

# **Computer Implementations with 3D Simulations of Models for Quick Estimations of Fragments Trajectories, Penetrations and Safety Evaluations Due to Detonations of Explosives**

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**Abstract:** The explosive Engineering field is a costly one in which not every organization can effort the time and money it takes to performed field tests on its explosives. The purpose of this article is to present a program that was developed in the Israeli Navy for performance estimations and safety issues of warheads and explosives. With a relative small developing time one can create a tool that gives preliminary results in a few minutes without the need to design and order a field tests or run finite elements analyses. By implementing a few known models, in this tool, the user can evaluate, graphically, the hazardous areas around the detonation point, determine the fragments penetrations of plates (or decks) and their densities. Theoretically, this allows the user to specify requirements from future explosives designs. Additionally this tool can assist in defining the preferable placements of personal and equipment/ammunitions in a giving area by creating a safe/no safe map of known explosives used by the organization or enemy forces so it can be better prepared against enemy explosives.

**Keywords:** Explosive, Gurney, Shapiro, Fragmentation, detonations, Simulations

## **1 Introduction**

One of the primary concerns for the Israeli Navy's Explosive Engineering section is ability to evaluate the survivability of its ships due to explosives detonations and fragments penetrations of the ships' decks. The standard options to use are: 1) perform real explosion and analyze the results later which requires a lot of resources (in both time and money) or 2) perform computer simulations using commercial programs such as AnsysAutodyn which can requires a lot of computation time and dedicated/expensive hardware for accurate results (with order of magnitude of million cell and above for accurate meshing).

Therefore, a new initiative was selected: developing a program to allow quick and

graphical estimations of various properties that are most relevant for safety issues. While commercial products can offer better results an in house development has the advantages of giving greater control over the implemented models, allows for modifications and implementation of specific features not existing in other products and to incorporate knowledge gathered in the organization over the years.

The developing process was started with identifying key models of interest. The models were grouped in the following categories:

Initial detonation phase: this phase deals with evaluating the initial state of the fragments after detonation which involves determining the velocities, angles, masses and total fragments' count immediately after detonation

Free flight phase: after each fragment has its own trajectory vector it is needed to calculate its position and velocity over time. For short ranges flights, gravity can be ignored but for a long ranges both gravity and drag effects should be taken into account.

Impact phase: for each fragment that reaches a predefined location it should be determined its energetic state and/or if it penetrates a plate with defined boundaries. Those plates can represent the ship's deck.

### **1.1 Detonation Phase**

Fragmentation can typically be separated into two categories: primary and secondary fragmentations. Primary fragments are typically produced from the casing of the charge or in manufacturing process in which the casing and the attached material are designed to fail at specific location and produced well defined fragments. Secondary fragments are produced when a shock wave hit objects near the source of the detonations. For this work only primary fragments were considered.

The flight trajectory of fragment depends upon the charge geometry, the metal casing and the interaction between the casing and the explosive charge. In 1940 R.W Gurney developed a model that can predict the initial velocity of fragments with cylindrical geometry. Gurney equation for the common cylindrical charges was:

$$\frac{V}{\sqrt{2E}} = \left( \frac{M}{C} + \frac{1}{2} \right)^{-0.5} \quad (1)$$

For spherical charges:

$$\frac{V}{\sqrt{2E}} = \left( \frac{M}{C} + \frac{3}{5} \right)^{-0.5} \quad (2)$$

Where: V – initial velocity of fragments

$\sqrt{2E}$  – Gurney Energy Constant (has unit of velocity)

M – Mass of casing (the accelerated shell which is usually metal) [kg]

C - Mass of the explosive charge [kg]

The angle of fragments with cylindrical geometry can be calculated from the following equation (Taylor formula):

$$\alpha = \arcsin \left( \frac{V_o}{2V_D} \right) \quad (3)$$

Where:  $V_o$ - Initial Gurney velocity [m/s]

$V_D$ – Detonation velocity in explosive [m/s]

Gurney equations and Taylor formula are reasonably accurate for a large number of configurations. At the edges, due to free end effects Gurney loses its accuracy but a modified equation for edges calculation can be used for better results.

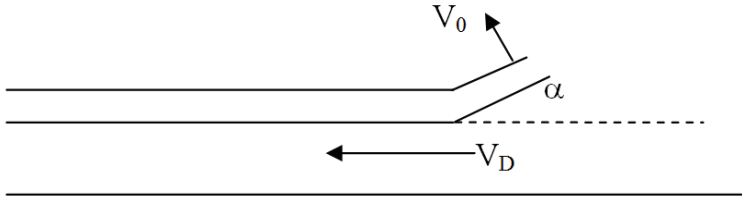


Figure 1: Taylor angle

Once we have the initial velocity and angle of fragments it is desirable to know the fragments masses distribution. This can be achieved using Mott Equation:

$$N(m) = \frac{M_0}{2M_k^2} e^{-\left(\frac{m^{1/2}}{M_k}\right)} \quad (4)$$

Where:  $N(m)$  – number of fragments with a greater mass of mass  $m$ .

