# Investigation on a LPG accident
# with application of different mathematical models

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## 1) ABSTRACT

An LPG storage accident was reconstructed through several simulation models, with the aims of the reported and filmed effects and damage.
The accident happened in Italy on 1996 and was characterized by complex phenomena: from a choked release of LPG from a tanker there was a dispersion in calm wind and, after forty minutes about, a flash fire followed by a transient jet release and BLEVE.
The evolution of phenomena was studied by application of some available models. The primary purpose of these applications was to check the possible use and the efficiency of the simulation models using comparisons and evidences on the dynamics of accident. Another purpose was to get more detailed information on the dynamics of accident.
The complex situations, like the dispersion of heavy gas in a semiconfinated area, with calm wind and variable atmospheric stability, prolonged time of release with different type of flow, various type of fire (flash fire, transient jet fire, BLEVE and fire ball) were simulated with adaptation of models or input to obtain some realistic results.
The examined case suggest once again the importance of the knowledge of models, and the definition of limits and validations of models, and the necessity to optimize the simulation of some particular phenomena through specific models.
The uncertainty of the information about some input or the lack of data makes difficult to choose the appropriate model to correctly describe the events, nevertheless the models represent an useful approach to conduct hazard assessment and to investigate on accidental events.

## 2) CHRONOLOGICAL SEQUENCE OF THE EVENTS RELATED TO THE ACCIDENT

At about 7 a.m. the unloading of a 52 $m^3$ LPG tank truck started. Shortly afterwards, probably because of a lower flow, the operator intervened on the truck valve to increase the flow rate.
For reasons not yet clarified, a leakage took place around the valves of the tank truck, inside the valves protecting box. A two-phase propane jet filled the valves box, overflowing and forming a limited pool of undercooled liquid on the asphalt of the ground. While the surrounding area was interested by a thick low cloud of vaporized propane, the operators provide to carry out the emergency plan, stopping the work, breaking off the electrical system, evacuating the area and calling the National Fire Brigade. Some minutes after the arrival of these, at 7.40 a.m., a spark caused a flash fire, wich several damages to different utilities. Meantime, an explosion took place in a building some tenth meters from the sorce of the plume, seriously damaging part of the building.
A fire broked out from the pool of liquid propane and the flames wound the back side of the truck. The increased internal pressure and the mechanical stress due to the high temperature, caused a wide rupture of the tank wall with gas release, very similar to a fire-ball followed by the combustion of the released gas like a flare.
The initial flash-fire also caused damages to the loading arm connected to a 15 $m^3$ nearby tank truck, that containing LPG no more than 10% of its volume.

At 8.40 a.m. the wall of this tank truck, heated by the jet fire generated from the damaged loading arm, broke out and a BLEVE took place, followed by a fire ball; the BLEVE destroyed the second tank truck.
Since about 9.00 a.m. the effort of Fire Brigade was rewarded, putting the situation under control, limiting the fire area and leaving the gas flowing out of the first tank to burn till exhaustion. The fire was completly put out at 5 p.m.

## 3) ADOPTED CRITERIA FOR THE STUDY OF THE EVENT

The most important conditions and aspects related to the present study, will be examined according to the chronological sequence of the events.

### A) Initial outflow

The initial outflow can be considered as a two-phase flow in a half-closed environement with starting point of the initial jet in the valves protecting box placed on the back side of the tank.
A subdivided spout created presence of liquid propane in the box, undercooled gas due to lamination with isenthalpic flash and spillage of liquid propane from the valves box to the ground asphalt.
For simulation purposes by models, the above described scenario can be considered as an atypical scenario, as the modelling common options are referred either to free two-phase jet or to a single phase flow. Hovewer, the calculation were performed taking into account the lenght of the pipe placed before the valve (one meter lenght and 25 mm diameter).

