ABSTRACT

As required in the French regulations, the behavior of the nuclear fuel reprocessing or fabrication plants and nuclear power plants must be assessed for a set of various normal and accidental situations including explosions due to operation hazards or malevolent acts. In this last case, the assessment gathers both safety and security aspects and lead to undertake studies accounting for loads due either to an explosion resulting from an aggression with a large amount of explosive or to an attack with a High Energy Density Device as a conical shaped charge. In order to provide the Authority with elements of appreciation and in support of the expertise of the studies performed by the operators, the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) has initiated a program including experiments and development of numerical models concerning the evaluation of the consequences of such aggression in terms of mechanical damage to the plants and radiological release in the environment. The French approach for assessing the consequences of malevolent acts is based on a sensitivity study aiming at determining the critical components, followed by a vulnerability study for assessing the behavior of the facilities, depending on the type of weapons chosen in compliance with the threats. So for introduction, this approach will be briefly recall. The paper will focus on the technical tools to perform the vulnerability study in the case of an aggression by explosion.

1 – INTRODUCTION

For the nuclear facilities, the French regulations state that the consequences of aggressions aiming at generating a safety hazard and/or radiological releases in the environment must be assessed. These consequences have to be evaluated in terms of safety, pollution in the environment and radiological consequences for the population. These studies aim to determine the extent to which the facilities are protected. The procedure to assess the consequences of such acts is the following (J. Aurelle, 2001 and R. Venot 2002) : the competent authority requires that the operators perform analyses and provide them with the threats to be considered for their own facilities. These studies are assessed by the technical support body to the competent authority: the Radioactive Materials Security Department of IRSN. The conclusions of this assessment are presented to a board of experts (an interministerial advisory group) providing recommendations which can be transformed (globally or partially) in requests to the operator by the authority.

IRSN has defined a long-term program of which the general objective is to establish the behaviour of a pool or tank filled with water and loaded by an internal explosion and a building subjected to an external or internal explosion. This program is based on numerical simulations with computer codes and on experiments. Simulations and experiments are aimed at validating wave propagation resulting from the detonation of explosive device and the mechanical response of the structure.

2 – THE FRENCH APPROACH

Concerning malevolent action, threats have been defined and considered as internal and external threats. To this term ‘threats’ are associated the risk of aggression and the means used by malevolent people. These means are considered as a basic assumption in the studies performed to assess the foreseen or the already existing protection measures.

The approach adopted for considering sabotage affecting the design and operation of nuclear facilities is aimed at determining the extent to which the facilities are protected. When carrying on these studies, the operators have to demonstrate that they are complying with the objectives set by the Competent Authority for reducing the risk of internal or external malevolent actions.

Several types of threats are taken into account for the purposes of these studies :

- Demonstration of a hostile crowd,
- Internal threats involving actions taken by insiders acting alone or not,
- External threats involving actions by small groups of attackers. Two assumptions are made when testing the ability of protection systems to counter aggressions of this type. The first one involves a small team of attackers with limited resources, and the second one takes into account a larger team with more sophisticated resources.

Assumptions are also made as to the type of actions which could be taken by malevolent workers in sensitive zones and the aggravating factors to be considered. As an example the loss of the offsite power supply could be taken into account. Acceptable consequences are taken as being those leading to levels of radioactive releases lower or equal to those taken into account in the facility safety report.

A specific list of the malevolent actions is made from the compilation of events related by media, by French intelligence
agencies or reported by the staff facilities. In 1990, the competent authorities asked the operators of nuclear facilities to declare, without delay, the malevolent actions which may happen in their facilities and to make a report when there is reason to suspect that any malevolent activity has occurred. The criteria selected to characterize the malevolent actions to be declared were specified in 1995 and are similar to those used by the US NRC.

The procedure to evaluate the consequences of terrorism against facilities needs two stages. The first one is the sensitivity study which aims to determine what could be the consequences (on the safety of the facility and in terms of radiological releases) of the destruction or lose of functionality of components, circuits or systems, taking into account the radioactive product inventory and the possible accident situations. The second stage is the vulnerability assessment which aims to quantify the difficulty to perform the aggression: difficulty and delay to penetrate into the facility, type and quantity of tools, explosive or weapons necessary to perform the action and the compatibility of these resources with the considered threats.

