EFFEX : a tool to model the consequences of dust explosions

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EFFEX: A Tool to Model the Consequences of Dust Explosions

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ABSTRACT

Some accidents, such as the explosion of the silo in Blaye in August 1997, remind us that explosions of combustible dust can have serious consequences, not only for the industrial installations concerned but also for the environment. The necessity of being able to estimate the effects of an explosion of this type became apparent at the beginning of the 1990s. Owing to the complexity of this subject which involves the mechanical resistance of structures, flame propagation and fluid mechanics, etc., a simulation tool clearly had to be developed. It was in these circumstances that EFFEX was developed. EFFEX is not a software based on the discretization of space but it solves differential equations, each variable of which is considered to be a time function. This is therefore an "integral" type of software code. It is made up of a set of eight modules covering the characterisation of the explosion conditions, the estimation of the mechanical behaviour of the containment and the evaluation of the consequences. Comparison of the results for each of the main modules shows satisfactory consistency with available experimental results. Trials using EFFEX to simulate past accidents, including the transmission and reinforcement of the explosion between subsequent volumes, in order to verify the satisfactory linking of the various modules gave results that were similar to the actual consequences. Several tens of calculation were made so far on silo type of equipments and a synthesis is proposed in addition to a general description of the software.

Introduction

Dust explosions still represent a major threat. Some accidents, such as the explosion of the silo in Blaye in France (August 1997, 12 victims : Masson, 1998), remind us that explosions of combustible dust can really have serious consequences, not only for the industrial installations concerned but also for the environment.

The necessity of being able to estimate the effects of an explosion of this type became apparent at the beginning of the 1990s. Owing to the complexity of this subject which involves the mechanical resistance strength of structures, flame propagation and fluid mechanics, etc., a simulation tool clearly had to be developed. EFFEX originates from this need and was built brick by brick within a few years, beginning by a flame propagation module (the core of the software), completed later by peripheral tools aiming at predicting turbulence characteristics, combustion rates, mechanical resistance, projection of debris and external pressure effects (Proust et al., 2000). EFFEX is not a CFD code but a rather precise phenomenological software. As it is difficult to envision carrying out full-scale tests, the choice was made to select models which could be qualified separately and to verify overall consistency with respect to accidents. Most of the physics is derived from fundamental research. The operational version of EFFEX (version 3) contains eight modules which solve at least 40 non-linear time-differential equations. Hereafter is briefly described the physics which is being handled and data given for comparison with experimental findings. The simulation case of an accident is proposed and compared to the observed consequences. Due to its operability, this code is being widely used in France to analyse the safety of silos. Sometimes modifications of the structure of the silo are proposed, based on the simulations to reduce the consequences of a potential explosion. Hundreds of simulations have been made, the results of which have been summarised.

Modelling of the basic phenomena

Inside a vessel, a cloud of combustible particles and air is formed around an ignition source. The ignition source triggers the combustion of the nearest particles which are heated to a high temperature by the combustion and become, in turn, an "ignition source" for the surrounding particles. This creates a "combustion zone" or "flame" which propagates itself through the cloud. As it passes, the flame transforms the "cold" reactive medium (20°C) into "hot" combustion products (at temperatures of between 1,000 and 2,000°C), so that a portion of the cloud crossed by the flame undergoes thermal expansion. This generation of volume causes the pressure increase in the equipment in which the explosion occurs. If this equipment is not strong enough, it breaks and fragments are formed and propelled into the environment. The overpressure and the flame which were, up until that point, contained within the vessel, are released and, in this way, can have damaging effects. The purpose of the various modules of EFFEX is to represent these various stages.

Turbulence

In most situations, turbulent movement is caused by jets inside the items of equipment concerned, sometimes due to explosion and pressure development in the neighbouring vessels. A confined jet theory has been implemented (**Hinze,** 1972) to build a predictive tool ("TURBULENCE" module) with has the ability to predict even transient turbulence. Measurements have been picked up from the literature (**Hauert** et **al.,** 1994) and extracted from our own measurements in large vessels (Roux and Proust, 2002) and compare very favourably with predictions not only in intensity (figure 1) but also in scale. On that respect a **"k-epsilon"** model (**Tamanini,** 1998) does not appear to be as precise.

