ExProtect ©
A software response to important questions on safety in dust and gas explosions

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Abstract

ExProtect is an expandable software-package under WINDOWS 3.1/3.11 resp. WINDOWS 95/NT containing the programs SIMEK, STS, VENT and AD-formula.

SIMEK was created on the basis of extensive experimental investigations to give answers on the required thickness of fastenings (hinges resp. ropes) and the demanded size of explosion doors and explosion lids for dust-explosion endangered containers and buildings. By using expanded versions of the VDI 3673 guidline-formula for reduced pressure and the cubic law, SIMEK estimates the time-pressure curve of a dust explosion in the considered container. With this, SIMEK solves the equation of motion for explosion doors or explosion lids numerically and simultaneously the searched for values of fastening-thickness is derived.

STS is used to find out how far the debris of bursting containers or buildings will be catapulted after a dust explosion. With a few data about the considered building and burnable dust STS finds the initial velocity of a fragment by using the equation of Gurney. The following calculation of the fragments trajectory is done numerically. Computed and in praxis observed distances of flying debris after dust explosions are in satisfactory agreement.

If suitable vent areas for explosion endangered rooms or containers are searched for, VENT will give the answers. The calculations of VENT are correct for pressure relief devices without any mass inertia. The computer-code of VENT uses formulas of well-known guidelines and publications. Furthermore it contains some additional tools, which are the result of extensive experimental research.

AD-formula is a program to answer questions about the stability of containers standing under pressure and is based on the corresponding AD-instructions.

1   Introduction

In practice, primitive pressure relief devices are in use which most of the times can prevent the container from bursting but are dangerous for the immediate environment in case of an explosion. Such relief devices often consist of one or several metal or concrete panels that are tied to the container with ropes or chains. If an explosion occurs, these ropes or chains are in most cases too weak to hold the relief devices in place; they will break and the relief devices will be catapulted away.

A grave accident in recent times gave the impulse for experimental research in order to be able to define the forces on those ropes in the event of a pressure relief. In Kappelrodeck (Black Forest), where an experimental plant of the FSA is situated, a series of experiments was done with explosion lids of different masses on a 1 m^3-vessel, using different explosion parameters [1]. The explosion lids were tied to the vessel with steelropes, connected to a force measuring device which made it possible to measure directly as a function of time the force put on the explosion lid by the safety-ropes when the ropes abruptly stopped the catapulted lid during the explosion. Forces of up to some 100 kN were ascertained.

Later, the project was expanded to the testing of explosion doors. On a 9.4 m^3-vessel, explosion doors of different masses were exposed to the effect of light to heavy dust explosions. With the help of an incremental encoder the opening angle of the explosion door was recorded as a function of time. The test results gave access to all desired factors. Figure 1 shows for example the maximum force on the explosion door's hinge as a function of maximum reduced pressure $p_{\text{red}_{\text{max}}}$ and explosion door resistance Q. As a consequence to the experiments a vast study was initiated that deals with the mechanics of explosion doors and explosion lids on a theoretical and an experimental basis, including data from experiments with larger test containers [2]. In the testing, explosion doors were hinged to the container on one side, explosion lids were tied to the container with several ropes (see figure 2). The results of experiments [1] and [2] were entered into the DOS program SIMEK[1] (written in QuickBASIC 4.5). SIMEK is capable of dimensioning fastenings and areas of explosion doors and explosion lids for containers as described in VDI 3673. Furthermore, the venting capability of the pressure relief devices in question is derived (at least approximately).

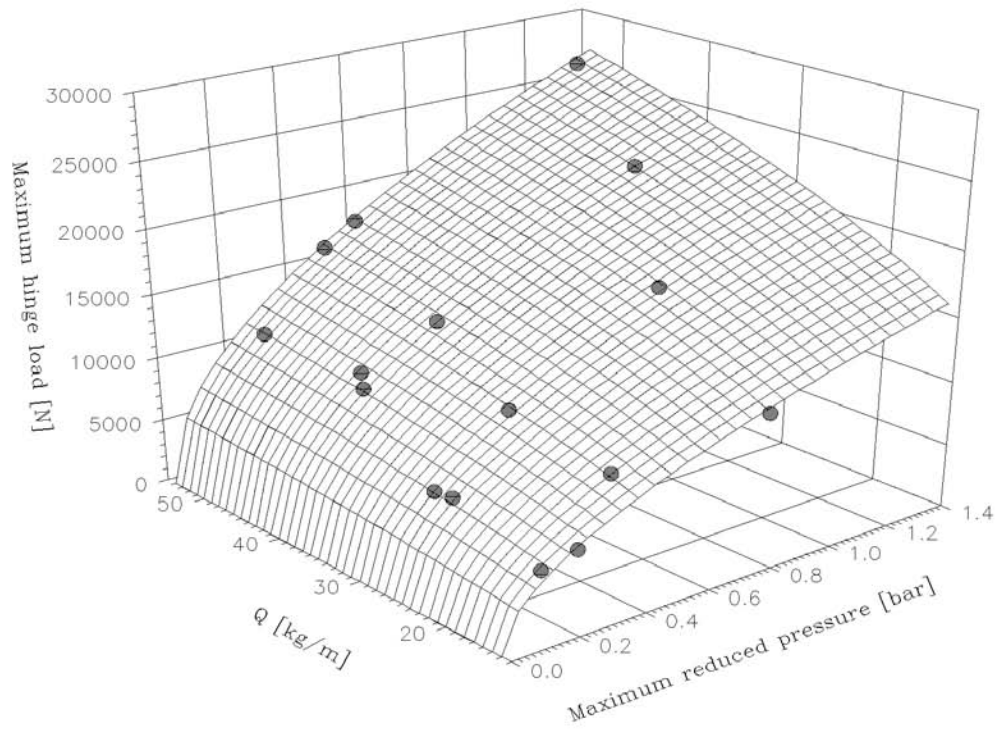[1]Simulationsrechnung zur Mechanik von Druckentlastungsklappen

Figure 1: Maximum hinge load of the explosion door as a funktion of maximum reduced pressure $p_{\mathrm{red_{max}}}$ and explosion door resistance Q. Every point is the middle of three measurements.

When planning or surveying industrial plants the question often arises of how big the safety distance to the neighbouring buildings has to be for them not to be affected in the event of an explosion. One aspect in the process is the evaluation of how far explosion debris will be catapulted and it's kinetic energies. So far, a commonly accepted solution for this problem does not exist. Therefore experience from [1] and [2] was taken as a basis together with the know-how from [12] to create an appropriate calculation method. The outcome of these
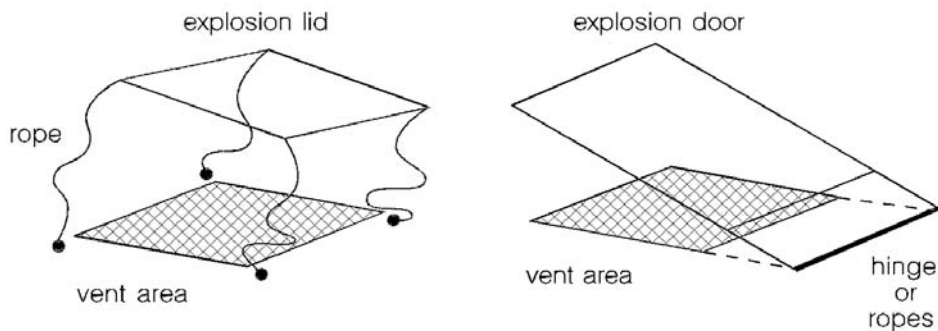

Figure 2: An explosion door and an explosion lid shown schematically.

efforts resulted in the DOS program STS[2] (also written in QuickBASIC 4.5) which is able to calculate the probable and the maximum range of flying debris, taking into account the basic data on the building in question and the known explosion characteristics of the burnable dust. Comparing experimental experience and measured distances of flying debris after actual dust explosions with the results received from STS, the STS results are well to relatively satisfactory [10], [11]. However, this is only valid for occurances where large parts of a building's wall are being destroyed, i. e. catapulted away. In order to find out distance range for torn away pressure relief devices, SIMEK must be applied.

Since SIMEK and STS are DOS programs, thus rather user unfriendly, and DOS is hardly in use any more, the rewriting of SIMEK and STS for WINDOWS application was initiated in 1997. Our department was then working with other programs dealing with dust explosion protection on a DOS basis. The integration of those programs into the new WINDOWS version was a goal, so for the new program a modular structure was chosen. The integration of further programs into the new WINDOWS program, which is now called *ExProtect* (written in Visual BASIC 3.0 resp. 4.0) is easily feasable. Additionally to SIMEK and STS, *ExProtect* also contains the programs VENT and AD-formula (both also still exist in a DOS format). VENT is for calculation of vent areas and for calculation of the maximum reduced pressure in explosion endangered containers; pressure relief devices without any mass inertia are always a prerequisite. Several formulas from well-known technical literature are used in VENT [9], [23], [24], [25]. Additional to other tools, VENT offers the option to choose from different kinds of silo fillings for calculation of vent areas. Consequently, the results received vary when applying [9] and the quantitative changes were confirmed in our experimental plant [20], [21], [22].

The AD-formula program is an early and not quite complete DOS version of the AD-instructions. At present the program is being completed and improved.

In the near future *ExProtect* will be expanded by another program which will give information on the temporal increase of pressure in closed vessels and such with vent areas and will allow statements on velocity of flames in pipes [27].

