### NEOShield

A Global Approach to Near-Earth Object Impact Threat Mitigation

<table>
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<tr>
<th>Contract No.:</th>
<th>FP7-SPACE-2011-282703</th>
<th>Project start:</th>
<th>01. January 2012</th>
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<tr>
<td>Project Coordinator:</td>
<td>DLR</td>
<td>Project Duration:</td>
<td>41 Months</td>
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#### WR2 Deliverable 7.3

**D7.3 Assessment of blast deflection and other mitigation concepts**

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<th>WP Leader</th>
<th>Task Leader</th>
<th>TsNIImash</th>
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<td>Astrium-UK</td>
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- **Editor**: Sergey Meshcheryakov
- **Contributors**: TsNIImash: D-r Yu.M. Lipnitsky, D-r S.A. Meshcheryakov, S.I. Lezhnin

- **Verified by**: -
- **Version**: 32
- **Dissemination level**: PU

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<th>Deutsches Zentrum für Luft -und Raumfahrt (DLR)</th>
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<td>University of Surrey</td>
<td>Surrey</td>
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Title: D7.3 Assessment of blast deflection and other mitigation concepts

EU/FP7 Grant agreement No.: 282703

Document No.: NEOShield-7.3- Issue 1.1

Prepared by:
Yuri Lipnitsky, TsNIImash
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Distribution
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(Dissemination level PU= public)

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Objectives

Investigate in details the effectiveness of alternative mitigation concepts (in particular the blast-deflection approach) and provide a quantitative analysis of their usefulness/feasibility in realistic circumstances (most probable size, mineralogy, structure, etc. of hazardous NEO, prevention time prior to impact, probability of success, etc.) identify and address critical open issues.

The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement № 282703
## Change Record

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<td>1</td>
<td>**</td>
<td>All</td>
<td>First issue of complete document</td>
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<tr>
<td>2.0</td>
<td>17.10.2013</td>
<td></td>
<td>Sections “Physical properties” and “Alternative methods…” excluded</td>
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<tr>
<td>2.0</td>
<td>17.10.2013</td>
<td></td>
<td>Section 3.2.2 changed for the new text</td>
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<tr>
<td>2.0</td>
<td>17.10.2013</td>
<td></td>
<td>Accordingly the text in the Summary is changed</td>
</tr>
<tr>
<td>2.0</td>
<td>17.10.2013</td>
<td></td>
<td>The detailed description of the method of calculation of a disturbed asteroid motion is included</td>
</tr>
<tr>
<td>2.0</td>
<td>17.10.2013</td>
<td></td>
<td>Formula for impact parameter $\chi \equiv b_1 \equiv d_{\text{min}}$ dependency</td>
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**Version 1.0**

$$\chi = \Delta v \cdot t_0 \cdot \left( \frac{3}{2} - 2 \frac{\sin \beta}{\beta} \right) \cdot \sqrt{2(1 + \cos \phi)}$$

where $t_0 = \frac{r_0 \beta}{v_0} = T \cdot \frac{\beta}{2\pi}$ is a warning time,

$\beta$ is a warning angle,

**Versions 2.0**

Calculation of a minimal orbital distance (impact parameter)

$$d_{\text{min}} \approx \frac{2}{\pi} \Delta v \cdot t_0 \cdot \sqrt{\frac{1}{2} (1 + \cos i) (3\pi - 2 \frac{T}{t_0} \sin(2\pi \cdot \frac{t_0}{T}))^2 + \frac{T^2}{t_0^2} (1 - \cos i)^2}$$

Here $\phi \equiv i$ is the inclination of an asteroid orbit.

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<td>2.0</td>
<td>17.10.2013</td>
<td>Accordingly the previous item the Fig 2.3, Fig 2.4 and Fig 2.6 have all been updated in the versions 2.0 and 2.1</td>
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<tr>
<td>17.10.2013</td>
<td>42</td>
<td>Formula $I_{\text{buriedN}} \approx 4592 \cdot W^{7/6} \cdot G_{\text{buriedN}}(\bar{h})$, and the table for $G_{\text{buriedN}}(\bar{h})$ included</td>
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<td>Formula</td>
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<td></td>
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<td>[ I_{\text{buriedTNT}} \approx 4592 \cdot \frac{W}{6} \cdot G_{\text{buriedTNT}}(\tilde{h}) ].</td>
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<td></td>
<td></td>
<td>and the table for ( G_{\text{buriedTNT}}(\tilde{h}) ) included.</td>
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<td>3.0</td>
<td>15.04.2014</td>
<td>Assessors’ query 1:</td>
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<td></td>
<td></td>
<td>Introduction - changed</td>
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<td></td>
<td></td>
<td>3.1.4 On the neutron effects of a nuclear explosion - added</td>
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<tr>
<td></td>
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<td>3.4 Analysis for asteroid fragmentation at impulsive action – added</td>
</tr>
<tr>
<td></td>
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<td>4 Summary – changed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 References – changed</td>
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<td>3.1</td>
<td>28.04.2014</td>
<td>Assessors’ query 2</td>
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<tr>
<td></td>
<td></td>
<td>“According to the afore said ideas, here are two conceptions of the protection of Earth. In the first one the main attention is paid to deflection of hazardous bodies without their essential destruction if the prevention time allows. It can be made using small nuclear charges. The area of applications is asteroid hazard mitigation. There are many unknown NEA and at the most probable case a hazardous asteroid will be detected in the “flow” of new discoveries. Evidently such asteroid shall have small sizes and a kiloton explosion will enough for its deflection. Probably the explosion could be made even at some distance of the asteroid surface and the asteroid will be deflected without fragmentation. The sections 2 and 4.1 are devoted to this idea. In the section 4.3 the use of chemical charges (TNT) is considered as a hypothetic variant. The second conception is devoted to deflection of larger hazardous bodies in the case of very late prevention. There are needed very powerful charges which destroy the hazardous body to some extent. The probable area of application may be defined as deflection of comets. The comets come up from the outer region of the Solar System, usually have larger sizes and high relative velocities. The prevention time could be very short. Counteraction to a hazardous comet will demand power thermonuclear charges. At such action the considerable part of a comet will be destroyed and taken off, in principle, the total disintegration of the hazardous body could be imagined. The second conception can be important also for asteroid deflection in the extremely short prevention time. The estimation of thermonuclear charges needed in these cases is considered in the section 4.2. As alternative method in the section 5 a sublimation method of deflection of hazardous comets is proposed. The technique is to provoke comet activity.”</td>
</tr>
<tr>
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<td>changed for</td>
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<tr>
<td></td>
<td></td>
<td>To estimate results of stand-off nuclear bursts we need to solve the transport problem for x-rays (chapter 3.1.1) and thermodynamics of</td>
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sublimation (chapter 3.1.2). There is no other way. And we gave the results to have possibilities for discussion. The estimations of deepened explosions are made more accurately using an interpretation of known experimental data on powerful industrial bursts.

It is believable that the buried option doesn’t need a landing and drilling system.

So we think that any reasonable comparison doesn’t prevent our estimations.

3.1 28.04.2014 22 Assessors’ query 3:
Calculation of a minimal orbital distance (impact parameter)

![Diagram](image1)

Fig. 2.1.4 Scheme of crossing the ecliptic plane by an asteroid.

_changed for_

Calculation of an impact parameter.

![Diagram](image2)

Fig. 2.1.4 a) Scheme of crossing the ecliptic plane by an asteroid.
b) Scheme of the close approach in the coordinate frame anchored to the Earth, $b_1$ is an impact parameter.

3.1 28.04.2014 22 Assessors’ query 4:
“For example, about 2/3 of space bodies impacting Earth have a comet origin.”

This text deleted

3.1 28.04.2014 24 Assessors’ query 5:
“Note that $d_{\text{min}} \equiv b_1$.”

This text additionally included

3.1 28.04.2014 25 Assessors’ query 6:
“- Increase in the pericenter of the asteroid’s orbit.”
_changed for_

“- Increase in the perigee of the asteroid’s orbit.”

3.1 28.04.2014 25 Assessors’ query 7:
“to increase its pericenter up to \( r' \)"
changed for
“to increase its perigee up to \( r' \)”

3.1 28.04.2014 25 Assessors’ query 8:
“then needed additional velocity is \( \Delta v \equiv 0.046 \text{ m/sec} \)
changed for
“then needed additional velocity is \( \Delta v \equiv 0.12 \text{ m/sec} \)”

3.1 28.04.2014 26 Assessors’ query 9:
“pericenter at the Earth’s radius (so the asteroid will only grazed the
pass a diameter above the Earth).”
changed for
“perigee through the Earth’s radius (so the asteroid will only graze
the Earth).”

3.1 28.04.2014 26 Assessors’ query 10:
“Fig. 2.4. The prevention time dependences of needed additional velocity for
deflection through 3 Earth’s radii. “
changed for
“Fig. 2.4. The prevention time dependences of needed additional velocity to
increase the asteroid’s perigee through the Earth’s radius.”

3.1 28.04.2014 26 Assessors’ query 11:
“where \( \Delta \eta \) is the needed variation of pericenter.”
changed for
“where \( \Delta \eta \) is the needed variation of the asteroid’s perigee.”

3.1 28.04.2014 27 Assessors’ query 12:
“Fig. 2.7. Orbital deflection. The prevention time dependences of needed
additional velocity for deflection the orbit of asteroid through the radius of Earth”
changed for
“Fig. 2.7. Orbital deflection. The prevention time dependences of needed
additional velocity to increase the MOID between the asteroid and Earth through
the radius of Earth.”

3.1 28.04.2014 27 Assessors’ query 13:
“- Deflection of asteroid’s orbit through the radius of Earth.”
changed for
“- Deflection of asteroid’s orbit through the radius of Earth
(change of the MOID). “

3.1 28.04.2014 31 Assessors’ query 14:
The transport problem for X-rays is solved in the quasi-one-dimensional approach, i.e. the one dimensional problems are solved independently for each point of exposed surface of an asteroid. (Fig. 3.1.1.2).
changed for
The transport problem for X-rays is solved in the quasi-one-dimensional approach, i.e. the one dimensional problems are solved independently for each point of exposed surface of an asteroid. (Fig. 3.1.1.2). It is obvious that 1D solution doesn’t limit the accuracy.
### Assessors’ query 15:

The radius of asteroid is $R = 75$ m, the power of explosion is 10 kt. The effective temperature of the emitting fireball is $T_{\text{rad}} = 2.6$ keV.

1. XI-2012 version.
2. XI-2013 version (there were made technical changes).

![Graph](image1)

**Fig. 3.1.3.3.** Momentum versus altitude above the surface of an asteroid. The radius of asteroid is $R = 75$ m, the power of explosion is 10 kt. The effective temperature of the emitting fireball is $T_{\text{rad}} = 2.6$ keV.

### Assessors’ query 16:

Table 3.1.3.1. Altitude dependence of momenta, N·sec, for nuclear explosion of power of 10 and 100 kt above a 150 m asteroid (the XI-2013 code system).

*changed for*

Table 3.1.3.1. Altitude dependence of momenta, N·sec, for nuclear explosion of power of 10 and 100 kt above a 150 m asteroid.

![Graph](image2)

**Fig. 3.1.3.3.** Momentum versus altitude above the surface of an asteroid. The radius of asteroid is $R = 75$ m, the power of explosion is 10 kt. The effective temperature of the emitting fireball is $T_{\text{rad}} = 2.6$ keV.

### Assessors’ query 17:

The method is based on estimations of momenta of shattered soil ejected from craters. The momenta of “boiler kettle” gases can be neglected. 

*changed for*

The method is based on estimations of momenta of shattered soil ejected from craters while the momenta carried by vaporized matter is neglected. It is a direct interpretation of available experimental data. At the blast’s location a vapor cloud is created. The size of the cloud is determined by X-rays’ transport processes and partly by convections. This vaporized matter is called as a “boiler kettle gases” or “boiler gases”. (Adushkin V.V. and Spivak A.A.)

Expanding boiler gases drain through the soil. They are pushing and entraining the soil. The mass of the gases much smaller than the mass of the soil. We are estimating the momentum given to the soil by the gases assuming that the own momentum of the gases is small. Of course, such assumption is wrong if the explosion is made near the Earth’s surface. But it is enough good approach even for small depth. It can be seen from the physical ideas and it is confirmed by comparisons with known numerical results. We would say rather that it was wonderful that they had calculated so exactly because we have direct experimental results.

We easily use our results for asteroids because the gravitation doesn’t play a role in the initial phase of the buried nuclear explosion.