$m_0$  – mass of casing.

$M_k$  – fragment distribution factor:

$$M_k = B \cdot t^{5/16} \cdot d^{1/3} \cdot \left(1 + \frac{t}{b}\right) \quad (5)$$

Where: B – Explosive constant

t – Average casing thickness

d – Average inside diameter of casing

For an explosive charge with well-defined fragments geometry such as those produced in a manufacturing process, a better model can be used for estimations of the initial angle of each fragment. This model, known as Shapiro equation can have varying radius of geometry. The angle of each fragment depends on the initiation point (D) Initial Gurney velocity ( $V_o$ ) and the detonation velocity ( $V_m$ ). The equation is a follow:

$$\tan \theta = (V_o/2V_m) \cos(\pi/2 + \phi_2 - \phi_1) \quad (6)$$

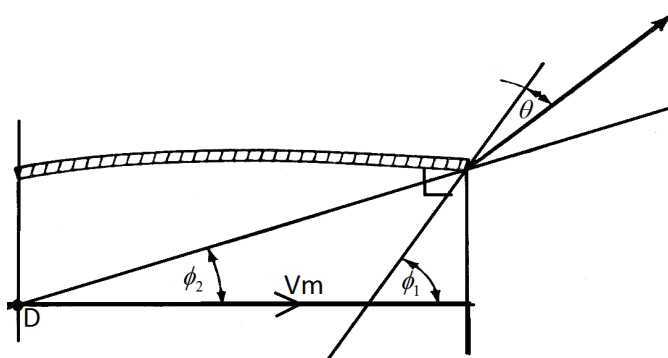


Figure 2: Shapiro angle

## 1.2 Flight Phase

After each fragment leaves the charge, it is governed by gravity (for long range flight). The fragment flight's path is deepened upon its velocity drag coefficient, height and additional parameters that changes with each moment and position

For short ranges when gravity can be ignored the following equation can be used for calculation the velocity and position of fragment. Only drag forces that slow it down is taken into account:

$$V_f = V_o e^{-\left(\frac{C_d \cdot S/m \cdot \rho \cdot R}{1.81}\right)} \quad S = 0.55 \cdot m^{2/3} \quad (7)$$

Where:

$V_f (V_o)$ – Final (initial) velocity [m/s]

$C_d$ – drag coefficient (for natural/irregular fragments is customary to use the value 0.7)

S – Normalized cross section (for natural/irregular fragments it can be substituted with value above).

m – fragment's mass [gr].

$\rho$  – Air density [gr/cm<sup>3</sup>]

R – distance away from detonation point [m]

For long ranges additional parameters should be taken into account such as:

- Changes in air density as a function of height
- Changes in drag coefficient which depends on Mach number and fragment type:  $C_d = f(M, fragment\_shape)$

The drag on fragment can be expressed:

$$F_{drag} = \frac{C_d \cdot s \cdot \rho}{1.81} V^2 \quad (8)$$

The governed equations can be obtained with a free both diagram and substitution of relevant parameters. For example, Y axis equation is:

Y axis:  $ma_y = -F_{dragY} - mg$

$$\begin{aligned} -F_{dragY} - mg = ma_y &\Rightarrow -\frac{C_d \cdot s \cdot \rho}{1.81} \cdot V^2 \cdot \sin \theta - mg = m \frac{dv_y}{dt} \Rightarrow \\ &-\frac{C_d \cdot s / m \cdot \rho}{1.81} \cdot V \cdot V_y - g = \frac{dv_y}{dt} \quad (9) \end{aligned}$$

The final equations are therefore: for irregular fragment:

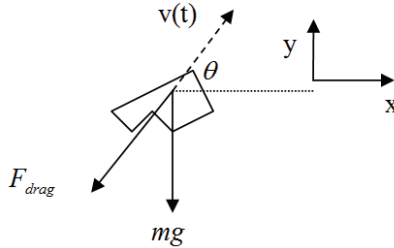


Figure 3: Free body diagram of a generic fragment

$$\dot{V}_y = -g - \frac{C_d \cdot \rho}{1.81} \cdot \sqrt{V_x^2 + V_y^2} \cdot V_y \cdot \frac{0.55}{m^{1/3}} \equiv f(t, V_x, V_y) \quad (10)$$

for specific fragments, as was mentioned  $s/m$  is evaluated as  $0.55 \cdot m^{2/3}$

In the same way, the equation for  $x$  axis is:

$$\dot{V}_x = -\frac{C_d \cdot \rho}{1.81} \cdot \sqrt{V_x^2 + V_y^2} \cdot V_x \cdot \frac{0.55}{m^{1/3}} \equiv g(t, V_x, V_y) \quad (11)$$

The air density changes with height:

$$\rho(h) = \frac{P(h) \cdot M}{R \cdot T(h)} = P_0 \cdot \left(1 + \frac{L \cdot h}{T_0}\right)^{-\frac{g \cdot M}{R \cdot L}} \quad (12)$$

Where:

$P_0 = 101325 [Pa]$  air pressure at sea level

$L = -0.0065 [K/m]$  (air temperature changes coefficient)

$h[m]$ — height

$T_0 = 288.15 [K]$  — Kelvin temperature

$g = 9.80665 [\frac{m}{sec^2}]$

$M = 0.0289644 [Kg/mol]$ - mole value of dry air.