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[2]Simulationsrechnung zum Trümmerflug bei Staubexplosionen

2 How it works

2.1 SIMEK

From the entered detail data on vessel volume V, vent area A_{E}, K_{St}-value, mass of pressure relief device m etc., SIMEK at first estimates the temporal pressure change in the vessel, applying for it the modified function of Gauß

$$p(t) = p_{\mathrm{red_{max}}} \cdot \exp\left(-\frac{1}{2} \cdot \left(\frac{|t-a|}{0,637 \cdot p_{\mathrm{red_{max}}} \cdot \left(\frac{dp}{dt}\big|_{\mathrm{red_{max}}}\right)^{-1}}\right)^2\right) \tag{1}$$

At least the rising part of the pressure-time curve can be described satisfactory with (1), and this is basically important in the calculation of the opening process of a pressure relief device. Numerous tests with vessels of 1 m^3 to 60 m^3 volume at our experimental plant confirm it [1], [2], [4], [5], [6]. The variable a in (1) localizes the maximum pressure on the time axis and is therefore of no significance here. For $p_{\mathrm{red_{max}}}$ one has to fill in:

$$\begin{aligned} p_{\mathrm{red_{max}}} &\approx \left[\left(3,264 \cdot 10^{-5} \cdot p_{\mathrm{max}} \cdot K_{\mathrm{St}} + \frac{1}{4} \cdot (p_{\mathrm{stat}} - 0,1)\right) \cdot \frac{\sqrt[4]{V^3}}{A_{\mathrm{E}}}\right]^{\frac{7}{4}} \\ &\quad \cdot \exp\left(2,35 \cdot 10^{-3} \cdot \frac{K_{\mathrm{St}}}{V^{\frac{3}{5}}} \cdot \sqrt{Q}\right) \qquad Q = \frac{\Theta_{\mathrm{K}}}{A_{\mathrm{E}} \cdot h} \end{aligned} \tag{2}$$

Q stands for the explosion door resistance and is derived from the momentum of inertia Θ_{K} referring to the rotation axis of the (round or rectangular) explosion door, the explosion door area A_{E} and the effective lever h. As can be seen, (2) is a variance of the formula from VDI 3673 guideline for calculation of vent areas. Adding the exponential factor makes it possible to describe all test results with respect to $p_{\mathrm{red_{max}}}$ from [1], [2], [4], [5], [6] (see also figure 3). When calculating $p_{\mathrm{red_{max}}}$ according to (2), the V in the exponential factor will never exeed 60 m^3 because for larger volumes no experimental experience exists. For the fact that the influence of inertia of pressure relief devices with a given mass decreases with the increase of the vessel volume, the calculated results are in any case applicable in practice. Furthermore, the exponential factor tends to go towards zero when the mass of the pressure relief device approaches zero. This corresponds with the expectations.
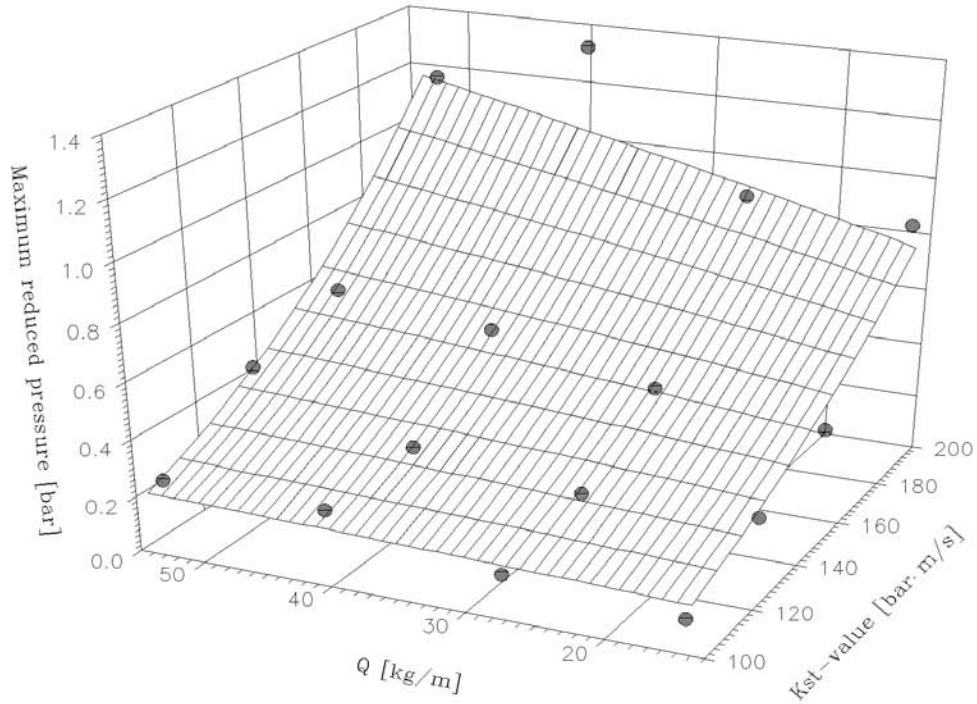
Figure 3: Observed maximum reduced pressure as a function of K_{St}-value and the resistance of the explosion door Q. Every point is the middle of three measurements in a 9.4 m³-vessel. The fitted surface is described by (2) with a correlation coefficient of $R^2 \approx 0.9$.

The maximum reduced rate of pressure rise is calculated by:

$$\left.\frac{dp}{dt}\right|_{\text{red}_{\max}} \approx 1,72 \cdot \frac{K_{\text{St}}}{\sqrt[3]{V}} \cdot \frac{p_{\text{red}_{\max}}}{p_{\max}} \tag{3}$$

Equation (3), also, was derived from bringing it into line with the above mentioned test results, as can be seen in figure (4).

If the pressure relief device is a explosion lid, it's being treated like an explosion door when calculating $p_{\text{red}_{\max}}$ and $\left.\frac{dp}{dt}\right|_{\text{red}_{\max}}$.

The pressure development received as a result will serve to identify the force F_{Ex} that accelerates the explosion door during the explosion. In the initial phase of the pressure relief this force is simply obtained from the pressure put on the area of the explosion door according to $F_{\text{Ex}} = p(t) \cdot A_{\text{E}}$. Later in the process, this pressure force disappears due to a variable factor and is gradually substituted by a frictional force (Newton friction), created by the vessel content being blasted against the explosion door. The exit velocity of the vessel
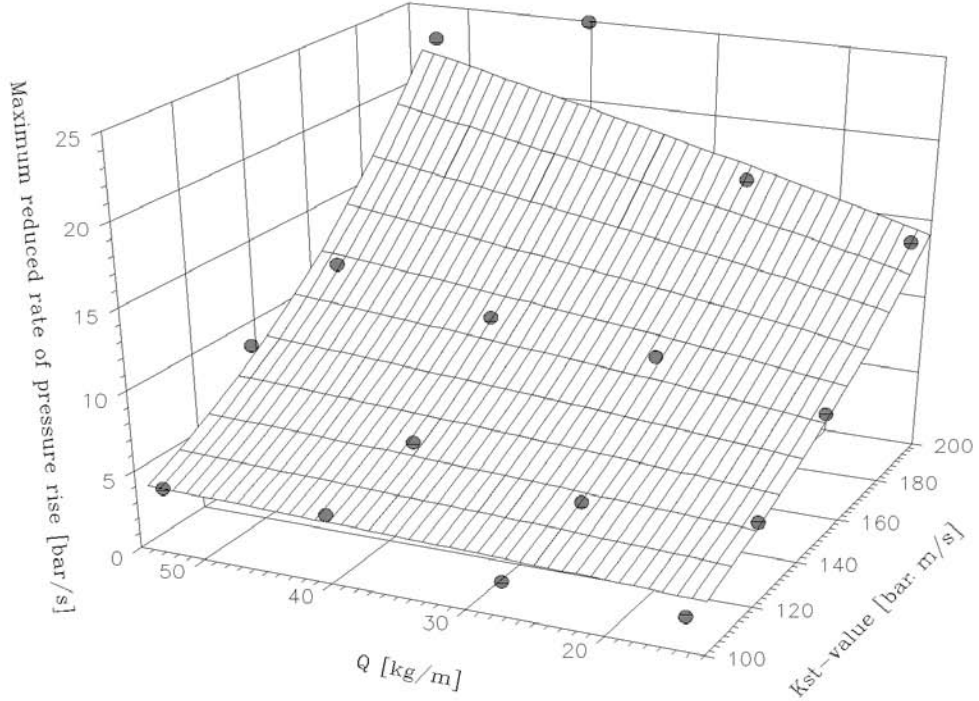
Figure 4: Observed maximum reduced rate of pressure rise as a function of K_{St}-value and explosion door resistance Q. Every point is the middle of three measurements in a 9.4 m³-vessel. The fitted surface is described by (3) with a correlation coefficient of $R^2 \approx 0.9$.

content is calculated with the help of the pressure development timewise. At the end, the opening angle $\varphi(t)$ of the vent door versus time resp. the position $y(t)$ of the explosion lid over the vent area versus time is the result of the differential equations

$$\ddot{\varphi}(t) = \frac{S}{\Theta_{\mathrm{K}}} \cdot \left((F_{\mathrm{ex}}(t) + F_{\mathrm{gr}}) \cdot \cos\varphi(t) + F_{\mathrm{af}}(t) + F_{\mathrm{hf}} \right) \qquad \text{(explosion door)} \qquad (4)$$

$$\ddot{y}(t) = \frac{1}{m(t)} \cdot \left(F_{\mathrm{ex}}(t) - F_{\mathrm{gr}} \cdot + F_{\mathrm{af}}(t) \right) \qquad \text{(explosion lid)} \qquad (5)$$

with Θ_{K} as momentum of inertia with respect to the rotation axis of the explosion door, S as distance between the centre of gravitiy of the explosion door and the rotation axle and $m(\mathrm{t})$ as mass of explosion lid plus safety-ropes. The effective forces F_{i} are marked by indices: ex = force as consequence of the explosion, gr = gravity, af = air resistance and hf = hinge friction. The forces last mentioned are calculated from the physical data of the pressure relief devices (mass, area etc.).

The resolution of (4) resp. (5) will be done numerically with the help of the famous Runge-Kutta method [13]. In the process, the physical quantities within the vessel as e. g. density

will always be brought in line. The calculated time-dependent opening angle of an explosion door will give easy access to the needed load $F_K(t)$ on hinges or safety-ropes of this explosion door. From the time-dependent position of an explosion lid over the vent area the load on the safety-ropes $F_D(t)$ of the referring explosion lid can be derived. The corresponding formulas are:

$$F_K(t) = \sqrt{\left(m \cdot S \cdot \dot{\varphi}^2(t) \right)^2 + \left(\frac{\Theta_S}{S} \cdot \ddot{\varphi}^2(t) \right)^2} \qquad \text{(explosion door)} \qquad (6)$$

$$F_D(t) = n \cdot E \cdot A_S \cdot \frac{\Delta l(t)}{l} \qquad \text{(explosion lid)} \qquad (7)$$

In (6), m is the mass and Θ_S the momentum of inertia of the explosion door. The latter refers to the rotation axis through the centre of gravity of the explosion door. $\dot{\varphi}$ and $\ddot{\varphi}$ are the time-dependent angular velocity and the angular acceleration of the explosion door. In (7), n is for quantity, E for modulus of elasticity, A_S for area of cross-section and l for length of the safety-ropes. $\Delta t(t)$ is the safety rope streching during the catching process.