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<td>query 18:</td>
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<td>for the part of the excavated matter that falls back into a crater. changed for for the part of the excavated matter that falls back into a crater. Debris falling back into the crater at the Earth will be thrown out of the crater at an asteroid and we should consider their input to the reactive pulse. There is a problem to determine the initial crater’s depth $D$. We assume that it equals to the depth of the charge location.</td>
<td></td>
</tr>
<tr>
<td>28.04.2014</td>
<td>query 19:</td>
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<td></td>
<td>Blue rectangles show the regions where the accuracy of the formulas is something reduced because additional momentum of “boiler kettle” gases which is neglected. changed for Blue rectangles show the regions where the accuracy of the formulas is something reduced because additional momentum of vaporized matter is neglected.</td>
<td></td>
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<tr>
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<td>neglecting the momenta of “boiler kettle” gases. changed for neglecting the momenta of vaporized matter.</td>
<td></td>
</tr>
<tr>
<td>28.04.2014</td>
<td>query 21:</td>
<td>56</td>
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<tr>
<td></td>
<td>it doesn’t account the momenta of “boiler kettle” gases. changed for it doesn’t account the momenta of vaporized matter.</td>
<td></td>
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|            | In our opinion, it is necessary to accumulate the results obtained by the Consortium in form of a data base, which combines data on NEO, possible means of counteraction, and computation tools; that is it is required to develop a system analogous to ones developed on
the problem concerned with “space debris”: “Master” or “ORDEM”. It will be more comfortable for the project participants to make estimations using codes.

In our opinion, it is necessary to accumulate the results obtained by the Consortium in form of a data base, which combines data on NEO, possible means of counteraction, and computation tools.
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Glossary

Designations in 2.1

\( v_0 \) orbital velocity of asteroid
\( \Delta v \) Additional asteroid velocity after impact
\( \beta \) prevention phase angle
\( t_0 \) prevention time
\( n \) prevention time in revolutions
\( T \) orbital period of an asteroid
\( \chi \) impact or sighting parameter
\( \phi \) inclination of the asteroid orbit
\( r_1 \) pericenter of the primary asteroid orbit (perihelion or perigee depending on a considered gravitational center)
\( r_1' \) pericenter of the secondary asteroid orbit
\( R_E \) radius of the Earth

\[ \bar{R}_E = R_E \cdot \frac{v_0^2}{\mu} \] dimensionless radius of the Earth

\( v_\infty \) relative asteroid speed when it enters the gravitational field of the Earth
\( \Delta \eta_1 \) needed change of a pericenter

\[ \Delta \chi = \Delta \eta_1 \] needed change of an impact parameter.

Designations in 3.1.1

\( \bar{\rho}(\varepsilon, T) \) density of a spectral distribution of fireball radiation

\[ \bar{\rho}(\varepsilon, T) = \frac{4}{\pi^2 T^4} \cdot \frac{\varepsilon^3}{e^{\varepsilon/T} - 1} \] for Plank spectra

\( \varepsilon \) primary energy of quantum,

\( \varepsilon' \) energy of quantum after Compton scattering,

\( \theta \) angle of Compton scattering, angle of incidence

\[ \frac{d\sigma}{d\Omega} \] differential section of Compton scattering,

\( T \) temperature in the energy units

\( m_e c^2 \) energy of an electron in rest

\( \alpha \) central angle of a surface point

\( R_a \) asteroid’s radius

\( h_1 \) altitude of explosion above the surface of asteroid

\( d_2 \) distance from the center of explosion to the surface of asteroid

\( d_{heat} \) heated mass depth, g/cm²

\( m \) mass coordinate, g/cm²
Qₙ specific energy release, J/g

**Designations in 3.1.2**

- $p$: pressure
- $T$: temperature, K
- $V$: volume of one mole
- $V₀$: initial value of the mole volume
- $R$: universal gas constant
- $a, b$: parameters of the Redlich-Kwong equation
- $U_{RK}$: internal energy of an Redlich-Kwong substance
- $H_{RK}$: enthalpy of an Redlich-Kwong substance
- $Φ_{RK}$: Gibbs’ potential of an Redlich-Kwong substance
- $F_{RK}$: free energy of an Redlich-Kwong substance
- $S$: entropy
- $p_c, V_c, T_c$: critical parameters
- $ρ₀$: Initial density
- $c_v$: mole heat capacity
- $μ_1, μ_2$ and $μ_3$: chemical potentials of $\text{Mg}_2\text{SiO}_4(l)$, $\text{MgO}(v)$, and $\text{SiO}_2(v)$.
- $η$: effectiveness of released energy (the ratio of a work to released energy)
- $Q$: specific released energy, J/mole

**Designations in 3.1.3**

- $i$: specific momentum, N·sec/m²
- $I$: total momentum, N·sec/m²
- $α$: central angle
- $h$: Altitude of explosion above the asteroid surface

**Designations in 3.2.1 и 3.3**

- $v_e$: averaged velocity of ejecta, m/sec
- $g$: gravitational acceleration near the Earth’s surface, m/sec²
- $h$: depth of a crater, m
- $D$: depth of an explosion, m
- $k_r, k_{apr}$: fitting coefficients
- $W$: explosion power (in kilotons for nuclear and in tons for chemical
- $R$: crater radius
- $I$: total moments, N·sec
- $ρ_I$: density of the soil through industrial nuclear explosions
- $k_ρ$: ratio of the asteroid density to the density of the soil through industrial nuclear explosions
- $V$: Increase in asteroid velocity, km/sec
- $R_a$: radius of an asteroid, m

**Designations in 3.4**
\( \alpha \)  Central angle for an asteroid surface point  
\( R_a \)  Radius of the asteroid  
\( h_E \)  Altitude of an explosion above the asteroid’s surface  
\( e \)  Coefficient of porosity of the asteroid matter (soil)  
\( \rho \)  Density  
\( \rho_0 \)  Density of grains  
\( w_a \)  Sound speed (the speed of a small signal)  
\( p \)  Pressure  
\( p_a, p_c \)  Material constants for regions \( a \) and \( b \)  
\( k \)  Deformation constant  
\( \alpha_r = 0.3 \)  Coefficient of porosity restitution after relief  
\( \sigma^+, \sigma^- \)  Compression and tensile strength strengths.

**Indices**

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<td>f</td>
<td>final</td>
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<td>Earth</td>
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<tr>
<td>l</td>
<td>ejecta</td>
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**Abbreviations and terms**

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<tr>
<td>NEO</td>
<td>near-Earth object</td>
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<tr>
<td>prevention time</td>
<td>time it takes for the asteroid to move from the nuclear impact to the Earth</td>
</tr>
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<td>kt</td>
<td>kilotons</td>
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<tr>
<td>Mt</td>
<td>megatons</td>
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<tr>
<td>n.e.</td>
<td>Nuclear explosion</td>
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<td>TNT</td>
<td>trinitrotoluene</td>
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<tr>
<td>a.u.</td>
<td>astronomical unit</td>
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<tr>
<td>SW</td>
<td>Shock wave</td>
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<td>KNT</td>
<td>Klein-Nishina-Tamm</td>
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1 Introduction

The report devoted to analysis of several interrelated tasks solving the problem of using nuclear or chemical blasts for deflection of dangerous asteroids. The needed values of velocities are estimated for different scenarios. Then there were analyzed mechanical impulses transmitted to an asteroid by a nuclear or chemical explosion. By this way there were developed numerical codes for calculation of thermodynamic characteristics of silicates, for solution of the transport problem of Roentgen radiation and for estimation of the momenta from stand-off nuclear explosions. Then the new interpretation of results of industrial explosions was proposed that allowed to estimate the momenta due to nuclear and chemical blasts.

To estimate results of stand-off nuclear bursts we need to solve the transport problem for x-rays (chapter 3.1.1) and thermodynamics of sublimation (chapter 3.1.2). There is no other way. And we gave the results to have possibilities for discussion. The estimations of deepened explosions are made more accurately using an interpretation of known experimental data on powerful industrial bursts.

It is believable that the buried option doesn’t need a landing and drilling system. So we think that any reasonable comparison doesn’t prevent our estimations.

The presented numerical estimations completely support the works on the demo mission for blast deflection of an asteroid.

There were made many simplifications and there are many prospects for our advance. But firstly, we need experimental investigations of properties of asteroid matter analogues and analysis of flows of supercritical vapour-liquid mixtures. It should be noted that realization of the demo mission with a nuclear explosion will be the next important step in solution of the problem, they would allow to check some integral estimations, but the better thing would be detail experimental investigations in vitro. The exploration of extremal states of matters is a hard but fruitful direction to work. Then there are many questions for investigation of asteroid matters in situ. The experimental possibilities of TSNIIImash are limited and we wait for appropriate proposals from our partners.

The were done severe comments from the consortium (files Deliverables.doc, 282703_Consolidated_Review_Report100040463_20131114_162712_CET.pdf, and recommendations.pdf attached to the report). They are shortly as following.

bad English and necessity of additions containing the follow things:
1. Detail description of simplifications and estimation of according errors (influence of neutrons and simplification of interaction of radiation and asteroid matters, vaporization of asteroid matters).
2. There were digestions on analysis of influence of neutrons and unwanted fragmentation of an asteroid due to nuclear explosions near it.
3. The commentators didn’t find implications of results.

Several comments are not clear. For example, there were statements that our physical modeling is incorrect but it is unclear what is our error. We suppose that our results are ratable but they are enough for scientific technological support of the demo mission on blast deflection.

We suppose that the most actual is the comment on unwanted asteroid fragmentation. This problem should be resolved in the any case of impact. And it is very important from the physical side. So the attention was paid to this problem.

Our results on the account of the influence of neutrons are also given in a special section.
2 Ballistic analysis of deflection of hazardous asteroids

This section is devoted to preliminary estimation of character values of force impulses which needed for deflection of asteroids. There is used an approach of local Kepler’s orbits (farther named as adjoined Kepler orbits). Thus far away of the Earth an asteroid moves around the Sun in an elliptical orbit, but in the nearest vicinity of Earth this asteroid moves around the Earth along hyperbolic orbit. It is a primary crude but useful approximation to answer our questions about comparative effectiveness of blast deflection in different scenarios.

More accurate calculations for a selected orbit will be done in deliverable 8.4

Motion around the Sun

![Diagram showing asteroid and Earth in orbital paths](image)

Fig. 2.1.1 An orbital closing problem. The asteroid and the Earth are initially moving in crossing circular orbits.
Momentum given to an asteroid is directed opposite its velocity. Changes in the asteroid’s orbit.

![Diagram of asteroid orbit deflection](image)

The given momentum decelerates the asteroid and its orbit becomes slightly elliptical with the aphelion in the point of impact.

Equations for the disturbed motion.

Energy equation

\[ v_1^2 - \frac{2\mu}{r_1} = v_2^2 - \frac{2\mu}{r_2} \]

Momentum equation

\[ v_1 \eta_1 = v_2 \eta_2 \]
\[ v_2 = v_0 - \Delta v \]

Here \( v_1 \) and \( r_1 \) are velocity and radius of the asteroid in perihelion. \( v_2 \) and \( r_2 \) are velocity and radius in aphelion, \( v_0 \) and \( r_0 \) are velocity and radius correspondent to the initial orbit, \( \Delta v \) is a given decrease in velocity.

From these equations we can explicitly draw the equations for the parameters of disturbed orbit.

\[ e \approx 2 \frac{\Delta v}{v_0} \] is an eccentricity,
\[ p \approx r_0 (1 - 2 \frac{\Delta v}{v_0}) \] is a latus rectum,
\[ \eta \approx r_0 (1 - 4 \frac{\Delta v}{v_0}) \quad r_2 = r_0 \]
Parameters of elliptic plane crossing.

The initial and disturbed orbits are complanar ones. It makes calculations easier.\[ \Delta r \approx r_0 \cdot e \cdot (1 - \cos \beta) \] is a displacement of the point of intersection.

Here \( \beta \) is a phase angle between the point of impact on the asteroid and the point of “meeting” of the asteroid and Earth, \[ t_0 = \frac{r_0 \beta}{v_0} \] is a prevention time.

So \[ \Delta r \approx 2 \cdot \frac{\Delta v}{v_0} \cdot r_0 \cdot (1 - \cos \beta). \]

Of course, there is a periodical variation of \( \Delta r \) versus the prevention time.

The time of motion of the asteroid to the ecliptic plane is

\[
t = \frac{p^{\frac{3}{2}}}{\sqrt{\mu}} \int_{\pi}^{\pi + \beta} \frac{d\beta}{(1 + e \cos \beta)^2}.
\]

and \[ t \approx \frac{p^{\frac{3}{2}}}{\sqrt{\mu}} (\beta + 2e \sin \beta) \] and

\[
\Delta t \approx -e \cdot T \cdot \left( \frac{3}{2} \frac{t_0}{T} - \frac{\sin(2\pi \cdot \frac{t_0}{T})}{\pi} \right) \text{ is a time lag.}
\]

Here \( T = 2\pi \cdot \frac{t_0}{\beta} \) is an orbital period.
Table 2.1.1. Comparison of the terms in the expression of the time lag.