The two differentialequations (10, 11) are solved using forth order numerical approximations (Runge-Kutta).

### 1.3 Impact Phase

At the impact phase, two safety issues are of concerned: impact of personal by fragments and/or impact and damaging/breaching of structural elements such as ship decks or any other structures Hazardous fragments for personal are those with kinetic energy of 70 Kj.

The equations for penetration of plates are given by Thor Equations:

$$V_r = V_s - 10^c e^\alpha \omega^{2\alpha/3+\beta} K_f^{-2\alpha/3} \left(\frac{1}{\cos(\theta)}\right)^\gamma V_s^\lambda \quad (13)$$

Where:

$V_s$  – impact velocity.

$V_r$ – residual velocity after impact. Positive values indicated penetration.

$W$  – fragment mass.

$c, \alpha, \beta, \gamma, \lambda$  — Constants taken from tables (not presented in this paper)

$K_f$ — shape factor:

$$K_f = \frac{w}{A_p^{3/2}} \quad (14)$$

$A_p$  is the presented area and depends upon the fragment type and geometry. For brevity those equations are omitted.

## 2 Program Presentation

Once key models were identified, the programming phase started. It was decided early on to use the .NET platform for its rapid application development and extensive user interface support.

Each model was program as a stand-alone module while the 3D visualizer incorporated all the modules to a single uniform application for the user. The end result was the 3D visualizer but each module has its own usefulness: Thor model is quite useful for plates penetrations estimation, the free flight of fragments, long or short ranges, can be used to evaluate the maximum distance fragments can reach and the distribution calculation module can estimated the density of fragments at a given radius away from the detonation point.

### 2.1 Gurney and Mott Implementations:

The Gurney and Mott modules are straightforward. The user input the geometric properties of the charge (available from updateable database or by manual input) and from Gurney's equation gets the angle and velocity after fragmentation.

Mott Module is using the data inputted in Gurney module. The user needs to specify the constant B which depends upon the explosive properties and is selected from the program database. The end result is a figure showing the fragments distributions.

### 2.2 Fragments Flights

Sometimes it is desirable to know the final distance a given fragment can reach and/or the fragments velocity at a specific location or the time it took to reach that position.

Two free flight modules were implemented: short range flight (equation7) that gives the final position and velocity in the position along the path. Figure X shows the module for shot ranges trajectories. The user can probe the figure to get the values at the desired location.

While the short ranges module has places where it is accurate enough, the long ranges module is more usable because it takes into account the effects of drag forces