The results of (4) and (5) create the basis for the calculation in the event that the fastenings of the pressure relief devices are too weak and cannot hold them in place. With the parameters of initial velocity, start height and start angle the equation of movement for the oblique throw with Newton friction

$$m \cdot \ddot{\vec{r}}(t) = -\frac{1}{2} \cdot \rho_a \cdot \hat{N}(t) \cdot \dot{r}(t) \cdot \dot{\vec{r}}(t) - m \cdot g \cdot \vec{e}_y \qquad (8)$$

can be solved by numerical integration. The result is the trajectory of the catapulted away pressure relief device. ρ_a stands for density of air, $\vec{r}(t)$, $\dot{\vec{r}}(t)$ and $\ddot{\vec{r}}(t)$ stand for time-dependent vector of location and its derivations, m for the mass of the torn away pressure relief device, g for gravity and $\vec{e}_y$ is the normalized vector in y-direction. The flying pressure relief device will always be assumed to be a rotating disk. This assumption is taken into consideration in (8) by the variable tensor $\hat{N}(t)$ and is described in the following. In Newton's friction law appears, besides the above mentioned quantities, the bodycharacteristic drag coefficient c_w and the body's cross-sectional area. A round disk flying through the air has two fundamentally different cross-sectional areas A_x, A_y resp. drag coefficients c_x, c_y as can easily be recognized in figure 5. This circumstance can be described quite well by the tensor (9).
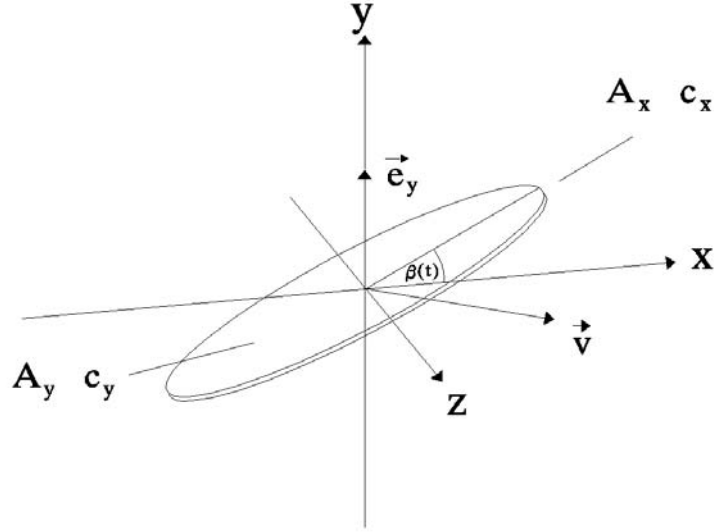
Figure 5: Sketch of a round disk flying through the air with a velocity of $\vec{v} = \dot{\vec{r}}(t)$ and a momentary inclination $\beta(t)$ towards the horizontal line.

$$
\hat{N}(t) = \begin{pmatrix} c_x \cdot A_x \cdot \cos^2 \beta(t) + & \\ c_y \cdot A_y \cdot \sin^2 \beta(t) & 0 \\ & c_x \cdot A_x \cdot \sin^2 \beta(t) + \\ 0 & c_y \cdot A_y \cdot \cos^2 \beta(t) \end{pmatrix}
\tag{9}
$$

This perspective bases on the legitimate assumption that the disk rotates rigidly around the horizontal z-axis and the velocity vector is always parallel to the xy-plane. The sinus and cosinus functions of the angle $\beta(t)$ in $\hat{N}(t)$ express the time-dependent orientation of the body[3] with respect to the also horizontal x-axis. They represent the calculation of the effective cross-sectional areas in the direction of the coordinate axis and the approximate change of the drag coefficents caused by the oblique stream that body areas are being exposed to. In contrary to STS, which is used for calculation of debris trajectories when dealing with the destruction of large parts (walls) of buildings through a dust explosion, SIMEK allows an evaluation of flight distances when small wall parts are affected.

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[3]Usually a torn away pressure relief device carries an angular momentum with it.

2.2   STS

STS is for calculation of trajectories of debris catapulted away after a dust explosion in a building or container. Prerequisite for the application of STS is that large parts of the container were destroyed. As a result the trajectory of debris with the most probable and with the largest possible flight range together with the respective kinetic impact energies will be found. The fundament for the calculation of debris' trajectories after a dust explosion is – as in SIMEK – the numerical solving of equation (8). However, when applying STS the difficulty is to determine the initial conditions like start velocity, start angle, start height etc. of the debris, which are needed for calculating the trajectory. In the following the formulas for the determination of the initial conditions are sketched. The derivation of these formulas is stated more precisely in [10].

The calculation of the initial velocity v_0 of the debris is done by using a combination of the equation of Gurney and of an ideal gas as well as the first main proposition of thermodynamics:

$$v_0 \approx \sqrt{2 \cdot c_\mathrm{v} \cdot T_0 \cdot \left(\frac{p_\mathrm{b}}{p_0} - 1\right)} \cdot \left(\frac{m}{((p_\mathrm{b} - p_0) \cdot p_\mathrm{max}^{-1} \cdot \rho_\mathrm{s} \cdot V} + \frac{1}{2}\right)^{-\frac{1}{2}} \tag{10}$$

Here, p_b is the pressure within the building at the point the building bursts, T_0 resp. p_0 is the norm temperature resp. the norm pressure, c_v is the specific heat capacity of air at constant volume, ρ_s is the density of the dust/air-mixture, V is the volume filled with the dust/air-mixture, m is the torn off mass and p_max is the dust explosion characteristic of the maximum explosion gauge pressure. If $p_\mathrm{red_{max}} > p_\mathrm{b}$, the former will substitute p_b in (10). ρ_s is assumed to be $2\ \frac{\mathrm{kg}}{m^3}$ in the program. The rest of the data for a building can be entered quite easily. Formula (10) is for cylindrical buildings. If the building in question is cuboid, the fraction $\frac{1}{2}$ within the brackets of (10) has to be substituted by $\frac{3}{5}$.

The start angle α (with respect to the horizontal line) of debris for the trajectory with maximum range is described by

$$\alpha = \arccos\left(\frac{\sqrt{2 \cdot (v_0^4 + 3 \cdot v_0^2 \cdot h \cdot g + 2 \cdot h^2 \cdot g^2)}}{2 \cdot (v_0^2 + h \cdot g)}\right) \tag{11}$$

h is the initial height, g is the gravity and v_0 is the start velocity of debris. For evaluating the most probable trajectory of debris, $\alpha = 0$ rad is assumed.

The initial height h is derived from the location of the upper edge of the destroyed wall (maximum range) resp. from the location of the centre of the destroyed wall (most probable range).

With the known density ρ_s and the thickness of the wall material c_s of the building and with the area A_y (see figure 5) of a typical fragment, the mass of this fragment is derived from

$$m = \rho_w \cdot A_y \cdot c_s \tag{12}$$

For there flight through the air the fragments of debris are being taken as rotating round disks, just like in SIMEK. The calculation of the trajectories and the kinetic impact energies will then be done, as described in 2.1, through numerical integration of the equation (8).

In order to demonstrate the efficiency of this calculation method, we will in the following compare experimental results from [11] with the hereafter done calculations with STS. In the experiment in [11] a glass area of 17.6 m^2 and 7 mm thickness was broken from a wall of a cubic room with a volume of 324 m^2 by a dust explosion. With $p_{max} = 8.8$ bar, $m = 280$ kg and the measured $p_{red_{max}} = 0,082$ bar, STS calculated the trajectories from figure 7. The shattering of the debris observed after the experimental explosion is shown in figure 6. A comparation of both pictures shows the significant correspondance of observation and calculation (see also [10]).

2.3   VENT

VENT can either evaluate vent areas or maximum reduced pressures for dust explosion endangered vessels (tool „dust"), for explosion endangerd rooms in common (tool „rooms") and for containers in which gas may occur (tool „gas"). The results reached with VENT are only applicable, when pressure relief devices with no inertia are used. VENT calculates a problem's solution applying several methods, in order to be able to judge comparitively.

To compute vent areas resp. maximum reduced pressures for dust explosion endangered vessels, VENT applies parallely to formula (15) from [9], the formula

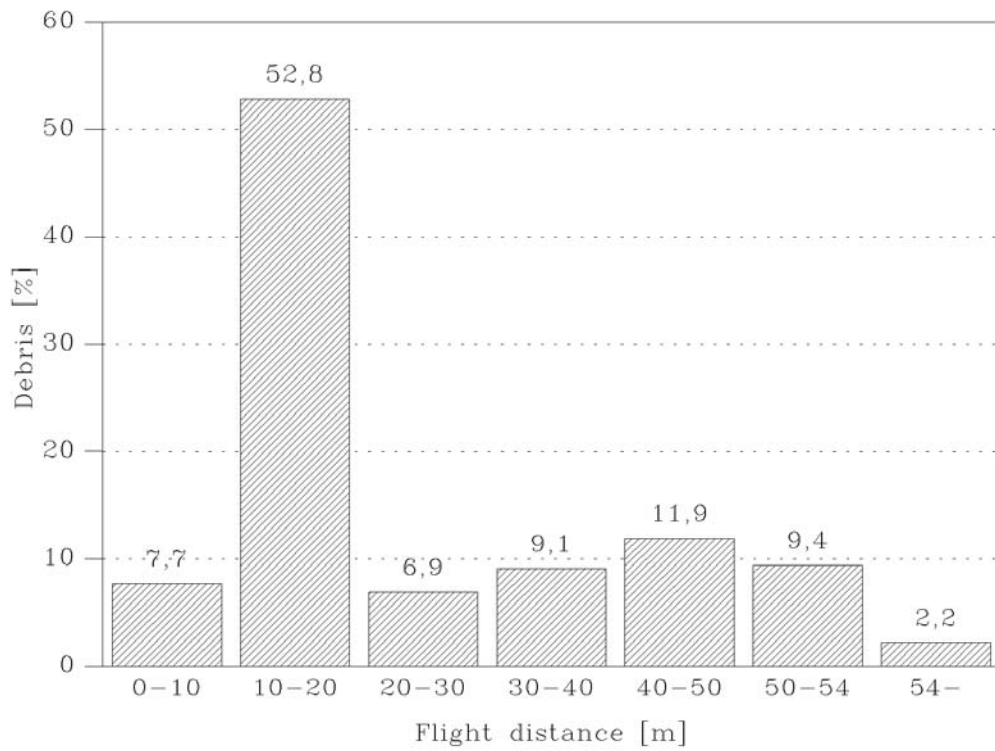$$A_E = \left(a + \frac{b}{p_{red_{max}}} \right) \cdot V^c \tag{13}$$