<table>
<thead>
<tr>
<th>$t_0/T$</th>
<th>$3t_0/2T$</th>
<th>$\sin(2\pi \cdot \frac{t_0}{T})/\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.15</td>
<td>0.187</td>
</tr>
<tr>
<td>0.15</td>
<td>0.225</td>
<td>0.2575</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3</td>
<td>0.3027</td>
</tr>
<tr>
<td>0.203</td>
<td>0.3045</td>
<td>0.3045</td>
</tr>
<tr>
<td>0.21</td>
<td>0.315</td>
<td>0.3083</td>
</tr>
<tr>
<td>0.22</td>
<td>0.33</td>
<td>0.3126</td>
</tr>
<tr>
<td>0.25</td>
<td>0.375</td>
<td>0.318</td>
</tr>
</tbody>
</table>

In the linear approximation we have the following effect (Table 2.1.1.).
If the prevention time $t_0$ is less than 0.203, i.e. the phase angle is less than 73.1°, then the pulse deceleration of the asteroid leads to a real lag, but in the opposite case for greater prevention time intervals we have a lead.
This effect can essentially affect our possibilities to deflect an asteroid in the case of late prevention.

**Calculation of an impact parameter.**

In the nearest region of collision point the motion of the Earth is described by the following equations

$x_E = v_0t$

$y_E = 0$

$z_E = 0$

There are two components of the asteroid velocity in the orbital plane.
\[ v_r = -e \sin \beta \sqrt{\frac{\mu}{p}} \]
\[ v_\theta = (1 - e \cos \beta) \sqrt{\frac{\mu}{p}} \]

So this implies
\[ v_y = e \sin \beta \sqrt{\frac{\mu}{p}} \]
\[ v_x = (1 - e \cos \beta) \cdot \cos i \cdot \sqrt{\frac{\mu}{p}} \]
\[ v_z = -(1 - e \cos \beta) \cdot \sin i \cdot \sqrt{\frac{\mu}{p}} \]

or
\[ v_y \cong e \sin \beta \cdot v_0 \]
\[ v_x \cong (1 - e \cos \beta) \cdot \cos i \cdot v_0 \]
\[ v_z \cong -(1 - e \cos \beta) \cdot \sin i \cdot v_0 \]

where \( i \equiv \phi \) is an inclination of the asteroid’s orbit.

So the equation of motion of the asteroid in the vicinity of the Earth is
\[ \Delta x = v_x \cdot (t - \Delta t) \]
\[ \Delta y = -\Delta r + v_y \cdot (t - \Delta t) \]
\[ \Delta z = v_z \cdot (t - \Delta t) \]

Note that the term with \( \Delta r \) is of the second order value and can be omitted here.

The square of the distance between the asteroid and Earth is
\[ d^2 = (x_a - x_E)^2 + (y_a - y_E)^2 + (z_a - z_E)^2. \]

The equation for time \( t_m \) appropriated to the minimal distance between the asteroid and Earth is
\[ [v_x \cdot (t_m - \Delta t) - v_0 t_m] \cdot (v_x - v_0) + [-\Delta r + v_y \cdot (t_m - \Delta t)] \cdot v_y + [v_z \cdot (t_m - \Delta t)] \cdot v_z = 0 \]

So
\[ t_m = \frac{[(v_x - v_0) \cdot v_x + v_y^2 + v_z^2] \cdot \Delta t + \Delta r \cdot v_y}{(v_x - v_0)^2 + v_y^2 + v_z^2}, \]
and
\[ t_m = \frac{1}{2} \cdot \Delta t = -e \cdot \frac{T}{2} \cdot \left( 3 \cdot \frac{t_0}{T} - \frac{\sin(2\pi \cdot \frac{t_0}{T})}{\pi} \right) \]

The minimal distance is
Gravitational focusing by the Earth

The above obtained expression for minimal distance in an orbital closing problem can be used as an impact parameter \( \chi \) or \( b_1 \) in a collision problem. \( \chi \equiv b_1 \equiv d_{\text{min}} \) is a minimal distance in an orbital closing problem.

The asteroid enters into the gravitational field of the Earth. So it moves in an about hyperbolic trajectory. \( r_1 \) is a “perigee” here.

To solve the problem we cast dimensionless parameters

\[
\tilde{r} = \frac{v_0^2 r}{\mu}, \quad \tilde{\chi} = \frac{v_0^2 \chi}{\mu}, \quad -\infty < \chi < \infty, \quad \tilde{b}_2 = \frac{v_0^2 b_2}{\mu}
\]

\[
\tilde{v} = \frac{v}{v_0}, \quad \tilde{T} = \frac{v_0^3}{\mu} \cdot \tilde{t},
\]

\( v_0 \) is a velocity at “infinity”.

The equation of the hyperbola is

\[
\tilde{r} = \frac{\tilde{\chi}^2}{1 - \cos \theta + \sin \theta \cdot \tilde{\chi}}.
\]

Then

\[
\tilde{b}_2 = \frac{\tilde{\chi}^2}{1 + \tilde{\chi}}
\]

is a nondimensional distance in a b-plane after gravitational focusing.
\( \hat{\eta} = \frac{\hat{\chi}^2}{1 + \sqrt{1 + \hat{\chi}^2}} \) is the minimal distance between the asteroid and Earth (a “perigee”),

An inverse expression can be also useful.

\( \hat{\chi}^2 = (2 + \hat{\eta}) \cdot \hat{\eta} \)

where \( \beta = 2\pi \cdot n \), \( t_0 = T \cdot n \),

\( T \) is an orbital period.

Let consider the following scenarios of the asteroid deflection.

- **Regional deflection** when the asteroid is avoided from a large city (Fig. 2.2).

![Fig. 2.2. A scheme of regional deflection of an asteroid. 0 denotes asteroid’s initial trajectory, 1 denotes asteroid’s trajectory after influence.](image)

![Fig. 2.3. Regional deflection. The dependences of needed additional velocity on prevention time for regional deflection. The upper curve corresponds to \( \phi = 3.33^\circ \), the lower curve corresponds to \( \phi = 20^\circ \).](image)

Let change the point of asteroid fall for 2000 km. The appropriate impact parameter should be of 4350 km.

If initial inclination of the asteroid’s orbit is \( \phi = 3.33^\circ \) and prevention time is 1 year \( (t_0 = 3.1536 \times 10^7 \text{ sec}) \), \( \beta = 2\pi \) then needed additional velocity is \( \Delta v \equiv 0.12 \text{ m/sec} \). If averaged density of the asteroid is 2500 kg/m\(^3\) then the impulse of force of \( 1.65 \times 10^8 \text{ N \cdot sec} \) should be applied.

Figure 2.3 shows dependence of needed additional velocity on prevention time for two inclinations, 3.33° and 20°. Note that the larger inclination requires the minor impulse of force.

- **Increase in the perigee of the asteroid’s orbit.**

Suppose that the ahead collision between an asteroid and the Earth is predicted and it is needed to deflect the asteroid to increase its perigee up to \( \eta' \).

The needed impact parameter can be determined using the following expression

\( \hat{\chi}^2 = \hat{\eta}^2 + 2\eta' \cdot \frac{R_E}{R_E} \),
where $R_E$ is the Earth’s radius, $\bar{R}_E = R_E \cdot \frac{v_\infty^2}{\mu}$ - the dimensionless Earth’s radius,

$v_\infty$ is the relative velocity of an asteroid when it is entering into the gravitational field of Earth.

Figure 2.4 shows dependence of needed additional velocity on prevention time to deflect asteroid’s perigee through the Earth’s radius (so the asteroid will only graze the Earth).

Fig. 2.4 The prevention time dependences of needed additional velocity to increase the asteroid’s perigee through the Earth’s radius.

This case can be named as delay deflection. The upper curve corresponds to orbit of $\phi=3.33^\circ$, the lower curve corresponds to orbit of $\phi=20^\circ$.

- «Drawing» of an asteroid away from «a key hole» (Fig. 2.5). In this case there is needed only a minimal mechanical impulse.

The impact parameter should be changed through a magnitude equal to

$$\Delta \chi \cong \sqrt{1 + \frac{R_E}{\eta \cdot \bar{R}_E}} \cdot \Delta \eta,$$

where $\Delta \eta$ is the needed variation of the asteroid’s perigee.

The dependences of needed additional velocity on prevention time is shown in Fig. 2.6.

Fig. 2.5 Scheme for asteroid “drawing” away from “a key hole”.

Fig. 2.6 Key hole deflection. The prevention time dependences of needed additional velocity for asteroid “drawing” away from “a key hole” (Inclination $\phi=3.33^\circ$).
In the above considered cases only a time of crossing the Earth’s orbit is varied. Thus collision with Earth is delayed for an ambiguous time.

- **Deflection of asteroid’s orbit through the radius of Earth (change of the MOID).**
  In this case the orbit is changed in such manner that any collision of the asteroid with Earth is ruled out. 
  Fig. 2.7 shows the needed additional velocity versus prevention time (or, rather, versus a phase angle).

![Graph showing orbital deflection](image)

**Fig. 2.7. Orbital deflection.** The prevention time dependences of needed additional velocity to increase the MOID between the asteroid and Earth through the radius of Earth. The upper curve corresponds to orbit of $\phi=3.33^\circ$, the lower curve corresponds to orbit of $\phi=20^\circ$. 
3 Momenta due to blasts

When the impulse of force due to a blast is calculated the following chain of physical problems must be resolved: estimation of problem nuclear explosion spectra, solution of the transport problem in asteroid’s substances for X-rays, determination of thermodynamics of asteroid’s substances, consideration of the motion of a vaporized matter and forming of the mechanical impulse.

The nuclear explosions could be stand-off or buried.

The main idea of this work is that the stand-off explosions are the most favorable ones because they allow maintaining an asteroid as a whole object.

But anyway we explore the both variants. And even some attention is paid to explosions of TNT.

In the case of stand-off explosion its Roentgen radiation is absorbed in a thin surface layer of the matter of asteroid. This layer is vaporized and its end up creates reactive force acting on the asteroid. The value of this force is determined by the product of two factors: mass thickness of the vaporized layer and the absorbed energy. It is likely that there is some optimal spectrum which leads to a maximum force impulse for a given power charge. Radiation of temperature of 2.6 keV is absorbed in a very thin layer so the vaporized mass and final force impulse will be relatively low.

And too hard radiation passes deeply and the absorbed heat may be not enough for vaporization of high temperature materials such as forsterite or carbon which are typical for asteroids. Thus, the optimal spectra are characterized by energies in the 10keV-60 keV interval.

The time of X-ray action is also determined by the temperature of a fireball and it can be varied in an interval of $10^{-10}$ – $10^{-6}$ sec. So this time is much lower then the character gas dynamical time of vaporized matter spreading (especially, in the case of dimensional spreading). The upper limit of the fireball lighting time is near the same as the character time in the stage of one dimensional vapor motion but it is unlikely it has a great influence on the total force impulse value.

Besides the Roentgen radiation there is a gas flow of the vaporized materials of a bomb. As a matter of fact, any nuclear charge has a strong massive hull. But really this factor should be considered as a minor one that could be essential only for special low power nuclear charges.

Note that calculations mentioned below show that buried nuclear explosions allow passing much greater mechanical impulse to an asteroid. Therefore, in the case of a small prevention time usage of buried explosions will be inevitable. For us the estimation of buried explosions is simpler because there are experimental results accumulated during industrial explosions and generalized in several works (Adushkin and Spivak, 2007), (Vortman, 1968, 1969), (Howard, 1969).

The chemical charge before explosion should be buried, of course.

3.1 Stand-off nuclear explosions

To have useful estimates let decide in favour of two types of spectra: monolines in the interval 10-60 keV which help us to do common methodical conclusions and Plank spectra having maxima in the same interval to do estimates which help us to answer on the main question “to be, or not to be”.

A Plank spectrum determined by the following normed distribution

$$\bar{\rho}(\varepsilon, T) = \frac{4}{\pi^4 \cdot T^4} \cdot \frac{\varepsilon^3}{e^{\varepsilon/T} - 1}.$$
If use dimensionless parameter \( x = \frac{\varepsilon}{T} \) (it is an argument of the function and a distribution parameter, simultaneously), then

\[
\bar{\rho}(x, T) = \frac{15}{\pi^4} \cdot \frac{x^3}{e^x - 1}, \text{ где } \frac{\pi^4}{15} = K_3 \approx 6.4939
\]

Here energy may be in keV, accordingly temperature should be in keV too. The point of maximum described by equation

\[
3Te^2(eT - 1) - \varepsilon^3eT = 0
\]

Dimensionless equation is following

\[
3(e^x - 1) - xe^x = 0.
\]

Its solution is \( x = C = 2.82144 \), and \( \varepsilon_{\text{max}} = C \cdot T = 2.82144 \cdot T \) (it is a ratio of spectrum maximum to the body temperature). You see that the “tail” of the distribution is spreading far more than the temperature and the spectrum maximum too (Fig. 3.1.1.1). For example, if the body temperature equals 10 keV, the spectrum is spreading up to 100 keV.