3 - BEHAVIOR OF A POOL FILLED WITH WATER AND LOADED BY AN INTERNAL EXPLOSION

3.1 – Brief pool description

IRSN has focused the present analysis on the most common nuclear plant pools which are rectangular with a width equal to one fourth of the length and a height equal to 15% of the length, pool walls are made of reinforced concrete with iron bars. The water height is equal to 80% of the total height of the pool. The dimensions are sufficiently significant to have numerous reflections on the walls and on the free surface and to have shock wave attenuation. In addition, a thin stainless steel liner ensures the pool tightness. The model of the pool loaded by an internal explosion has to take into account both 3D and free surface reflections on the walls and on the free surface and to have shock wave properties. It is assumed that pool walls do not move; wall movements do not affect the pressure field (i.e. that the wave propagation durations differ significantly from wall eigenperiods).

3.2 – General method

The dynamic analysis of the pool requires two stages:

Firstly, a simplified method called MOI (Method Of Images) has been developed to estimate the wave propagation resulting from the detonation of an explosive device and to determine the pressure applied on the walls of a pool or a tank loaded by an internal explosion. A validation has been made by comparison with the underwater experimentation and are dependent on energy and distance. In all cases, the fluid is assumed to be at rest. Each reflected wave is generated from a virtual source at the symmetric position of the explosive charge with respect to the plane interface.

Reflection wave properties are to be in compliance with initial wave properties, except the free surface wave (negative amplitude). The reflected overpressure range is corrected by a reflection coefficient dependent on water and concrete density and sound velocity.

The explosive behaviour is represented by the semi-empirical law set out by Swisdak, 1978. The maximum pressure at a point located at a distance r from an explosive mass W, versus time is given by the following equations:

\[ P(r, t, W) = P_{\text{max}}(r, W) e^{\frac{r}{\theta}} \]

\[ P_{\text{max}}(r, W) = \rho_p \left( \frac{W^{1/3}}{r} \right) \alpha_p \]

\[ \theta(r, W) = \kappa_\theta \left( \frac{W^{1/3}}{r} \right) \]

TNT explosive parameters are the following:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_p ) in Pa</td>
<td>( 524 \times 10^3 )</td>
</tr>
<tr>
<td>( \alpha_p )</td>
<td>1,13</td>
</tr>
<tr>
<td>( \kappa_\theta ) in s</td>
<td>0.084 ( 10^{-6} )</td>
</tr>
<tr>
<td>( \alpha_0 )</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

The reflection coefficient \( K \) expression is only dependent on water and concrete density and sound velocity.

\[ P_{\text{reflected}}(r, W) = P_{\text{incident}}(r, W) * K \]

\[ K = \frac{\rho_w C_w - \rho_c C_c}{\rho_w C_w + \rho_c C_c} \]

Where the pair of values \((W, r)\), W represents the mass of the explosive, \( r \) the distance from the center of the explosive sphere, \( \rho_w \) or \( \rho_c \) and \( C_w \) or \( C_c \) are respectively the density and velocity in water and in the concrete.

Figure 1 shows the MOI general layout. Point 1 is the explosive source and points 2 to 16 are the virtual sources used to assess the various reflections (wall, bottom and free surface).

The MOI Code is compared with the CEA/DAM HESIONE Hydrodynamic Code and the ESI PAMSHOCK Hydrodynamic, figure 2. The first stage of the comparison corresponds to propagation before wave reflection and the second stage corresponds to propagation after the first reflection. A very refined
Concerning the reinforcement, the weak zones are the longitudinal stress (290 MPa) is lower than the ultimate stress (470 MPa). The stainless steel vessel wall is plastified practically in all elements and when stresses reach the yield stress state, cracks appear and tensile stiffness vanishes.

