to the fuel burning, have been preliminary evaluated in order to determine the bearing capability of the considered repository to withstand safely to all the effects (primary and secondary ones) of the aircraft crash.
The obtained results were analysed to check the disposal facility safety margins.

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Preliminary evaluation of an aircraft impact on a surface RWs disposal facility

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Summary

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According to the international safety and design guidelines and to the stress tests requirements for the security track, a military or civil aircraft impact (considered as a ‘beyond design basis’ event) into a nuclear facility like the Spanish disposal facility of El Cabril has been considered.

In order to perform a reliable analysis of such a large-scale structure and to determine the structural effects of the mentioned types of impulsive loads, (in terms of response of their effects on the specific types of containment structures), a realistic, but still operable numerical model with suitable materials characteristics was used by means of that model the mean relevant physical phenomena were simulated and analysed.

The dynamic/ impulsive loads as well as the possible thermal load of the fuel burning fire, have been preliminary considered in order to verify the residual RWs general containment capability of the considered repository type to withstand safely to all the main effects of the considered accident or vicious induced aircraft crash.

The obtained results were preliminarily analysed to check the disposal facility general safety margins.

1. Introduction

Taking into account the preliminary lessons learned from the Fukushima Dai-ichi NPP 2011 accident, a comprehensive safety and risk assessment must be performed on all nuclear plants/facility (that is the aim of the stress tests) along two parallel tracks: a safety track to assess how nuclear installations can withstand the consequences of various extreme external events and a security track to analyse security threats and incidents due to malevolent or terrorist acts [1].

International regulatory bodies suggest and require the development of systematic approaches (deterministic or probabilistic ones) for identifying and assessing the hazards associated with an external event, such as e.g. an aircraft impact (among the man-induced most severe external events). Apart from the possible effects on a NPP containment structure, in the proposed study the dynamic effects of an aircraft impact into a near surface disposal facility have been analyzed.

The risk of an aircraft impact in a disposal plant is strictly related to the radioactive wastes (RWs) inventory temporarily stored in suitable packaging system in this type of repository facility and to the structure characteristics.

The potential hazard to the environment and population is represented by a possible leakage of RWs, which are characterized by a radioactive content, activity concentration and physical and chemical properties.

It is worthy to note that radioactive waste can be generated by a wide range of activities varying from activities in hospitals and industries to nuclear power plants to mines and mineral processing facilities: the RWs are generally processed to produce stable and solid forms, reduced in volume and immobilized, as far as practicable, to facilitate their storage, transport and temporary or final disposal. Therefore their potential associable hazards can range from large to trivial: this variation characterize the management and the disposal options necessary for the various types of waste. The safety principles to be applied in all activities for radioactive waste management are set out in the IAEA Safety Fundamentals [1].

In the framework of the RWs managements, of course both disposal and storage options are designed to contain wastes and to isolate them from the biosphere to the extent necessary: in particular the storage is a temporary measure following which further conditioning or packaging and, ultimately, its final disposal may be planned [2].

A number of design options for disposal facilities have been developed and various types of storage and/or disposal facilities have been constructed in many States and presently operated. These design options have different degrees of containment and isolation capability appropriate to the radioactive waste that they will receive.

In general the specific aims of disposal are:

(a) To contain RWs;

(b) To isolate the waste from the accessible biosphere and to reduce substantially the likelihood and all possible consequences of inadvertent human intrusion into the waste facility;

(c) To inhibit, reduce and delay the migration of radionuclides at any time from the waste to the accessible biosphere;

(d) To ensure that the amounts of radionuclides reaching the biosphere due to any migration from the disposal facility are such that possible radiological consequences are acceptably low at all times.

Actually the preferred strategy for the management of low and intermediate level radioactive wastes is to safely contain and store them in suitable superficial or near surface repositories [3, 4] that of course must be designed to withstand any external (natural and man induced) events.

In general nuclear designers are confident of the safety of structures and systems that characterize any nuclear facilities, which have to be able to withstand dynamic loads, natural or malevolent events, as flooding, earthquakes, hurricanes, aircraft impact, explosion etc., even though in the past they were not specifically designed for this type of conditions.

Particularly in this study, as it was already said, the aircraft impact has been in particular considered: the aircraft impact accident has become very significant in the nuclear design after the tragic 11 September 2001 event in USA, also due to the raised public concern about the potential damaging effects that a large civilian airplane impact could bring in safety related structures.

For this reason the aircraft impact analysis, although considered a “beyond-design-basis” condition, is considered necessary to properly assess the general safety level of a nuclear facility in many countries.

The main structural effects of the “structure-structure interaction”, related to bodies undergoing dynamic contact, and the failure mechanisms of the fast moving and deformable aircraft structure impacting into rigid and/or deformable bodies, as building or industrial structures, should therefore analyzed.

To this purpose accurate simulations of the contact behaviour at material interfaces, defined by means of “slave and master” segments approach, were performed in order to provide realistic predictions of the crashing phenomenon.

Suitable contact algorithms, as the ones implemented in a suitable dynamic finite element code were used in this application to evaluate the structure deformation associate to the interface boundary conditions.

As a result of the considered impact, a finite amount of kinetic energy, which depends upon the inertial and stiffness properties of both the missile and target structures, is transferred from the “striking” aircraft to the impacted walls: the repository structure will be deformed elastically and also beyond the point of permanent yielding, while some components of the aircraft sufficiently tough (assumed as rigid projectiles) will strike and eventually might be able to penetrate the building walls.

Moreover, even at least rough, the thermal effects induced by the set a fire fuel, ejected from/during the crashing (and disintegrating) airframe should be considered. In this contest it is generally considered that the fireball accompanying the impact typically consumes less than 10% of the aviation fuel, while the remainder 90% may be available for burning intensely, reaching and sustaining high temperatures capable of triggering secondary and delayed collapses of the impact damaged and fire-exposed structure.

2. Types of disposal facility for radioactive waste

A number of design options for disposal facilities have been developed and various types of disposal facility have been constructed and are in operation around the world. Within any State or region, a number of different designs of disposal facilities may be required in order to accommodate radioactive waste of various types.
According to the IAEA approach [5], six classes of waste are identified and used as the basis for the classification scheme shown in figure 1:

(1) Exempt waste (EW): Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes as described Safety Guide of IAEA [5];

(2) Very short lived waste (VSLW): Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body for uncontrolled disposal, use or discharge. VSLW includes waste primarily containing radionuclides with very short half-lives often used for research and medical purposes.

(3) Very low level waste (VLLW): Waste that does not necessarily meet the criteria of EW, but which does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Concentrations of longer lived radionuclides in VLLW are generally very limited.

(4) Low level waste (LLW): Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. LLW (a very broad range of waste) may include short lived radionuclides at higher levels of activity concentration and long lived radionuclides, but only at relatively low levels of activity concentration.

(5) Intermediate level waste (ILW): Waste that, because of its content, particularly of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision or only limited provision for heat

dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular alpha emitting radionuclides, which will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon.

(6) High level waste (HLW): Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.

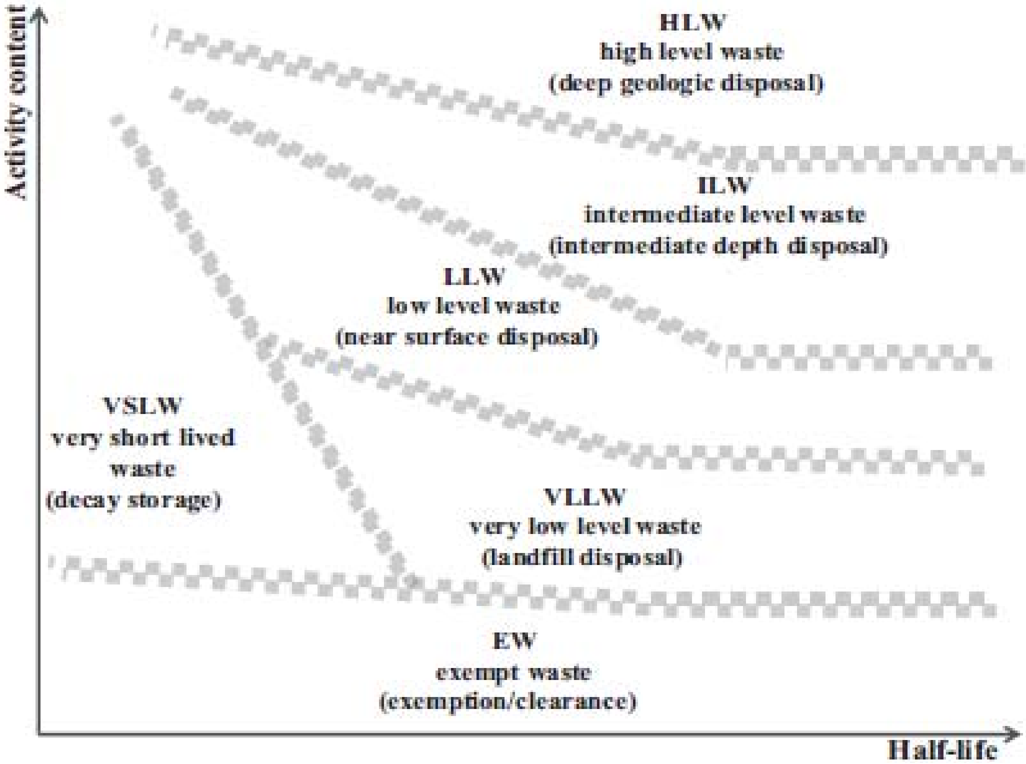


Figure 1: RWs classification scheme [5].

The disposal options, which have been considered or adopted in some Country, are indicated in the following figure 2 [6]. They are based on the RWs classification:

(a) Specific landfill disposal: Disposal in a facility similar to a conventional landfill facility for industrial refuse but which may incorporate measures to cover the waste. Such a facility may be designated as a disposal facility for very low level radioactive waste (VLLW) with low concentrations or quantities of radioactive content [5]. Typical waste disposed of in a facility of this type may include soil and rubble arising from decommissioning activities.

(b) Near surface disposal: Disposal in a facility consisting of engineered trenches or vaults constructed on the ground surface or up to a few tens of metres below ground level. Such a facility may be designated as a disposal facility for low level radioactive waste (LLW) [5].

(c) Disposal of intermediate level waste: Depending on its characteristics, intermediate level radioactive waste (ILW) can be disposed of in different types of facility [5]. Disposal could be by emplacement in a facility constructed in caverns, vaults or silos at least a few tens of metres below ground level and up to a few hundred metres below ground level. It could include purpose built facilities and facilities developed in or from existing mines. It could also include facilities developed by drift mining into mountainsides or hillsides, in which case the overlying cover could be more than 100 m deep.

(d) Geological disposal: Disposal in a facility constructed in tunnels, vaults or silos in a particular geological formation (e.g. in terms of its long term stability and its hydro geological properties) at least a few hundred metres below ground level. Such a facility could be designed to receive high level radioactive waste (HLW) [5], including spent fuel if it is to be treated as waste. However, with appropriate design, a geological disposal facility could receive all types of radioactive waste.

(e) Borehole disposal: Disposal in a facility consisting of an array of boreholes, or a single borehole, which may be between a few tens of meters up to a few hundreds of meters deep. Such a borehole disposal facility is designed for the disposal of only relatively small volumes of waste, in particular disused sealed radioactive sources. A design option for very deep boreholes, several kilometers deep, has been examined for the disposal of solid high level waste and spent fuel, but this option has not been adopted for a disposal facility by any State.

(f) Disposal of mining and mineral processing waste: Disposal usually on or near the ground surface, but the manner and the large volumes in which the waste arises, its physicochemical form and its content of long lived radionuclides of natural origin distinguish it from other radioactive waste. The waste is generally stabilized in situ and covered with various layers of rock and soil.