Fig. 3.1.1.1. Dimensionless Plank spectrum. Differential and integral (cumulative) distributions.

There many kinds of constructions of nuclear charges. The charges giving a maximum yield of X-rays may be most effective in our applications and here they are considered. In the moment of explosion the constriction of the charge is converted into a fire ball of extremely high temperature.
The maximum possible value of the temperature corresponds to density of energy in nuclei. But the real temperature is much lower. Nevertheless the main part of burst energy is transformed into energy of hard X-rays. The real spectrum strongly depends on the construction of a bomb. The limits are following. There are results of experimental measurements of the temperature of an aluminium sample posed just near a bomb (Fortov, 2010). This temperature was about 6 millions degrees that correspondent to X-rays with temperature of 2.6 keV. It can be said that this temperature is a lower estimate. The upper estimate is given by (Barsukov, 2011), where the temperature about 1-10⁹ K (428 keV) is said in the center of a nuclear explosion. Such temperature provides a maximum harder X-ray spectrum possible for nuclear explosion. Evidently, variations of a bomb construction lead to practically any spectrum in this very wide interval.

Choosing the power of nuclear explosion it is necessary to consider ability of contemporary rocket systems and weights of nuclear charges. From the one side, there are no problems to deliver a payload of 100 – 500 kg now. There are no need in developing new giant rocket systems and the most attention can be paid to maximizing assurance resources and accuracy of a mission. From the other side, there are data on the contemporary nuclear weapon (Dronov et al., 2011) which said that a character weight of a nuclear charge having power about 170 kt is about 115 kg. Considering also estimates of (Barsukov, 2011), where such weight have a usual plutonium charge of 10 kt power, will take calculations for explosions of 10-100 kt. Also suppose that the yield of Roentgen radiation is unit.

### 3.1.1 X-rays transport in substances

Solving the transport problem in a thin layer of a substance for quanta with above mentioned energy it is enough to consider only photo effect and incoherent (Compton) scattering. We neglect coherent (Rayleigh) scattering and transport of fluorescent X-rays having minor effects, and also transport of energy by electrons. But note that while the transport of energy by electrons doesn’t have essential effect on the depth of heated substance it can seriously change parts of energy absorbed by different components and have a great effect on a total value of mechanical impulse. However, there is supposed that the asteroid substance is homogeneous.

The problem posed here can be solved using data by (Storm and Israel, 1970), (Veigele, 1973). Numerical estimations showed that the used in this work assumptions about scattering by bound electrons are close to classic solution by Klein-Nishina-Tamm (KNT) for scattering on free electrons. So the angular distributions given by KNT with a some little correction can be used for the transport problem in substances.

According to KNT the differential cross section of electron scattering described by the following equation

\[
\frac{d\sigma}{d\Omega} = \frac{\hat{\epsilon}^2}{2} \left( \hat{\epsilon} + \frac{1}{\hat{\epsilon}} - 1 + \cos^2 \theta \right),
\]

where \( \hat{\epsilon} = \frac{\hat{\epsilon}'}{\hat{\epsilon}} = \frac{1}{1 + \epsilon(1 - \cos \theta)} \),

\( \hat{\epsilon} = \frac{\epsilon}{m_e c^2} \ll 1 \) is a dimensionless energy of a quantum before scattering,
\( \varepsilon' \) is a dimensionless energy of the quantum after scattering, 
\( \theta \) is an polar angle of scattering.

According to the KNT formulas the averaged change of energy due to incoherent scattering determined by the following formula

\[
\Delta KNT \approx \varepsilon^2 \frac{1 - \frac{14}{5} \varepsilon}{1 - 2\varepsilon}
\]

To agree above formulas with the data by Veigele it is enough to apply a correction factor into the averaged energy change. This multiplier is different for different elements and depends on the energy of quantum but any way it is most nearly to unit.

To calculate energy release the Monte Carlo method is used for integration of three scattering knees. We solve the transport problem in a half space but calculate the energy release only near the surface where vaporization has place. According to the section below the lower boundary of vaporization of forsterite under the assumption of the ensuing adiabatic spreading is 914 J/g. Because we are interested in calculation of heat just near the exposed surface then such calculation have enough high accuracy even when consider X-ray transport in carbon.

In conclusion, let consider the base calculations of the energy release field in forsterite ((Mg\(_2\)SiO\(_4\) is a kind of olivine) for a nuclear explosion of 10 kt power and three spectra: 1) monoline of 20 keV, Plank distributions for temperatures of 2) 20 keV and 3) 60 keV. The diameter of asteroid is 150 m, the asteroid has strongly spherical form, the altitude of explosion above the surface is 25 m.

<table>
<thead>
<tr>
<th>Z</th>
<th>H</th>
<th>C</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg(_2)Si(_2)O(_5)(OH)(_4)</td>
<td>0.0145</td>
<td>-</td>
<td>0.5196</td>
<td>0.2631</td>
<td>-</td>
<td>0.2027</td>
<td>-</td>
</tr>
<tr>
<td>Mg(_2)SiO(_4)</td>
<td>-</td>
<td>-</td>
<td>0.455</td>
<td>0.345</td>
<td>-</td>
<td>0.200</td>
<td>-</td>
</tr>
<tr>
<td>(MgFe)SiO(_4)</td>
<td>-</td>
<td>-</td>
<td>0.372</td>
<td>0.141</td>
<td>-</td>
<td>0.163</td>
<td>0.324</td>
</tr>
</tbody>
</table>

The transport problem for X-rays is solved in the quasi-one-dimensional approach, i.e. the one dimensional problems are solved independently for each point of exposed surface of an asteroid (Fig. 3.1.1.2). It is obvious that 1D solution doesn’t limit the accuracy.

Calculation of irradiance of an asteroid surface is described by the following formulas.

\[ \theta = \alpha + \beta \]
α is the central angle of a surface point, 
θ is the angle of incidence of a radiation.

\[
x = R_a \cos \alpha \\
y = R_a \sin \alpha \\
\]

Denote \( w = h + R_a (1 - \cos \alpha) \)

\[
d^2 = w^2 + R_a^2 \sin^2 \alpha \\
\cos \beta = \frac{w}{d^2} \\
\]

It is straightforward to determine the solution of the transport problem using mass coordinates. Even the same solution allows to do some conclusions about a mechanical impulse that created by vaporized asteroid matter. For example, consider influence of the hardness of radiation on the value of the impulse. 

In Table 3.1.1.2 there are given values of two functionals of an energy release profile for two different spectra (monoline) of a nuclear explosion. It is \( Q_s \) that is a limit energy release in a surface point, \( J/g \), and \( d_{heat} \) that is the depth of heated substance where the energy release is greater than vaporization heat. In the case of forsterite it is 914 J/g. It is a limit value for mechanical impulse creation.

<table>
<thead>
<tr>
<th>Specrum energy</th>
<th>2.60 keV</th>
<th>6 keV</th>
<th>10 keV</th>
<th>20 keV</th>
<th>30 keV</th>
<th>60 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_s, J/g )</td>
<td>0.4190E+09</td>
<td>0.3872E+08</td>
<td>0.8427E+07</td>
<td>0.1008E+07</td>
<td>0.2954E+06</td>
<td>0.3912E+05</td>
</tr>
<tr>
<td>( d_{heat}, g/cm^2 )</td>
<td>0.167E-01</td>
<td>0.148E+00</td>
<td>0.581E+00</td>
<td>0.348E+01</td>
<td>0.914E+01</td>
<td>0.346E+02</td>
</tr>
</tbody>
</table>

This table show that increase in the hardness of radiation leads to large increase in mechanical impulse. 

Fig. 3.1.1.3 and 3.1.1.4 show energy release profile when the energy of quanta is 2.6 and 30 keV/ 

The linear behavior of the energy release in the case of 2.6 keV is explained by major role of photo effect. In the case of 30.0 keV near the surface, the graphs are falling linearly too. But for larger depth (but where it is still some influence on mechanical impulse) the linearity is violated by incoherent scattering. You see that the linearity is violated even for energy of 2.6 keV when the quanta hit surface more obliquely. This effect is explained by high order of attenuation of the primary radiation and can get some influence on the impulse due to it has place on a large part of the surface. So the incoherent scattering should be considered anyway.
Fig. 3.1.1.3. Energy release $Q$, J/g, profiles for central angles of $0^\circ$ (normal incidence), $6.9^\circ$, $13.8^\circ$, $20.7^\circ$, $27.6^\circ$ и $34.5^\circ$. The energy of primary quanta is $2.6$ keV.

Fig. 3.1.1.4. Energy release $Q$, J/g, profiles for central angles of $0^\circ$ (normal incidence), $6.9^\circ$, $13.8^\circ$, $20.7^\circ$, $27.6^\circ$ и $34.5^\circ$. The energy of primary quanta is $30$ keV.

### 3.1.2 Thermodynamics of sublimation

Knowledge of thermodynamic properties of asteroid substances is relevant to pursue the estimation of force impulse. There are many ways to analyze thermodynamics. Firstly, there are many data on meteorites and, to some extent, on comets. But needed data for asteroids are absent.

Let suppose initially that the asteroids are similar to meteorites and have a chondrite structure that is some porosity. It allows to estimate only the mechanical impulse created by sublimated matter and neglect the motion of condensed phase. It is known that the chondrules have a wide spectrum of sizes and are fitted enough tightly. So we can neglect the influence of porosity on X-ray transport (at this stage of exploration) and on the motion of vaporized phase.

According to (Krinov, 1981) the most character materials of meteorites are as following.

1. Magnesium silicate (the Earth’s analogue is a mineral forsterite)
2. Iron-magnesium silicates, with mass content of iron equals to $25.6$ % (the counterparts are different olivines which account of the main part of the earth's crust).
3. Iron-magnesium silicates, with mass content of iron equals to 89.7% \( (\text{analogues are iron meteorites}). \)

4. Water ice, but it is the feature matter of comets, not of asteroids.

So the main attention must be paid to thermodynamics of silicon, magnesium and iron oxides and appropriate silicates. May be our results could be used also for analysis if the influence of stand-off nuclear explosion on a comet because the surfaces of comets are covered by some crust of such unvolatile components. That must determine the mechanical impulse due to a stand-off nuclear explosion.

Let do some remarks on comets here.

1. The thickness of the comet crust must be estimated.
2. It can be a great difference if the stand-off nuclear explosion is made in the tail or coma of the comet. The gas-dust cloud is able to absorb the main part or Roentgen radiation and so to change the mechanism of forming of a mechanical impulse.

To calculate the motion of matter we need a complete set of thermodynamic functions which includes equations of thermodynamic potentials, namely: internal energy, enthalpy, free energy and Gibbs or chemical potential and also expressions for the most important thermodynamic parameters: pressure and entropy.

Such equations which must describe both the vapor and condensed phases are usually named “wide-range” equations (Valko et al., 2010). The simplest ones are two-parameters equations. The Van-der-Waals equation is the most known model. It describes phenomenologically the transition between vapor and condensed phase. There are many equations of such kind for different matters (but, mainly, for hydrocarbons). The equation by Redlich and Kwong is accounted as one of the best universal approximations (Redlich, 1949), (Reid and Prausnitz, 1982).

The crucial thing is a baric equation of state (equation for pressure).

\[
p = \frac{RT}{V-b} - \frac{a}{\sqrt{TV(V+b)}}.
\]

It is not enough to determine the behavior of a matter completely. But in the most favorable way we can get the following expressions for the thermodynamic functions.

\[U_{RK} = \frac{3a}{2b\sqrt{T}}\ln\frac{V+b}{V} + c_v T\] is an internal energy,

\[H_{RK} = \frac{3a}{2b\sqrt{T}}\ln\frac{V+b}{V} + c_v T + \frac{RTV}{V-b} - \frac{a}{\sqrt{T}(V+b)}\] is an enthalpy,

\[\Phi_{RK} = -RT\ln(V-b) + \frac{a}{b\sqrt{T}}\ln\frac{V+b}{V} + c_v T(1 - \ln T) + \frac{RTV}{V-b} - \frac{a}{\sqrt{T}(V+b)}\] is a Gibbs’ potential,

\[F_{RK} = -RT\ln(V-b) + \frac{a}{b\sqrt{T}}\ln\frac{V+b}{V} + c_v T(1 - \ln T)\] is a free energy.

The expression for entropy is following.

\[S = R\ln(V-b) + \frac{a}{2b\sqrt{T^3}}\ln\frac{V+b}{V} + c_v \ln T.\]
It should be noted that the appearance of the last term (thermal one) is chosen completely on the analogy of the similar expression for the Van-der-Waals gas and it can really be enough arbitrary function.