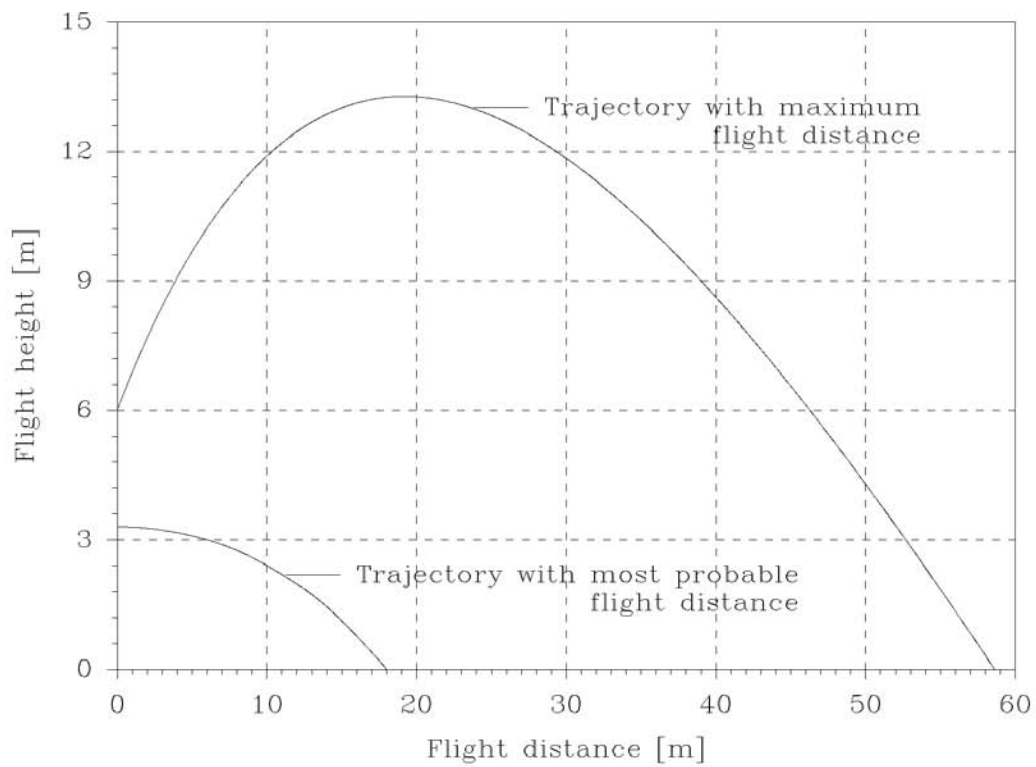Figure 6: Results of the experimental research about the flight distances of glas-debris [11].

Figure 7: With STS calculated trajectories of glas-debris for the parameters described in [11].

a, b and c are empirically defined coefficients. They depend on the dust hazard class and also on whether the maximum reduced pressure is above or below 0.5 bar. Based on the research results of [20], [21], [22] in the calculation of A_E with the help of (15) a correction can be chosen that takes into consideration the way of filling[4] of the vessel.

To calculate vent areas A_E resp. reduced pressures p_{red} for explosion endangered rooms, VENT employs the four evaluation methods (14), (15), (16) and (17) simultaneously, so it is possible to compare these results directly:

$$A_E = \frac{7.5 \cdot F_O}{p_{red} \cdot 100} \tag{14}$$

F_O is the surface of the inner walls of the room. Here, the reduced pressure p_{red} is defined as the pressure of the weakest wall structure will only just withstand. Formula (14) is taken from [24]. The following two methods of evaluation (15) and (16) can be found in a newer and an older version of [9]:

$$A_E = (3.264 \cdot 10^{-5} \cdot p_{max} \cdot K_{St} \cdot p_{red}^{-0.569} + 0.27 \cdot p_{red}^{-0.5} \cdot (p_{stat} - p_{red})) \cdot V^{0.753} \tag{15}$$

$$A_E = (3.264 \cdot 10^{-5} \cdot p_{max} \cdot K_{St} \cdot p_{red}^{-0.569}) \cdot V^{0.753} \tag{16}$$

The fourth and last calculation method (17) is mentioned in [23]:

$$A_E = \frac{C \cdot F_O}{\sqrt{p_{red}}} \tag{17}$$

Here C is a constant. Its values are tabulated in [23].

The formula for the calculation of vent areas for gas explosion endangerd containers

$$A_E = (0.1265 \cdot \log(K_G) - 0.0567) \cdot p_{red_{max}}^{-0.5817} \cdot V^{\frac{2}{3}} \tag{18}$$

can be found in publication [25].

2.4 AD-formula

In the AD-formula software only equations are in use, which can be consulted in the pocket-book or CD-ROM edition of the AD-instructions. For more information the reading of [26] is recommended.

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[4]Filling of the vessel pneumatical tangential, pneumatical vertical or mechanical.

3   How to use it

At present *ExProtect* is a usually WINDOWS 3.1/3.11 resp. WINDOWS 95/NT application.
It owns a simple routine to install the program easily on every IBM-compatible computer.
After running this little install program under WINDOWS 3.1/3.11, a new group appears in
the WINDOWS main menu, which is titled „FSA". It contains the FSA logo to start *ExProtect*
by a double mouse-click on it. The install routine under WINDOWS 95/NT creates the icon
for starting *ExProtect* in the WINDOWS start menu.

After clicking twice on the icon the main menu of *ExProtect* will appear (see figure 8). As
can be seen in figure 8 the main menu of *ExProtect* contains twelve buttons. The first four
buttons are used by SIMEK, STS, VENT and AD-formula and the other eight buttons are
ready for the integration of new programs. Above the field containing the program buttons
there is a little button marked with a questionmark. A double mouse-click on this button
opens the information window of *ExProtect*, which is shown in figure 9.
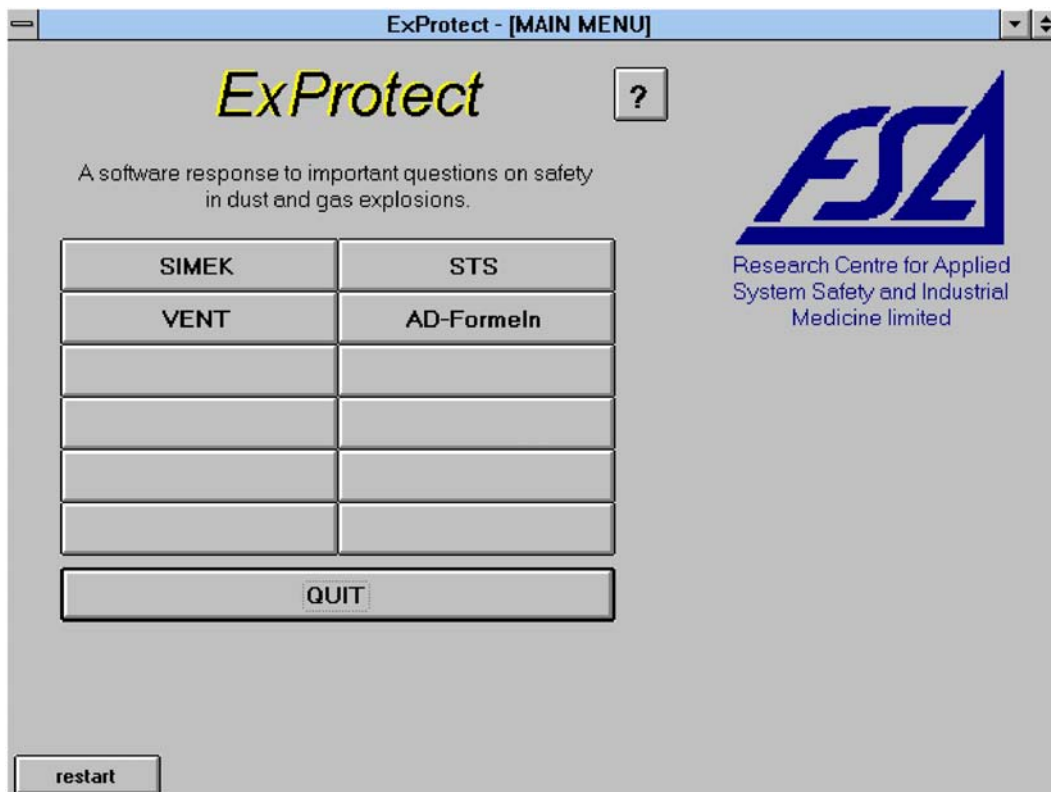
Figure 8: The main menu of *ExProtect*.
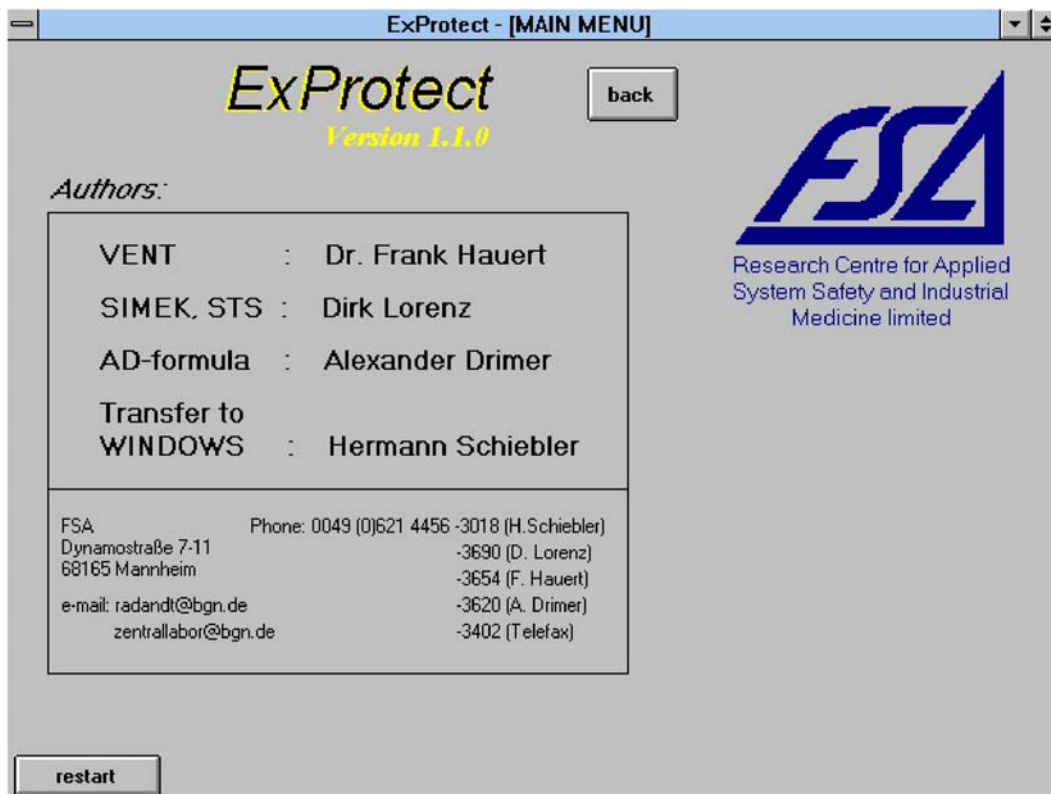
Figure 9: The information window of *ExProtect*.