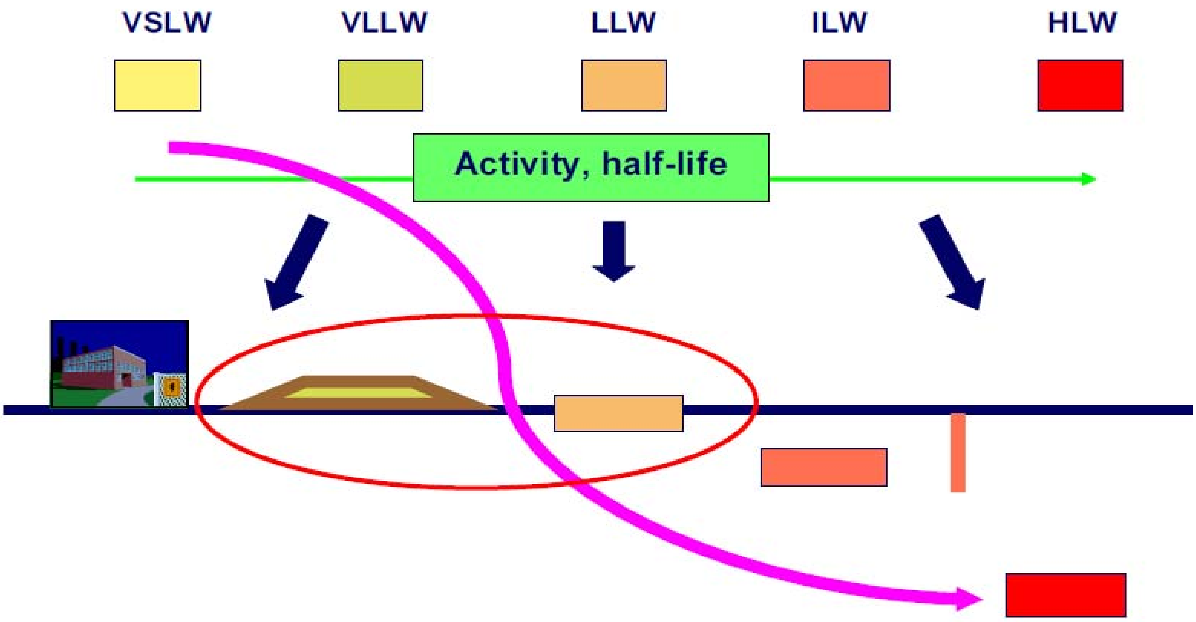


Figure 2: Relevant disposal options for radioactive waste.

3. Near surface disposal concepts: multiple barrier concept

The near surface disposal of radioactive waste is intended to isolate the waste from the accessible environment during a period sufficiently long to allow substantial decay of the shorter lived radionuclides and, in the longer term, to limit releases of the remaining radionuclides. In order to achieve these objectives, a multiple barrier concept is employed in which the waste form, the engineered barriers and the site itself all contribute to the isolation of the radionuclides.

The multiple barrier concept has been developed for both near surface and geological disposal options [9, 10]. It has reached a state of maturity due to the experience gained from developing and operating near surface repositories, and from associated research and development; both have provided valuable information for improvements in repository design and the technologies needed to implement them.

Robust designs of engineered barrier systems may be employed in which a combination of physical barriers and chemical controls can provide a high level of containment [11]. Previously a multiple barrier system was viewed as a set of independent individual barriers working sequentially, but this concept is now viewed in a more integrated and synergistic manner, with complementary barriers operating concurrently and in conjunction with each other.

The internationally accepted approach to developing a high safety solution focuses on the integration of repository design and site characteristics. Defence in depth is provided by using, as appropriate, engineered design features in combination with favorable site conditions, controls on the form and content of the wastes, operating procedures and institutional controls [12].

The relative contributions of the various barriers to the overall safety of the disposal facility will depend upon the characteristics of the waste, the site conditions and the disposal system concept. The relative importance of the barriers may also change with time. The duration of post-closure institutional controls can be expected to be up to a few hundred years.

A period of 300 years, for example, would correspond to around ten half-lives of radionuclides such as 137Cs and 90Sr, which are considered important form a safety stand point radionuclides in short lived LILW. Even after that period, it can be anticipated that the degraded engineered barriers will continue to limit releases of longer lived radionuclides, largely by physicochemical processes such as absorption and solubility control.

The near surface disposal concept usually envisages continued monitoring and surveillance of the site as a part of active controls to be in effect for a period of several decades to a few hundred years after repository closure [13].

During this period, the already mentioned monitoring and surveillance represent an additional safety measure and contribute to the confidence in the satisfactory performance of the facility. The acquisition of data from monitoring also contributes to general scientific and technical knowledge that can be used in the development and improvement of mathematical models for radionuclide transport and for assessing repository impacts.

Typical examples of near surface disposal concepts currently in use in various IAEA Member States are shown in Fig. 3 [14].

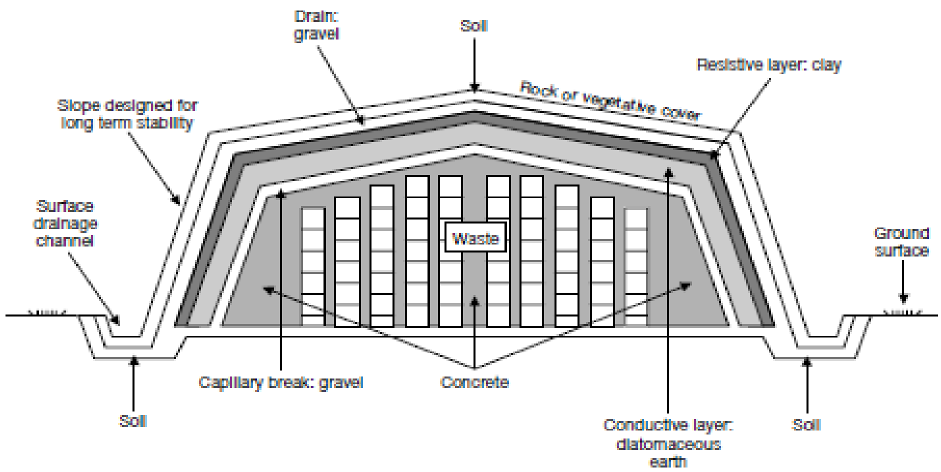


Figure 3: An engineered disposal mound based on the multi-barrier concept [26]

3.1 Disposal systems

In principle, the higher the activity and the longer the half-live of major radiocontaminants, the deeper the facility should be.

A range of technical solutions are feasible for the emplacement of radioactive waste in the near surface environment, and the selection of a particular option depends on many factors, such as the sources, characteristics and inventories of the waste, climatic conditions, characteristics of the site, national legislative requirements and radioactive waste management policies.

Near surface disposal options include two main types of disposal system [10]:

(a) shallow depth facilities consisting of disposal units located either above (mounds, etc.) or below (trenches, vaults, pits, etc.) the original ground surface;

(b) facilities where the waste is emplaced at greater depths in rock cavities or boreholes.

In the first case, the thickness of the cover is typically a few metres, while in the second case, the layer of rock above the waste can be some tens of metres thick. These depths can be compared with the case of geological disposal of long lived radioactive wastes, where the wastes are emplaced at depths of hundreds of metres.

During the past 50 years, concepts for radioactive waste disposal have developed considerably. Most experience has been gained for near surface disposal facilities. During this period, there have been many examples of successful repository development, but also of failures in repository performance.

Examples of such failures include the rapid leaching of radionuclides from wastes and radionuclide releases due to the flooding of disposal trenches by rainwater or a rising water table (bathtubbing).

The reasons for some of these negative experiences include inadequate characterization of the site, unsatisfactory performance of engineered barriers, and inadequate control of the nature and inventory of radionuclides and other toxic substances introduced into the repository.

The lessons learned from these experiences have led to the adoption of improved concepts and technologies, such as those applied at IRUS in Canada [15], Centre de l'Aube in France, Rokkasho-mura in Japan, El Cabril in Spain, Drigg in the United Kingdom, and Barnwell and Richland in the United States of America [10].

In near surface facilities, the basic disposal units (typically trenches or vaults) are often located in the unsatured zone, even if in some countries, local conditions require the disposal units to be constructed in the saturated zone. In both cases, the disposal units have to be designed and constructed to limit the flow of water through the waste.

To this end, near surface repository designs may include engineered components such as impervious covers, drainage systems, leaching collection systems and cut-off walls. A network of ditches may be used to facilitate the drainage of rainwater and avoid surface accumulation of stagnant water in the vicinity of the disposal units. Underground drains may be used to keep the disposal units dry, if the wastes are placed above the water table.

A leachate national collection system may be used to collect any water that has infiltrated the disposal units. Cutoff walls may be constructed to limit horizontal groundwater flows or to provide structural integrity to a disposal facility. Rock cavities can be either natural or excavated in various geological formations [10]. A rock cavity repository, SFR, has been constructed at Forsmark in

Sweden, in crystalline rock about 60 m below the sea. It consists of different types of mined chamber designed to accommodate LILW [9].

Two rock cavity repositories, similar to the mentioned Swedish repository in terms of both the design and the type of host rock, are in operation in Finland at Olkiluoto and Loviisa [16].

3.2 Repository design components

As already mentioned, the major components of a disposal system generally include the waste form, the waste package, the engineered barrier system, the natural barrier system (geosphere) and the biosphere. The waste form is generally the solid matrix in which the radionuclides are immobilized after treatment and/or conditioning, prior to packaging. Some wastes may not be conditioned. In this case the waste form will consist of the originally contaminated material (paper, rubber, wood, animal carcasses, etc.), possibly in a compacted form.

Different types of conditioning material are used to stabilize waste, with cement being the most commonly used material [10]. Bitumen and polymers are some of the other materials that have been used. Combustible wastes, such as contaminated clothing, plastics, paper, wood and other organic matter, are often incinerated and the ashes incorporated into a solid matrix [10].

The waste package, consisting of the waste form and container, is designed to meet the requirements for handling, transport, storage and disposal. In order to limit the release of radionuclides and other contaminants, some packages include additional features such as absorbing materials and liners. Concrete and carbon steel are the most commonly used materials for waste packages. Plastics, such as high density polyethylene (HDPE), are being used for the fabrication of high integrity containers (HICs).

The integrity of waste packages is particularly important, considering the potential for the retrieval of waste.

The engineered barrier system may consist of a number of separate components, including structural walls, buffer or backfill materials placed around the waste packages, chemical additives, liners and covers.

Depending on the disposal system concept, the engineered barrier system may be supplemented by other engineered components, including leachate collection and drainage systems, cut-off walls, gas vents and monitoring wells.

Because of the variety of the possible engineered components that can be used in a disposal facility [10], a repository developer has a great deal of flexibility in selecting the appropriate components to address the specific performance requirements of a planned disposal facility:

- “*Below the water table, the disposal units can be lined with clay, concrete, bitumen or other materials to improve the isolation of the waste; above the water table, the same materials could be used to produce impermeable covers to prevent or minimize the ingress of percolating water into the disposal units.*

- *The space between the waste packages may be backfilled (for example with cementitious grout) to provide structural support for the waste packages.*

- *In some designs, wastes are combined with protective materials in monolithic blocks in special overpacks to facilitate their retrieval (for example at El Cabril in Spain).*

- *Capillary barriers (consisting of a coarse grained material, for example gravel, that has a higher permeability than the surrounding finer grained materials) may be used to limit the ingress of water into the disposal units.*

- *Weatherproof buildings (for example those at Centre de l’Aube in France), and water diversion and drainage systems can be constructed to direct water away from the disposal units.*

- *The disposal units can be protected from intrusion by a layer of rock (in rock cavity type repositories) or by capping (as in the case of the reinforced concrete roofs in the IRUS facility design in Canada), and from erosion by the planting of vegetation or the use of a rock rubble cover”* [10].

In order to ensure that the engineered barrier system is robust enough to perform as specified in the design, materials should be used that have the necessary characteristics to maintain their function and integrity under anticipated repository conditions for the required period of time. The repository near field consists of the waste, the engineered barriers and the adjacent geological media disturbed by excavation and other construction and operational activities.

The natural barrier system consists of the geological media hosting the repository and any other geological formations contributing to waste isolation.
In safety assessments, the natural barrier system is often referred to as the far field or the geosphere (whose aim is to protect the disposal facility and retard and dilute any radionuclides released from the near field). The natural barrier system is normally long lasting, although it may be affected by erosion, climate change, seismic events, and other processes and events.
Moreover in a repository design, the compatibility of the engineered barriers with the waste and site characteristics (i.e. the chemical properties of waste and groundwater and the mechanical properties of rocks and soils) should be considered.