The forsterite $\text{Mg}_2\text{SiO}_4$ is likely to be the most typical substance for asteroids. It has the following parameters. 1 mole of forsterite is 0.1406 kg. The density is 2900 kg/m$^3$, specific volume is $V = 1.55 \cdot 10^4$ m$^3$/kg. Vaporizing forsterite is decomposed as follows (Pahlevan et al., 2011)

$$\text{Mg}_2\text{SiO}_4(l) = 2\text{MgO}(v) + \text{SiO}_2(v)$$

Magnesium and silicon oxides are partially dissociated too (Kazenas and Tsvetkov, 2008).

Parameters of the Redlich/Kwong equation can be coarsely determined from thermodynamic investigations on oxide and silicate decomposion and also from numerous works on meteorites, lunar substances and even on kinetics of the matter in protosolar nebula. The shortest way is to use critical parameters of aluminium silicate $\text{CaAl}_2\text{Si}_2\text{O}_8$ given in (Ghiorso, 2009). They are: $P_c = 1.257$ GPa, $T_c = 1624$ K.

Using the critical values of pressure and temperature the parameters of the Redlich/Kwong equation are following.

$$a = 2.5 \frac{J \cdot m^3 \cdot \sqrt{K}}{\text{mole}^2} \quad b = 0.931 \cdot 10^{-6} \frac{m^3}{\text{mole}}.$$ 

Thereafter the critical value of specific volume is

$$V_c = 0.361 \cdot 10^{-5} \frac{m^3}{\text{mole}}$$

that corresponds to ratio $\frac{V_c}{b} = 3.88$.

Note that it is essentially lower than value determined in the same work, $\rho'_c = 2695$ kg/m$^3$.

The initial value of density is $\rho_0 = 2900$ kg/m$^3$ that corresponds to $\frac{V_0}{b} = 52.6$.

The value of specific heat capacity has a fundamental magnification because it determines Poison adiabat.

Estimations of the molar heat capacity $c_v$ of forsterite (condensed phase) (Chopelas, 1990), (Pan’kov, 1998) are given in Fig. 3.1.2.1.
The estimate for the vapor phase considering molar ratio in the reaction equation is: $c_v = \frac{7}{3} \times 8.31 \approx 24.3 \frac{J}{mole \cdot K}$.

There is some uncertainty in effective value of the molar heat capacity. So in future the parameters should be made more exact.

Other problem is following. The real substance of an asteroid is multi-component one. In principle, such substance could be defined using integral approach. But it may be more complicated than using individual equations. In future the equation of state will be made more accurate.

The isotherms of the chosen equation by Redlich/Kwong are shown in Fig. 3.1.2.2.
The isotherms can have negative values in minimums. It is no matter because these of the curves are not realized.

Note that the region where the isotherms are not monotone ones is to the far left of the real adiabats of expansion. So the adiabats fall at the critical isotherm from from directly above. In this moment the condensed phase appears and the adiabat is violated due to non-equilibrium in heat transfer from condensed phase to vapor.

But even suppose the temperature balance is realized we cannot use the Maxwell rule or equality between thermodynamic potentials of vapor and condensed phases.

Really. The equation of phase and chemical balances is as following

$$\mu_1 = 2\mu_2 + \mu_3,$$

where $\mu_1$, $\mu_2$ and $\mu_3$ are the chemical potentials of $\text{Mg}_2\text{Si}_4\text{O}_4$ (l), MgO (v) and SiO$_2$ (v).

These potentials can be written through the potential by Gibbs for liquid and vapor phases as following

$$\mu_1 = \frac{\Phi_l}{0.1406}, \quad \mu_2 = \frac{\Phi_{\text{MgO}}}{0.0403}, \quad \mu_3 = \frac{\Phi_{\text{SiO}_2}}{0.06}.$$

Here we can write roughly $\Phi_v = 2\Phi_{\text{MgO}} + \Phi_{\text{SiO}_2} \cdot$

The equation of the chemical balance becomes

$$\frac{\Phi_l}{0.1406} = 2\frac{\Phi_{\text{MgO}}}{0.0403} + \frac{\Phi_{\text{SiO}_2}}{0.06} \quad \text{или} \quad \frac{\Phi_l}{0.1406} = 2 \cdot 3.5 \cdot \Phi_{\text{MgO}} + 2.34 \cdot \Phi_{\text{SiO}_2} \approx 2.7 \cdot \Phi_v$$

So the Maxwell rule doesn’t work.

To calculate vaporization we suppose that there are momentary energy release in a surface layer due to Roentgen radiation of a nuclear explosion. The part of the matter heated above some critical
temperature is sublimated and flows away. The released energy transforms into kinetic energy of the vapor. But there are some losses. One of them is due to non-equilibrium of expansion of two phase mixture. When the matter occurs in the two phase region the pressure drops drastically so there is only inertia motion and it can be considered that mechanical impulse is already formed.

Fig. 3.1.2.3 shows adiabatic change of the vapor pressure when the initial temperature due to X-ray heating is about 2000 K, here is given also the pressure on the critical isotherm. The transform of released energy into kinetic energy is completed when the vapor crosses the critical isotherm.

![Fig. 3.1.2.3. Adiabatic change of the vapor pressure and critical isotherm. T₀=2000.](image)

Fig. 3.1.2.4 shows adiabatic change of the vapor temperature when the initial temperature due to X-ray heating is about 2000 K, here is given the critical temperature too.

![Fig. 3.1.2.4. Adiabatic change of the vapor temperature and critical isotherm. T₀=2000.](image)

Fig. 3.1.2.5 shows adiabatic change of the vapor pressure when the initial temperature due to X-ray heating is about 2500 K, here is given also the pressure on the critical isotherm. In this case the specific volume is so changed that there are starting 3-D effects. The following simplification is that the input to the directional momentum is ceased at this moment. The final volume is 200 times initial one.

![Fig. 3.1.2.5. Adiabatic change of the vapor pressure and critical isotherm. T₀=2000.](image)
Fig. 3.1.2.5. Adiabatic change of the vapor pressure and critical isotherm. $T_0=2500$.

Fig. 3.1.2.6 shows adiabatic change of the vapor temperature when the initial temperature due to X-ray heating is about 2500 K, here is given the critical temperature too.

Fig. 3.1.2.6. Adiabatic change of the vapor temperature and critical isotherm. $T_0=2500$.

There transform of released energy into kinetic energy completed when the vapor crosses the critical isotherm.

Fig. 3.1.2.7 shows the energy release dependence of the final coefficient of conversion of energy release into kinetic energy of vapor of forsterite.
Fig. 3.1.2.7 Energy release dependence of the final coefficient of conversion of energy release into kinetic energy of vapor of forsterite.
3.1.3 Momenta in different cases

Here is used the known integral method to calculate the values of momenta. The integral method is based on estimates of the useful work that can be done by an isentropically spreading gas considered above. Also it was noted above that the spectrum of the X-radiation of the fireball of a nuclear explosion is variable to some extent. So initially we calculate the variations of momenta with energy of X-radiation. The total value is calculated with integration of the specific momentum impulse on the exposed asteroid surface that strongly varied with distance from the epicenter of nuclear explosion (Fig. 3.1.3.1). It is associated entirely with increase of angle of incidence. Also there is a strong influence of the energy of quanta on the total force impulse. We don’t have a foundation to calculate the radiation of any harder spectrum, but to illustrate this effect we give a quantum energy dependence of momentum for monolines (Fig. 3.1.3.2). There calculations were also made for power of 10 kt.

Model calculations.
There real spectra are not a monoline ones. But Plank spectrum is another outermost case but it seems to be more truthful thing. And it is enough conclusive the evidence by (Fortov, 2010) that the spectrum of a standard nuclear explosion is similar to the Plank spectrum of 2.6 keV temperature. Tables 3.1.3.2 - 3.1.3.4 gives the calculated momenta due to explosions of power of 10, 100, and 1000 kt. Fig. 3.1.3.3 gives the altitude dependencies of momenta for temperatures of a fireball with the effective temperature of 2.6 degrees calculated by code’s different versions. The power of explosions is 10 kt in this case. Obviously it should be a strong increase in the momentum with harder spectrum (see fig. 3.1.3.2), and the increase in energy of quanta may be more effective than the increase in power. Fig. 3.2.1.9, 3.2.1.3, and 3.1.3.3 shows that there is a minimum in the momentum at altitudes 0 – 30 m. But this minimum should be depends on the spectrum of X-rays.

Note, somewhere in this region there is a boundary of applicability of the methods used to calculate stand-off explosions. For the lower altitude of explosion the soil of asteroid is pressed out of the central zone and this effect hasn’t been considered here (it can be called as excavation effect. Calculation through the distances closer than 5 m doesn’t be done at all by this cause.

![Graph](image-url)

Fig. 3.1.3.1 Central angle dependence of specific momentum through monolines of 2.6, 10, 20, 30, and 60 keV. The red line shows the specific momentum through Plank spectrum of a 10 keV temperature fireball.
Fig. 3.1.3.2. Quantum energy dependence of momenta for monoline spectra. 10 kt power explosion.

Table 3.1.3.1. Altitude dependence of momenta, N·sec, for nuclear explosion of power of 10 and 100 kt above a 150 m asteroid.

<table>
<thead>
<tr>
<th>( h, \text{m} )</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>40.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q=10\text{kt} )</td>
<td>0.995E+08</td>
<td>0.132E+09</td>
<td>0.150E+09</td>
<td>0.161E+09</td>
<td>0.166E+09</td>
<td>0.168E+09</td>
<td>0.166E+09</td>
</tr>
<tr>
<td>( Q=100\text{kt} )</td>
<td>0.350E+09</td>
<td>0.464E+09</td>
<td>0.529E+09</td>
<td>0.568E+09</td>
<td>0.586E+09</td>
<td>0.597E+09</td>
<td>0.597E+09</td>
</tr>
</tbody>
</table>

Fig.3.1.3.3. Momentum versus altitude above the surface of an asteroid. The radius of asteroid is \( R = 75 \text{ m} \), the power of explosion is 10 kt. The effective temperature of the emitting fireball is \( T_{\text{rad}} = 2.6 \text{ keV} \).
Summary tables for asteroids of different size

Table 3.1.3.2. Momenta due to Q = 10 kt explosions, \(N*\text{sec.}\)

<table>
<thead>
<tr>
<th>(h, m)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.556E+08</td>
<td>0.820E+08</td>
<td>0.995E+08</td>
<td>0.113E+09</td>
<td>0.123E+09</td>
<td>0.134E+09</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.132E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>0.150E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.161E+09</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>25</td>
<td>0.555E+08</td>
<td>0.117E+09</td>
<td>0.166E+09</td>
<td>0.204E+09</td>
<td>0.235E+09</td>
<td>0.260E+09</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.168E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.305E+08</td>
<td>0.866E+08</td>
<td>0.146E+09</td>
<td>0.202E+09</td>
<td>0.253E+09</td>
<td>0.299E+09</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.685E+08</td>
<td>0.122E+09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.147E+08</td>
<td>0.487E+08</td>
<td>0.919E+08</td>
<td>0.140E+09</td>
<td>0.189E+09</td>
<td>0.237E+09</td>
</tr>
</tbody>
</table>

Table 3.1.3.3. Momenta due to Q = 100 kt explosions, \(N*\text{sec.}\)

<table>
<thead>
<tr>
<th>(h, m)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.189E+09</td>
<td>0.285E+09</td>
<td>0.350E+09</td>
<td>0.401E+09</td>
<td>0.440E+09</td>
<td>0.481E+09</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.464E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>0.529E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.568E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.186E+09</td>
<td>0.412E+09</td>
<td>0.586E+09</td>
<td>0.730E+09</td>
<td>0.847E+09</td>
<td>0.943E+09</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.597E+09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.112E+09</td>
<td>0.320E+09</td>
<td>0.541E+09</td>
<td>0.752E+09</td>
<td>0.944E+09</td>
<td>0.112E+10</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.262E+09</td>
<td>0.470E+09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.591E+09</td>
<td>0.196E+09</td>
<td>0.373E+09</td>
<td>0.568E+09</td>
<td>0.769E+09</td>
<td>0.970E+09</td>
</tr>
</tbody>
</table>

Table 3.1.3.4. Momenta due to Q = 1000 kt explosions, \(N*\text{sec.}\)

<table>
<thead>
<tr>
<th>(h, m)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.631E+09</td>
<td>0.962E+09</td>
<td>0.120E+10</td>
<td>0.138E+10</td>
<td>0.152E+10</td>
<td>0.168E+10</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.159E+10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>0.181E+10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.193E+10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.638E+09</td>
<td>0.139E+10</td>
<td>0.199E+10</td>
<td>0.249E+10</td>
<td>0.291E+10</td>
<td>0.326E+10</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.203E+10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.379E+09</td>
<td>0.109E+10</td>
<td>0.186E+10</td>
<td>0.260E+10</td>
<td>0.329E+10</td>
<td>0.392E+10</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>0.906E+09</td>
<td>0.163E+10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.208E+09</td>
<td>0.695E+09</td>
<td>0.132E+10</td>
<td>0.203E+10</td>
<td>0.276E+10</td>
<td>0.348E+10</td>
</tr>
</tbody>
</table>

Approximating formula

\[ I = Q^{0.554}(1 - \sqrt{\frac{h^2 + 2hR}{R+h}}) \cdot W, \]
where $W = W(h)$ determined by the table 3.1.3.5.