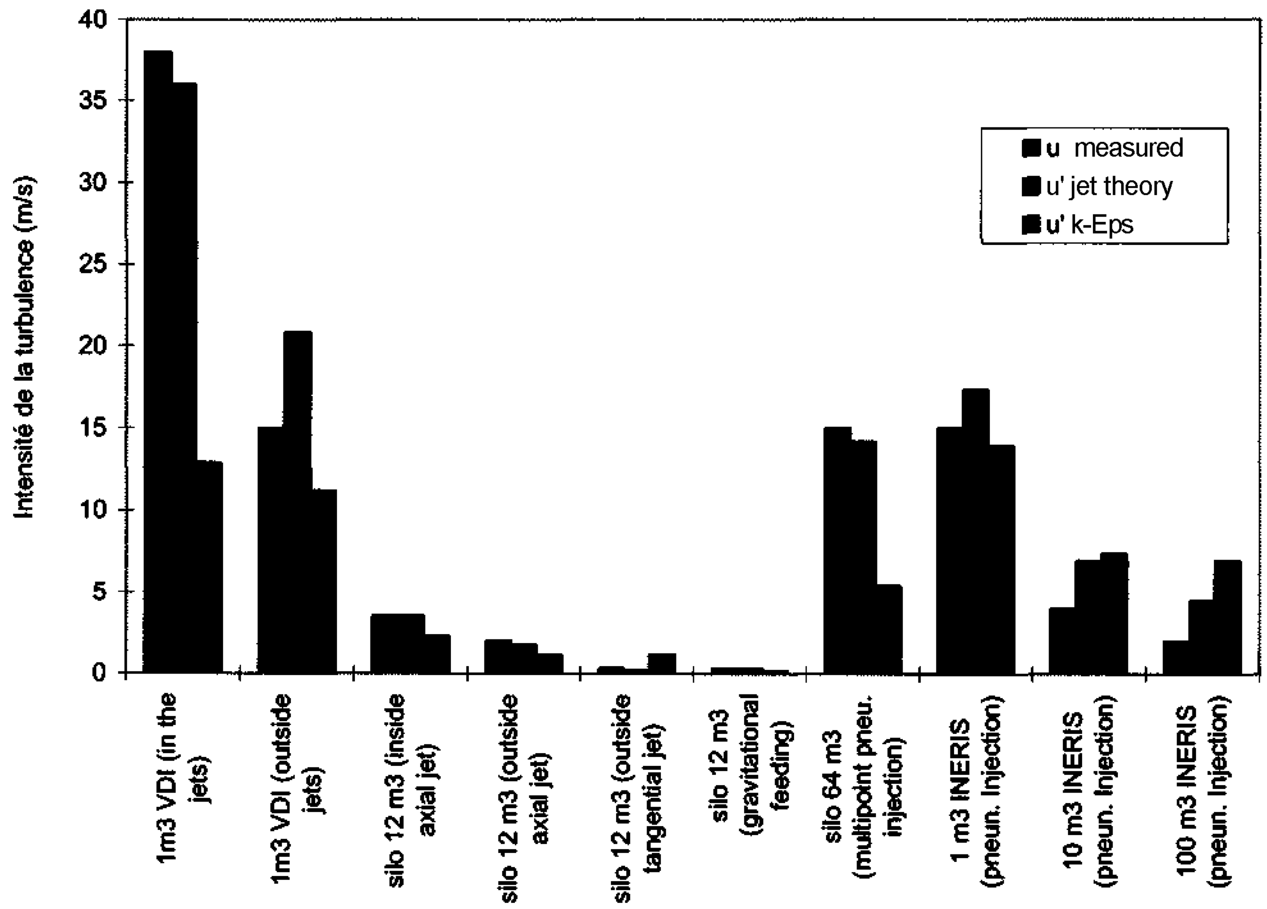


Figure 1: comparison between turbulence measurements in realistic situations and prediction by means of the present "jet theory" and "k-epsilon" approach (Tamanini, 1998)

Generation ofvolume byflame

The validity of predictions depends to a great extent on whether this parameter is sufficiently accurately estimated. This depends on the speed at which the flame burns the **reactants** (combustion rate) and, also, the rate of expansion of the combustion products. It is fairly generally accepted that the expansion rate depends almost entirely on the nature of the reactive mixture (Proust and Veyssière, 1988; **Rzal et al.,** 1991).

As shown previously **(Amyotte,** 1985), the combustion rate ("burning" velocity) depends to a significant degree on the turbulence of the cloud. Fundamental work (Proust and Veyssière, 1988; Rzal et **al.,** 1991) suggests that there are similarities with the behaviour of premixed gas flames. The turbulent combustion rate should depend on the size of the turbulent structures, their intensity and the specific reactivity of the mixture. A correlation ("COMBUSTION" module), similar to that used for premixed gaseous flames (Gouldin, 1987; Peters, 1986) has been developed and compared favourably (figure 2) to available data (Proust and Veyssière, 1988; Rzal et **al.,** 1991; Tezok et **l.,** 1985; Pineau et **al.,** 1978; **Eckhoff**et **al.,** 1984, 1986; Roux and Proust, 2002).

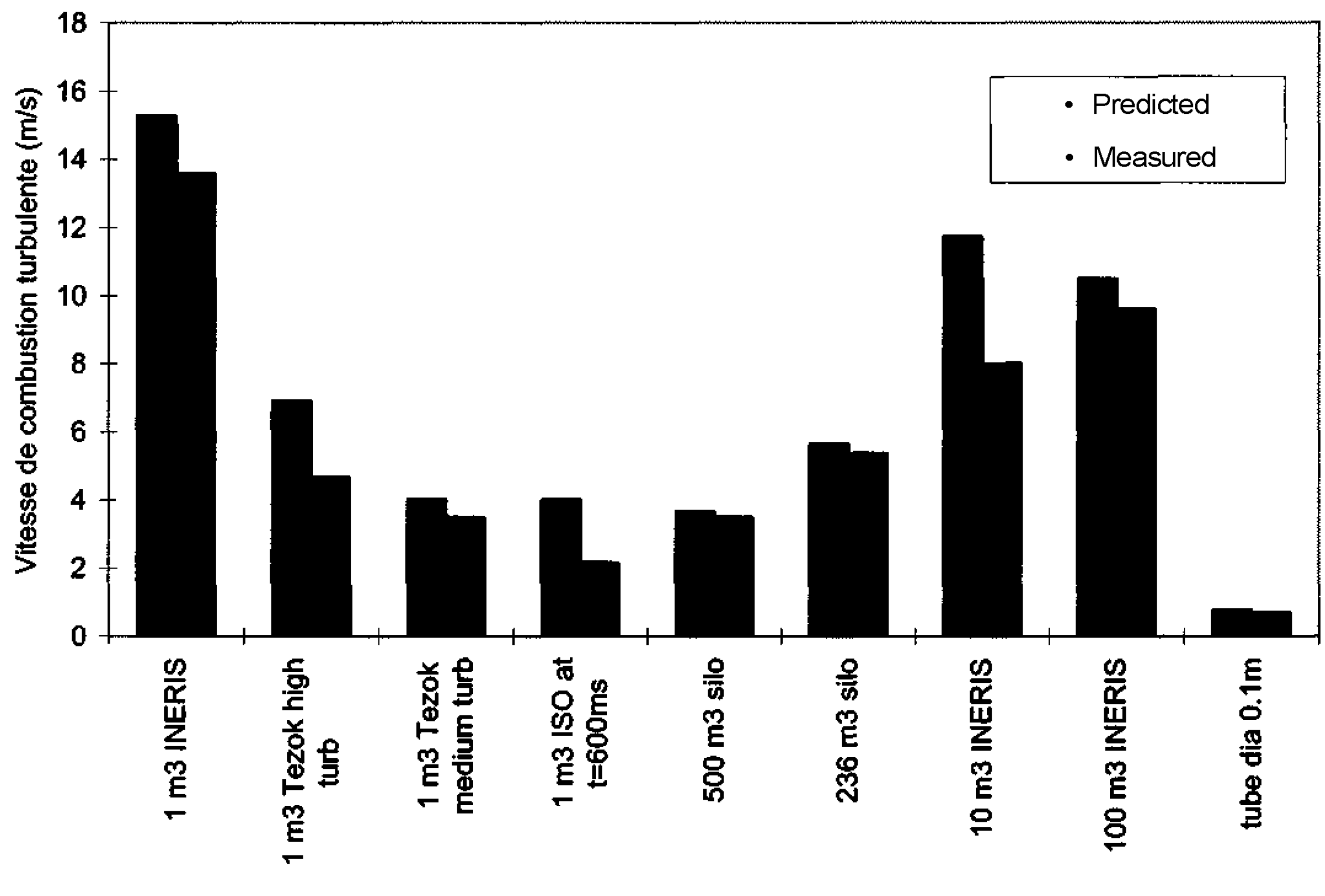


Figure 2: comparison betweenpredicted and measured turbulent burning velocities (starch-air clouds)