### B) Gas dispersion .

With reference to the beginning of the events, the site atmospheric conditions were obtained from the data supplied by two different weather stations, located few kilometers far from the area of the accident.

| | first station | second station |
|---|---|---|
| wind velocity | 0.5 m/s | 0.5 m/s |
| temperature | 5 °C | 6 °C |
| wind direction | 100° | 250° |
| relative humidity | 80% | 85% |

The low wind velocity, referred to a standard altitude of 10 m., and, therefore lower if referred to ground level, excludes the possibility of recourse to gaussian models, which have some limits for low velocity, particularly lower 1 m/s.
With reference to the sky overcasting ratio (from 4/8 to 7/8 ) and to the wind velocity, according to Pasquill scheme, a stability class B can be considered.
Referring to the standard deviation of the wind direction (NRC) and considering that no variation in the wind direction takes place at 0.2 m/s velocity at the altitude of two meters, a stability class F could be assumed.

**C) Flash fire and fire**

The reconstruction of this phase was not closely examined**,** due to several difficulties in defining the initial steps of the flash fire and the geometry of the cloud.

**D) Burst of the first tank**

Few minutes after flash fire an explosion wrent the wall of the tank, due to the overheating caused by the flame generated from the pool and jet fire, that lapping on the surface of the tank. The typical pulsating effect of this kind of phenomena, is not considered by most models (normally referred to a steady combustion with an average heat emission divided among conduction, convenction and radiation).

Assuming that 30% of the developed heat is propagated by radiation, we can consider 70% of the combustion heat of LPG to evaluate the overheating. Relevant to the failure of the tank construction material, it must be first outlined that only 1/3 of the total surface of the tank was heavily interested by overheating for the flame action (as verified in a second time). On the remaining parts, interested by radiation, only superficial effects have been found.

In this calculation it must pay attention to the irregular shape of the rupture area with dimensions 40 by 60 cm, located in the connection between the cylinder and the hemyspheric bottom of the tank. The size of the opening is important for the analysis of the release of the burning gas: according to the above said description, it can't be classified as a classic fire ball, as related to BLEVE, which is normally generated by a very large opening or by the collapse of the vessel.

**E) Consequences of the fire on the second tank: BLEVE**

The flash fire and the subsequent fire around the first tank damaged the loading arm connected to a nearby second tank truck, causing the failure of gaskets and other components. LPG flowing from the damaged connection device caught flame impingement on the second tank and brought to a final phenomenon that can be classified as a BLEVE.

## 4) ANALISYS AND RECONSTRUCTION OF THE EVENTS

### 4.1) Study of the crack phenomena in the first tank

Even if several models are available to study similar events, the peculiarity of the above described accident, that took place with a partial rupture of the vessel instead of a complete destruction as in the classic BLEVE phenomenon, required some adaptation of a mathematical model, particularly to carry out a thermomechanical analysis relevant to a mobile vessel wound by fire and containing a two-phase flammable fluid. This has been carried out according to the calculation code ANSYS 5.3, allowing the study of structures under mechanical and thermal stress, also variable during the time. Due to the tickness of the vessel wall (about 1 cm ), the theory of thick-walled pressure vessels has been used. The model of the structure is explained in fig.1

The fire around the back side of the tank has been simulated with a variable thermic flux, whose intensity has been calculated by considering a complete combustion of the gas flowing out of the tank, also if, probably, there was an unburnt fraction of LPG.

The thermal load, computed according to the above said criteria, has been related to the part of the tank wall wound by the flames of the pool-fire and its variation in dependance of time corresponds to "LPG FIRE CURVE" reported in UNI.ENV. 1991-2-2 standard (see fig.2).
Also in the hypothesis, for computing simplification, of an isotropic behaviour of the construction material, two aspects related to the construction criteria of this kind of vessels must be underlined. Taking into account that the spherical shape has a higher resistence than the cylindrical, the thickness of hemispheric bottoms is normally lower than the thickness of the cylindrical walls. In the stress situation created by fire, the strains in the hemispheric part are different from the ones of the cylindrical part; one can say, to simplify, that in the cylindrical part there are three components (radial, longitudinal, tangential ) as in the hemispheric part there are only two components (radial and tangential). This causes a tension-state located at the interface cilynder-sphere because the cylinder tends to "open " more than the sphere but this deformation is blocked by the sphere itself. The spherical part transmits a moment and a shearing stress to the cylinder and viceversa and this new tension condition, caused by fire, must be added to the "normal" stress condition related to a vessel working under internal pressure. The semplified result is reported in fig. 3.
In spite of the adopted semplified hypotheses, the above said considerations take into account the most important aspects related to the weakening and the rupture of the vessel. The application of the program allowed the determination of the temperatures distribution at the rupture moment ,obtaining the stress configuration of the structure, relevant to the thermic and pressure loads, the value of the plastic deformation and the location of the rupture point (see fig. 4).
The obtained results are in accordance with the reports of the people attending to the accident.