Table 3.1.3.5. Altitude dependency of the momentum due to a stand-off explosion $W(h)$.

<table>
<thead>
<tr>
<th>$h$</th>
<th>5.0</th>
<th>25.0</th>
<th>70.0</th>
<th>150.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>0.416E+08</td>
<td>0.134E+09</td>
<td>0.286E+09</td>
<td>0.488E+09</td>
</tr>
</tbody>
</table>

The approximation is accurate to 30%.

Note that the presented here results somewhat differ from (Meshcheryakov S., Lipnitskiy Yu., 2013) because there were some improvements in the algorithm but the difference is within the frame of errors of calculations.

There can be indicated following things.
1. The data on momenta through 2.6 keV stand-off explosions (theoretical calculations) agree with data through buried explosions (see lower, data by industrial nuclear explosions). There is an extremum in the altitude dependence at the altitude of 17-25 m (see Fig.3.1.3.3).
2. The approximating formula describes the momentum in the region above this extremum and doesn’t catch the decrease in momentum at lower altitudes, it is supposed that there is no sense to do an explosions close with the asteroid’s surface.
3. The harder spectrum, the greater momenta. It is also take place for buried explosions but to a lesser extent.
3.1.4 On the neutron effects of a nuclear explosion

“Technically speaking, all low yield nuclear weapons are radiation weapons, that is including the non-enhanced variant, from 0 up to about 10 kilotons in yield, all have prompt neutron radiation”

_Wikipedia_

In a fission bomb, the total radiation pulse energy which is composed of both gamma rays and neutrons is approximately 5% of the entire energy released. The energy of neutrons is in the range of 1 – 2 MeV. It is fast neutrons. The main process that determined transport of energy by such neutrons is the elastic dispersion (Beckurts and Wirtz, 1968). The cross-sections and energy losses are given in (Atlas of effective neutron sections, 1952), (Gordeyev, 1960) < (Medvedev, 1981) and so on.

It can be supposed that there is an isotropic scattering.

The following aspects can be indicated.

The main part of a nuclear burst is a thermal roentgen emission/ If the bomb is exploded above the surface of an asteroid the energy is absorbed by a thin surface layer of about ten centimeters. This matter is vaporized and so a pulse of pressure is created. The energy of neutron radiations passes to the depth of about a meter and so doesn’t have a part in the vaporization processes. In the case of a solid matter the instantaneous heating leads to a pressure wave enough for asteroid destruction. Firstly, a facial scabbing can be / But there is no such effects in a porous matter (see the section 3.4). Any way the mechanical effect of neutrons is lesser than 5% of total one. Such accuracy answers to the challenges raised by the asteroid deflection mission.

Other thing is a neutron bomb. The total radiation pulse energy which is composed of neutrons would be closer to 40%. The neutrons emitted by a neutron bomb have a much higher average energy level, closer to (14 MeV). There are two cocurrent processes of evaporation and scabbing. The facial scabbing can be created/ So the mechanical impulse is enhanced (up to 2-4 times) and the total destruction of an asteroid can appear.

Neutron bombs are very expensive because requires large amount of tritium. The tritium has a very short half-life (12.32 years). So the neutron bombs have usually a power about 1 kt, but the bombs of tens and hundreds kt of TNT can be also produced.

The first step in the direction is made. The 1D hydrocode presented if this report can solve the problem of propagation of pressure waves near the facial surface of an asteroid (of cause, the total problem of fragmentation needs 2D and 3D numerical codes). To solve the transport problem of neutrons in the above mentioned approach there is no problem too. But TSNIImash needs some time for such work and for passing different Federal services. Also TSNIImash needs data on material constants of asteroid matters. The thermo-mechanical properties such as coefficients by Gruneisen, thermal expansion and capacity, Young module, sound velocity, dynamical strength, porosity are needed/ Also there are needed coefficients specific for the model proposed in the section 3.4 (i.e. porosity, density and sound velocity in consolidated phase, the coefficient of restitution, crushing limit). In this respect we rely on the help of our partners.
3.2 Buried nuclear explosions. Engineering approaches to momenta

3.2.1 Momenta values using data on industrial nuclear explosions

The buried nuclear explosions are important reserves for the protection of the Earth. The data on excavation of soil through industrial nuclear explosions are the most conclusive base for determination of momenta. The generalizations had been made till 70th. They are given in (Adushkin and Spivak, 2007), (Vortman, 1968, 1969), (Howard, 1969).

The idea of disintegration of a danger body is not a productive one. Such asteroid should be deflected. So the nuclear explosion should be done at a small depth of 10 – 50 m. The higher value of momenta seems to be intuitively. But there is the danger of fragmentation of an asteroid when there is an unpredictable motion of fragments. And there can be very hazardous fragments. Besides the falling of ten millions of dust seems to be not seriously better the an impact of the whole body. Anyway, for capturing various cases is necessary to have algorithms for calculation of buried explosions. A 3-d hydrocode would be a best tool but it needs data on physical and structural properties of asteroids. And due to high complexity of the motion of disintegrated matter under forces exerted by products of a nuclear explosion any code needs checking by comparisons with experiments that is not possible now. And not only hydrocodes themselves but thermodynamic codes are the most important things.

So results of the industrial excavation explosions are preferable. The difficulty is that there are no data on velocity distributions only crater sizes data. So we need additional physical suppositions. There is another way, to use data on seismic waves exited by nuclear explosions. But here are other difficulties. The main attention is paid to investigations of shock wave fronts but the “tails” of seismic waves were missed. These “tails” carry the most part of momenta. So this approach seems to be unreliable.

There are coarsely two kinds of explosions. The first bursts were conducted in alluvial soils and the other bursts were conducted in rocks. Naturally, we use results of nuclear explosions inside alluvia that is a weakly bound soil that can be easily dispersed. It seems to be rather similar to asteroid matter. The explosions inside basalts or granites have no common features with explosions inside asteroids.

The “A” method

The method is based on estimations of momenta of shattered soil ejected from craters while the momenta carried by vaporized matter is neglected. It is a direct interpretation of available experimental data. At the blast’s location a vapor cloud is created. The size of the cloud is determined by X-rays’ transport processes and partly by convections. This vaporized matter is called as a “boiler kettle gases” or “boiler gases”. (Adushkin V.V. and Spivak A.A. Underground explosions. RAS, Institute of dynamics of Geospheres. Moscow, 2007. 578 p.). Expanding boiler gase for the part of the excavated matter s drain through the soil. They are pushing and entraining the soil. The mass of the gases much smaller than the mass of the soil. We are estimating the momentum given to the soil by the gases assuming that the own momentum of the gases is small. Of course, such assumption is wrong if the explosion is made near the Earth’s surface. But it is enough good approach even for small depth. It can be seen from the physical ideas and it is confirmed by comparisons with known numerical results. We would say rather that it was wonderful that they had calculated so exactly because we have direct experimental results.
We easily use our results for asteroids because the gravitation doesn’t play a role in the initial phase of the buried nuclear explosion. There is a numerous material on crater sizes in nuclear surface and buried explosions that is generalized by (Vortman, 1968). The recalculations are based on a single-stage approximation of crater depth \( h \) dependence of averaged velocity of ejecta \( v_e \):

\[
\frac{v_{e1}^2}{2} = 2k_i gh \quad \text{for the irretrievable part of the matter that excavated from a crater,}
\]

\[
\frac{v_{e2}^2}{2} = 0.5 \cdot k_i gD \quad \text{for the part of the excavated matter that falls back into a crater.}
\]

Debris falling back into the crater at the Earth will be thrown out of the crater at an asteroid and we should consider their input to the reactive pulse. There is a problem to determine the initial crater’s depth \( D \). We assume that it equals to the depth of the charge location. These velocity estimates correspond to (Howard and Tewes, 1969). The apparent increase in the averaged velocity with increase of the depth of explosion is explained by the shattered soil is dragged by the gas products of an explosion. So if there is a small depth then the gases quickly come out and have no time to entrain the soil.

Fig. 3.2.1.1. Primary and secondary craters in an excavation explosion.

In the experiments the apparent radii \( R \) and depths \( D \) of secondary craters are measured. The primary craters become partly filled by returned debris. The depth of charge location the primary crater can be considered as the depth of primary crater.

The Tables 3.2.1.1 \& 3.2.1.2 present the results by (Vortman L.J., 1969) on reduced charge location dependences of reduced crater sizes:

\[
\overline{R_c} = R_c \sqrt{W}^{1/3}, \quad \overline{D} = D \sqrt{W}^{1/3}, \quad \overline{h} = h \sqrt{W}^{1/3},
\]

Where the linear dimensions are given in meters and the power of explosion is given in kilotons.

<table>
<thead>
<tr>
<th>( \overline{h} )</th>
<th>( \overline{D} )</th>
<th>( \overline{h} )</th>
<th>( \overline{D} )</th>
<th>( \overline{h} )</th>
<th>( \overline{D} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.2855E+01</td>
<td>0.2746E+01</td>
<td>0.1246E+01</td>
<td>0.1275E+02</td>
<td>0.9481E+01</td>
<td>0.2137E+02</td>
</tr>
<tr>
<td>-0.1747E+01</td>
<td>0.3662E+01</td>
<td>0.2820E+01</td>
<td>0.1567E+02</td>
<td>0.1529E+02</td>
<td>0.2415E+02</td>
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<tr>
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<td>0.5775E+01</td>
<td>0.4170E+01</td>
<td>0.1729E+02</td>
<td>0.1872E+02</td>
<td>0.2542E+02</td>
</tr>
<tr>
<td>-0.4470E-07</td>
<td>0.8944E+01</td>
<td>0.4913E+01</td>
<td>0.1810E+02</td>
<td>0.2213E+02</td>
<td>0.2658E+02</td>
</tr>
<tr>
<td>0.2076E+00</td>
<td>0.9930E+01</td>
<td>0.6626E+01</td>
<td>0.1944E+02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2.1.2. Reduced crater radius as a function of reduced radius of nuclear explosion.
The radius of primary crater is supposed to be equal to the radius of secondary crater (see Fig. 3.2.1.1). The part of the matter fallen back determined by difference between the depth of primary crater and the depth of the secondary crater as following.

\[
\chi_b = \frac{h - D}{h}
\]

If the difference \( h - D \) is negative (it is characteristic of small depths) then we suppose that all the matter of a crater gains the velocity according to the first of the formulas, i.e. \( \chi_b = 0 \).

In this way, the formula for the momentum is

\[
I = k_{app} \rho \cdot \sqrt{g} \cdot \frac{\rho_I R^2 L^{3/2}}{3} (2 - \chi_b),
\]

where \( L = \max(h, D) \), \( \rho_I \) is a density of rocks.

\( k_{app} \) is an adjustable parameter (in what follows suppose \( k_{app} = 1 \)), \( k_\rho \) is the ratio of asteroid density to Earth rock density (in what follows suppose \( k_\rho = 1 \)).

Let take data on explosions in alluvium and take the density of the alluvium as 2200 kg/m³. Finally, the value of momentum is determined by the formula

\[
I_{buried\,N} \approx 4592 \cdot W^{7/6} \cdot G_{buried\,N}(\bar{h}),
\]

where \( W \) is a power, kt,

\( \bar{h} = h \cdot W^{1/3} \), \( h \) is a depth of explosion, m.

The function \( G_{buried\,N}(\bar{h}) \) is given at the table 3.2.1.3.

### Table 3.2.1.3. Depth dependency for buried nuclear explosions \( G_{buried\,N}(\bar{h}) \).

<table>
<thead>
<tr>
<th>( \bar{h} )</th>
<th>-3</th>
<th>-1.75</th>
<th>-1.25</th>
<th>-0.744</th>
<th>-0.588</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{buried,N}(\bar{h}) )</td>
<td>0.536E+3</td>
<td>0.101E+4</td>
<td>0.157E+4</td>
<td>0.273E+4</td>
<td>0.345E+4</td>
<td>0.949E+4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \bar{h} )</th>
<th>0.208</th>
<th>0.623</th>
<th>1.25</th>
<th>2.66</th>
<th>4.17</th>
<th>4.91</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{buried,N}(\bar{h}) )</td>
<td>0.127E+5</td>
<td>0.191E+5</td>
<td>0.290E+5</td>
<td>0.530E+5</td>
<td>0.774E+5</td>
<td>0.882E+5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \bar{h} )</th>
<th>20.9</th>
<th>22.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{buried,N}(\bar{h}) )</td>
<td>0.243E+6</td>
<td>0.251E+6</td>
</tr>
</tbody>
</table>
To determine radius $R_c$, depth $D$, and parameter $L$ can be used Tables. 3.2.1.1 and 3.2.1.2. Note that the “A” method can be used also for nuclear explosions at low altitudes. But the error is largely increase because the great input is given by evaporated asteroid’s matter estimated above in section 3.1.
The benchmark for “A” method

Comparison with (Shubin, Simonenko et al., 1995).
In the above mentioned work there are only intervals of momenta so they have only a reference meaning (Fig. 3.2.1.2).

\[
I_{\text{N-sec}} \times 10^{11}
\]

Fig. 3.2.1.2. Depth explosion dependency of momenta for 1 Mt explosion (Shubin, Simonenko et al., 1995).