3.4 Examples of existing near-surface repository

The major near-surface disposal facilities currently in operation are in:

a) Spain: low and intermediate level radioactive waste disposal facility ("El Cabril" [20]);
b) France: Centre de l'Aube;
c) UK: Low Level Waste Repository at Drigg in Cumbria;
d) USA: three low-level waste disposal facilities at Barnwell, South Carolina, Richland, Washington and Clive, Utah.

a) El Cabril Repository

A consolidated management system for Intermediate and Low Level Radioactive Waste Management is placed on El Cabril: the volume of the waste disposed in El Cabril cells was 40 964 m^3 "as disposed", corresponding to 17 561 m^3 of "as delivered" waste.
This means that 39% of the El Cabril capacity of 45 000 m^3 of conditioned wastes had been used. According to the last operation permit issued by Ministerial Order of October 5th, 2001, ENRESA is authorized to operate El Cabril facility until the current disposal capacity is exhausted.
El Cabril centre was used for uranium production in the 1950's and later it was a waste storage facility. The facility (Fig. 4) is divided into two main areas: the disposal area, and the auxiliary building area. Both are separated by a brook that surrounds the disposal area and controls the behaviour of the underground water flow.

Figure 4: Overview of the El Cabril facility.

The El Cabril facilities were designed as near surface repository for LILW, therefore they must meet two basic objectives: protection of people and of the environment and free use of the site following a surveillance period of 300 years, without radiological limitations.

Furthermore, a basic objective sought in the design of El Cabril has been the possibility of recovering the wastes if circumstances were to make this advisable. To reach these objectives two main criteria are stressed: to isolate waste from the main vectors of radioactivity release (man and water) and to limit the activity disposed.

The disposal concept is based on a multibarrier system with the aim to isolate the metal packages containing the wastes that are stored inside concrete containers, which are allocated in the disposal vaults. In Fig. 5 it is represented a schematic design of El Cabril disposal facility [20].

A drain control system exists in inspection galleries constructed beneath the disposal vaults. These vaults are protected from the weather during their operation and sealed by a metallic shelter, which also supports the handling crane.

After completion of a disposal area, a multi-layer-engineered cap will be constructed to divert the rainwater and to provide long term protection for the containers as well as to ensure their durability.

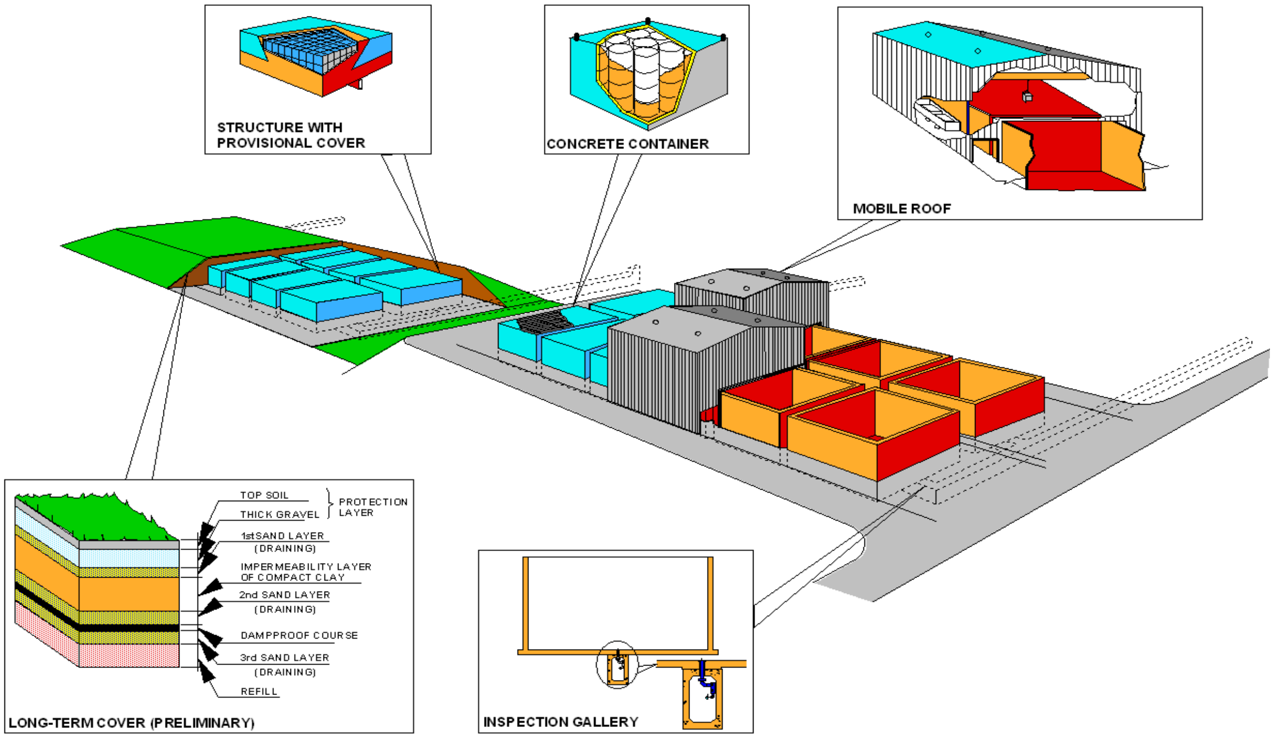


Figure 5: Schematic design of the El Cabril disposal facility.

The El Cabril facilities includes:

- a treatment and conditioning building, which includes institutional waste segregation, treatment (with incineration and super compaction) and conditioning, package transfer into disposal units, liquid waste collection and grout preparation and injection;

- a verification laboratory supporting waste acceptance and characterization activities and for technical verification of the waste packages. This laboratory is fitted with the equipment required for sampling, mechanical testing, the extraction of dry test pieces, equipment to characterize from a radiological point of view the waste package, a system for the leach testing of packages (drum removed) etc.

- a building for concrete container fabrication;

- auxiliary systems and buildings in support of operation, maintenance and surveillance of the facility.

Primary waste packages, containing immobilized waste arising from the super compaction process, are reconditioned in concrete overpacks to be disposed. Once containers are full and the lids have been placed on, they are transferred to the immobilization grout injection area.

b) France repository

France's experience in the management of radioactive waste is supported by 40 years of operational activities in the field of surface disposal of low-and intermediate-level short-lived waste (LILSLW) and of very low level waste (VLLW) [21].

The so-called Centre de la Manche started operation in 1969, and 527,000 cubic-meters of waste packages were disposed by the end of operation in 1994. More recently, in 2003, the Morvilliers disposal facility opened to accept very low level waste, in particular to accommodate waste generated by decommissioning activities.

The Centre de la Manche [21] disposal (Fig. 6) started in October 1969 although its design was continuously improved resulting in a dedicated water collection network to separate rainwater that may have been contaminated by waste packages from rainwater that fell outside disposal structures. This system includes an underground gallery for sampling and monitoring.

The design of the Centre de l'Aube [21] disposal facility fully takes into account French basic safety rules that were developed during the operation of Centre de la Manche.

The facility has a capacity of 1,000,000 m3 of waste packages. Disposal structures are designed to protect waste packages from rainwater during operations. A mobile roof that includes a crane and all control equipment and instrumentation is moved once a cell has been filled and covered with a watertight coating. A separate water collection system collects any water that may have seeped into the disposal system. Vaults are constructed above groundwater level.

Figure 6: Disposal vaults and mobile roofs .

The maximum activity of waste allowed at the facility varies by radionuclide, from 2x105 TBq for caesium-137, to 750 TBq after 300 years for alpha emitters. Thus, to comply with the license, the facility must manage the activity of the different wastes in each of the waste packages, in each of the disposal cells, and for the facility as a whole. Although the maximum activity permitted varies by radionuclide as at Centre de l'Aube, the maximum mean activity cannot be higher than 10 Bq per gram.

c) The Drigg Low Level Waste Disposal Site (UK)

The Drigg site [22] (see Fig. 7) is located on the West Cumbrian to the southeast of the British Nuclear Fuels Limited (BNFL) Sellafield site.
Until 1988, disposal was conducted solely by tipping waste into trenches, at which time disposal into an engineered vault began as part of a general upgrade of the site.
The total area occupied by the trenches is about 16 ha and the total volume of emplaced waste is about 500 000 m3. Due to the effects of self compaction in the trenches, about 800 000 m3 of loose waste was actually emplaced. Following cessation of disposal, operational facilities will be decommissioned and long term site closure constructed features and the site, its facilities and the environmental pathways will continue to be monitored.

Figure 7: Overview of the Drigg site.

d) Near-Surface disposal facilities in the USA

Although other concepts have been pursued in the past, the only two current concepts for disposal of LLW in the USA are above ground and near surface disposal [23].

They require, among other things, to avoid natural resources in the area, such as wildlife preserves; the site must be sufficiently isolated from groundwater and/or surface water and must not be in an area of geological activity (such as volcanoes or earthquakes).

Regardless of design, the ‘near surface facility’ is a land disposal facility in which radioactive waste is disposed of within the upper 30 m of the earth’s surface. The following are the five most common land disposal options for LLW in the USA:

(1) Shallow land burial (like the Hanford site Fig. 10 [23]) was in which are located in areas away from surface water and where travel of any groundwater is slow, the waste containers are placed in long, lined trenches, 8 m or more deep. The trenches are covered with a clay cap or other low-permeability cover, gravel drainage layers and a topsoil layer. They are then contoured and replanted with vegetation for drainage and erosion control.

(2) Modular concrete canister disposal consists of individual waste containers placed within concrete canisters, which are then disposed of in shallow land sites. The array of canisters has an earthen cover and additional engineered barrier system could be provided [23].

(3) Below ground vault disposal uses a sealed structure built of masonry blocks, fabricated metal, concrete or other materials that provide a barrier to prevent waste migration. It has a drainage channel, a clay top layer and a concrete roof to keep water out, a porous backfill, and a drainage pad for the concrete vault.

(4) Above ground vault is a reinforced-concrete structure that provides isolation on the earth's surface. Its sides and top are between 0.5 m and 1 m thick; it has a sloping roof to aid water runoff.

(5) Earth-mounded concrete bunkers are equipped with a drainage system and covered with impermeable clay and topsoil (Fig. 3), giving the facility a rounded shape. The waste is placed in below ground, concrete monoliths, and less radioactive waste is placed on top of the monoliths to create the mounds (they are not deep geological disposal).

Figure 8: LLW facility at the Hanford site.

4. Approach to aircraft impact analysis

The problem of the reliability of a nuclear facility, subjected to a severe external event like the aircraft impact (actually considered a beyond design basis accident), entails mainly with the assessment of the minimum wall thickness necessary to ensure the overall facility safety and, in the same time, prevent the local perforation, particularly when a large jet airliner crash is considered [24-25-26]. In fact the Nuclear Regulatory Commission (US NRC) has determined in the revision of 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities", and Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants", that the impact of a large, commercial aircraft must be considered a beyond-design-basis event.

Due to fact that the potential consequences of an aircraft impact are strictly related to the global or local structures, systems and components (SSCs) structural response, a realistic aircraft impact analysis approach might be adopted to evaluate the safety margin since this latter is considered at present one of the requirements of the international regulatory bodies (referred to acceptance criteria).

In this study, the attention has been paid to a near surface RWs repository building: the response of the repository as well as that one of any other nuclear building will depend to a large extent on the dynamic loads transferred, on the facility design and outer building wall thickness. In this framework, two distinct types of structural failure modes need to be evaluated:

- The global failure (plastic collapse);
- The local failure (scabbing and perforation).

The local failure is independent of the overall characteristics of the impacted structure, whereas the global one depends mainly on the general dynamic characteristics of the target structure.

The impact load, that is transferred during the striking of the aircraft is due to the kinetic energy, which is partially absorbed by the building in the form of local strain energy (dissipated by plastic deformation and fracture) and in part by the aircraft structure (crushing and breaking of the plane).

It is important also to note that a small contribution of the kinetic energy, that may be considered negligible, is dissipated by friction and converted in vibration.