3.1 SIMEK

The description of SIMEK will be done best by a demonstration of solving the following pro-
blem: an explosion door is needed for a vessel of 100 m^3 volume with a height to diameter
ratio of 1. The K_{St}-value of the burnable dust amounts 200 $\frac{\mathrm{bar \cdot m}}{s}$ and the maximum reduced
pressure $p_{\mathrm{red_{max}}}$ in the vessel has to be 0.5 mbar. SIMEK gives the solution of this problem:
activation of the „SIMEK"-button opens a window, which is reserved for the input of the
general data of the problem. First, the known data of the problem are entered in the
appropriate fields, like it is shown in figure 10. Now the kind of explosion relief device has
to be selected. In our case we want to use a rectangular explosion door, which we select by
mouse-click on „explosion door" and „rectangular" at the two little areas in the right half of
the window. Now we need the missing data at the area titled „necessary data" to continue.
Clicking on the button named „calculate vent area" is the easiest way to get the values. It
opens the window shown in figure 11. In the empty field we write our value of $p_{\mathrm{red_{max}}} = 0.5$
bar. Now SIMEK assumes explosion doors of quadratic form with $\frac{\mathrm{m}}{A_E} = 40 \ \frac{\mathrm{kg}}{m^2}$ and deter-

Figure 10: SIMEK-window for input of general data of the problem.

Figure 11: SIMEK-window to calculate the necessary vent area.

mines size and number of the needed explosion doors by using a trial and error algorithm
in combination with formula (2). If we select „VDI 3673-method" on top of the window,
we obtain the size of the vent area evaluated with formula (15). This feature is only for
comparison of both evaluated sizes of vent areas. In our case we use „SIMEK-method" for
the calculation and after the algorithm is finished we click on the button marked „use" to
return to the window for the data input. We notice, that SIMEK found a solution with two
explosion doors. To continue, the data for „optional input" are not necessary[5]. That's why
we click the „continue"-button in the right top corner of the window. This action opens
the subsequent window, which is for the input of the physical data of one of the uniform
explosion doors (see figure 12). Because we ran the feature of automatic search for explosion
doors the necessesary data of one of the (uniform) explosion doors are already written into
the appropriate fields. In case of unknown explosion door data (if we hadn't used the search
function) we have the possibility to employ a feature which is hidden behind the button

Figure 12: SIMEK-window to input the physical data of one explosion door.

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[5]If no optional data are given, SIMEK sets 0.75 $\frac{kg}{m^3}$, 9 bar and 0.1 bar.
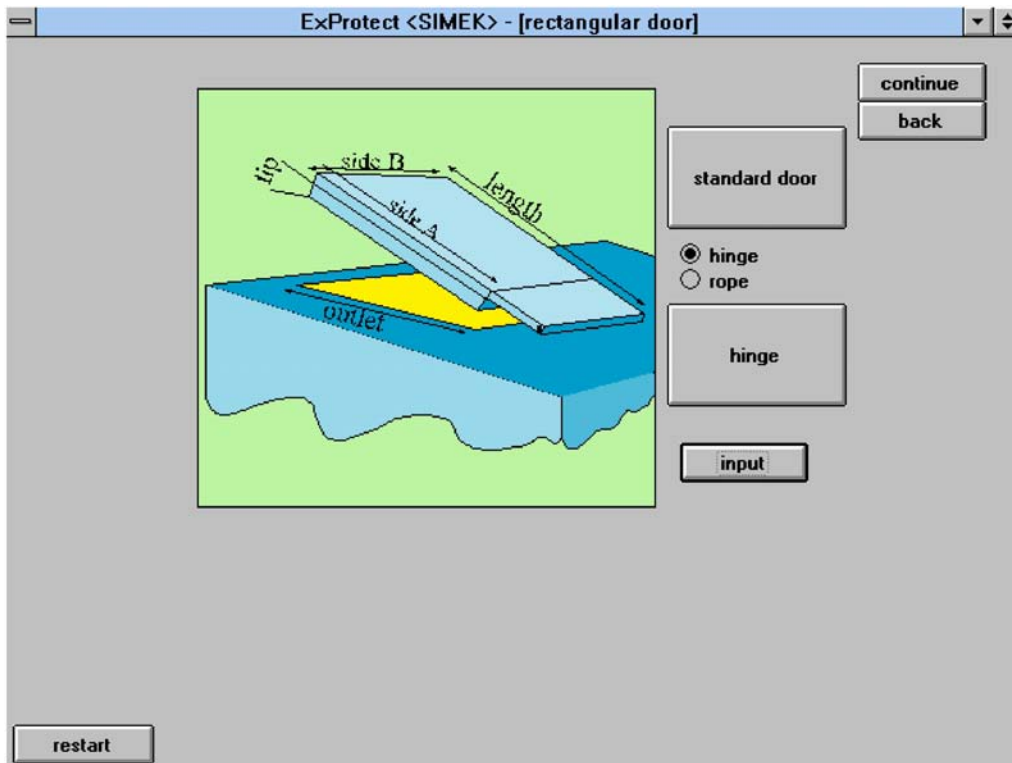
Figure 13: SIMEK-window to input the physical data of one explosion door in picture-mode.

titled „standard door". Pressing this button sets the required data. Clicking the „picture"-button activates a graphic tool and give a sketch of an explosion door to show the meaning of the asked explosion door data (see figure 13). The next step is to decide on the kind of fastening of our explosion doors. From hinge or rope we select hinge by mouse-click on the corresponding circle. With the „hinge"-button[6] it is possible to create a defined hinge for the selected explosion doors. At the moment we don't use this function and go on by clicking on the „continue"-button.

This action generates the calculation of the optional data missing in this window. Simultaneously it opens a new window (see figure 14) for showing us the estimated temporal evolution of pressure in the vessel calculated with formula (1). We notice, that the maximum of the here given pressure curve is equal to the maximum reduced pressure we entered earlier in the program. The venting capability E_F is evaluated from the two values of the vent area size obtained by the VDI 3673-method and by the SIMEK-method. In our example its value amounts to 87 % (± 5 % is to be the estimated absolute error in E_F).

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[6]In case of ropes as fastening of the explosion doors there is a button titled „ropes". This button leads in a data bank with variable types of ropes.
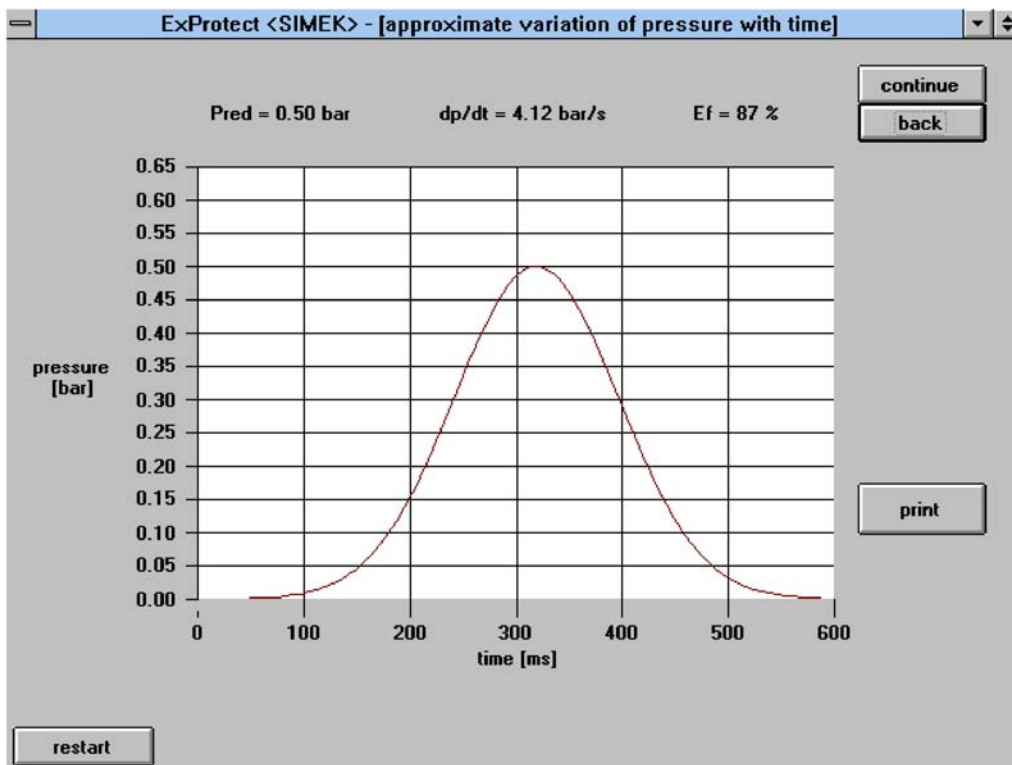
Figure 14: SIMEK-window for showing the estimated temporal pressure evolution in the vessel and the values of $p_{\mathrm{red}_{\max}}$, $\frac{\mathrm{d}p}{dt}\big|_{\mathrm{red}_{\max}}$ and E_{F}.

Pressing the „continue"-button again starts the simulation of the vent process and opens a window for plotting the obtained results. As we can see in figure 15 the hinge load of the explosions door versus time is plotted first. This happens because the button titled „hinge load [kN]" is activated (underlined). Moreover, the value of maximum hinge load is written at the left corner on the top of the diagram. So we need a hinge which is stronger than at least 32 kN. Before we design a suitable hinge we use the mouse and click on the „angle [°]"-button to see the opening angle of the explosion door versus time. As we can see in figure 16 the opening angle of 90° is reached after 100 ms. At this time the value of overpressure in the vessel amounts to a little more than 0.4 bar. Activation of the „pressure [bar]"-button gives us this information (figure 17).