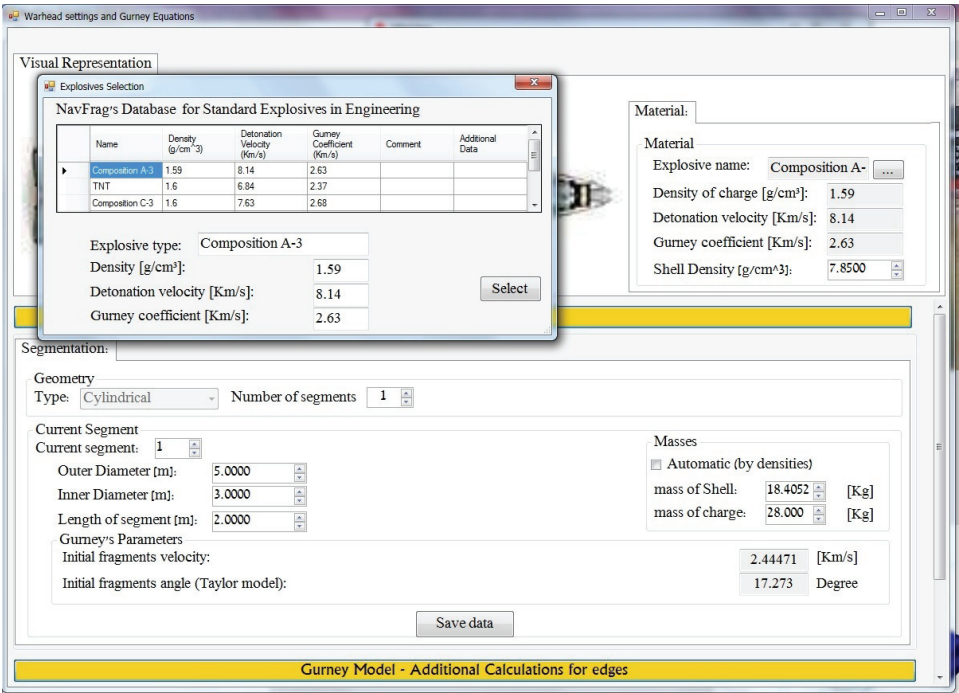


Figure 4: Gurney Input and Explosive/charge selection

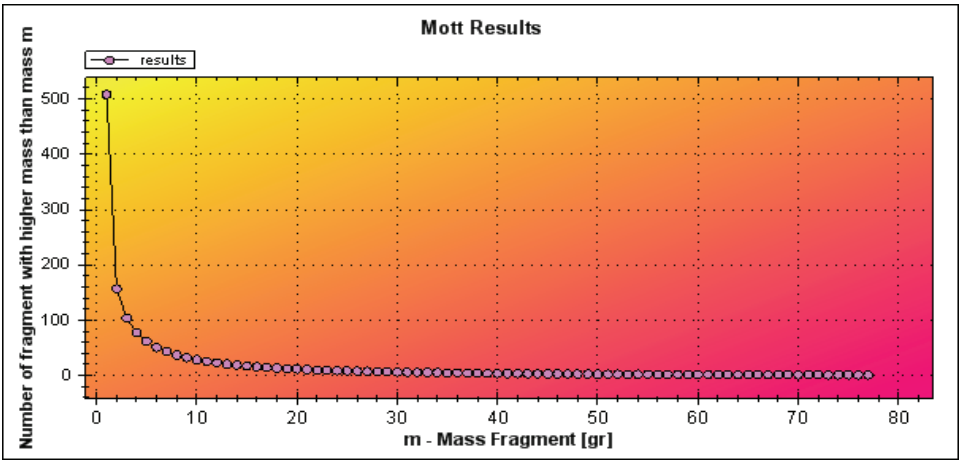


Figure 5: Mott Results



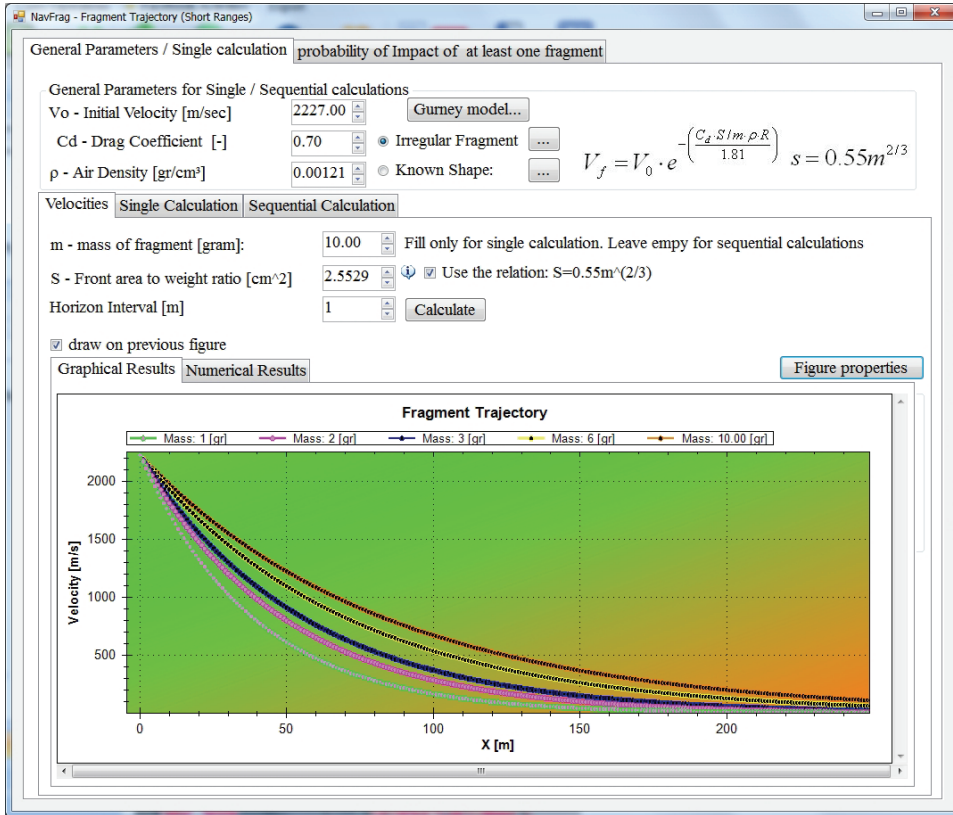


Figure 6: Short ranges trajectories module

and gravity. The results and equations agree well with independent calculations performed by RAFAEL which was used for validations. The long ranges module implements equations 10 and 11 and the 3D visualizer uses those equations for its spatial calculations. This module incorporates experimental data of drag coefficients as they change over time along with the velocity. The result also shows the kinetic energy and velocity at each calculated point along its path.