The sequence of localized loading effects consists of three stages-missile effects: penetration into the target; spalling and scabbing of the target and, potentially, missile complete or partial perforation completely through the target walls; these effects may be defined as follows [27]:

1. the penetration corresponds to the displacement of the missile into the target;
2. the spalling is the ejection of target material from the front face of the target;
3. the scabbing is to the ejection of material in the opposite the face of impact;
4. the perforation occurs when the missile fully penetrates and passes through the target walls.

As for the global response concerned it can be characterized by major structural damages, such as the collapse of large portions of the building walls, floors, and load carrying members.
The airplane impact will also potentially induce vibrations throughout the building, that are not considered in the present evaluation.

4.1 Description Of The Considered Surface Repository

A safety assessment of a near surface disposal facility, like the El Cabril one, subjected to aircraft impact (as suggested by the “stress tests” in the security track section) was performed using the recommended deterministic safety margin assessment (SMA) methodology, instead of the probabilistic safety assessment (PSA) one.
To analyze the performances of a surface repository (indicated in what follows with the acronym RWsC) a rather refined numerical methodology was employed.
The considered disposal facility was assumed to have as a reference the same layout and scheme of the abovementioned El Cabril facility, which is characterized by two zones: the disposal zone, and the conditioning and auxiliary buildings zone. The distribution of the different buildings and structures is shown in Fig. 9. The disposal zone hosts 28 storage cells grouped in two platforms: the north platform, with 16 cells, and the south platform, with 12 ones [28].

Figure 9: General scheme of the disposal facility

The platforms are horizontal and parallel surfaces some 90 m aside, excavated in trenches in the hillside, and side banks have been left to rest on the final cover, like represented in Fig.6.
In both platforms, the cells are half-buried and are laid out in two rows (Fig. 10), each of which is served by a sliding roof during the construction.

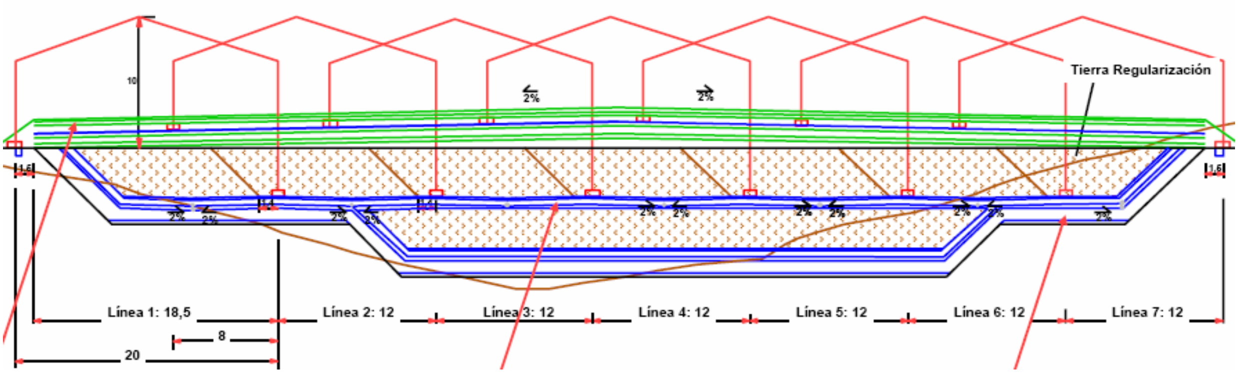


Figure 10: General scheme of platform [courtesy of ENRESA]

The storage cells have approximate external dimensions of 24 x 19 x 10 m [28]. The main element is the bottom slab, which is about 0.5 m thick and is coated with a waterproof layer of polyurethane and a 10-20 cm layer of porous concrete, resulting in a horizontal surface on which the containers are placed.

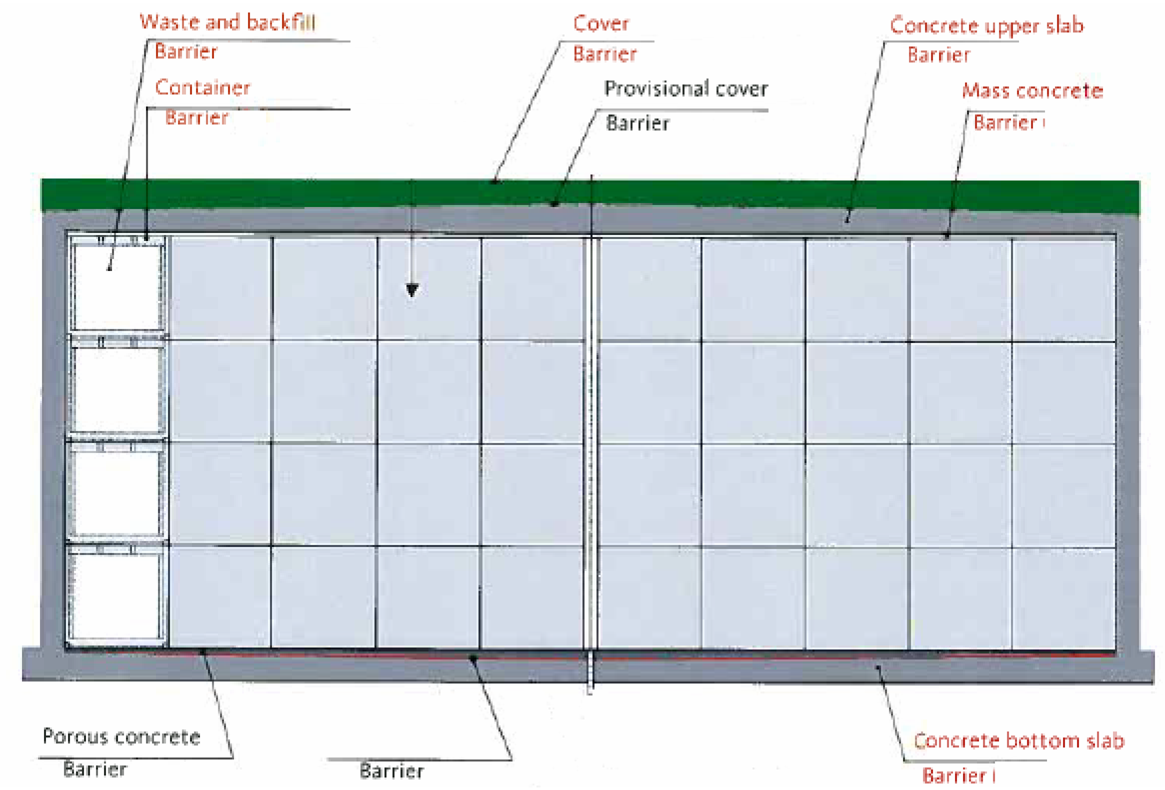


Figure 11: Scheme of the possible storage cell disposition [courtesy of ENRESA]

Moreover the bottom slab of each storage cell is linked to a network of pipes, located below the storage structures and installed for inspection purposes.

The waste packages (generally 0.22 m^3 drums) are immobilized previously inside concrete containers, with external dimensions of 2.25 x 2.25 x 2.20 m weighing some 24 tons, each of which may accommodate 18 drums [28]. The concrete containers are stored in piles of four levels and in contact with each other in the storage cells, like shown in the previous Fig. 11.

The central gap is left to allocate for container manufacturing or positioning tolerances.

Once each storage cell has been fully loaded, the central gap is filled with gravel to stiffen the assembly, and an upper closing slab is built.

In this study only one storage cell with its characteristic four levels, central gap and stored containers (indicated in what follows with the acronym RWsC) has been considered to set up and implement a refined FE model.

4.2 Global Response of RWsC

To determine the dynamic response of RWsC structure and to evaluate if its outer walls are robust enough to bear the considered aircraft impact event a deterministic method has been applied with reference to the structure disposition before the external soil coverage installation (conservative condition).

To this purpose non linear analyses have been performed implementing suitable feature capable to simulate the structural damage phenomena as well setting up a refined model of both the two considered structures (adopting MSC©codes) with reasonable hypotheses for the structural materials characteristics (e.g. concrete and steel) and geometrical dimensions, assuming also suitable boundary conditions for the foundation level.

The aircraft model impact phenomenon to be evaluated is considered to cause stresses in the RWsC beyond the elastic limits in an extremely short period; of course large deformations are possible depending on the building structural characteristics.

To analyze that phenomenon, non-linear dynamic FEM codes, based on an explicit method, were used to adequately simulate the contact conditions. An external coupling procedure involving structural (MSC©Marc) and dynamic (MSC©Dytran) codes was implemented.

Non linear analyses were thus performed setting up a quite refined finite element models for both the RWsC and airplane structures, taking into consideration the features need to simulate the interaction (approximate) between structural parts undergoing dynamic deformation following the postulated aircraft impact including self-contact, part-to-part contact and elimination of element due to destruction. In the performed analyses, the Lagrangian contact algorithm was adopted in addition to the classical initial, kinematic and dynamic constraints (boundary conditions of continuum mechanics) that govern the motion of the interfaces and possible boundary singularities to accurate modelling of the contact interfaces between bodies.

As already mentioned a Lagrangian contact algorithm was used: the nodes move with the velocity of the material medium and the moving interfaces can be treated explicitly as a set of surface nodes or continuous marker functions and cells.

The Lagrangian contact interface was defined by means of both the airplane and RWsC walls element regions and the contact force is calculated according to the conservation of the impulse.

4.2.1 Aircraft Model

In the performed analyses the impact of a civilian aircraft was considered; to the purpose a civilian airplane like the large Boeing 747 was considered.
The first step in the evaluation of the consequences induced by the impact of a such a type of airplane a finite element model representative, in as much detail as possible, of the real Boeing 747 (Fig. 12) was implemented. Moreover in this study it was assumed as horizontal impact direction that is perpendicular to the RWsC walls, which corresponds to the most unfavorable impact condition, in agreement also with the Riera formulation, while the impacting velocity was assumed equal to about 100 m/s (360 Km/h). This hypothesis has been done to consider adequately and conservatively the velocity of the airplane in the descending phase without stall phenomenon.
In any case with th eset up model any other reasonable impact speed may be considered.

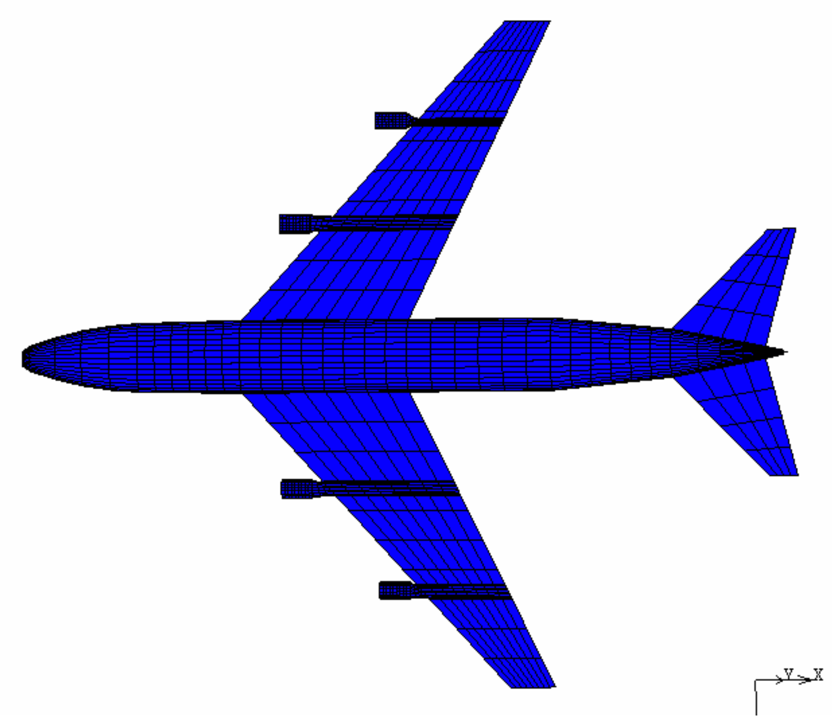


Figure 12 – View of the Boeing 747 FE model

4.2.2 Surface Repository (RWsC) Model

To perform the safety assessment of a near surface disposal facility, a numerical approach has been adopted, as already mentioned, considering a repository configuration like the El Cabril one.