If we didn't use hinges to fix our explosion doors at the pressure relieved vessel they would blow away. Now, we assume this worst case to demonstrate the trajectory-tool of SIMEK. A click on the respective button opens the window for trajectory calculations. This window is shown in figure 18. To get a realistic result we have to fill out the field for the vertical start position (at left top corner of the window). That means the distance between the ground
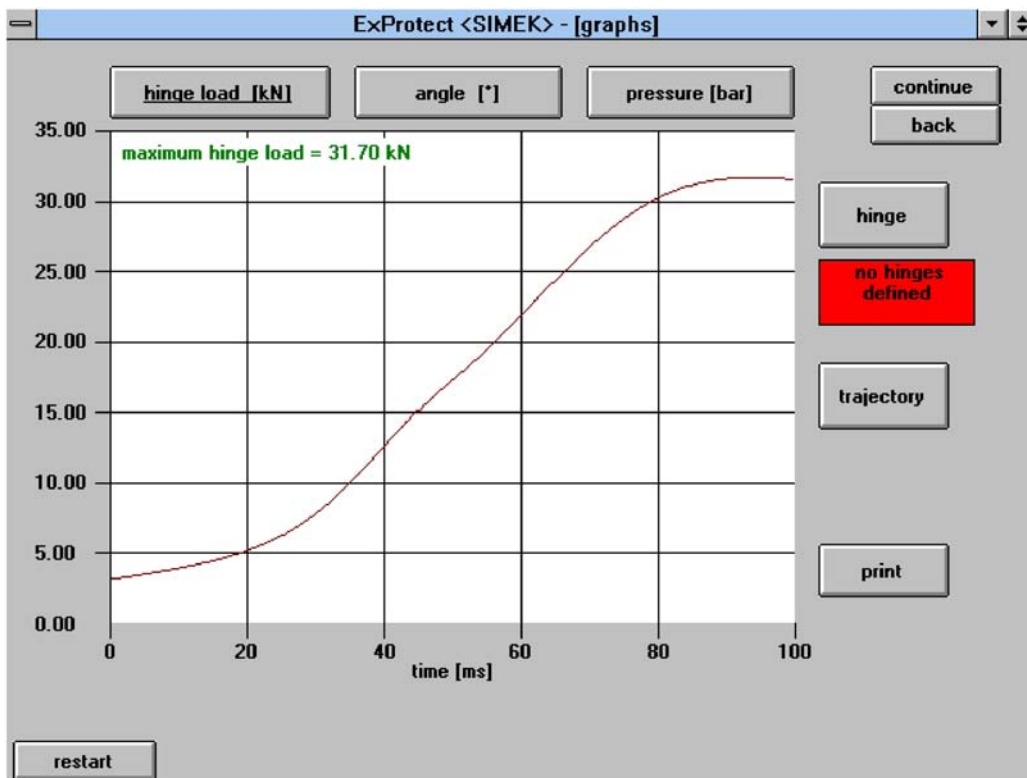
Figure 15: SIMEK-diagram of the results of the main calculation. Because the „hinge load [kN]"-button is activated the solution of equation (6)is drawn.
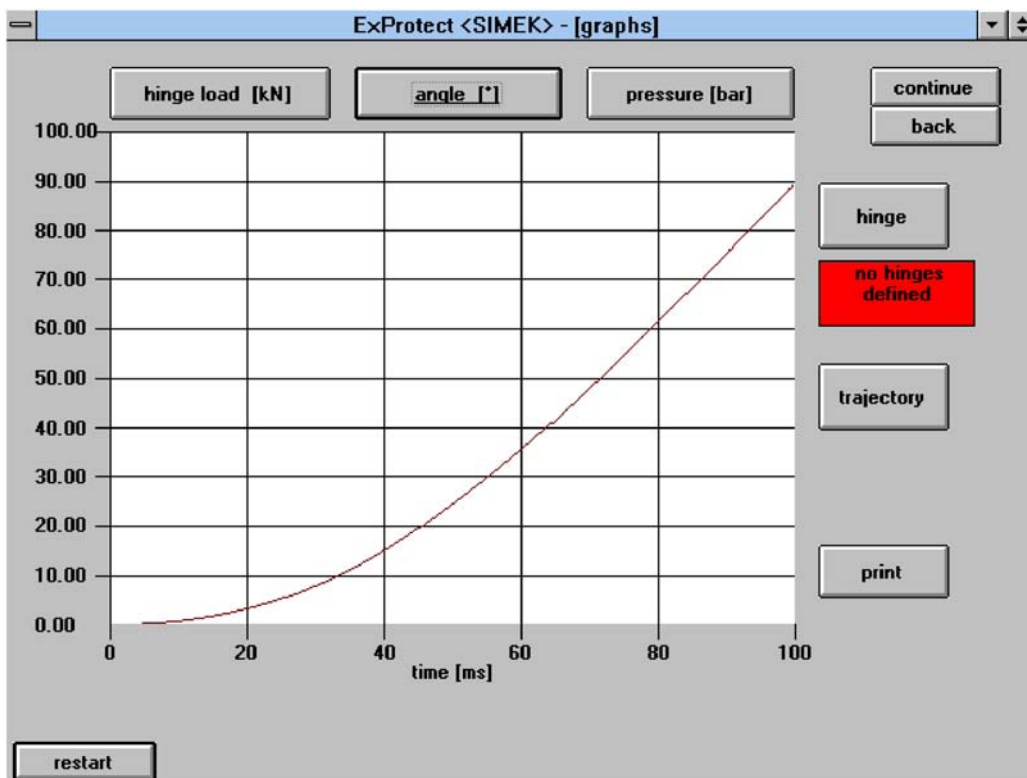

Figure 16: SIMEK-diagram of the results of the main calculation. Because the „angle [°]"-button is activated the solution of equation (4) is drawn.
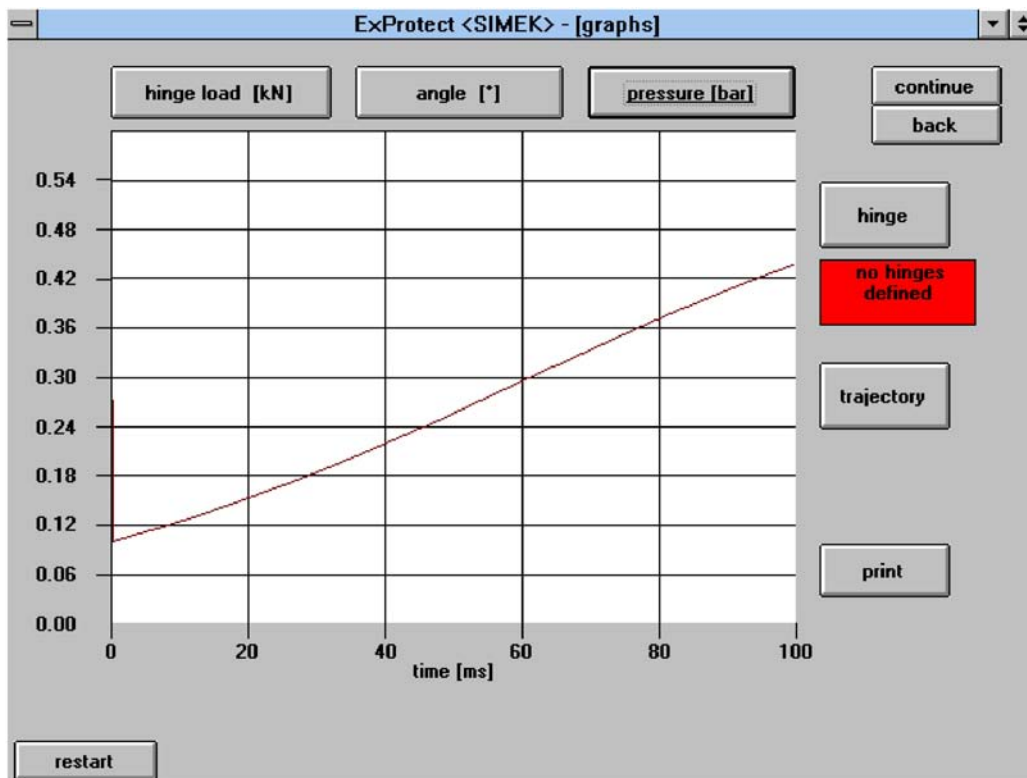
Figure 17: SIMEK-diagram of the results of the main calculation. Because the „pressure [bar]"-button is activated the solution of equation (1) is drawn.
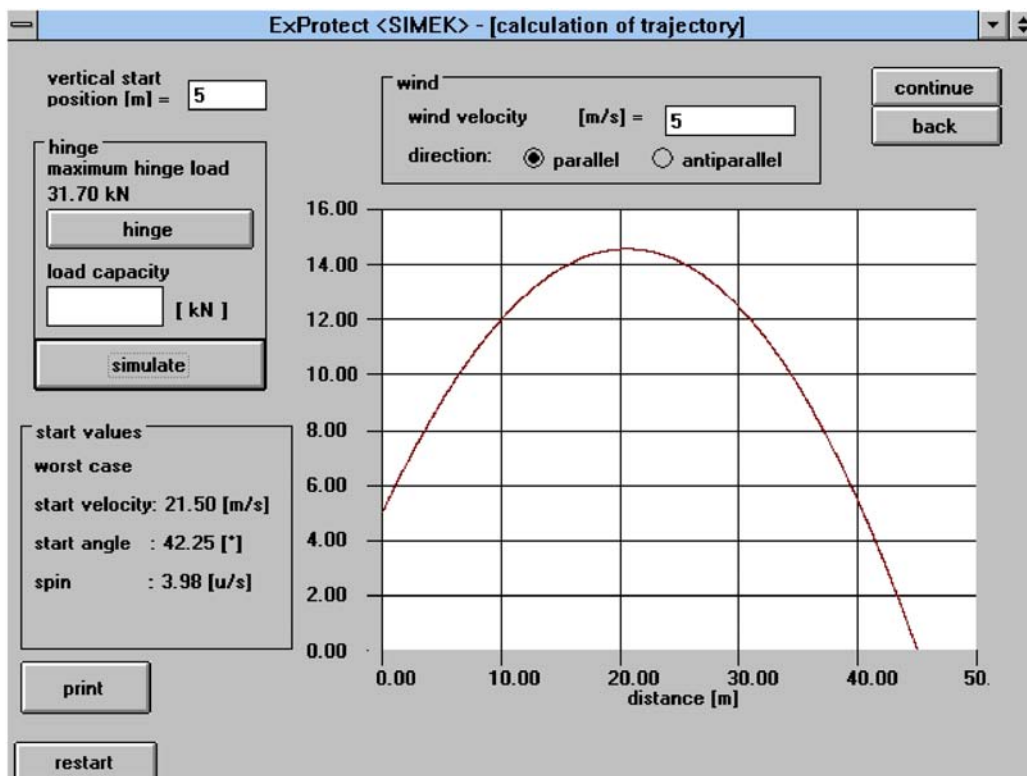

Figure 18: SIMEK-window to simulate the flight of a pressure relief device as consequence of a hinge or rope breakage.

and the height that the explosion door is fixed. In our example we assume a vertical start position of 5 m. Moreover, it is possible to take a wind velocity and a wind direction into consideration. We select a wind of 5 $\frac{m}{s}$ which blows in flight direction (parallel). We enter this value of wind velocity in the reserved field and click with the mouse on the circle titled „parallel" (both at the centre on top of the window). Pressing the „simulate"-button starts the calculation and after a short time the trajectory of our explosion door is plotted. As a flight distance we obtain about 45 m and the value of maximum height of flight amounts to about 15 m. At the left bottom corner of the window we can read the start parameters of our worst case calculation. The trajectory depends on the load capacity of the hinge, which can be written into the reserved field.