### 2.3 Thor Model

Once the velocity and mass of fragment at a given location is calculated (using the modules presented earlier) it is desirable to know if it has enough energy to perforate a plate at the given location. For this, the Thor equation is available for use. The user needs to enter the geometry properties of the fragment, its mass and velocity (or load from previous used modules), select or manually enter Thor coefficients

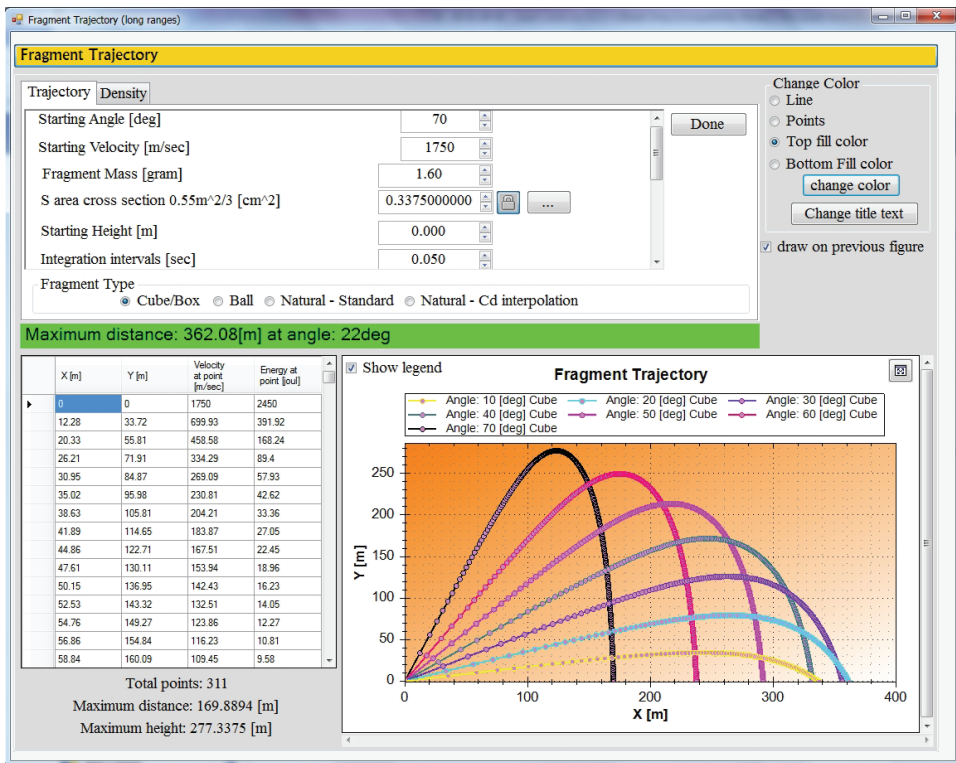


Figure 7: Long ranges trajectories module

and specify the plate's properties. A positive residual velocity indicates that the plate has been perforated. Additional equation calculates the residual mass after impact.

## 2.4 Safe/unsafe area of fired explosive module

Additional safety concern is the probability of premature initiation of explosive that is fired from a vessel toward a target. While fire explosives have safety mechanisms to prevent premature detonation there is still a chance of that occurrence, either by malfunctioning explosive or impact with obstacles. In order to evaluate minimum safety distances a module was developed that displays the unsafe area of explosive. In this module the user can select the type of vessel and specify the relevant properties of the explosive the user would like to evaluate.