Therefore based on the above geometrical description and main data of the storage cell a FE model,as mentioned, representative, at this first stage, of only one storage cell of the RWsC (Fig. 13) has been set up and implemented.

This model allowed to represent the four levels of each cell, the central gap, that symmetrically subdivide the cell and the stored containers.

A refined FE model was thus assembled with more than 80000 elements: as for example Lagrangian solid and/or shell iso-parametric type elements werechosen to adequately represent/simulate the dynamic behaviour of each storage cell structures during the crushing of airplane and the fuel burning.

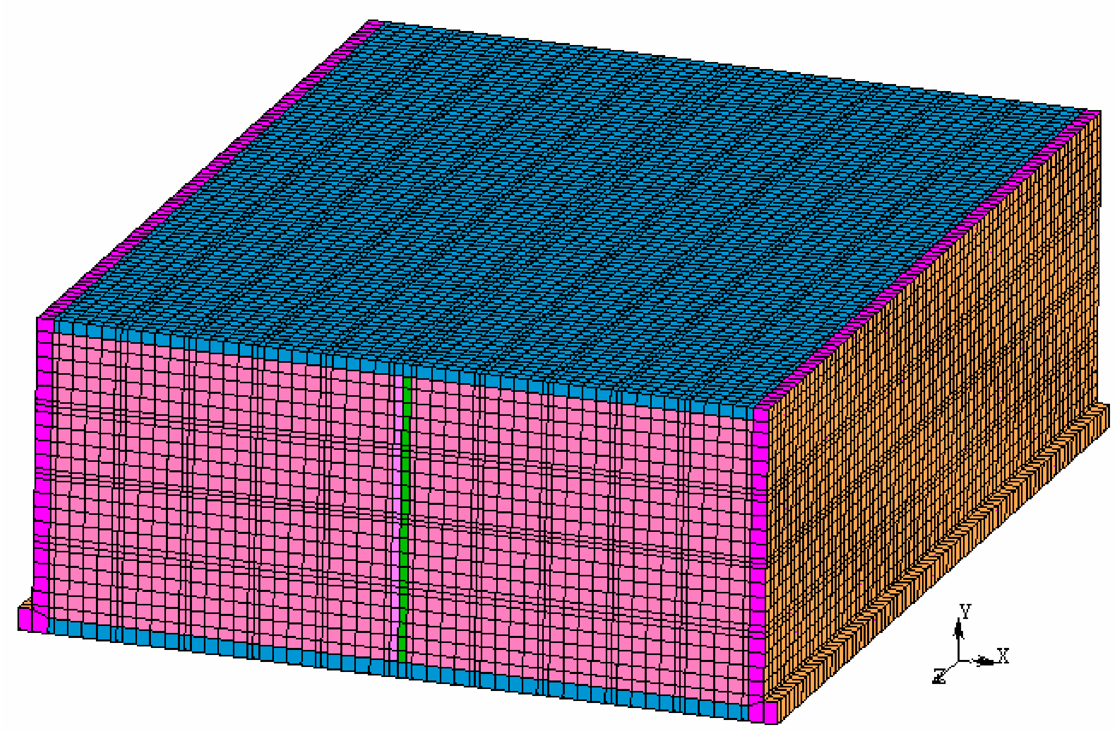
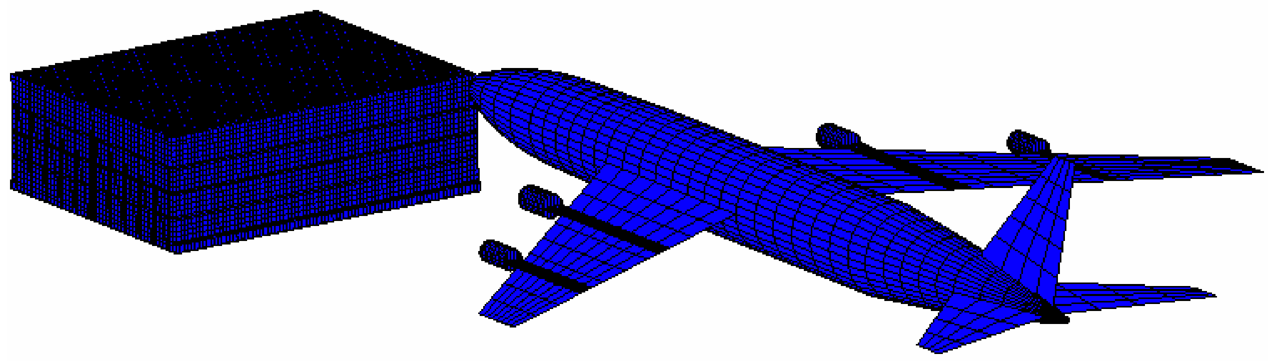
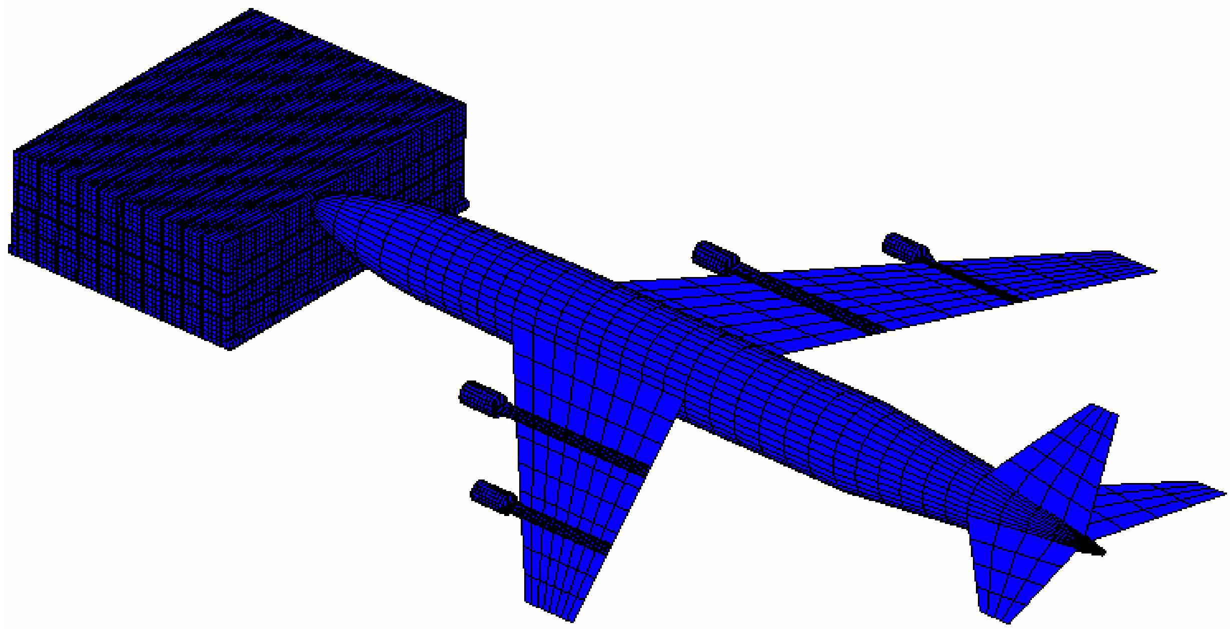


Figure 13 - RWsC FEM model

In the performed analyses the two considered area of impact were located in correspondence of the disposal cell roof, at the edge and at the middle of the RwsC lateral wall (orthogonal to the x axis) as shown in Figs. 14 (a) and (b).



(a)



(b)

Figures 14 a, b – View of the impact area: (a) at the edge and at the middle (b) of the RwsC

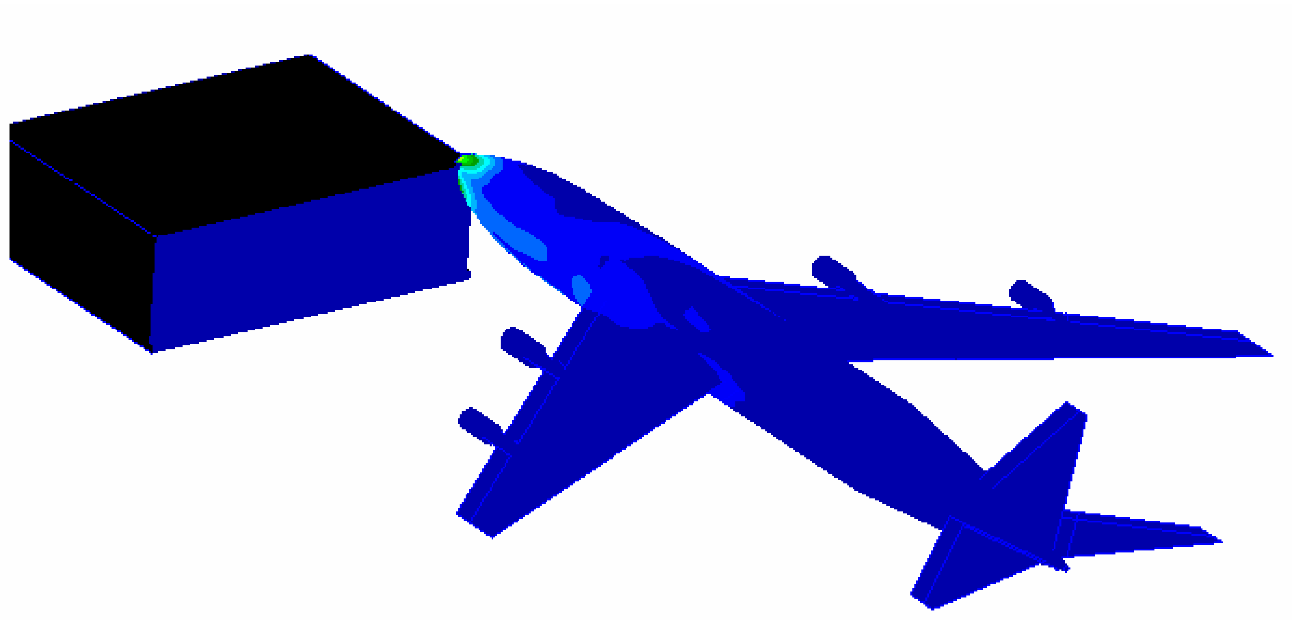
The two structures are interacting through the CQUAD4 shell elements, characterized by 6 DOFs and constant thickness over the element. Moreover the materials' behaviour was assumed to be isotropic, elastic-plastic with a failure criterion based on a maximum plastic strain limit.

5. Main aircraft crash analyses results

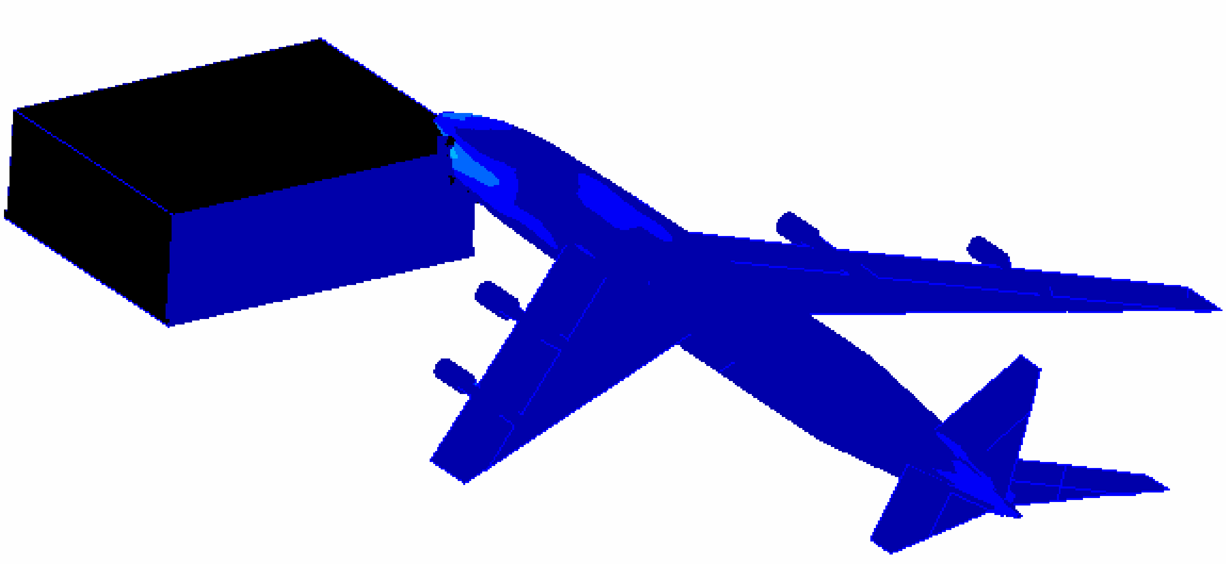
Analysing the obtained results from the impact analyses, it was observed that the RWsC structure dissipated the impulsive loads (airplane kinetic energy) through the plastic deformation of its outer walls.