But now we return to the window before (shown in figures 15, 16 and 17) and to get there we use the button titled „back". We remember that we need well designed hinges for our explosion doors. For getting solutions to this kind of problem another tool was integrated in SIMEK. We start this tool by clicking on the „hinge"-button which opens the corresponding window (see figure 19).
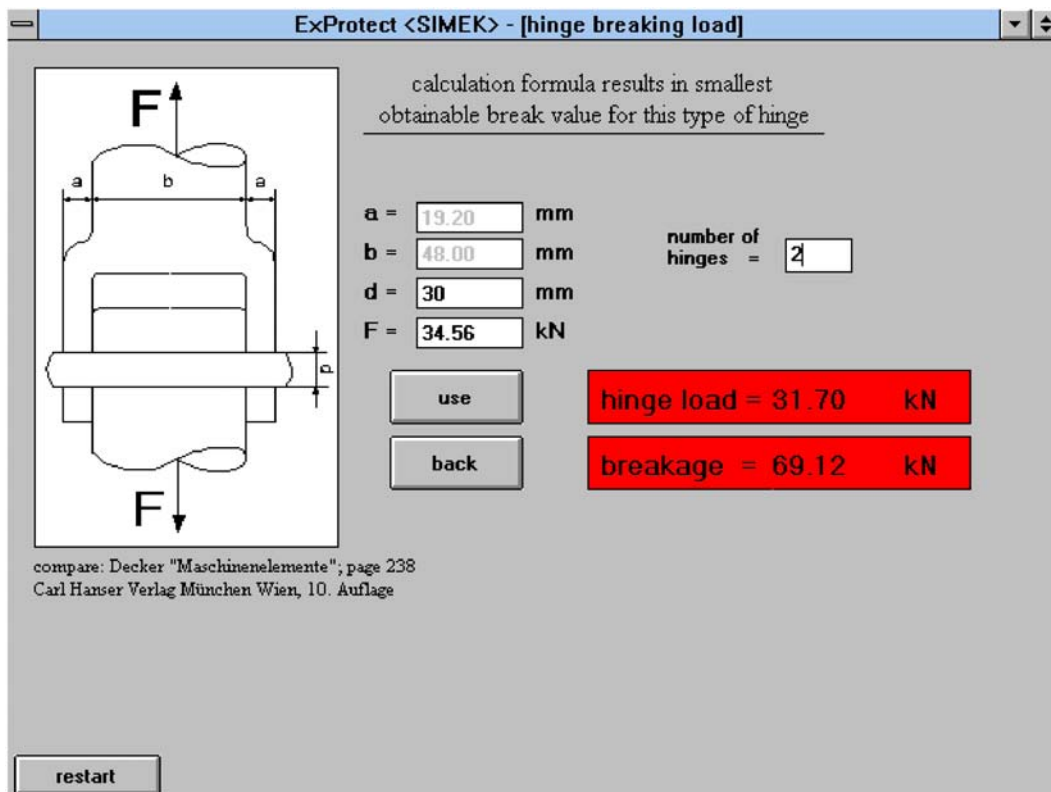

Figure 19: SIMEK-window to design hinges for explosion doors.

At the left half of this window a sketch of a special type of hinge is shown. The here employed evaluation method is only valid for this special kind of hinge, but because it is the weakest typ of hinge the here obtained results are also useful for other hinge types. First we need to fill out the field where the number of hinges (per explosions door) is asked for. We want to use two hinges per explosion door and write this value into the field. To calculate the break load of our two hinges we also need the diameter d of the hinge axle. We write into the field „d = " the estimated value of 30 mm and look at the two red fields at the right half of the window. The upper of these fields shows the maximum load on our two hinges and the lower field the actual break load of our two hinges ($d = 30$ mm). We recognize that the break load is more than double of the maximum load on the hinges. This is a satisfying result and we accept it by clicking on the „use"-button.
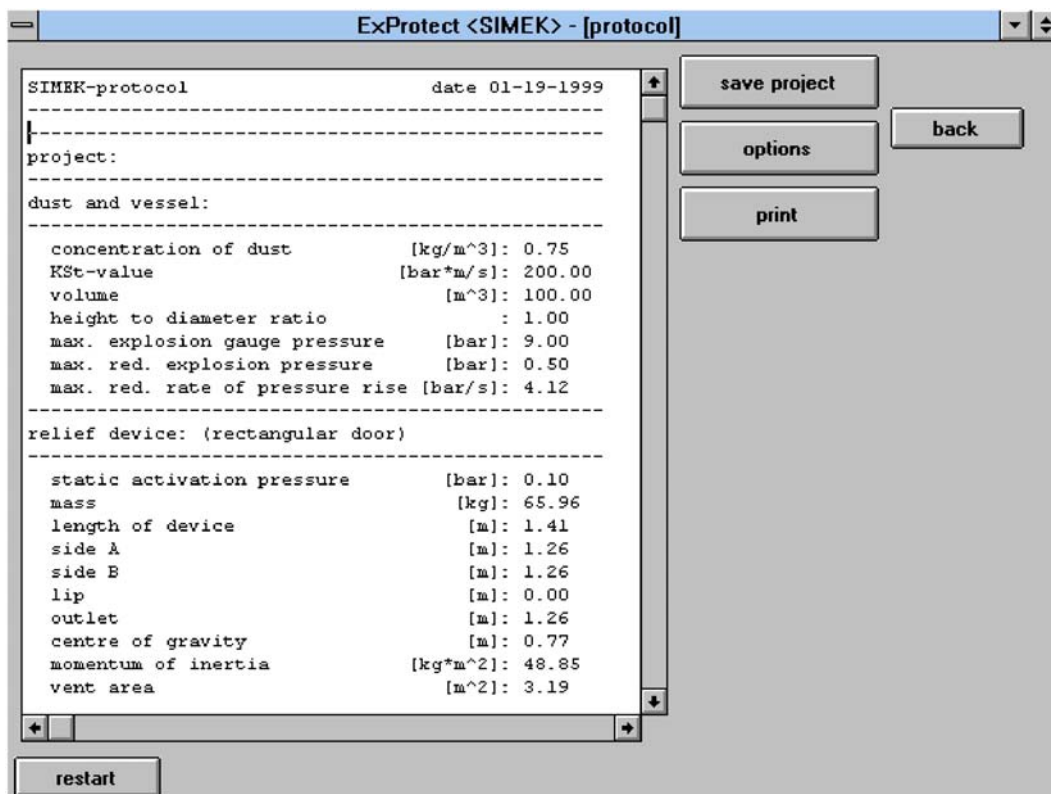

Figure 20: SIMEK-protocol to give the total results of all done calculations. Here the upper part of the data table is shown. To see the lower part of the table, use the WINDOWS scroll bar which is not printed here.

After returning to the window from which we started the trajectory tool we now open the last window of SIMEK by pressing the „continue“-button. The SIMEK-protocol window opens and gives the complete results of all of our calculations in one table (see figure 20). As we can see, SIMEK offers as one possible solution to our problem resp. example: the pressure relief has to be done by employing two explosion doors. Mass and area of every explosion door amounts to 65.96 kg and 1.59 m^2. Every explosion door has to be fixed at the vessel by two hinges assuming that the diameter of the hinge axle amounts to at least 30 mm. With the buttons at the right side of the window it is possible to print the data table or to save the project. Furthermore the design of the printout can be changed by using the „options“-button.

As it was demonstrated in our example, SIMEK is a very useful tool to solve different pressure relief problems in context with explosion doors or lids.

3.2   STS

As mentioned before, STS was written to calculate the flight distances of debris of a bursting vessel or building as a consequence of a dust explosion inside. To demonstrate the efficiency of STS the following example is to be contemplated: a cuboid building (height to diameter ratio is 1) of 1000 m^3 volume and is made of masonry of 150 mm thickness bursts due to a dust explosion inside. We assume that a quadratic area of 100 m^2 of the building wall is catapulted away. The masonry will burst at a pressure equal or higher than 0.1 bar. The explosion characteristics of the burnable dust are to be $K_{St} = 200 \frac{bar \cdot m}{s}$ and $p_{max} = 9$ bar. What is the maximum flight distance of the debris and at what distance will the maximum debris mass be found?

To solve this problem we press the „STS“-button in the main menu of *ExProtect* (see figure 8 again). A window forseen for the input of the main data of the respective problem opens. We enter the data of our example into the appropriate fields and select „cuboid“ form (of the building) with a mouse-click at the circle on top of the window. To select the material of the buildung walls we open a little data bank by pressing the button marked with an arrow at the field titled „material“. In the now open data bank we click at „masonry“. At the subsequent field the „area of fragments“ is asked for. That means the

Figure 21: STS-window to input the data of the problem dealt with.

largest area of an average fragment. In most cases this parameter is unknown, so STS sets it on 0.5 m². This is the most observed value in pertinent experimental determinations. The asked "centre of area hm" at the last field is the distance between the centre of the bursting area and the ground, like it is shown in the sketch at the right half of the window. In our case this value amounts to 5 m. We click on the „continue"-button at the right top corner of the completely filled out window, thus starting the calculations described in section 2.2. At the same time, the window for the presention of the results opens. At the shown diagram the trajectories with the maximum and with the most probable flight distance are drawn, as one can see in figure 22. We recognize that the maximum flight distance amounts to nearly 10 m and the main mass of the debris will impact at a distance of about 6 m. The printing of the trajectories can be done by using the corresponding button.