Comparison with (Kondaurov and Fortov, 2002).
Fig. 3.2.1.3 shows acceleration of an asteroid due to 1 and 10 Mt nuclear explosions. This power is more above than the interval interested for us now. But there no many data are available and any data are interesting for comparison.

Estimations by “A” method are shown by red curve. They are made for narrow interval of depths and not for high depths when there is a great risk of a camouflet explosion with a zero momenta or can occur the asteroid fragmentation that is extremely unwanted. Of course, it is not for stand-off explosions which described by another way.

The comparison shows that “A” method gives a satisfactory agreement with known data. Moreover, the discrepancy is much less that it could be. Note that the the most part od data
Concerns megaton expressions that is something above the region of interest.

**Comparison with (Adushkin and Spivak, 2007).**

(Adushkin and Spivak, 2007) (for example, see Fig 1.1 of this book) describes influence of depth and altitude of explosion on the part of energy transferred to soil through a contact explosion. Unfortunately, there are no data to “suspend” the data to explosion power values. Except that the notion of the transferred energy is not enough accurate there.

The averaged momenta of explosion products are determined by integration on velocity. If suppose that maximum velocity of asteroid’s ejecta material don’t depend on depth of explosion then it can be supposed that the coefficient of momentum increase about proportional to coefficient of increase in energy. So in the lower comparison the relative value of the transferred energy can be interpreted just as a coefficient of momenta increase. Fig. 3.2.1.4 - 3.2.1.6 show the depth \( h \) dependency of momenta (or altitude dependency if value of \( h \) is negative) in the cases of 10 kt, 1 Mt, and 10 Mt explosions. Red lines show the results by “A” method and green lines show the calculations using data by (Adushkin and Spivak, 2007).

According these graphs “A” method set the momenta through buried explosions low somewhat, the error increases with explosion power.

But the comparison with (Kondaurov and Fortov, 2002) doesn’t confirm this supposition. And if the conservation of energy is considered as a base then discrepancy with (Adushkin and Spivak, 2007) will be lesser. So we can be sure in our approximations.

![Fig. 3.2.1.4. Comparison with data by (Adushkin and Spivak, 2007). Momenta (left figure) and additional velocity of a 140 m asteroid as functions of the depth in 10 kt explosion.](image)

Thus, the analytical formulas (1) и (2) have been verified and can be recommended for calculations in a wide interval of nuclear explosion power and depth. Fig. 3.2.1.7 and 3.2.1.8 show momenta and acceleration of a 140 m asteroid by 10 kt nuclear explosion. The maximum momenta is provided by explosion at 20 m depth and it equals to \( 0.99 \times 10^{10} \) N-sec. The additional velocity is 2.2 m/sec. Blue rectangles show the regions where the accuracy of the formulas is something reduced because additional momentum of vaporized matter is neglected.

Comparison of momenta due to stand-off and buried explosions (Fig. 3.2.1.9) shows that the last method is more effective.
Fig. 3.2.1.5. Comparison with data (Adushkin and Spivak, 2007). Momenta (left figure) and additional velocity of a 140 m asteroid as functions of the depth of 1 Mt explosion.

Fig. 3.2.1.6. Comparison with data (Adushkin and Spivak, 2007). Momenta (left figure) and additional velocity of a 500 m asteroid as functions of the depth of 10 Mt explosion.

Fig. 3.2.1.7. Charge depth dependency of momenta due to 10 kt explosion.

Fig. 3.2.1.8. Explosion depth dependency of additional velocity due to 10 kt explosion. 150 m asteroid density is 2500 kg/m$^3$. 
A 10 kt explosion acts on a 150 m asteroid. D is the depth of an explosion, it has positive value for buried explosions and it has negative value for stand-off explosions.

Surprisingly good correspondence agreement between results of such different methods for buried and stand-off explosions is a good sign but rather it should to be considered as a random coincidence because there are used very coarse approaches in the both cases.
3.2.2. **Blast method to prevent collisions of asteroids/comets with Earth in the case of later detection**

We could name thus case as a “quick response roadmap”.

Nobody can say about the catastrophic collision with a body larger than 1 km that a distributed impact of a cloud of dust and rocks, debris and larger fragments is better than localized impact of an intact body of the same mass. No, opposes in the most probable cases any attempt to disperse a hazardous body just in the nearest vicinity of Earth would have worse consequences for the climate of Earth. The defense of Earth would encompass at farthest regions from the Earth. In the case of comets it should be the region of giant planets. Then the defensive principles would be the same. But of course, such great impact can be also considered *de bene esse*.

So we could use a series of buried explosions to deflect a dangerous space body in this extreme case. The intervals between explosion must be enough for ending up of matter motion. The crater size and the mass ejection can be comparable with the whole size and mass of body. The formulas obtained in 3.2.1 we use with according corrections.

To calculate ballistics we can use a simplified approach (see Fig. 3.2.2.1 below).

![Diagram](image)

Fig. 3.2.2.1 Calculation of an impact parameter in the case when impacts on a dangerous body are doing at several lunar distances.

For the impact parameter after \( n \) explosions we have

\[
\chi_{n+1} = (\chi_n + r_n \cdot \cos \varepsilon) \cdot \cos \phi = \chi_n \cdot \cos \phi + r_n \cdot \sin \varepsilon \approx \chi_n + r_n \cdot \varepsilon_n
\]

The distance to Earth is

\[
r_n = r_0 - n \cdot v \cdot \tau
\]

where \( \tau \) is the time interval between consecutive explosions.

Let use the charge of 1 Mt deepening to 5 m and time interval equals 30 min. Consider deflection of an asteroid similar to Apophis. Its initial diameter consider to be of 300 m and density is of 2300 kg/m³.
Fig. 3.2.2.2 The number of needed rockets for deflection of the above mentioned asteroid depending on distance of the first impact.

Note that the considered asteroid would be fragmented after the first – maximum the third impact. The yellow colour shows the region where we don’t manage to deflect the asteroid due to its fragmentation. The boundary of this region corresponds to 22 days if the asteroid’s flight to Earth. So the conception of protection based on revealing and immediate deflection of an asteroid unexpectedly appeared and running just to Earth is unreasonable.

### 3.3 Buried chemical explosions (TNT)

The presented approach is similar to that for nuclear explosions and it accounts only the momenta created by disintegrated ejecta, neglecting the momenta of vaporized matter. The calculations are based on the data on craters after powerful surface and buried chemical explosions. The appropriate approximation is given in (Vortman, 1969). The momenta calculation itself is based on a single-stage approximation of crater depth $h$ dependence of averaged velocity of ejecta $v_e$ as it was has been done in section 4.2.1.

Then the momentum is determined by

$$I_{\text{burriedTNT}} \approx 4592 \cdot W^{7/6} \cdot G_{\text{burriedTNT}}(\bar{h}),$$

where $W$ is a power, $t$ of TNT, $\bar{h} = h \cdot W^{-1/3}$, $h$ is a depth of explosion, m, the function $G_{\text{burriedTNT}}(\bar{h})$ is given at the table 3.3.1.
Table 3.3.1 Depth dependency for buried TNT explosions $G_{buriedTNT}(\bar{h})$.

<table>
<thead>
<tr>
<th>$\bar{h}$</th>
<th>-0.54</th>
<th>0.0</th>
<th>0.5</th>
<th>1.14</th>
<th>2.02</th>
<th>2.54</th>
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<tr>
<td>$G_{buriedTNT}(\bar{h})$</td>
<td>4.9</td>
<td>23.7</td>
<td>65.2</td>
<td>121.6</td>
<td>225.0</td>
<td>299.3</td>
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<table>
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<th>$\bar{h}$</th>
<th>4.0</th>
<th>5.37</th>
<th>6.21</th>
<th>6.83</th>
<th>8.13</th>
<th>9.31</th>
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<td>$G_{buriedTNT}(\bar{h})$</td>
<td>540.7</td>
<td>874.9</td>
<td>1083.0</td>
<td>1202.0</td>
<td>1314.0</td>
<td>1312.0</td>
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</table>

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<th>$\bar{h}$</th>
<th>10.65</th>
<th>11.71</th>
<th>13.21</th>
<th>14.14</th>
<th>15.4</th>
<th>15.78</th>
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<tbody>
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<td>$G_{buriedTNT}(\bar{h})$</td>
<td>1118.0</td>
<td>850.6</td>
<td>420.9</td>
<td>248.4</td>
<td>114.6</td>
<td>86.7</td>
</tr>
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</table>

Fig. 3.3.1 and 3.3.2 show the momenta and acceleration of an 140 m asteroid of 2500 kg/m$^3$ density after 0.5 t TNT explosion. The maximum momentum is about $0.27 \times 10^7$ N⋅sec and it is achieved when the explosion depth equals 7 m. The additional velocity is 0.8 mm/sec. Note that at shallow explosions the proposed formula gives too small momenta because it doesn’t account the momenta of vaporized matter. And the influence of such gases will be more essential than in the case of a nuclear explosion.

Anyway, the chemical charges are interesting only for the scenario of “drawing” from “a key hole.”

Fig. 3.3.1 Explosion depth dependency of the momentum acting on an asteroid due to 0.5 t TNT explosion.
Fig. 3.3.2 Explosion depth dependency of the additional velocity of a 140 m due to 0.5 t TNT explosion.
3.4 Analysis for asteroid fragmentation at impulsive action

It is intended to estimate maximal momentum, which can be imparted to an asteroid without destruction.

Impact conditions

Impact with the help of distant blast is more “delicate”. Let’s discuss deflection of an asteroid with diameter 150 m. As it follows from the estimations conducted, a distance about 30 m from the surface of such asteroid is optimal for the blast. In this case an area of exposed surface will be limited as it is illustrated in Fig.3.4.1. The limiting value of the central angle is defined by the condition

\[ \alpha_{\text{max}} = \frac{R_a}{R_a + h_E}. \]

![Fig.3.4.1 Exposure geometry](image)

It is difficult to approximate the impulse distribution over the exposed surface (Fig.3.4.2). The easiest approximation could be a linear distribution like \( f(\alpha) \propto \alpha - \alpha_{\text{max}} \). Obviously, a cosine function is a poor approximate for the distribution. And approximations with second or third degree of cosine functions are not better – they have poor reproduction of the distribution “tail” at large angles. The large angles are important since integration is executed with a weighting coefficient proportional to \( \sin^2 \alpha \).

![Fig.3.4.2 Central angle dependence of specific momentum through monolines of 2.6, 10, 20, 30, and 60 keV. The red line shows the specific momentum through Plank spectrum of a 10 keV temperature fireball.](image)
Equation of state for soil

\[ e \text{ – porosity coefficient,} \]
\[ e = \frac{\rho_0}{\rho} - 1, \text{ or } \rho = \frac{\rho_0}{e+1} \]
\[ \rho \text{ – current density of soil,} \]
\[ \rho_0 \text{ – density of solid particles (grains).} \]

Basic property of asteroid substance is its porosity. Let’s examine a structure, which is destroyed under certain pressure. When pressure is relieved, some restitution of initial volume is possible. This property is specific for each soil. It is obvious for cellular or chondrite materials, and even for sand there is a certain structure defined by relative position of grains of various dimensions, by distribution of grains in order of size. At compression the grains move in such way that more compact package appears. Assume that temperature does not influence on mechanical properties of substance. This assumption is fully justified because we examine dynamics of soil in case when only pressure waves act. Let’s use the constitutive equation by N.A. Tsytovich, who is known expert in the field of soil mechanics.

**Region a** (elastic region)
Dynamics of wave in the soil is determined completely by sound speed and substance density:

\[ w_a^2 (\rho - \rho_1) = p, \text{ since } \rho = \frac{\rho_0}{1+e}, \text{ then} \]
\[ p = w_a^2 \rho_0 \frac{e_1 - e}{(1+e)(1+e_1)}. \]
\[ w_a \text{ – velocity of a small disturbance propagation in the region } a. \]

**Region b** (region of loading with destruction)
This region is defined by a point 2, where destruction of soil structure begins and by constants, which are determined basing on fixed speed of disturbance propagation at zero porosity. The constitutive equations are the following:

\[ e_2 - e = k_b \ln \left( \frac{p + p_b}{p^2 + p_b} \right) \]
\[ p + p_b = (p_2 + p_b)e^{k_b} \]  
\[ w^2 = \frac{(p_2 + p_b)\rho_0}{k_b\rho^2} \left( 1 + k_b - \frac{\rho_0}{\rho} \right) \]

\( k_b \) – deformation constant in the region \( b \),  
\( e_2 \) – porosity index in the point 2,  
\( w \) – velocity of small disturbance,  
\( p_b \) – constant.