### 4.2) Analysis and reconstruction of the events by simulation models

The amount of gas still present in the first tank after the explosion and the vapour release has been calculated on the basis of the combustion time and the vaporization rate of propane, provided that the controlled combustion of the contents lasted 8 hours. Starting from this evidence we have recontructed some of the events to verify if the calculations performed will be produced the same conclusion. The models listed here below were utilized to simulate the events:

- ARCHIE (Automated Resource for Chemical Hazard Incident Evaluation - Federal Emergency Management Agency, U.S. DOT, U.S. EPA)
- DEGADIS 2.1 (DEnse GAs DISpersion - U.S. Coast Guard, G.R.I. & A.P.I.-US EPA)
- HGSYSTEM 3.0 developed by Shell an distributed by A.P.I. (ed. 4636-1995 )
- RMP*Comp (only for flow rate calculation in the alternative mode) US EPA
- SIGEM -SIMMA developed by TEMA S.p.A. and used by the Italian National Fire Brigade
- STAR (Safety Techniques for Assesment of Risk – rel. 3) developed by ARTES S.r.l.

The reference points for the study of the different phenomena, obtained by information supplied by attending people, can be summarized as follows:

(a) the initial release of LPG, without fire, lasted about 50 minutes,
(b) after the flash fire there was a mixed fire (pool and jet fire) with flames wrapping the back side of the tank, causing the partial rupture of the shell of the tank with an intermediate phenomenon between fire ball and jet fire,
(c) due to the damage caused by flash fire on the loading arm there was a fire involving a second tank truck that, after some ten minutes, collapsed producing a BLEVE.

The flow rate has been determined by considering the presence of a deep tube, 1 meter long and an orifice with equivalent diameter 25 mm. LPG temperature was 278 K and equilibrium pressure about 5,4 bar(abs). The result of the calculations are reported in the following table.

| Model | Flow rate (kg/s) | Flow condition |
|---|---|---|
| ARCHIE | 11,6 (peak) | two-phase |
| RMP*Comp (1) | 8,87 | - |
| Sigem-Simma | 0,46 | gas |
| STAR | 2,25 | two -phase |

(1) The calculation has been performed with alternative scenario, vapor cloud fire option and hole in liquid space; with pipe release option the flow rate result 11,7 kg/s.

As the flow, even if not in steady condition for to the probable presence of ice in the orifice, lasted about 50 minutes and 1/3 of the content has been emptied, the only consistent result is the one referred to a flow rate of 2.25 kg/s. Tacking into account the above said time (50 minutes), a total amount of 6,75 tons of LPG flew out, that is about 1/3 of the initial content (21,4 t ), as testified by some people present on the site.
The quantity of LPG evaporated during the flash can be obtained by adding the amount of LPG evaporated inside the tube and the amount of LPG evaporated during the isenthalpic flash, that is about 23% of the total flow.
To evaluate the concentration in the air, several models have been utilized each one associated with the relevant flow rate; it must be underlined that the atmospheric conditions (stability class F and wind velocity 0,51 m/s) are of limited acceptability for most models. The results are reported in the following table:

| Model | flow rate | LFL | 50% LFL | flammable mass |
|---|---|---|---|---|
| ARCHIE | peak 11,6 kg/s | 140 m | 203 m | 1800 kg |
| Degadis | 2,25 kg/s | 160 m | 205 m | 1030 kg |
| HGSystem | 2,25 kg/s | 33 m | 55 m | n.c. |
| RMP*Comp | 8,87 kg/s | <160 m | n.c. | n.c. |
| Sigem Simma | 0,46 kg/s(gas) | n.r. | n.r. | n.r. |
| STAR | 2,25 kg/s | 38 m | 55 m | 157 kg |