Flamepropagation in a vessel

The simulation module used for this purpose is called EXPBAT and includes conventional equations which can be used to describe the propagation of flames in a vessel (Bradley and Mitcheson, **1976;** Kansa and Perlée, 1978, Lewis and von Elbe, 1987). Recent work has fully confirmed that these equations are perfectly applicable to dust explosions (Roux and Proust, 2002). To illustrate this point, are represented on figure 3, the measured and predicted variations in overpressure with respect to time in the completely closed "1 cubic metre" chamber (cylinder 1.2 m long with a diameter of 0.9 m and as per procedure ISO **6184/4)** in the case of an explosion of corn starch dust. The calculated pressure signal is derived from the theoretical equations, using as input data the measured trajectory of the flame (ionisation gages) : a very good level of consistency is found.

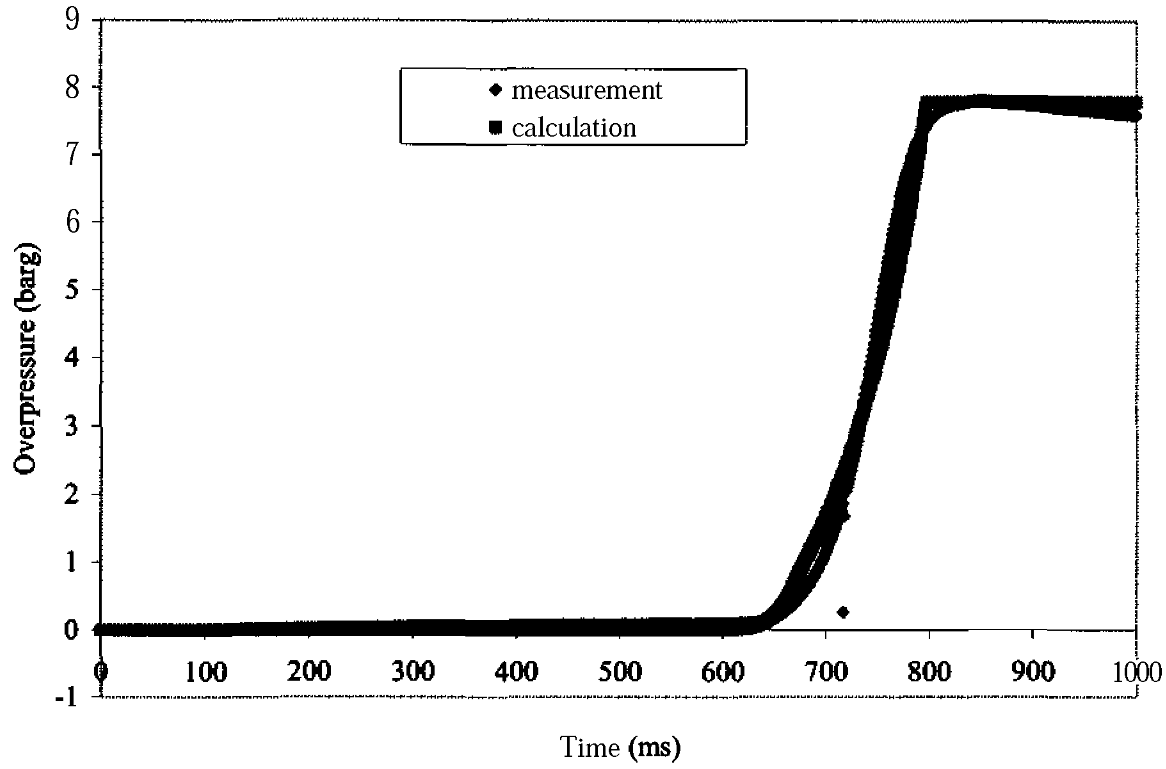


Figure 3: comparison between calculated and measured pressure evolution inside the closed ISO 1 m^3 vessel for a starch dust air explosion

Other comparisons were made in extremely varied configurations including, in particular, with the vessel fitted with an orifice (figure 4 with the data from Pineau et al., 1978; Eckhoff et al., 1984, 1986; Roux and Proust, 2002) or with the simulated explosion originating from another vessel and travelling through a connecting pipe (figure 5 data from Lunn et al., 1996; Holbrow et al., 1996). The level of consistency appears to be satisfactory.