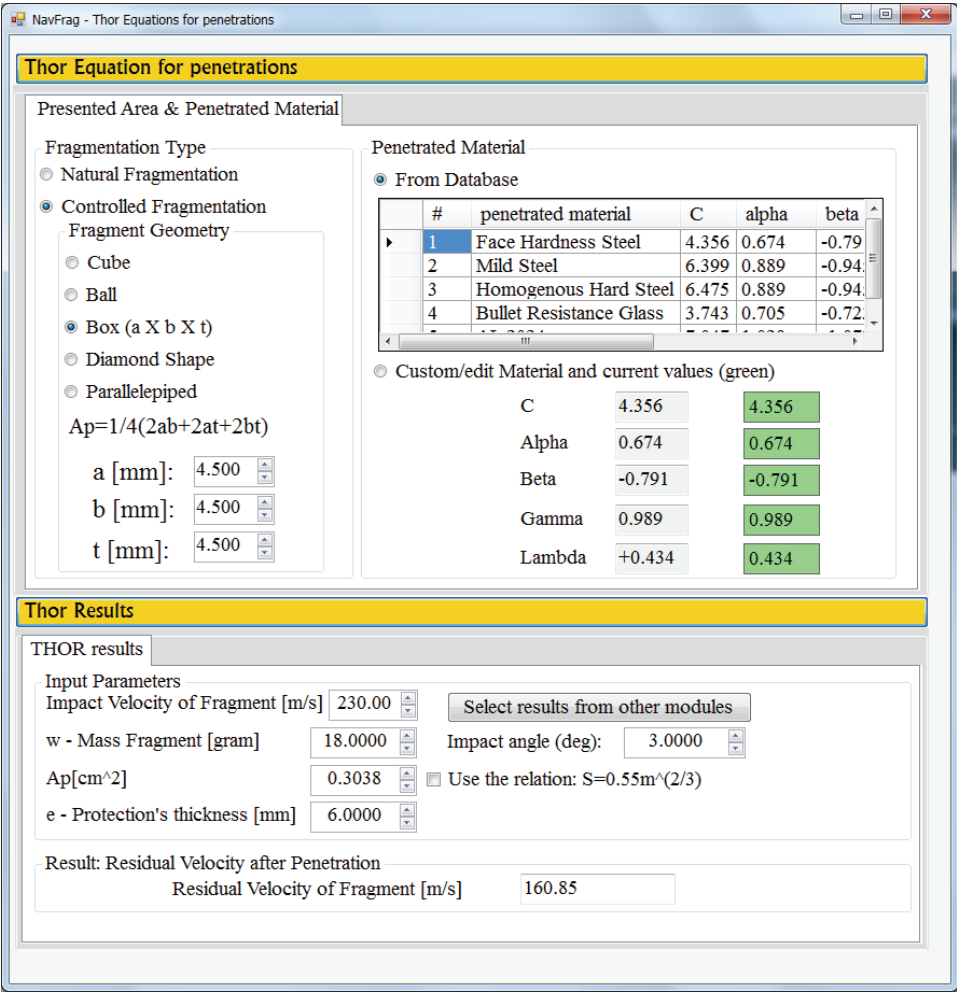


Figure 8: Thor module

### 2.5 Shapiro model

The input to Shapiro is a series of points along its length which represents the fragments at that location and their radiuses. The use can add plates by specifying their location and size to be added to the display. If a user decided to add plates s/he can view the impacted fragments per plate and indication by color (red/green) if each fragment penetrated the plate.

The following figures shows the side view with the angle vector already calculated and the densities calculated for a distance of 200 meters away from the explosive.

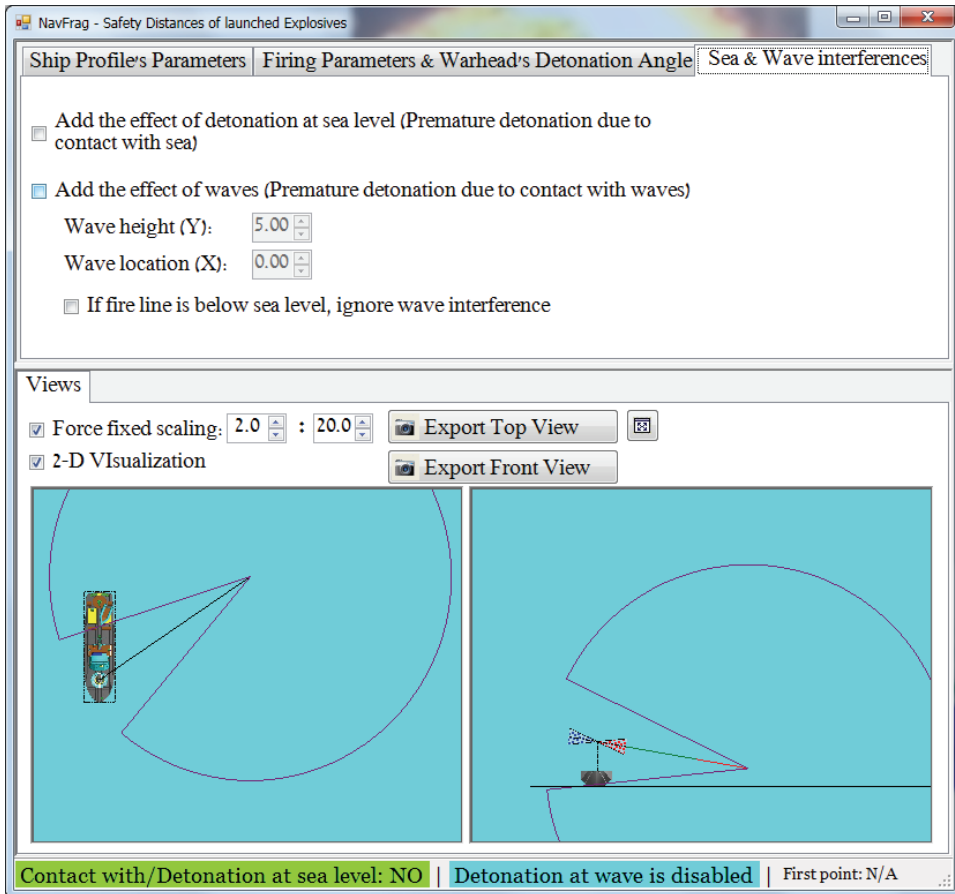


Figure 9: Safe/Unsafe Areas

## 2.6 3D Visualizer

The 3D visualizer is the module that combines all the other modules into a single application. With the use of the previous presented modules this module supports the following feature:

- Gravitation effects and Drag effects on each fragment
- Time-elapsd dispersal monitoring
- Calculations of plates penetrations by fragments
- Video Captures.