n.c= not calculated  n.r = not reached

Regarding the ARCHIE model it is clear that the vapour flow rate adopted for dispersion is lower than the peak value indicated in the results, but this datum is not supplied.
The results of Degadis model, in accordance with the Archie model, seems affected by the limit related to the wind velocity (minimum value suggested 1 m/s).
Similar limit (1.5 m/s) is requested by HGSystem, however the final result is considerably different in comparison with the result of ARCHIE model.
The results obtained with RMP*Comp is interested in view to observe that a relevant flow rate produce the same LFL distance of Degadis, that use a lower flow rate.

SigemSimma model lacks a calculation routine for dispersion of heavy vapours and areosols and the evaluation of the flow rate is referred to gas phase only.
The STAR model (box model like CRUNCH – SRD UK), that considers the presence of obstacles or buildings in the propagation of the gas, offers an indication of gas accumulated in the area in front of the building, without in substance modifying the distances of the flammability limits..

Disregarding the simulation of the initial flash fire, the radiation caused by the burning gas released from the first tank and the fire ball and BLEVE related to the second tank, will be analized.
The phenomenon related to the first tank in concomitance with the burst or structure rupture can be regarded as "transient jet release" that occurs when the substance in the vessel is not overheated.
According to relations obtained from different sources, the required time for the collapse of a vessel is a function of the geometry and characteristics of the flame wrapping the vessel; with the model of turbulent flame on the top of the vessel a time of 7 minutes can be estimated; for pool flames a time of 15 minutes can be considered.
On the basis of the survey, the opening of the first tank corresponds to a hole 50 cm in equivalent diameter; according to this indication the following criteria have been adopted to evaluate the effects of the phenomenon:

- simulation of a jet fire with flow rate equal to the initial flow rate, with pressure 17 bar and temperature 323 K,
- evaluation of the jet fire duration by calculation of the amount of the released gas for the time necessary to reach the atmospheric pressure inside the tank,
- evaluation of the radiated energy.

The initial flow rate has been calculated by two models, with very similar results (503 kg/s by SigemSimma; 523 kg/s by STAR).
The duration of the release has been calculated according to STAR model (about 3 seconds) and evaluating the amount to be released to reach, starting from the initial pressure 17 bar, the atmospheric pressure in the tank. Considering the quantity of LPG released before the burst (about 13 $m^3$), and the volume of the tank (52 $m^3$) filled by 80%, the volume occupied by the gas, before the burst, was 28 $m^3$ with a pressure of 17 bar, equivalent to 456 $m^3$ of gas, that is 12700 kg. With a flow rate equal to 520 kg/sec, about 24 seconds are necessary to decrease the internal pressure to the atmospheric value. The indications supplied by jet fire models have been considered to take into account the limited duration of the phenomenon by transforming the radiation into energy, as indicated in the following table.

| Model | 350 kJ / m2 | 250 kJ /m2 | 125 kJ / m2 |
|---|---|---|---|
| ARCHIE | 49 m | - | 106 m |
| SigemSimma | n.r | n.r | n.r |
| STAR | n.r | n.r | 110 m |

The results seem to have a very high caution, because people present at less than 100 m were not injured. We must underline that the evaluation of the phenomenon is affected by simplifications, mainly because the decrease of the flow rate and gas density were no related to the decrease of the pressure.

The phenomenon regarding the second tank is quite near to BLEVE theory, with a total collapse of the tank and pieces and metal splinters found 500 m far from the origin. By application of the simulation models and considering the collapse conditions similar to the conditions of the first tank (p=17 bar; T= 323 K), the results plotted in fig.5 have been obtained.
In this case the results are more homogeneus, but also in this case , with a good level of caution.
It must be considered that for small quantities the models supply conservative estimate and often not in accordance with the practical results; for phenomena of great magnitudo the results are more accurate.
As regards the projected pieces, two of them, with considerable size, were found at a distance of about 500 m; the first was a part of the tank shell with dimensions 1.2 m by 1.2 m and thickness 10 mm, the second was a part of a pipe (1 m long), probably part of the deep tube.
The simulation of the fragmentation and pieces projection is affected by great uncertainity related to the original shape of the pieces and to the leaving angle. With exception of STAR model, based on NASA studies and pubblications, it is no possible to consider in a correct manner shape and size of the pieces; for this reason the results obtained by using models different from STAR look quite rough. Sigem.Simma gives a range 314-1800 m; the results of STAR model, considering a leaving angle 35 °, are : 670 m for the first piece and 520 m for the second.