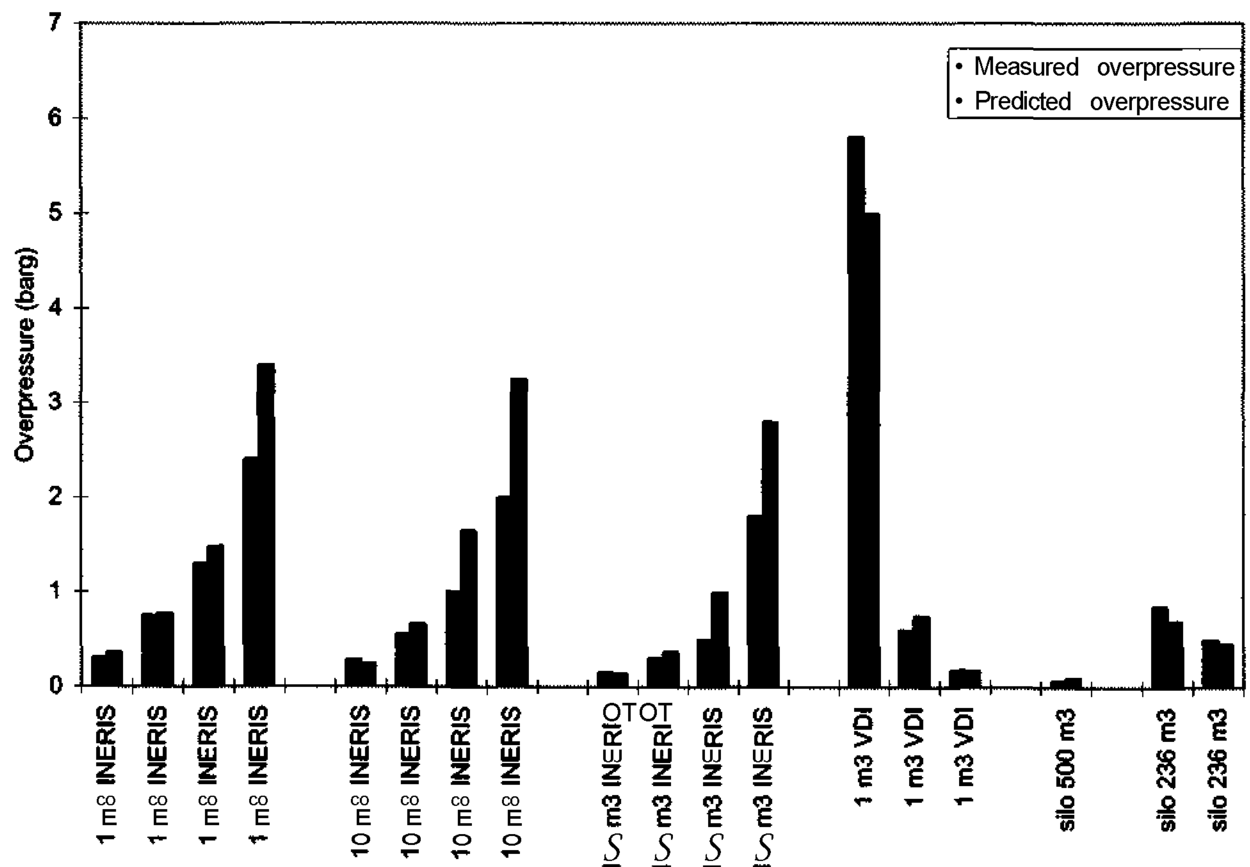


Figure 4: comparison between predicted and measured overpressure in vented isolated vessels (starch dust-air clouds)

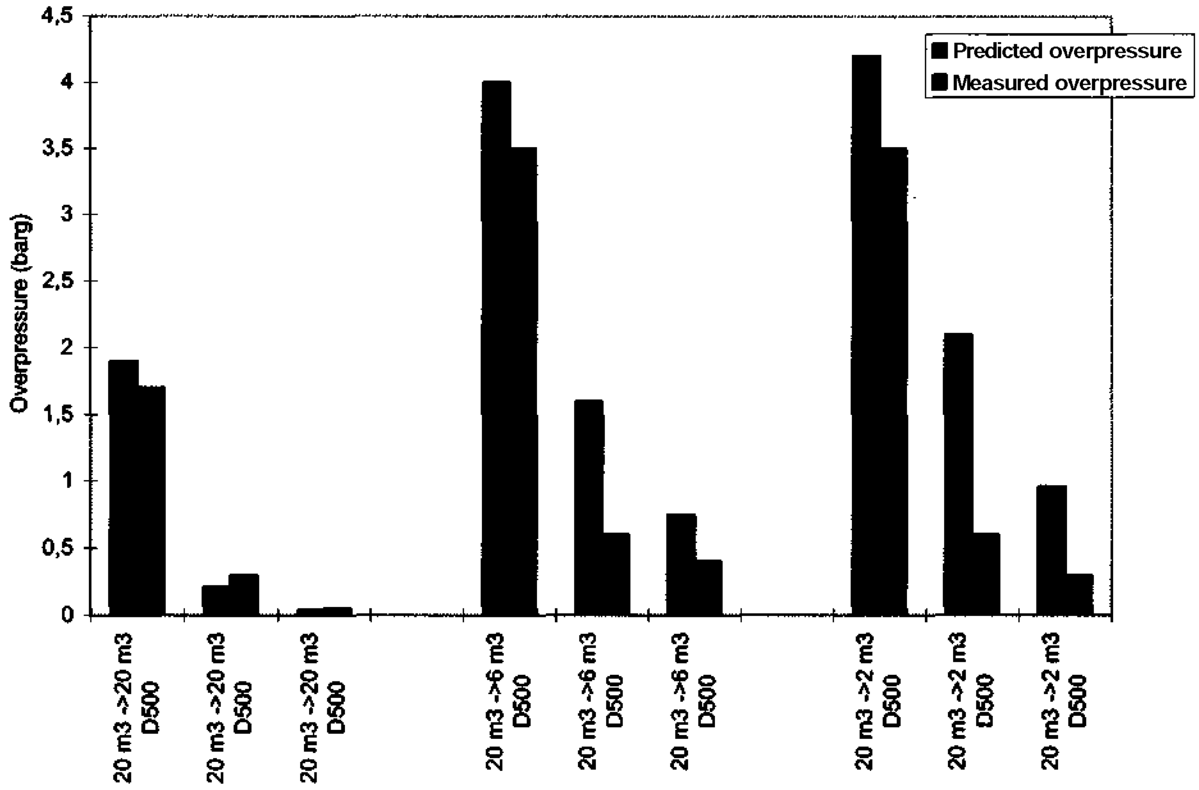


Figure 5: comparison between predicted and measured overpressure in interconnected vented vessels (coal dust-air clouds, overpressure in the receiving vessel through a 500 mm duct)

Bursting of the vessel

The aim is to estimate the overpressure at which the containment is completely or partially destroyed and, where applicable, evaluating the size of fragments. In general, it is not enough to know the conventional destruction overpressure for an installation (i.e. under static load), as it is very often observed that the structure is set into vibration as a result of the transient nature of the application of pressure (Norris et al., 1959). The STRUCTURE module is used to estimate the destruction overpressure of equipment under static load. Its equations are based on INERIS experiments in this field. Classic formula representing material strength are used. In order to allow for the vibratory aspect, we can use the BIMPACT modules (which simulate the behaviour of the structure represented in the form of a Mass-Spring model) when the application of the explosion impulse is liable to trigger only the fundamental vibration mode, or CIMPACT for more complex situations (for the solution of deformation equations by a spectral method). Basically, these tools are able to reproduce the spectrum of variation of the real bursting pressure upon explosion as compared to the static case. Note that the dynamic bursting pressure might be either higher or smaller than the static value which is fully confirmed by experiments (figure 6).