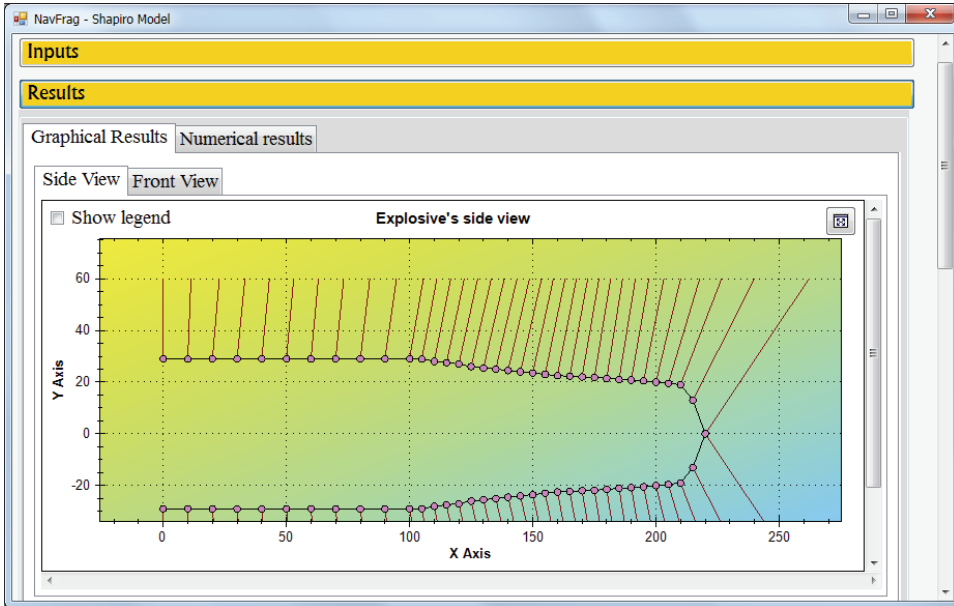


Figure 10: Shapiro model – explosive side view

With all the other modules incorporated into this, one can simulate a real-time explosion of explosives for defensive or offensive operations or for general estimations of explosives. A simulation of battle fields is not farfetched and there are advantages of using this module such as instant results as compare to Finite Elements simulations. The Following figures show some screenshots of this module. In order to keep the figure clean not all trajectories are shown.

The user has control over the display. S/he can add plates at specific location and get indication of penetrations by color coded trajectory path (red/green), get information for a specific point in space and as expected from 3D view, can control the display properties such as axes rotations, zooming and point of view.

### 3 Conclusion

As was shown in this paper, with a relative small effort one can create a tool which allows fast estimation of explosive dispersals, hazardous areas and general characteristics of explosives to be use for defensive or offensive calculations. The tool can be used for preliminary calculations which can save a lot of time and efforts. While the models presented here and the program itself forms adequate framework for the explosive engineering field, additional work should and could be done such

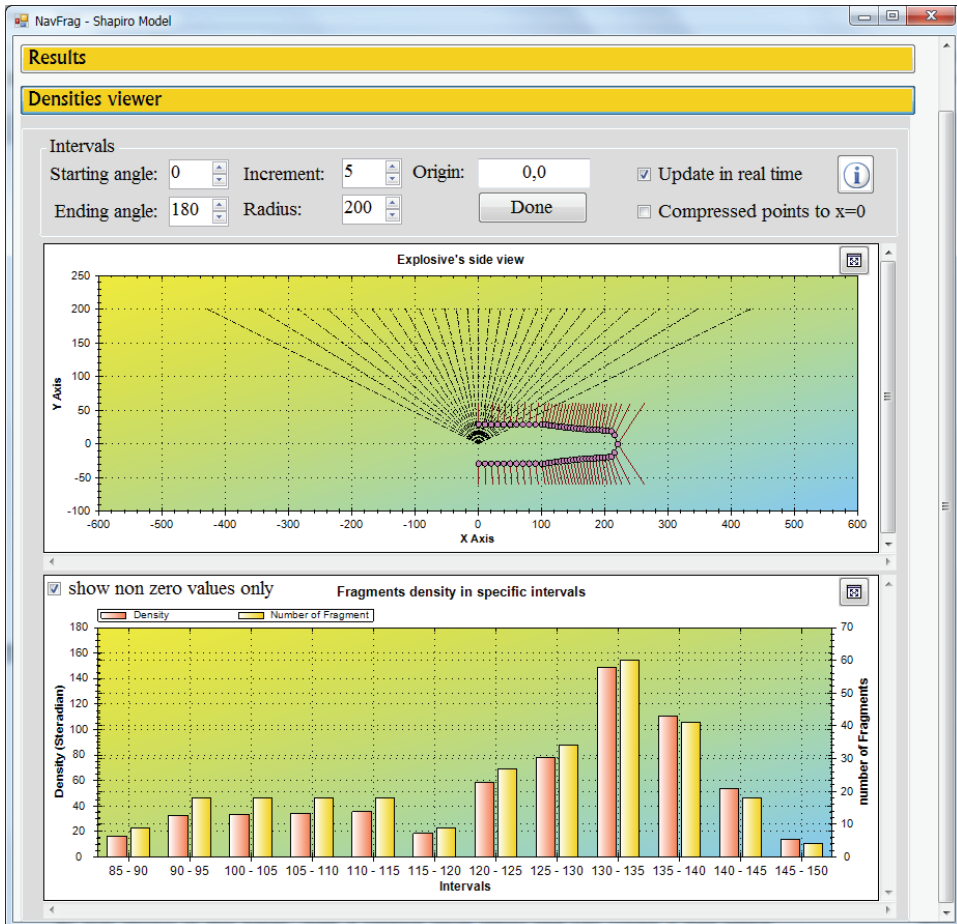


Figure 11: Shapiro model – densities and fragments distributions

as adding more models for different purposes (like additional models for fragment mass distributions such as Grady, Weibull or Held) and automating the creation of Finite Element models (and meshing) for use in commercial products