**Conclusions**

With reference to the hystorically registered accidents, the accident described in this study, related to a particular sequence of a great number of events and circumstances, can’t be considered as a single case. It can be emphasized a general difficulty in the description of the phenomena by simulation models. The above said answer appears no appropriate for complicated cases as the one in subject and in particular for the simulation of the diffusion of heavy gases in presence of obstacles; in this case the use of 3D models is suggested, particularly in case of absence of wind.
Nevertheless, with reference to the content of this study, it is clear that the answer supplied by the models adopted for risk analysis appears prudent, but however useful for forecasts and predictions as safety reports.

References:

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Born near Mantua on 1951, he received his degree in Chemical Engineering at University of Padua and gathered practical experience working as technologist in the petrochemical factory of Montedison, at Porto Marghera (Venice).

In 1988 he left this work to begin the job of public controller in the field of environment protection at the Environment Department of Regione Veneto, performing evaluation of studies and projects proposed from industry. Since 1990 he has been involved with the major risk problems from chemical industry, assessing the Safety Report to evaluate the risk of the industrial installation.

Fig. 1

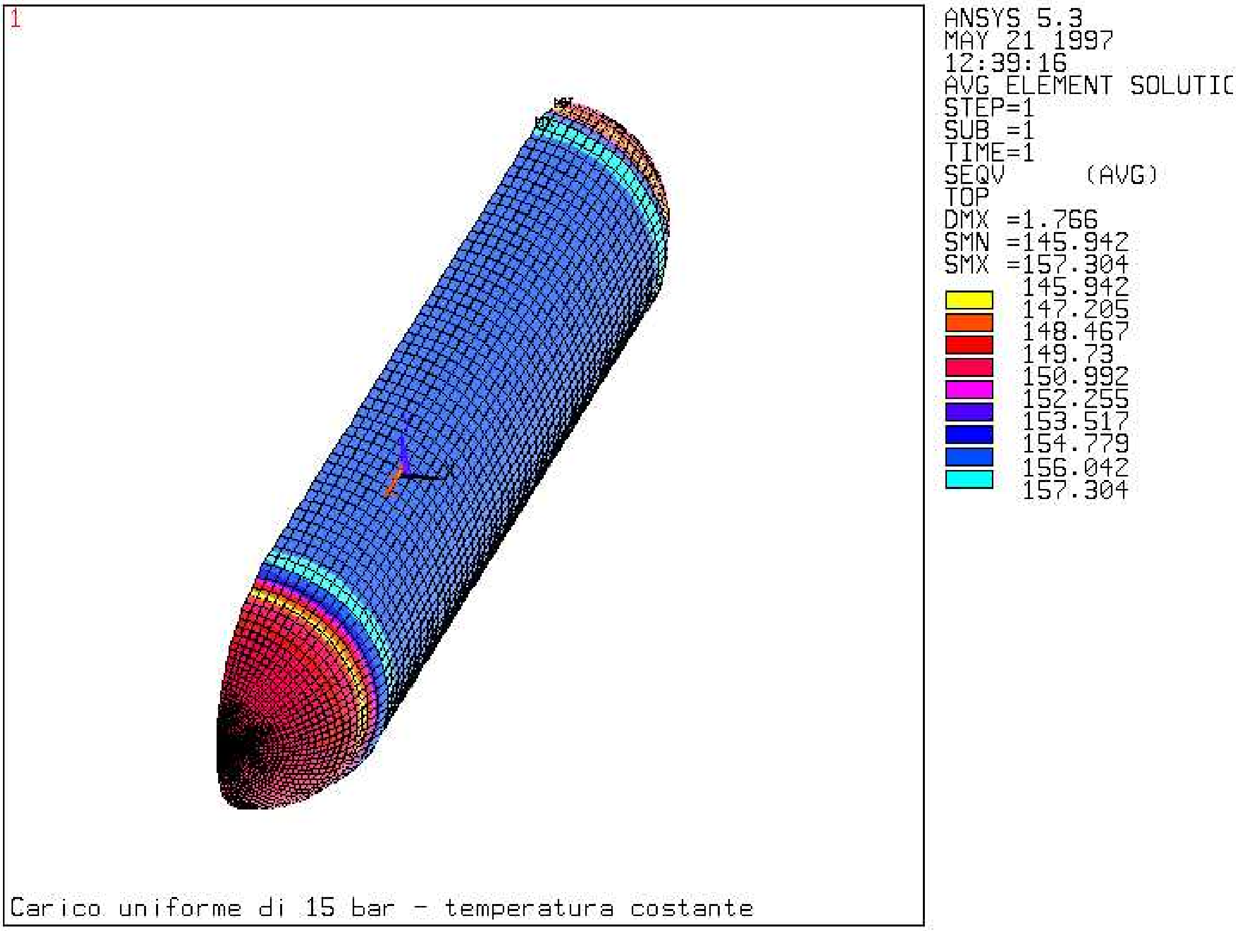


Fig. 2

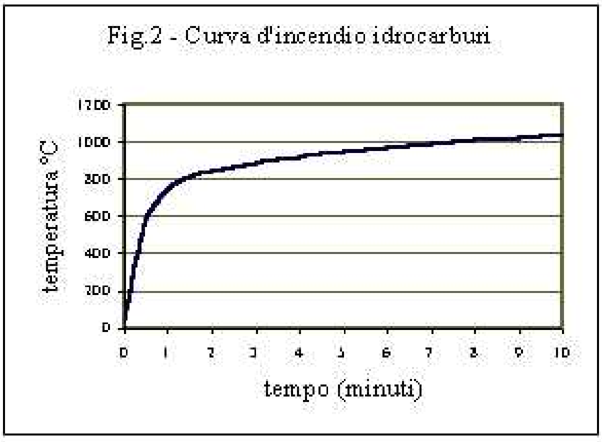

Fig.2 - Curva d'incendio idrocarburi

Fig. 3

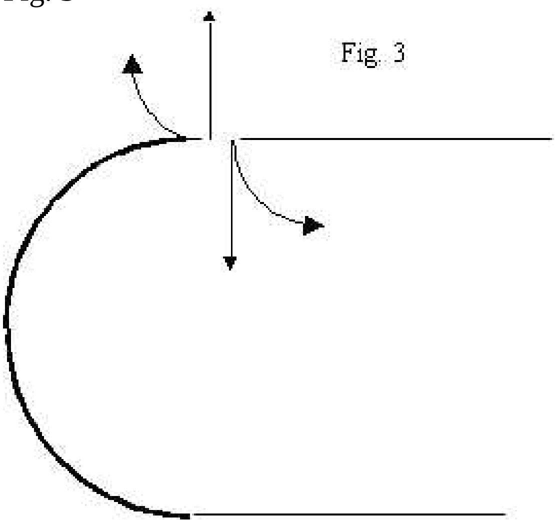


Fig. 4

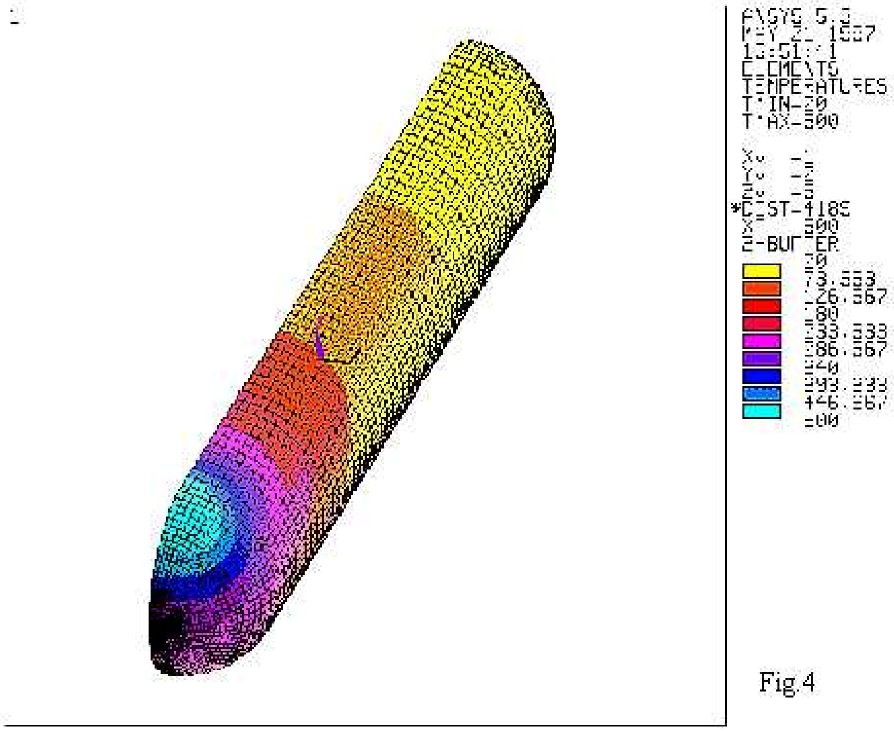

Fig.4

Fig. 5

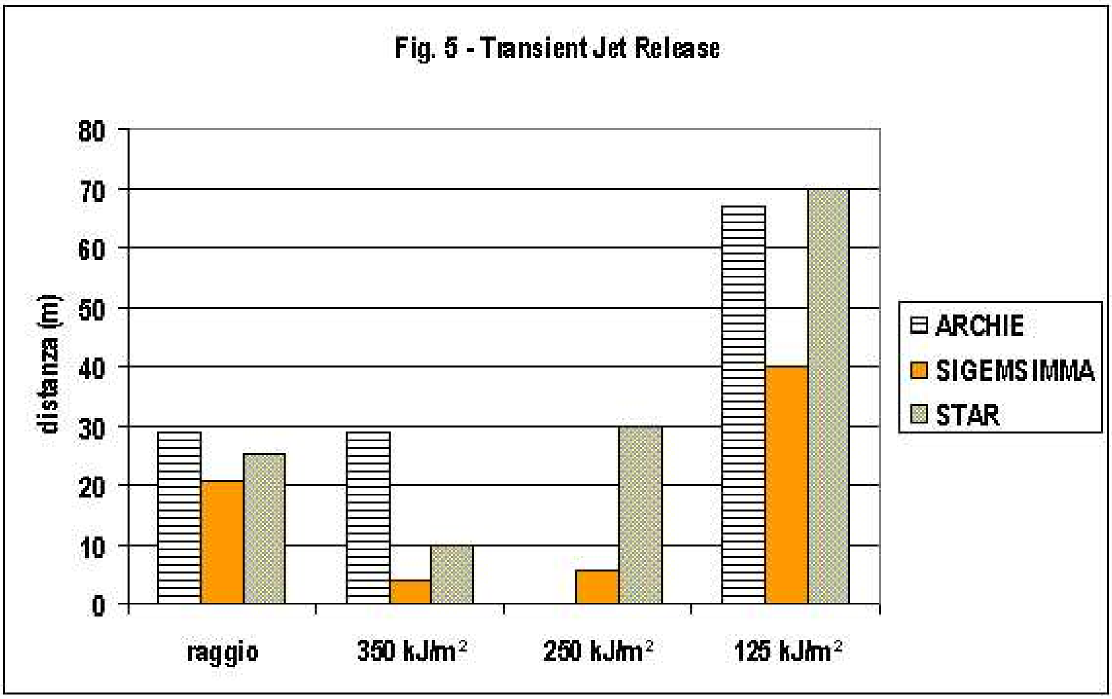
Fig. 5 - Transient Jet Release
80
70
60
50
40
30
20
10
0
distanza (m)
raggio
350 kJ/m²
250 kJ/m²
125 kJ/m²
ARCHIE
SIGEMSIMMA
STAR