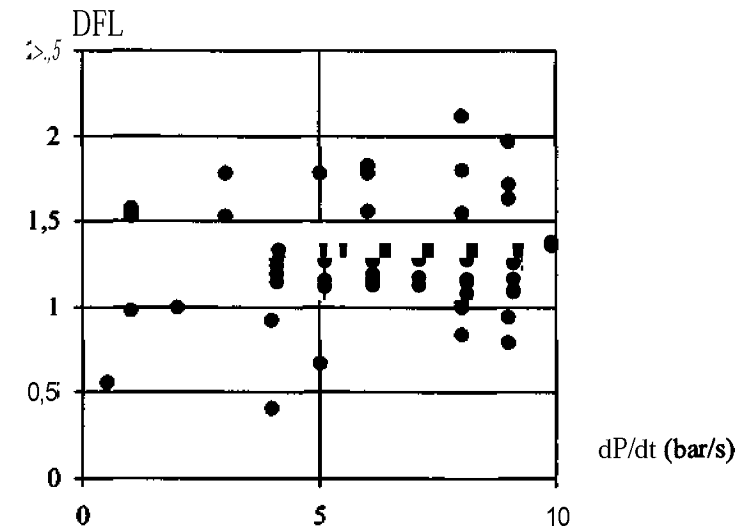


Figure 6: Dynamic load factor (DFL = dynamic bursting overpressure/static) measured for thin aluminium membranes (0,5 m^2) submitted to dust explosions of various violences

Projection of fragments

The MISSILE ballistic module is used to calculate the trajectory of fragments. The representative equations are completely conventional, and lift is not taken into account. We compared the **software's** performances with some rare previous experimental results and had recently the opportunity to compare with our own data (figure 7). We submitted a 10 m^2 steel panel wall to the pressure effects of starch dust explosion (100 m^3). We calculated the trajectory of the fragments with the measured pressure pulses and compared to experiments. The agreement is excellent.

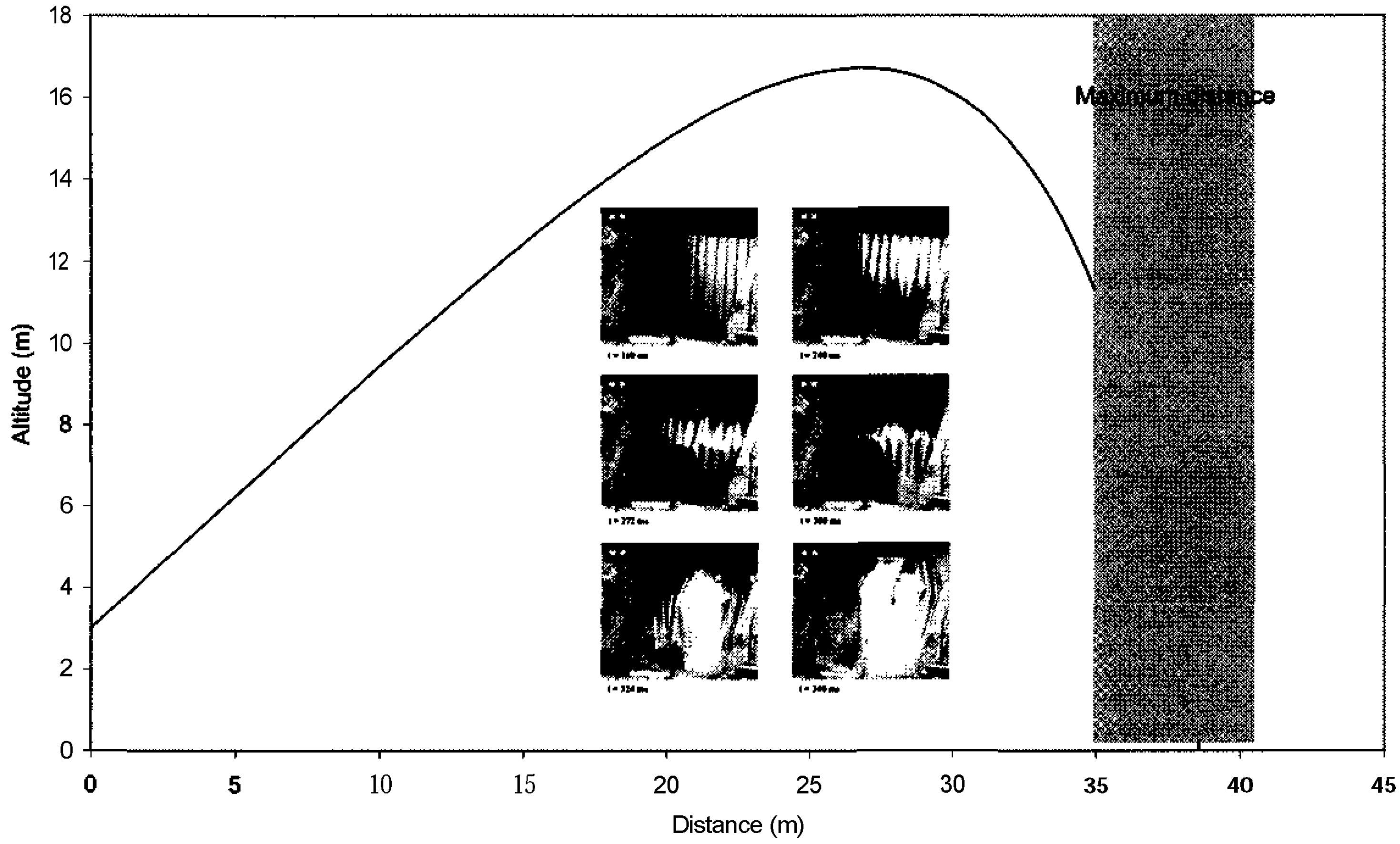


Figure 7: bursting of a 10 m^2 steel panel wall submitted to a 100 m starch dust explosion and projection of debris (curve = prediction ; grey zone = max. observed throw distance)

External pressure effects

After the failure of containment walls, the stored pressure and explosion products are released. The blast generated by bursting propels a pressure wave in the environment. The corresponding explosion energy is the containment failure energy, described as "Brode" energy, associated with conventional graphs representing the attenuation of air waves (Baker et **al.**, 1991). Obviously, there is a necessity to take into account possible external explosion effects (van Wingerden, 1993). However, the level of understanding of these is still not **sufficiently** good and work is going on. It can however be noticed that if total rupture of the **confinement** is assumed, then the prediction of the pressure effects ("BRODE" module), at least in the far field, are coherent (figure 8) with the measurements, even in those situations where external explosions have been acknowledged (Crowhurst et **al.,** 1995).