It was observed that, with the assumed RWsC wall thickness, material properties and initial and boundary conditions, the impact of the considered Boeing 747 determines at the beginning of the impact (phase characterized by the crashing of the “nose” of the airplane) an extensive penetration followed by the scabbing and by the perforation of the reinforced concrete outer walls.

It is worthy to note that, with the assumed conditions and material characteristics, in the area, where the impact is localized (at the edge, as in Figs. 15, or at the middle of cell wall), the main effects on the RWsC are characterized by the local damaging phenomena, while the response away from the impact area seems to ensure the stability and integrity of the structure itself.



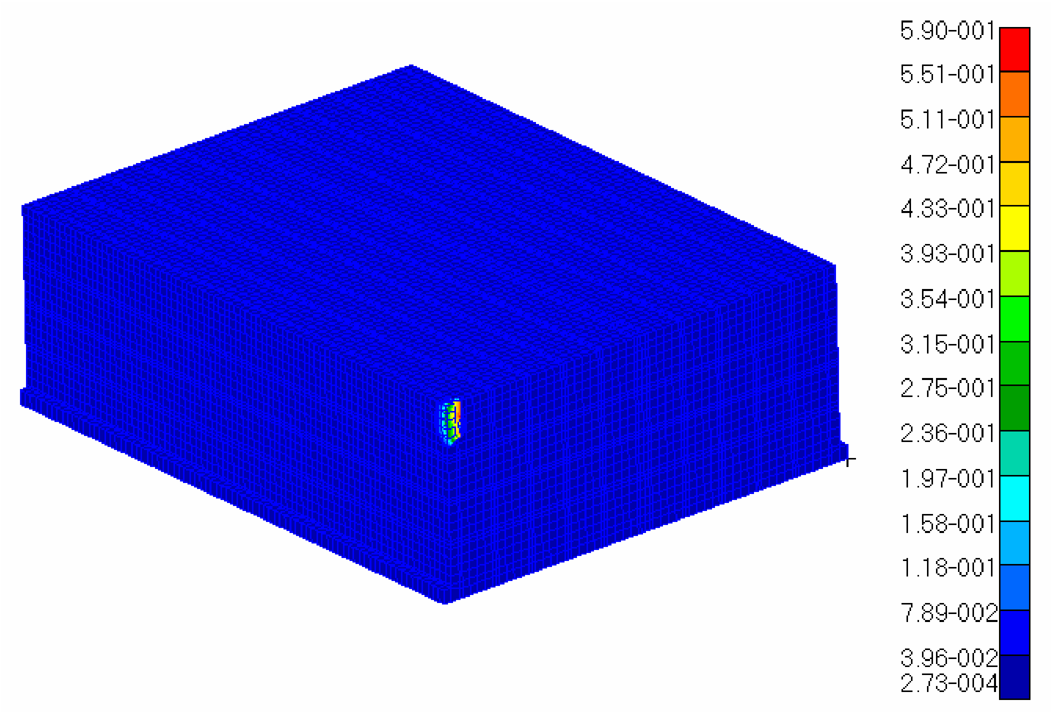
(a)



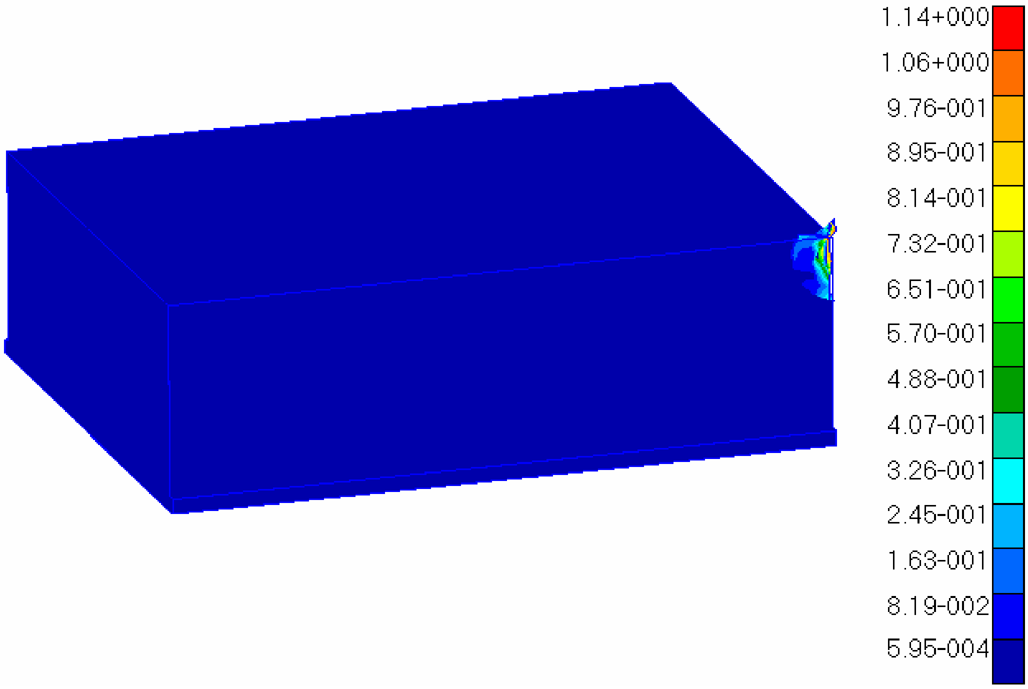
(b)

Figures 15 a, b: RWsC damaging phenomena: (a) initial penetration and (b) scabbing of wall.

Overviews of the preliminary obtained results in terms of penetration depth and wall displacement vs. time for the impact of the Boeing 747 at the edge and on the middle of RWsC cell wall, are shown respectively in the Figs 16, 17 and 18.



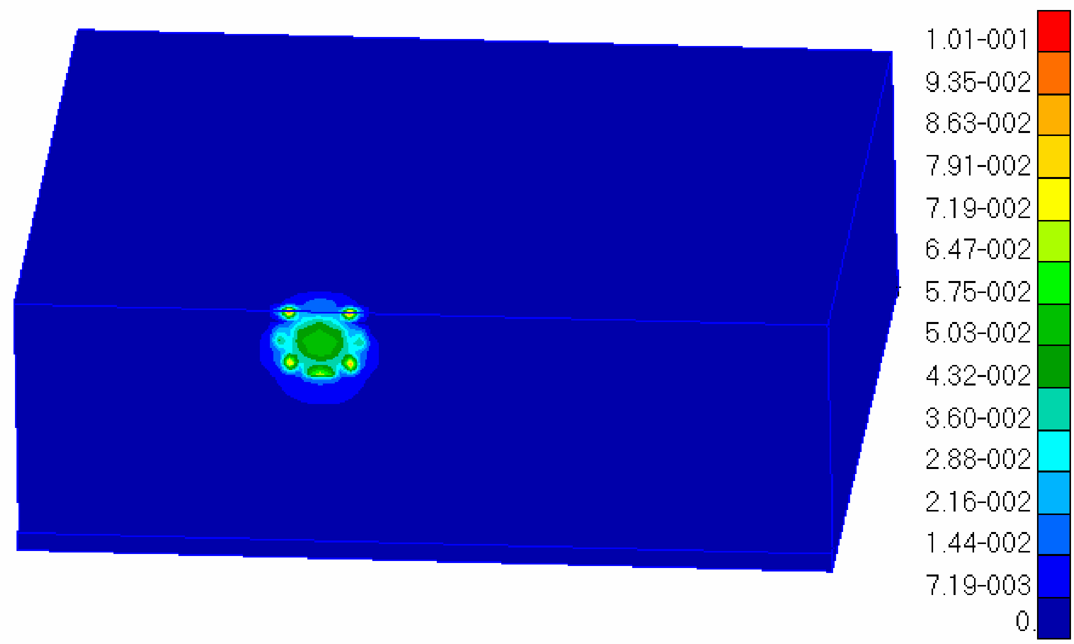
(a)



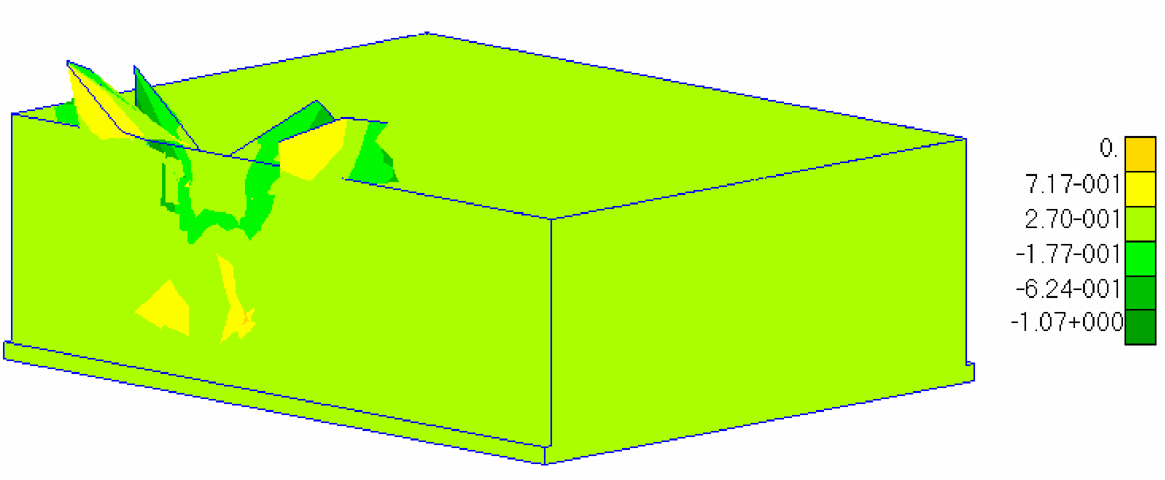
(b)

Figures 16 a, b: Penetration depth at the beginning of penetration (a) and perforation (b)

Moreover in Fig. 17 b it is also represented the scabbing phenomenon with the ejection of cell wall material in the opposite the face of impact.



(a)



(b)

Figures 17 a, b: Penetration depth at the beginning of penetration (a) and perforation (b)

Although the high local stress values induced by the impact, the structural failure of the overall considered repository does not occur in both two impact case (at the edge and at approximately the middle of cell wall represented in Fig. 18), even in presence of ongoing concrete progressive failure and perforation of the area of the impacted walls.