Some additional modules were not shown in this paper. Those modules automate some processes that are used in the explosive engineering field and expedite those procedures. With a close source product such additions could not have been made so a decision to develop in house product has many advantages.

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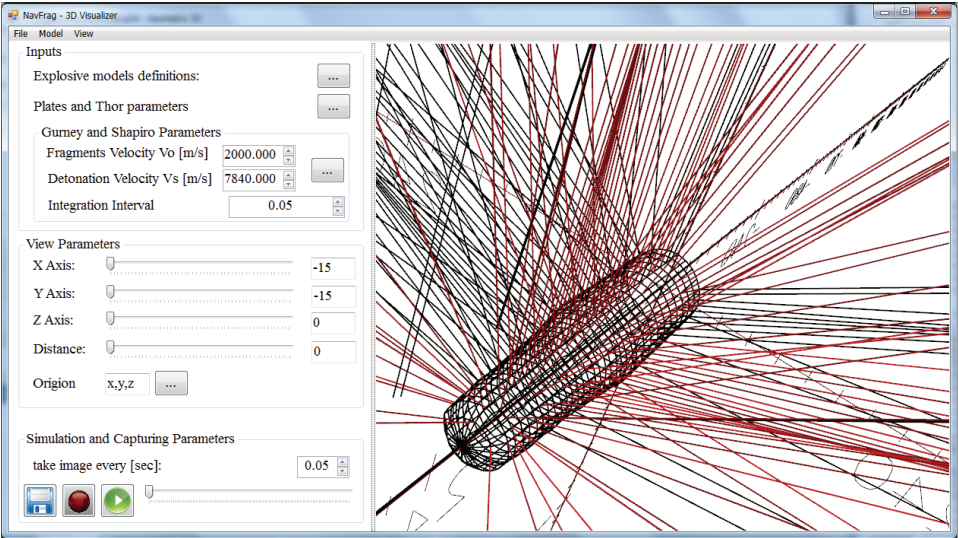


Figure 12: 3D Visualizer modules

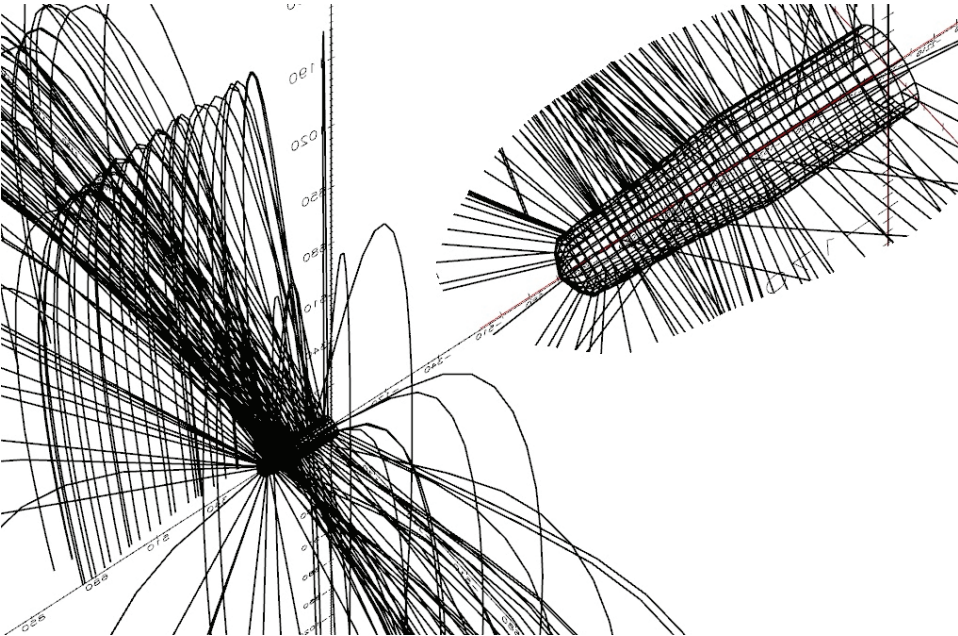


Figure 13: 3D Visualizer module with a zoom in of the explosive wireframe

program:

Commander Chaim Weitz, Head of gunnery and mining branch, naval architecture department, Israeli Navy.

Commander Oren Lotan, Head of explosive Engineering section, gunnery and mining branch, naval architecture department, Israeli Navy.

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