3.4 Results of the Applications
The preliminary results show that stresses due to the hydrostatic pressure and the weight of the structure are negligible (1/1000 of the maximum stress state). The first fifteen eigenmodes estimated are ranging from 8.4 Hz up to 21.1 Hz. It confirmed the difference between the wave propagation characteristic times and these eigenperiods is large enough to uncouple the two aspects. Some applications have been done in considering several tens of kilograms of TNT explosive. Two positions of the explosive source have been studied, at 36% of the water height from the bottom of the pool, two horizontal features: one at the horizontal cross section (case A) and the other at one third of the length and the half of the width (case B). Preliminary calculations show that the stress state is greater than the yield stress for all materials. It is therefore essential to take into account the material non-linearity for stainless steel vessel liner wall and reinforcement steel bars. The concrete model is non-linear and when stresses reach the yield stress level, cracks appear and tensile stiffness vanishes.

4 - BEHAVIOR OF CHIMNEY WALLS SUBJECTED TO AN INTERNAL EXPLOSION
The second example deals with Simulations the behavior of shells constituting the chimney walls and a room made of concrete material subjected to a pressure generated by an explosion of several tens of kilograms of TNT.

4.1 - Brief Description of the Installation
IRSN has focused this analysis on a room (nuclear material storage) existing in the nuclear plants and a typical chimney which ensures the ventilation of the room and located at a corner of the room. The section of the chimney is rectangular (1/7 x 1/6 of the length). Its height is divided into six floors. The shell thickness varies from 1.2 to 0.3 m from the bottom to the top. The thickness of the ceiling and the floor of the room is more than one meter. The width of the room is approximately 9 meters, the height is 5 meters and the length about 20 meters is not modelled due to the fast shock wave attenuation. The concrete is reinforced by two series of iron bars (longitudinal and transverse), their size and their number being a function of the shell thickness. The modelisation needs to take into account the 3D aspect of the waves propagation and the mechanical behavior. The explosive source is located at the middle of a grid located inside the chimney at the junction between the room ceiling and the chimney.

4.2 - Simulation of the shock wave propagation
The estimation of the overpressure generated by an explosive source and the propagation wave resulting from an explosion inside an installation uses also ESI Company finite element codes. The air is assumed to be a perfect gas. The explosive equation of state follows the detonic laws especially the John-Wilkins-Lee equation (1968), for which the coefficients are well known for TNT (explosive source used in the present study).

\[
P(\rho, e) = A \left(1 - \frac{\rho}{\rho_0}\right) \left(1 - \frac{\rho}{\rho_0}\right) \exp \left(-R_1 \frac{\rho}{\rho_0}\right) + \]
\[
B \left(1 - \frac{\rho}{\rho_0}\right) \left(1 - \frac{\rho}{\rho_0}\right) \exp \left(-R_1 \frac{\rho}{\rho_0}\right) + \omega (e - e_0) \rho
\]

The parameters of the equation of state for TNT explosive are the following :

\[\begin{align*}
P &= 101325 \text{ Pa} \\
\rho_0 &= 1.225 \text{ kg/m}^3 \\
\omega &= 4.20 \times 10^{-6} \text{ m}^3/\text{kg} \\
e_0 &= 1050 \text{ J/kg}
\end{align*}\]
Table 1 Pam-flow parameters for TNT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0$</td>
<td>1630 kg/m³</td>
</tr>
<tr>
<td>A</td>
<td>$3.71 \times 10^{12}$ Pa</td>
</tr>
<tr>
<td>B</td>
<td>$3.93 \times 10^{19}$ Pa</td>
</tr>
<tr>
<td>R1</td>
<td>4.15</td>
</tr>
<tr>
<td>R2</td>
<td>0.95</td>
</tr>
<tr>
<td>$\rho_r$</td>
<td>0.35</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>7 J/kg</td>
</tr>
</tbody>
</table>

The chimney and room walls are considered perfectly reflecting during the waves propagation. The calculation is stopped after the first reflection on a vertical wall of the room. The analysis of a TNT explosive source of several tens of kg was done, in a first step, to estimate the greatest overpressure of the spherical divergent wave before any reflection on the chimney wall. Then, the first step results are used as initial conditions for the shock wave propagation and walls reflections in the room and the chimney. During the simulation, the mesh is automatically adapted in the high gradient zone to take into account as accurately as possible the overpressures.