To proceed in STS we press the „continue"-button again and arrive at the final window which includes a table containing all important data and results of our problem. As we can read in figure 23, a typical fragment of the destroyed wall in our example has a weight of about 116 kg. Such a fragment is able to cover a maximum distance of 9.4 m and impacts
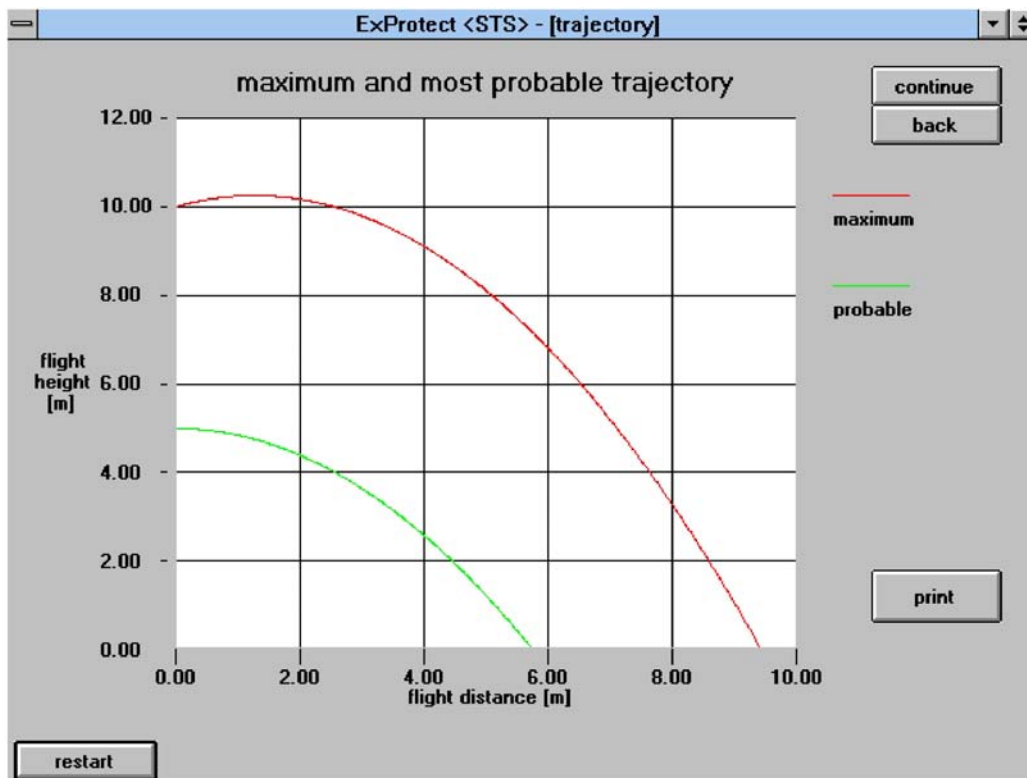
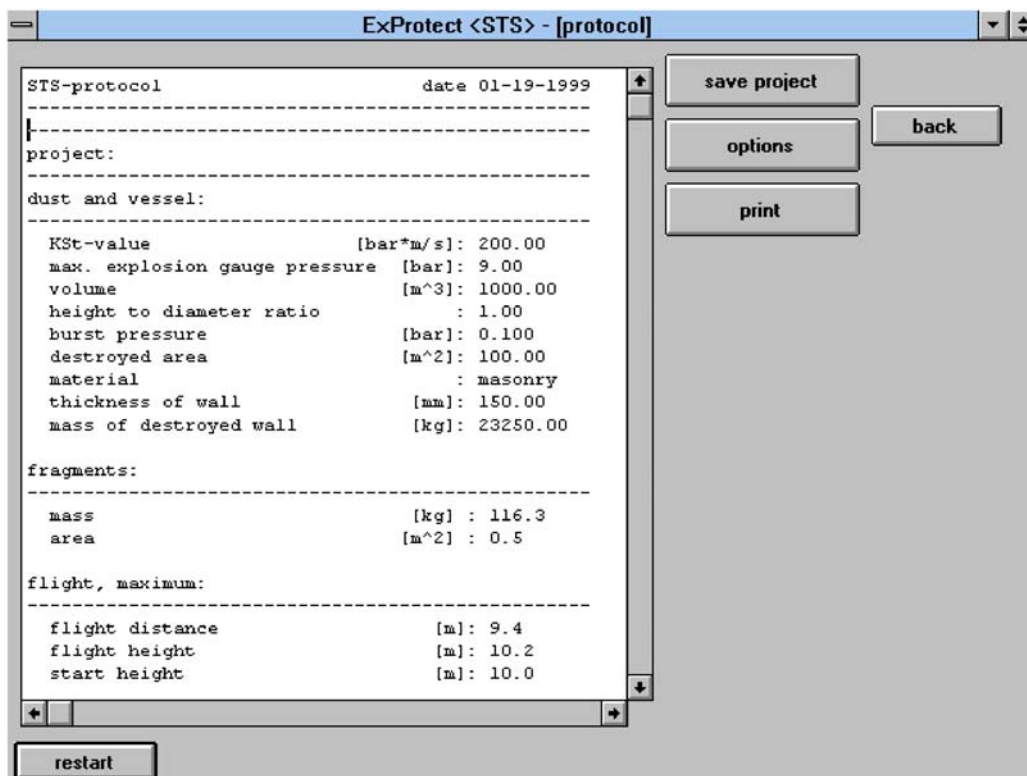Figure 22: STS-window for the graphic presentation of the evaluation results.

Figure 23: Protocol-window of STS (upper half) which contains all important data of the problem in question. To see the lower part of the table, use the WINDOWS scroll bar which is not printed here.

with an energie of 13 kJ. The main mass of the debris will be found at a distance of about 5.7 m from the bursted wall. These fragments with the most probable trajectory will have an impact energie of about 7.5 kJ. As explained before when talking about the protocol-window of SIMEK, saving and printing of the data is possible by using the relevant buttons. Again, the „option"-button is forseen for designing the printout of the data table.

As was shown in our example, the radius of the dangerzone referring to flying debris as a consequence of a dust explosion inside a silo, vessel, container or buidling can be given easily by employing the program STS of *ExProtect*.

3.3   VENT

At present only a German version of VENT exists and in addition it is complicated to get printouts of the VENT windows, thus we refrain from showing the windows of VENT in several figures. Instead of presenting pictures the functions of the program will be described verbally only.

As mentioned in section 2.3, VENT is able to solve different kinds of pressure relief problems by using pressure relief devices without any mass inertia. To demonstrate the tools of VENT we look back at our example we used in the SIMEK chapter. A vessel of 100 m^3 volume with a design strength of 0.5 bar is to be protected against damage from a dust explosion inside. In the main menu of *ExProtect* (figure 8) we click on the button titled „VENT" to calculate the required vent area. This action opens the main menu of VENT. In the upper half of this menu an information window can be seen and in the lower half a window to select of the four tools „dust", „rooms", „gas" and „end" exists. To find a solution to our problem we select the tool „dust" (per mouse-click). Now a window opens for the data input of the problem. First we have to choose from the calculation of the vent area A_E and the calculation of the maximum reduced pressure $p_{red_{max}}$. We select the first. In the subsequent fields we write the data of K_{St} = 200 $\frac{bar \cdot m}{s}$, p_{max} = 9 bar, p_{stat} = 0.1 bar, V = 100 m^3, height to diameter ratio is 1 and the length and the diameter of a vent duct are zero (no vent duct). In addition to that we can choose between four kinds of filling the vessel. To demonstrate this we select „mechanical" which means that the product (dust) is filled into the vessel from its top and falls freely into it (for

example by employing an elevator). Starting the calculation by pressing the „O. K."-button gives us the data of table 1 as a result. We notice, that the vent area for a mechanically filled vessel is less than half of the vent area which is required for a vessel containing a homogen dust/air-mixture. By using VENT's graphic tool a corresponding diagram can be created in which the maximum reduced pressure is viewed as a function of the vent area. Moreover it is possible to compare the results of two calculations as is shown in figure 24. The second curve is obtained by using a height to diameter ratio of 3. Data table and diagram can be printed easily and it is also possible to export the entered and computed values into a file.

dust/air-mixture	homogen	inhomogen	with formula (13)	mechanical filling
vent area [m^2]	2.79	0.80	2.79	1.12
recoil force [kN]	166.3	47.8	166.1	–

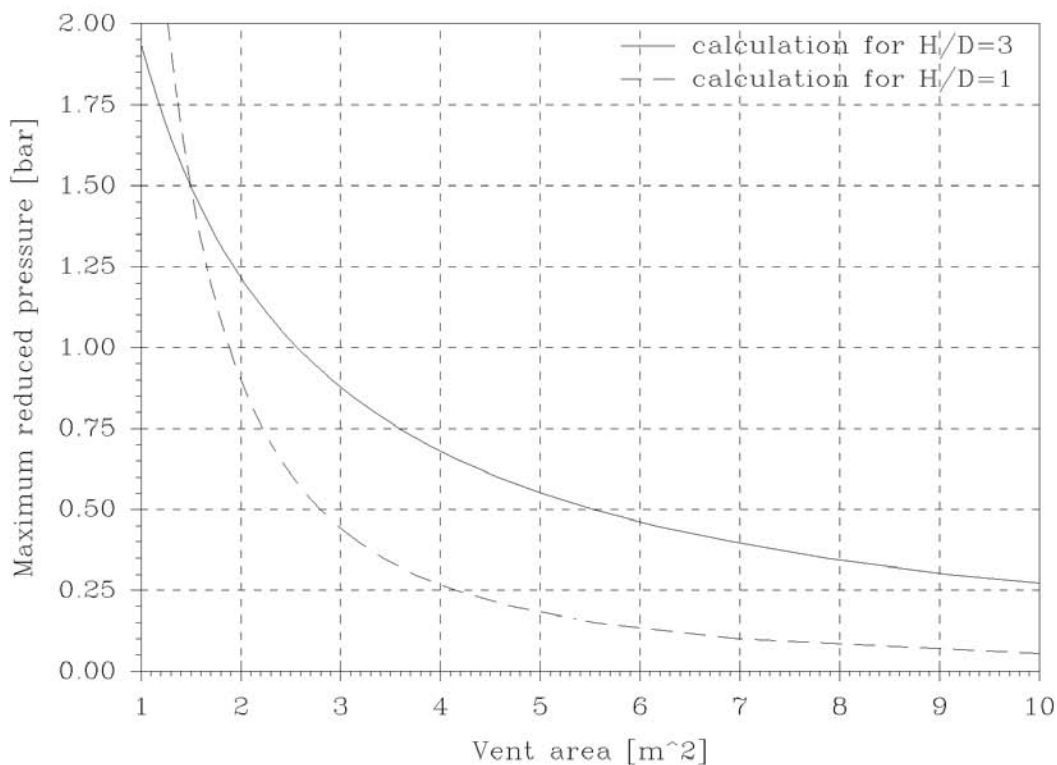Table 1: Calculated vent areas for a dust explosion endagered and pressure relieved vessel.

Figure 24: Maximum reduced pressure versus vent area calculated with VENT for two different height to diameter ratios of the vessel. Evaluations done with (16).

In the same way it is described above the two other tools „rooms" and „gas", employing the formulas (14) to (18), are to be used. We leave VENT by clicking with the mouse on „end" and return to the main menu of *ExProtect*.

As a conclusion it can be said that VENT is a software which makes the engagement of the standard calculation methods referring to pressure relief problems easier.

3.4   AD-formula

The actual version of AD-formula bases on a primitiv BASIC interpreter-code. Therefore it is of no use to show pictures of the program windows. Like VENT, AD-formula deals with menus to select the methods of calculation.

Entering AD-formula is done by pressing the corresponding button in the main menu of *ExProtect* (see figure 8 again). Here it is only possible to continue or to return. Going on in AD-formula opens the menu for designing four different structural members for vessels standing under pressure. These calculations are named B1 to B4 in the AD-instructions [26]. Additional to the existing possibility to return to the main menu a second menu can be opened with four more designing tools printed in B5 and B7 to B9 in the AD-instructions [26]. Every time such a designing tool is started one has to enter some data about the vessel in question. If the data input is finished the solution of the problem will be given by pressing the „enter" key of the computer keyboard. In general, AD-formula is controlled by entering numbers with the help of the keyboard. In the same way AD-formula can be left to return to the main menu of *ExProtect*.

The present version of AD-formula is userunfriendly and will therefore be improved in the near future. If this is done, AD-formula will be a useful help for the designing of vessels standing under pressure.

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