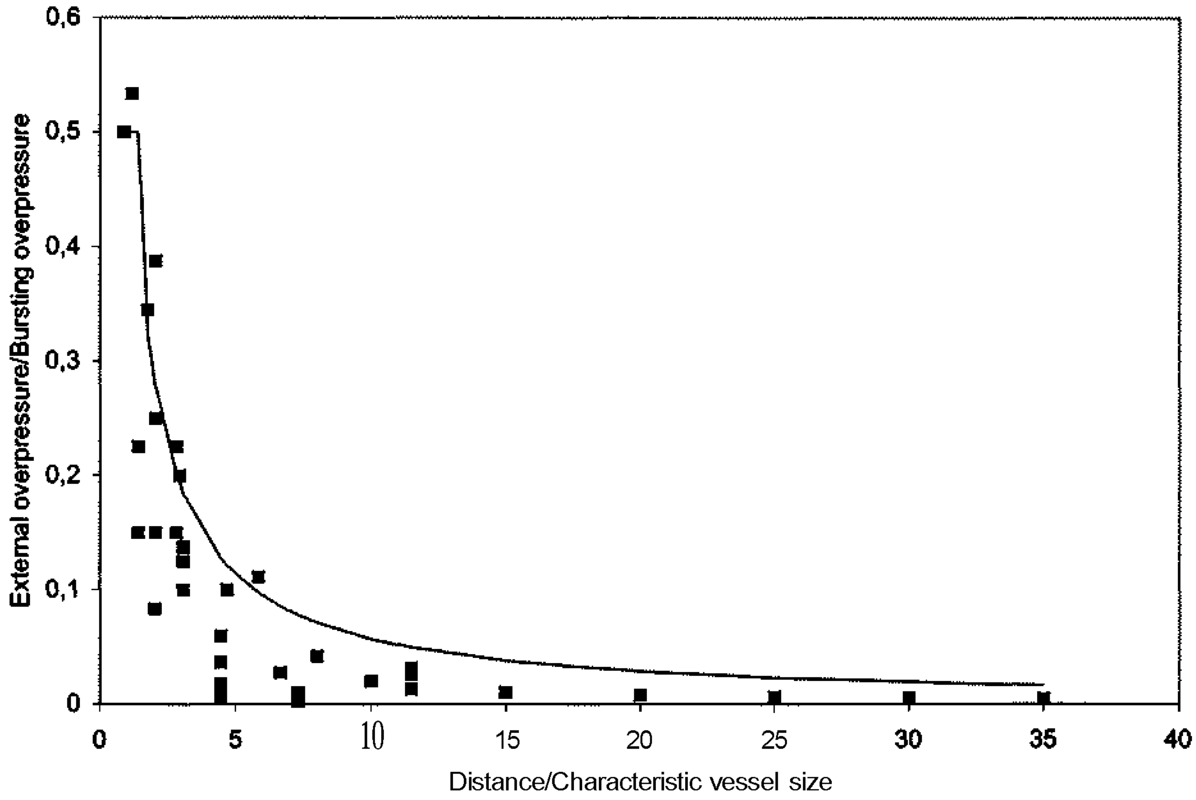


Figure 8: predicted (curve) and measured (squares) external overpressure

Presentation of the software

Procedure

For a given industrial installation, the first step is to describe the various volumes of the items of equipment (geometry, and discharge and communicating **orifices).** The second step consists in estimating the mechanical strength of the various sections for each item of equipment and the size of the fragments (STRUCTURE and **BIMPACT** modules). The third step is to imagine the explosion scenario or scenarios likely to lead to significant external effects. The TURBULENCE and COMBUSTION modules are then used in the fourth step. EXPBAT is used for the fifth step, to calculate the maximum overpressure generated and the impulse transmitted to any fragments produced. This initial value of the overpressure is used again as an input parameter in order to repeat steps 4 and 5 for subsequent volumes in which the flame is propagated. The calculation is continued in this way until the scenario is completed. Following this procedure (figure 9), the MISSILE and BRODE modules can be used to assess the external effects.