The first reflection of the shock wave occurs at 0.6ms after the detonation, the maximum value of the pressure is more than 20MPa. The reflection at the angle of two vertical walls of the chimney occurs at 1ms and with a maximum pressure of 30MPa, figure 4. The reflection of the shock wave on the bottom face of the room occurs at 2.15ms with a maximum pressure of 5.9MPa figure 5, and when the wave begins its propagation into the room. Then the shock wave reaches the top of the chimney at 19ms. At about 24ms, the shock wave is at the vertical face of the room, reflects and comes back to the chimney with a low value of pressure equal to 2.3MPa. The other reflections on the different faces of the chimney and the room are more difficult to follow due to the various combinations of the shock waves. As above mentioned, the maximum value of the pressure is equal to 30MPa. Such a value appears always at the angle of two faces (vertical or vertical and horizontal). It corresponds to the maximum effect of the reflection (numerous reflected waves combination).

4.3 - Simulation of the mechanical behavior
Due to the lack of symmetry of the wall thickness, the chimney and the room are fully meshed with eight nodes voluminous elements. Each vertical walls and the room ceiling are modelled with at least 5 elements in the thickness in order to represent the bending effect. The bottom wall of the room is supposed to be rigid (one element). The mechanical wall model takes into account, firstly, the concrete which is three dimensional with a one dimensional failure criterion based on the comparison between the principal stress and the ultimate stress in tension and an estimation of the crack density (cracked volume divided by the total volume), secondly, the iron bars which are defined in term of density (not meshed specifically) in the shell thickness. The mechanical behavior is modeled by a kinematic hardening law. The concrete and the iron reinforcement mechanical properties are the current values found in the open literature. To take into account the position and the density of the iron bars in the concrete, different zones have been modelled in the shell thickness. The concrete and steel strains are assumed to be the same in the element and separate constitutive relations for concrete and steel are used. Two types of dynamic calculations have been done; one considers that the chimney horizontal displacements are free along the vertical axis (case A); the second one considers that the chimney horizontal displacements are clamped in the perpendicular direction of the shell at each floor location (case B).

Concerning the displacement, the maximum value is about 6mm at 5ms. The time period of the shell is about 13ms which is longer than the applied load duration. It corresponds to the vertical eigenperiod of the shells located between two floors. The chimney displacements are still greater than the room displacements. Each part along the vertical axis of the chimney moves outward when the shock wave passes. The movement of each part affects the height of two floors. The chimney is cracked but not burst; the cracks are located at the centre of a shell and at the vertical junction of two shells in the lower parts of the chimney. The strains in compression of the iron bars remain elastic but in tension, the strains value reaches 1.1%. The maximum stress values are 24MPa in compression and 27MPa in tension at the junction of the shell near the room and chimney cross section. The approach presented (O. Loiseau et al. 2003) relies on a partitioning of the phenomena and their study by simplified methods.

5 - BUILDING SUBJECTED TO AN EXTERNAL EXPLOSION

The third example deals with the behavior of a nuclear plant building consisting in several rooms, made of concrete material submitted to a pressure generated by an external explosion of several hundreds of kilograms of TNT. The approach presented (O. Loiseau et al. 2003) relies on a partitioning of the phenomena and their study by simplified methods.