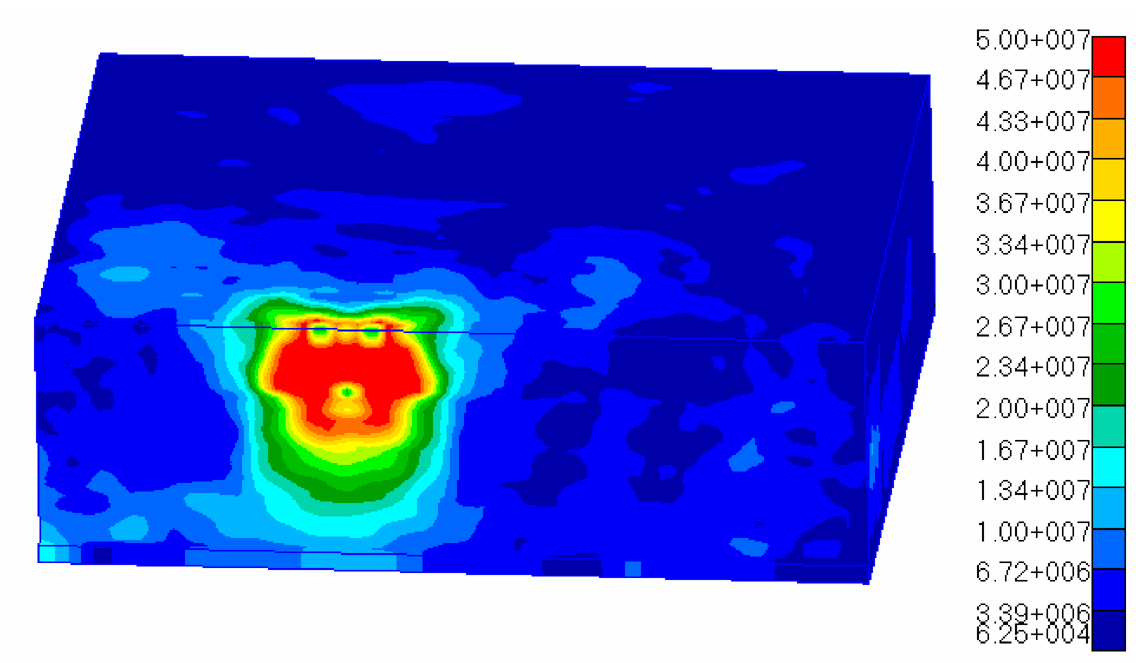
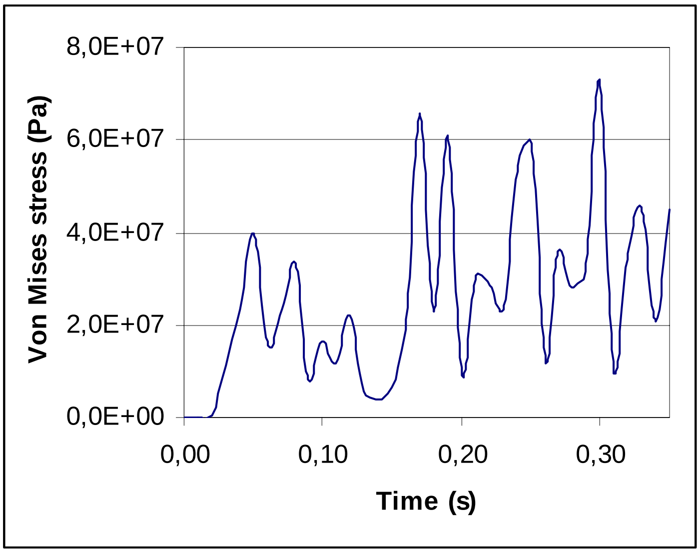
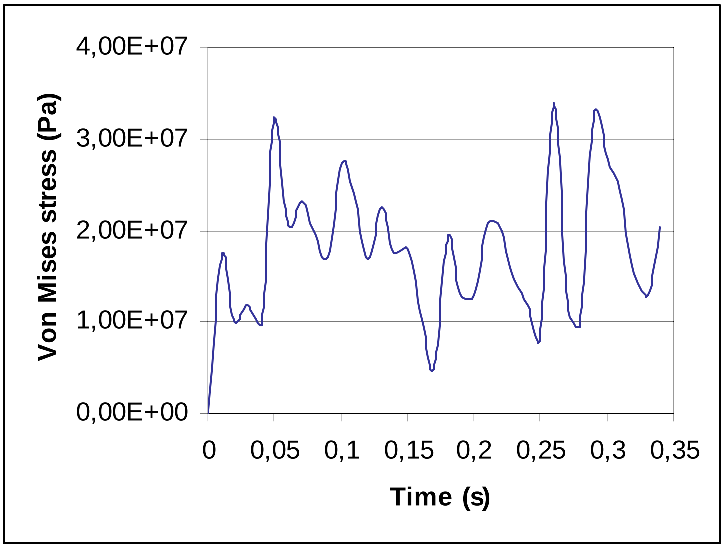


Figure 18: Von Mises stress distribution in the case of impact on the middle of RWsC cell

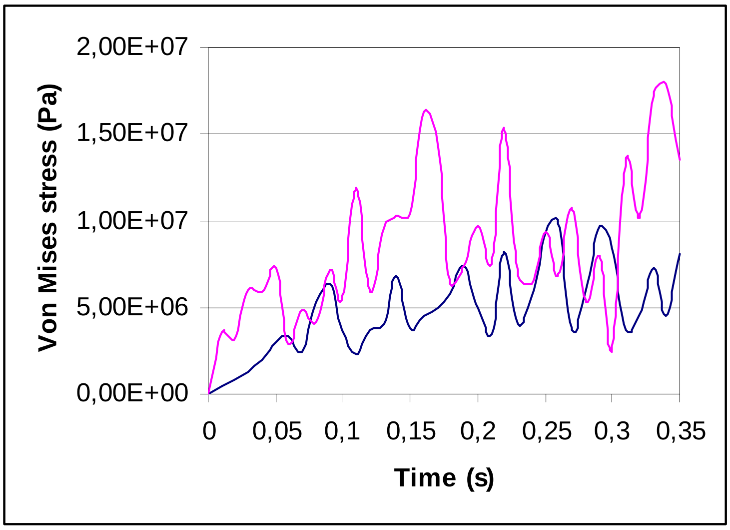
However it is important to stress that away from this impact area the integrity of structure seemed to be ensured (in Figs. 19, as an example, there are indicated the stresses behaviour in the case of impact at the edge of RWsC).



(a)



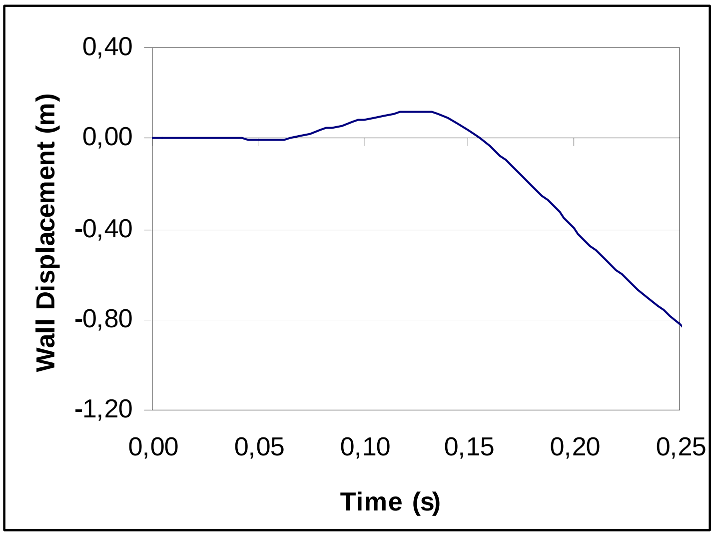
(b)



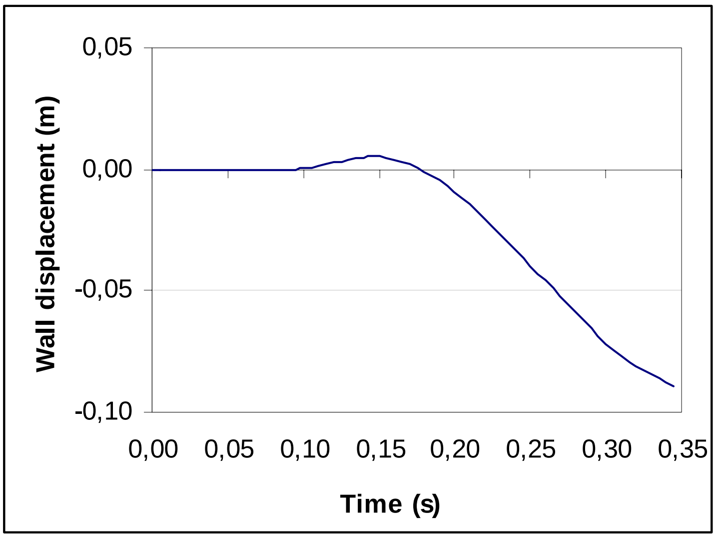
(c)

Figures 19 a, b, c: Von Mises stress behaviour in (a) the and away (b and c) the impact area

The progressive failure of the reinforced concrete walls was coupled to the forming of a rather wide and shallow penetration (with depth ranging about 0.8-1 m (Fig. 20) in the area where the impact was localized, like it is also shown in the previous Figs. 18) that, subsequently, as the load increases (progressive crushing of the airplane against the RWsC walls) results in the increase of the stress level up to the reinforced concrete limit value and in the perforation of the damaged outer wall.



(a)



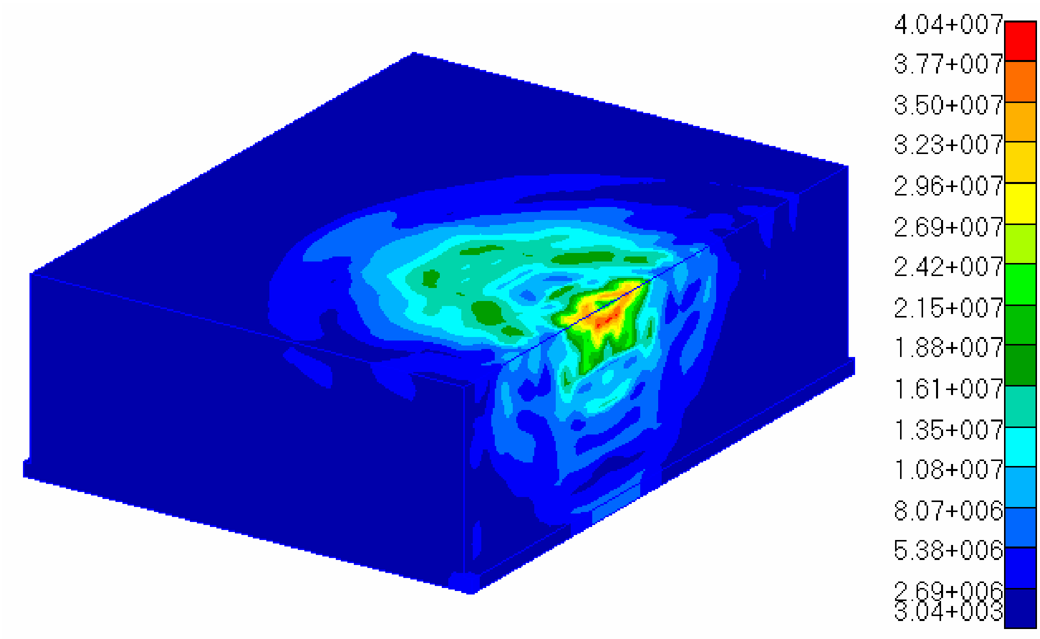
(b)

Figures 20 a, b: Penetration depth vs. time in (a) and away (b) the impact area

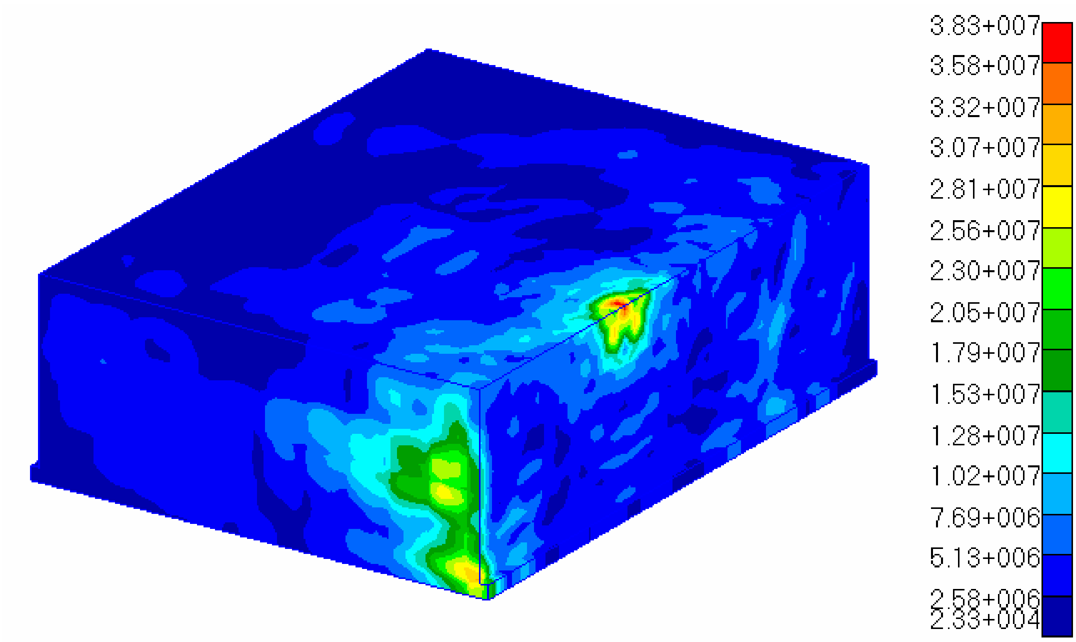
The horizontal impact of the Boeing 747 aircraft was observed to be so damaging to determine the perforation of the impact area (confirmed by the value of the calculated total displacement, of about 80 cm). The perforation occurred because the considered wall thickness (0.6 m) was not sufficient to safely withstand this type of impact and, of course, to absorb the energy transmitted during the reference airplane crushing.