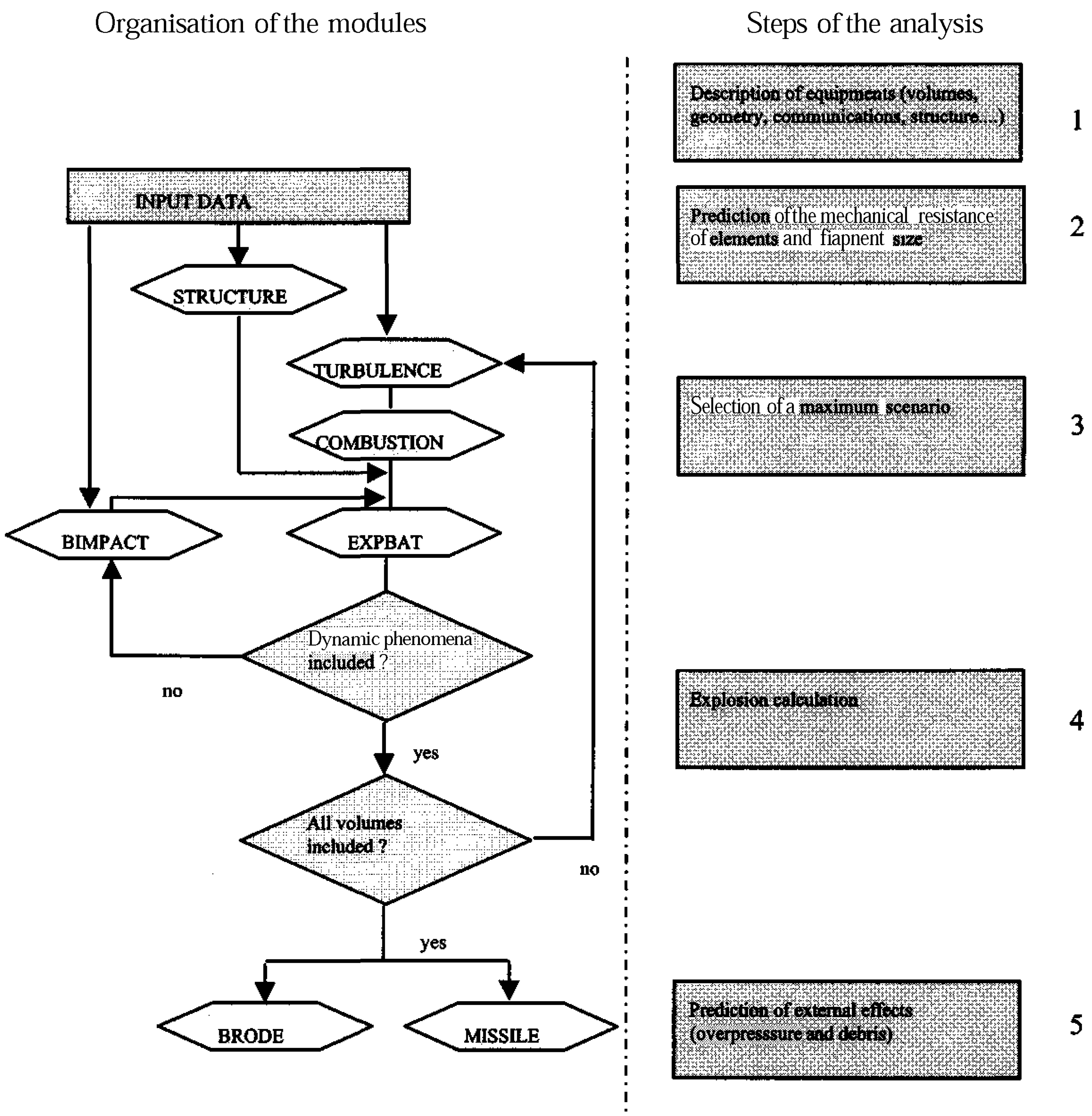
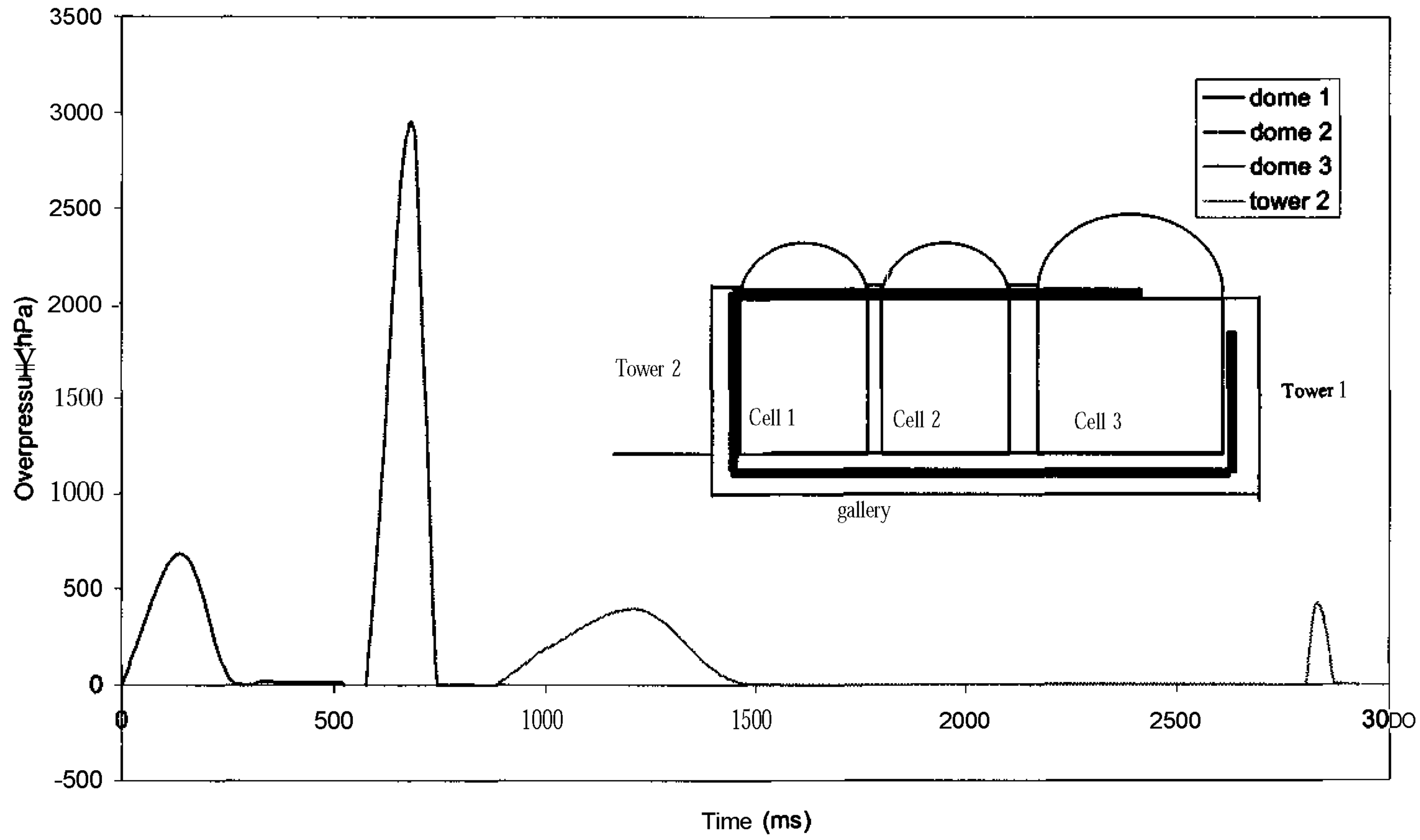


Figure 9: schematic view of the procedure and chaining of the modules

Performances

The purpose of the comparisons with actual accidents is firstly to demonstrate the suitability of the combination of modules to simulate the development of an explosion. This was done in the case of the several major explosions. The rather well documented (**Ronchail** et **al.,** 1982) and impressive explosion of the sugar plant at **Boiry-Sainte-Rictrude** in 1982 has been used. The plant consisted in three large concrete cells(30 to 50 m inner diameter, 50 m high), with dome-like communicating upper spaces (concrete also). The plant was also equipped with 2 towers and an underground gallery (figure 10). The analysis revealed that the explosion began in one tower, propagated through the gallery, joined the other tower and rushed through the domes. The predictions show that the explosion overpressure raises from volumes to volumes especially in the domes where up to 3000 **hPa** is calculated inducing rupture. Globally the predicted damages are similar to those observed and the debris are predicted to be thrown 450 m away in full agreement with the observations.