The loading of the structure resulting from the detonation of an explosive charge is computed by a numerical implementation of semi-empirical formulas (Kinney). During the propagation, the shock wave is always a spherical divergent one with a very small rising time followed by an exponential decay. The maximum overpressure and constant decay values were established by in air experimentation and are dependent on energy and distance. Due to the absence of building on the path of the shock wave, no reflection is taken into account. The model also allows to describe
the impact and the deflating of the shock wave along the external wall. The response of external walls elements, directly impacted by the aerial shock wave, is studied by a modal projection method, based on the use of analytical solutions from the thin plate theory. The study of the directly impacted wall is realized in the most precise way because of this part of the structure is in general the place where the most damage occurs. The method consists in a virtual decomposition of the wall in elementary plates. Each plate is treated independently by a dynamic resolution after projection on a reduced modal basis. The calculated maximal stress is compared to the resistance limit of the constitutive material. The longitudinal propagation of the shock through the floors and walls of the building, including material and structural damping, is modelled by a 1D approach. The response of the transverse walls after the shock has passed and examined with account for damping effect on the shock wave IRSN has focused this analysis on a typical building existing in the nuclear plants. The building is approximately parallelepiped (width : half of length and height : 2/5 of length). The thickness of the shell varies from 0.8 to 0.5 m. The study imposed a simplification of the building, no doors or windows have been modelled. The concrete reinforcement have not been considered in this study. The criterion of wall failure is when the stress reaches the compressive limit of the concrete. The explosive source is located outside of the building in front of one of its face. The influence of the distance between explosive source and the external wall is investigated. This method is well adapted to a global building behavior or in others words when the explosive source is not closer to the building than one meter (in this case it is necessary to account for the change of concrete equation of state due to high pressure shock wave passing through the thickness of the wall). The main results of the study was to draw an abacus, figure 10, the distance from the explosive source to the building versus the amount of explosive, which shows the beginning of the cracks initiation and wall failure.

6 - CONCLUSION

In order to provide the Authority with elements of appreciation and in support of the expertise of the studies performed by the operators, the Institut de Radioprotection et de Sûreté Nucléaire has initiated a program including experiments and development of numerical models concerning the evaluation of the consequences of such aggression in terms of mechanical damage to the plants and radiological release in the environment. Consequently, IRSN/DSMR has developed technical tools to estimate the mechanical consequences of malevolent actions. Then three examples concerning a pool, a chimney and a building will be presented. The first example is the study of a rectangular pool or tank with walls made of reinforced concrete, when an explosive located inside the pool is detonated. The second one is dedicated to a long chimney with a large room at the bottom which is subjected to an internal explosion. The third one is the behavior of a building subjected to an external explosion with a large amount of explosive. Concerning a pool subjected to an internal explosion, IRSN/DSMR has developed a simplified method based on semi-empirical laws of wave propagation in water validated by comparison with two hydrodynamic calculations. An interface has been drawn up with a mechanical computer code for the estimation of the pool walls. Concerning the consequences of an explosion on the mechanical behavior of a chimney, the simulations used a three dimensional model with two finite element codes, one for the wave propagation and the second one for the mechanical behavior. Two types of mechanical calculations were done, the first one with free horizontal displacement of the chimney and the second one with embedded horizontal displacement in the perpendicular direction of the shell at the each floor location and the vertical junction of two shells. The chimney is cracked but not burst. The cracks are located at the centre of a shell and at the vertical junction of two shells in the lower parts of the chimney. Concerning the consequences of an explosion on the mechanical behavior of a building, the simulations used a simplified method for the wave propagation estimation and also for the walls behavior of the building. The mechanical behavior is based on the virtual decomposition of the external wall in elementary plates with the dynamic response after projection on the reduced modal basis. Transmission shock inside de the structure is also studied by a 1D models. An abacus has been drawn, explosive mass versus the distance between the explosive source and the first face of the building, to estimate when cracks appear or a wall failure.

7 - REFERENCES


Figure 1 MOI general layout

Figure 2 MOI – HESIONE – PAM-SCHOCK - Comparison

Figure 3 – Case A Stress state in vessel wall
Figure 4 – Pressure equal to 32.5 MPa at 1.2 ms

Figure 5 – Pressure equal to 6 MPa at 2.15 ms

Figure 6 – Case A, Displacement at 5 ms

Figure 7 – Case 1, Displacement at 10 ms
Fig. 10. Distance-Mass diagram for various calculations conducted on a 5 m high, 10 m long and 0.8 m thick wall, clamped on one edge and simply supported on the other