Note that this equation describes repeated loading too, but with other constants in the equation.

**Region c (unloading of destroyed material)**

Equation of unloading (curve \( c \)) has the same form like the equation of loading at inelastic region, yet with another deformation constant \( k_c \). This constant is defined by the porosity \( e_5 \) at zero pressure (point 5), that, in turn, is defined by the coefficient of porosity restitution at unloading \( \alpha_r \):

\[ e_5 = \alpha_r e_1 + (1 - \alpha_r)e_4 \]

\[ e_4 - e = k_c \ln \frac{p + p_c}{p_4 + p_c} \]

\[ p + p_c = (p_4 + p_c)e^{k_c} \frac{1 + e_4 - \rho_0}{\rho k_c} \]  
\( p_c \) – constant.

Adduced equations describe standard behavior of soils in cycles loading-unloading, including soil consolidation at ramming.

**Soil parameters**

The following parameters of above relationships were used in estimations for a typical asteroid.  
\( w_0 = 1000 \text{ m/s} \)  
\( \rho_0 = \rho_3 = 2700 \text{ kg/m}^3 \) – density of solid particles (grains)  
\( \rho_1 = 2000 \text{ kg/m}^3 \) – initial soil density (point 1)  
\( \rho_2 = 2010 \text{ kg/m}^3 \) – soil density at boundary of elastic region (point 2)  
\( p_b - p_c = 1.0 \times 10^7 \)  
\( k_b = 6.387E-2 \)  
\( \alpha_r = 0.3 \) is a coefficient of porosity restitution at unloading (defines deformation constant \( k_c \)).

**Strength**

Material strength is an important characteristic of fragmentation. Known evaluations for “iron” meteorite Sikhote-Alin meteorite: strength of polycrystalline fragments was equal to 4.4 kg/mm² (4.4×10⁵ Pa). Investigations of stony meteorites show high strength (Table 3.4.1). Here \( \sigma^+ \) is a compression strength, 10⁵ Pa; \( \sigma^- \) is a tensile strength, 10⁵ Pa.
Table 3.4.1 Stony meteorite strength

<table>
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<tr>
<th>Meteorite</th>
<th>$\sigma^+$</th>
<th>$\sigma^-$</th>
</tr>
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<tbody>
<tr>
<td>Krymka</td>
<td>1600</td>
<td>220</td>
</tr>
<tr>
<td>Elenovka</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>Tsarev</td>
<td>2220</td>
<td>260</td>
</tr>
<tr>
<td>Kunashak</td>
<td>2650</td>
<td>490</td>
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<tr>
<td>Kyushu</td>
<td>980</td>
<td>110</td>
</tr>
<tr>
<td>Pultusk</td>
<td>2130</td>
<td>310</td>
</tr>
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</table>

Such a high scatter of properties. Therefore it is clear that these values for strength are only tentative due to high selectivity of investigations. Moreover, the rubble-pile model is widespread for asteroid substance. Thus, even zero strength is possible; so fragmentation feasibility is limited by gravitational forces only (the Van der Waals forces are eventual; they are weaker, certainly, than forces defining strength of the earth rocks like granite or basalt).

Typical graphs of pressure are plotted against density in Fig.3.4.4.

\[
\begin{align*}
\sigma \times 10^{-8} & \\
\rho \times 10^{-3} & \\
\end{align*}
\]

Fig.3.4.4 – Pressure dependency versus density in cycle “loading-unloading” (load-release)

\[
\begin{align*}
\nu \times 10^{-3} & \\
\rho \times 10^{-3} & \\
\end{align*}
\]

Fig.3.4.5 – Dependency for velocity of small disturbance propagation versus density in cycle “loading-unloading” and dependency for shock wave velocity versus density behind shock
Dependencies for velocity of small disturbance propagation for various cases are shown in Fig.3.4.5. It is seen in this figure that at high loads a shock wave has to originate, and at pressure reduction an elastic precursor is separated from it, and depression wave is expanded.

Destruction of material does not induce asteroid fragmentation by itself; residual velocities of fragments are of great importance. A plot of mass velocity behind shock is presented in Fig.3.4.6.

**Propagation of pressure wave in the asteroid body and its fragmentation**

When strong wave propagates in the asteroid substance, strong energy dissipation takes place. The first meters are of great importance for the dissipation.

Let’s consider pressure wave propagation in the asteroid with diameter 150 m and the above density. A wave induced by momentum, which imparts the asteroid acceleration at 0.1 m/s, is examined. Duration of impact is defined by characteristic gasdynamic time of dispersion of evaporated surface layer (rectangular distribution of momentum by time is considered).

Profiles of pressure distribution in the first moments after effect of blast are presented in Fig.3.4.7. Profiles of mass velocity distribution are presented in Fig.3.4.8.
Computations were executed with separation of shocks.

It follows from the plots adduced above that strength of shock wave at the very beginning is not very high, at any case an elastic precursor is separated in it.

Essential reduction of the wave strength takes place at the first meters of its propagation.

Mass velocity behind the shock is high enough, it is sufficient for dispersion of fragments of the asteroid discussed. Yet, at the first millisecond (see the curve for $t = 0.107E-02$ sec) a pressure wave (slv) is formed that causes reduction of this mass velocity. No front splinter takes place. This is just a wave; shock wave has no time to develop.

Thus, the asteroid behavior is defined, to a great extent, by propagation of elastic precursor in the asteroid body. This problem was analyzed using AUTODYN (ANSYS package). Soft concrete was used as a material-analog.

Figures 3.4.9-3.4.12 illustrate pressures in the asteroid body at the following characteristic time moments:

- $t = 2,502$ msec – formation of primary wave,
- $t = 19,3$ msec – the wave passes the asteroid center,
- $t = 29,3$ msec – the wave coming to the rear surface of the asteroid, and
- $t = 39,31$ msec – pressure field after wave reflection from the rear surface.

The study did not show the asteroid fragmentation due this load.
Fig.3.4.9 Velocity impulse 0.1 m/s. Computations with AUTODYN-2D (v14) (ANSYS package). $t = 2,502$-msec
Fig. 3.4.10 Velocity impulse 0.1 m/s. Computations with AUTODYN-2D (v14) (ANSYS package). $t = 19.3\text{-msec}$
Fig. 3.4.11 Velocity impulse 0.1 m/s. Computations with AUTODYN-2D (v14) из ANSYS пакаже. t = 29.3 msec
Let’s discuss feasibility of the asteroid acceleration at 1m/s.
Motion of the stronger wave in the asteroid body that cause the asteroid acceleration at about 1m/s (Fig.3.4.13-3.4.16); here characteristics time moments are the following:
\[ t = 2,505 \text{ msec} \] – formation of primary wave,
\[ t = 21,0 \text{ msec} \] – the wave passes the asteroid center,
\[ t = 31,01 \text{ msec} \] – the wave coming to the rear surface of the asteroid, and
\[ t = 36,0 \text{ msec} \] – pressure field after wave reflection from the rear surface.
In this case partial fragmentation of the asteroid takes place.

Note that in this case something like a crater begins to originate that may cause significant increase of momentum. Therefore a value of order 1 m/s can be taken as the upper boundary of velocity imparted to the asteroid with dimensions 150 m.

Fig.3.4.12 Velocity impulse 0.1 m/s. Computations with AUTODYN-2D (v14) (ANSYS package). \( t = 39,31 \text{ msec} \)
Fig.3.4.13  Velocity impulse 1 m/s. Computations with AUTODYN-2D (v14) (ANSYS package). $t = 2,505\text{-}\text{msec}$

Fig.3.4.14. Velocity impulse 1 m/s. Computations with AUTODYN-2D (v14) из ANSYS. $t = 21,0\text{-}\text{msec}$
Fig. 3.4.15. Velocity impulse 1 m/s. Computations with AUTODYN-2D (v14) (ANSYS package). $t = 31.01$ msec

Fig. 3.4.16. Velocity impulse 1 m/s. Computations with AUTODYN-2D (v14) (ANSYS package). $t = 36.0$ msec
Note
Feasibility of front splinter is defined to a great extent by the coefficient of restitution $\alpha_r$; if this coefficient exceeds 1 then in the first moments the velocity distribution illustrated in Fig.3.4.17 takes place.

\[ \begin{align*}
\nu, \text{ m/sec} \\
0 & \quad 0.1 \\
2 & \quad 0.2 \\
4 & \quad 0.3 \\
6 & \quad 0.4 \\
8 & \quad 0.5 \\
10 & \quad 0.6 \\
\end{align*} \]

Fig.3.4.17. Distribution of velocities in the first moments after impact at $\alpha_r > 1$.

In this case front splintering takes place. Front splinter carries away insignificant part of the asteroid mass, but this can induce a substantial increase of momentum acted on the asteroid and, consequently, a risk of asteroid fragmentation during propagation of pressure wave. However such a phenomenon can appear in dense medium only and it is connected with thermal expansion of substance. This event does not occur in porous medium.

4 Summary

The report presents two concepts on the Earth protection. The first conception is concentrated on deflection of hazardous bodies in cases when prevention time is not very short and it is possible to use nuclear blast of comparatively low energy in order to avoid fragmentation of a hazardous body. This case is the most probable if a hazardous asteroid is detected. In the second concept it is supposed that prevention time is very small. Hence it is required maximum powerful impact on a hazardous body in order to destroy noticeable part of this body. Such necessity may take place most likely in case of appearance of a hazardous comet.

There were developed numerical codes for calculation of thermodynamic characteristics of silicates, for solution of the transport problem of Roentgen radiation and for estimation of the momenta from stand-off nuclear explosions. The estimated value of final momenta have errors about 30% mainly due to uncertainty in thermodynamics.

Then the new interpretation of results of industrial explosions was proposed that allowed to estimate the momenta due to nuclear and chemical blasts.

It is shown that the neutrons of nuclear bombs have no additional effects on the transmitted momentum.

It is shown that the 150 m asteroid can take additional velocity up to about of 1 m/sec withtout fragmentation if it has properties of a soft concrete.

The demo mission will be planned for a stand-off nuclear explosion. The results of calculated momenta can be used for planning of this demo mission.
The members of consortium can implemented the code on Roentgen radiation transport and 1D hydrocode for pressure wave in soils as the most accurate codes for these processes.

**The results of development of the concept are the following.**

1. Analytical formulas are proposed for estimating the impulses of force required for deflection of a hazardous asteroid at the next scenarios:
   - «withdrawal» of an asteroid from a «keyhole».
   - regional deflection,
   - deflection at 3 radii of the Earth,
   - deflection of asteroid orbit at the radius of the Earth.

2. The techniques are suggested for calculating a value of mechanical impulse imparted to the asteroid at buried and near-surface nuclear explosions, and also at buried TNT explosion.

3. The techniques have been developed for solving three physical problems, which necessary calculate the effect of near-surface nuclear explosion: X-radiation transfer, thermodynamics and vaporization of asteroid substance, and mechanics of vaporized material dispersion.

4. The numerical technique has been developed for calculating X-radiation transfer taking into consideration incoherent scattering.

5. Forsterite (mineral) is chosen as a material, which simulates the matter of probable hazardous asteroid. The complete thermodynamic equation of state is proposed that describes forsterite vaporization.

6. A method is elaborated for solving one-dimensional problem on dispersion of evaporated substance based on the finite jump method.

7. As an example, mechanical impulse was calculated for buried and near-ground nuclear explosions, power 10 kt and 100 kt. Impulse was also calculated for buried TNT explosion, power 0.5 tons.
   The following capabilities of the mission on effect upon an asteroid being at an orbit of low inclination (Analog is asteroid “Apophis”).
   **Buried nuclear explosion** of 10 kt power will ensure solving any of the above problems, including
   - deflection of the orbit at the radius of the Earth with optimal choice of the point of application;
   - deflection of an asteroid at three radii of the Earth if prevention time for collision is at least 0.5 year.
   **Near-surface nuclear explosion** will ensure
   - «withdrawal» of an asteroid from a «keyhole»;
   - regional deflection of an asteroid if prevention time for collision is at least 0.5 years;
   - deflection at 3 radii of the Earth can be provided in that case only, if prevention time for collision is over 5 years.

   **Buried TNT explosion** may ensure «withdrawal» of an asteroid from a «keyhole» at rather weak limitations imposed on prevention time for the asteroid passing through the «keyhole».
In our opinion, it is necessary to accumulate the results obtained by the Consortium in form of a data base, which combines data on NEO, possible means of counteraction, and computation tools.
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