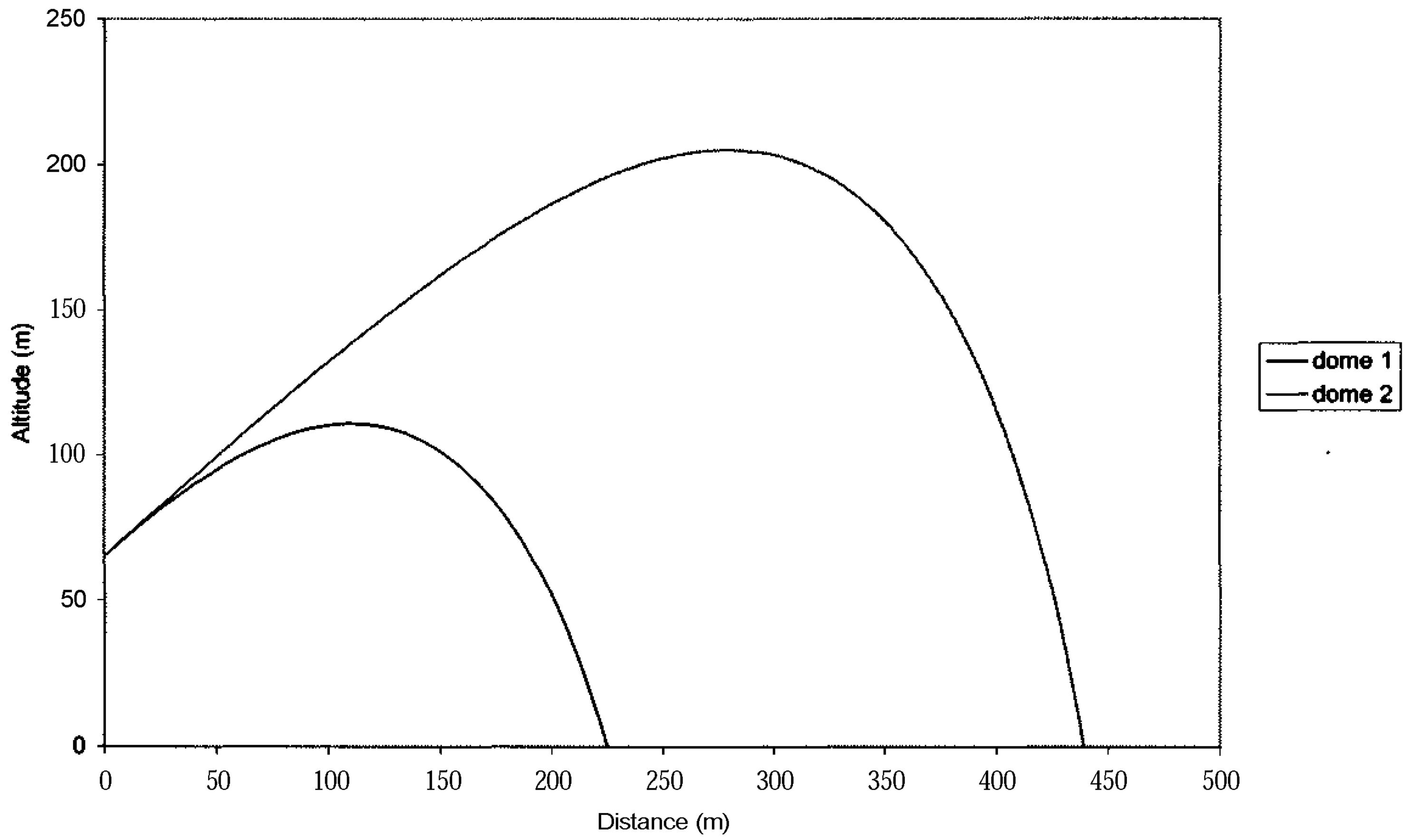


Figure 10: Simulation of the sugar dust explosion in the Boiry Sainte ***Rictrude*** *plant (1982)*

Application to silos

The first simulations pertaining to silos have been performed in 1992, and up to several hundreds have been performed up to now. The analysis of a single plant requires, for an experimented modeller, a few hours. We tried to extract a classification of the various silo plants on the basis of the potential consequences of dust explosions (major scenarios).

View	Description	Mechanical résistance	Maximum overpressure	**50 hPa** distance	Max. throw distance
	Warehouse with tiles like roof	10 to 30 hPa	20 to 60 hPa	**ND**	10 to 40 m
	Warehouse with steel panel roof	40 to 150 hPa	80 to 200 hPa	**ND**	10 to 100 m
	Open top vertical cells silo with light tower	**10 to 40 hPa**	**70 to 150 hPa**	70 to 180 m	20 to 60 m
	Open top vertical cells silo with heavy tower	10 to 40 hPa	500 to 1000 hPa	**160** to 300 m	60 to 130 m
	**Single** cell sugar silo	35 to 70 hPa	450 to 4600 hPa	**110** to 260 m	140 to 210 m
	Vertical concrete silo with steel panel coverage of the cells	25 to 150 hPa	**1000** to 4000 hPa	120 to 150 m	70 to 230 m
	Vertical concrete silo with concrete coverage of the cells	20 to 80 hPa	200 to 700 hPa	80 to 150 m	50 to 100m

Table 1 : Examples illustrating the incidence of the structure of the silo on the possible consequences of a major explosion

Conclusions

EFFEX is a phenomenological model able to predict the propagation of a confined dust explosion in a complex network of interconnected volumes. Internal and external pressure effects are modelled together with rupturing and projection of debris. The models are based on precise physical concepts and have been checked against experimental results step by step. The global software performance have been assessed with existing data extracted from well documented silo dust explosions. Hundreds of simulations have been performed on existing silos in France and required modifications proposed on the basis of the calculations. EFFEX is often seen as a first step of evaluation. Precise dimensioning of safety equipments like vents is done with dedicated methods and whenever a refined estimation of, for instance, pressure wave interaction with external structures is needed more sophisticated CFD software are used. The data from EFFEX are then considered as a starting point. It is planned to adapt EFFEX to gaseous explosions, following the same methodology. Several fundamental research activities have been decided to this aim including flame folding, turbulence interaction and flame instabilities.

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