Generally, on the basis of this preliminary results, it is possible to state that the considered RWsC structure will undergo local damage (perforation for Boeing 747, for the considered CB geometry and assumptions); away from the area subjected to the impact the integrity could be ensured despite some penetration and spalling of the concrete (chipping of material at the impact point). Moreover it was observed that away from the impact area the overall stability of the considered repository structure seemed to be ensured.

Furthermore a sensitivity analysis was carried out taking into account different wall thicknesses (from about 0.6 m to 1.5 m) of the RWsC repository structure. The obtained results (Figs. 21) seemed to confirm that an increase of the outer wall thickness may result in an increase of strength of the considered repository structure and in a minor damage effects induced by the airplane crashing on the RWsC walls: the impact of large commercial airplane may determine in many cases the penetration of the exterior walls, at least with wall thickness smaller than the one assuring the safety of the NPP containment in the same conditions.



(a)



(b)

Figures 21 a, b: Von Mises stress distribution for wall thickness equal to about 1 m (a) and 1.5 m

Finally a preliminary rough thermal-mechanical analysis, assuming conservative conditions (that quite all the airplane fuel capacity was involved in the burning, corresponding to a heat combustion of about 46 MJ/Kg), was carried out only on a sub-structure of the considered storage cell repository.

Steady-state analyses have been performed to evaluate the effects of the overall fuel burning temperature assuming, also, that the mentioned structure was in a not deformed state. The obtained results highlighted that the fire induced temperature propagated in/to the RWsC internal components (Fig. 22) reaching about 90 °C in correspondence of waste containers surface.

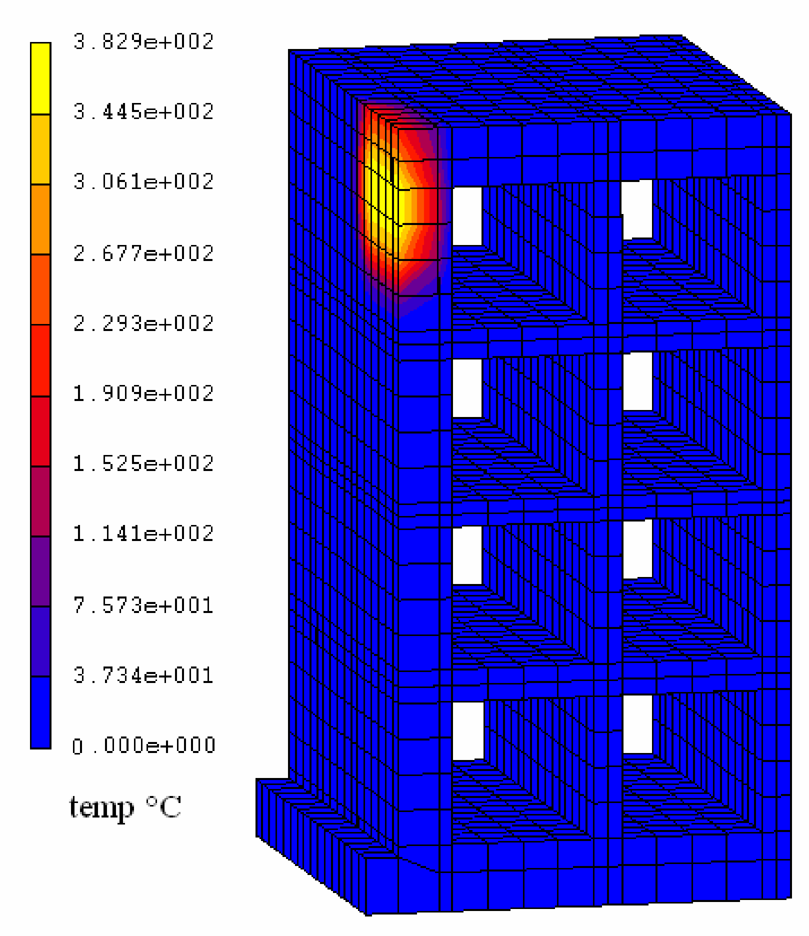


Figure 22: Temperature distribution in the storage cell substructure after 5 s fire

Moreover the stress distribution (Fig. 23) induced by the fuel burning highlighted that the structure seemed to be capable to withstand the postulated accident effects without loss of the structural integrity.

In addition it is important to stress that future study developments of the aircraft impact, considering a more in depth analysis of the aircraft impact and fuel burning effect (e.g. thermal transient analysis even on a deformed structure) seem necessary to correctly evaluate the performances of a near surface repository.

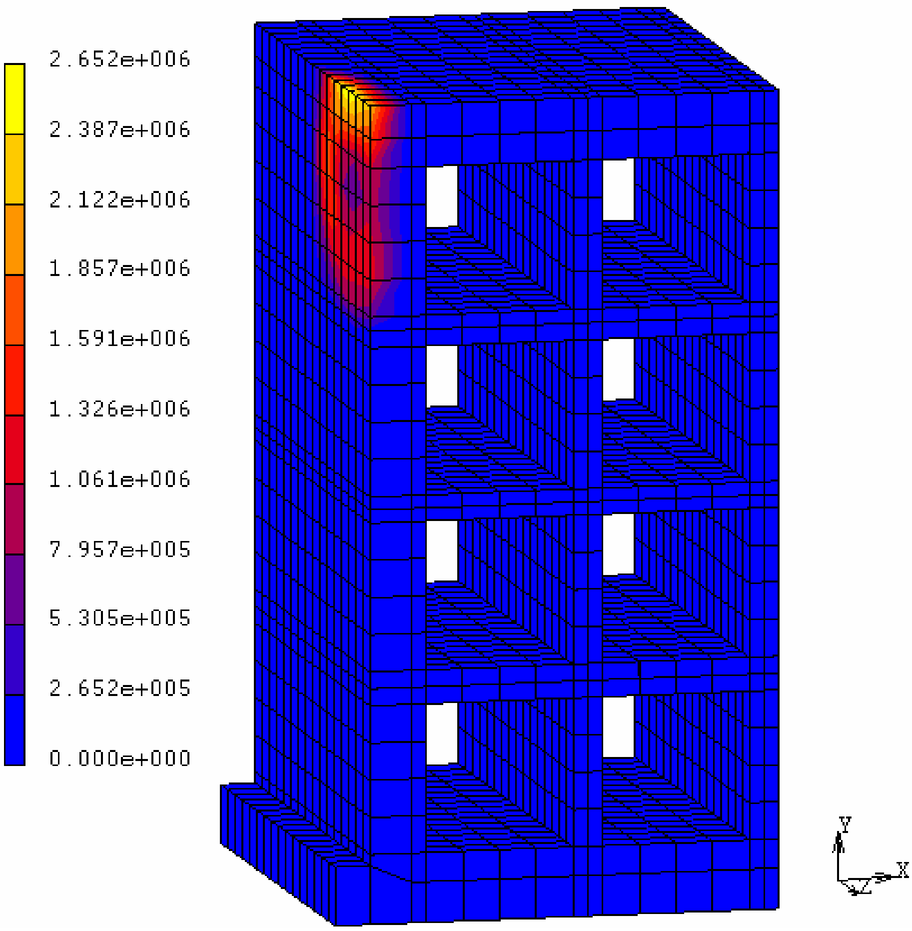


Figure 23: Von Mises stress distribution in the storage cell substructure after 5 s fire

6. Conclusion

In this study preliminary nonlinear analyses, simulating the horizontal impact (conservative approach) of commercial aircraft on a near surface disposal facility, with reference as an example to the El Cabril repository, has been performed in order to determine the global and local structural effects.

The global response of the repository was analyzed by means of finite element codes that required to set up adequate repository and aircraft models and take into account the non linear material behaviour of concrete.

The obtained results, with the assumed RWsC wall thickness, material properties and initial and boundary conditions, highlighted that the considered RWsC walls may undergo local damage: the Boeing 747 penetrates, during the impact, about 0.8-1 m into the assumed wall determining the progressive spalling and subsequently local perforation of the area where the impact is localized.

It was also observed that away from the impact area the overall stability of the structure seemed to be ensured.

A sensitivity analysis was carried out taking into account an increase of RWsC wall thickness, highlighting that the impact of large commercial airplanes may determine the penetration of the exterior walls.

Finally it is possible to state that the assumed RWsC configuration, with acceptable dimensions, showed a remarkable potential to withstand the impact of large civil aircrafts, even in presence of ongoing concrete progressive failure (some penetration and spalling of the concrete wall) and some perforation of the impact area.

Moreover a preliminary thermal-mechanical analysis (steady-state analysis), assuming that quite all the airplane fuel capacity was involved in the burning, was carried out on a sub-structure of the considered storage cell repository. The obtained results highlighted that, even if the calculated temperature at the RWs containers surface was quite limited, the structure seems to be capable to withstand the postulated accident effects without loss of the structural integrity, even if a more complete analysis in this field is advisable.

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8. Curricula of the research group members

The research group of the CIRTEN-University of Pisa is led by Prof. G. Forasassi and consists of: Dr. R. Lo Frano, Dr. G. Pugliese, Dott. V. Baudanza.

The prof. G. Forasassi is full professor of Nuclear Plants, of Structural and Mechanical Engineering Design and of Design of Complex Plant.

The research activity is documented in over 150 publications focused in particular on the study of the safety and design of components of complex systems and nuclear, the safe transport and storage of radioactive materials etc (http://arp.unipi.it/listedoc.php?lista=ALL&ide=1190&ord=C).

The prof. Forasassi, former Director of the Pisa University and Vice-Chairman DIMNP-AIN, is currently President of the National Consortium CIRTEN (Interuniversity Consortium for Nuclear Technological Research) which is participated by the University of Pisa since its foundation in 1994, together with the Polytechnic of Milan and Turin and the University of Padova, Palermo and Rome 1-La Sapienza and since 2010 by the University of Bologna.

- Dr. Rosa Lo Frano is junior researcher at the University of Pisa.

Since 2007 he has been/is assistant-professor courses: Techniques of construction machinery, chemical and nuclear design of the plant complex. The research activity concerning the study of security issues and design of nuclear facilities, the safe transport and storage of radioactive materials, is documented by more than 50 publications in international journals and conference proceedings of the field (http:// arp.unipi.it / listedoc.php? list = ALL & ide = 11443 & ord = C).

- Dr. Giovanni Pugliese holds a doctorate in mechanical engineering at the University of Pisa. From 2004-8 was/is assistant-professor at the Applied Mechanics course. The research activity concerning the study of problems of safety of nuclear installations and the safe transport and storage of radioactive materials is documented by more than 20 publications in international journals and conference proceedings in the sector.

-Dott. V. Baudanza has a degree in Energy Engineering at the University of Pisa and has currently a grant at the DIMNP- University of Pisa for the "Analysis of the main safety issues of nuclear reactors III and IV generation". He has participated in several international workshops on the subject of nuclear safety on the new reactors and new generation.