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# Investigation of Inner Channel Effect

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**Abstract:** The article deals with measurement of velocities of detonation in special charges constructed with an inner channel. The detonation course of these charges was investigated by measuring the velocities of detonation. The abnormalities found in the detonation course were interpreted as a consequence of the channel effect. For better understanding of the problem, the operation of channel effect was also investigated by means of a numerical simulation using the method of finite elements in the system ANSYS/LS DYNA3D.

**Keywords**: channel effect, cast TNT, VOD, numerical simulation, LS DYNA

## Introduction

The original impulse that initiated detailed study of the problem at hand was given by dealing with the technical problems connected with measuring velocities of detonation (VOD) in booster charges KIMPRIME (see the illustration picture in Figure 1; for the parameters of the charges tested see the survey below). These charges are produced by casting TNT from demilitarized ammunition. The basic purpose of the booster charges KIMPRIME is to reliably initiate BULK explosives in boreholes of larger diameters (minimum diameter bigger than *cca* 60 mm). The construction of the KIMPRIME charges is based on efficient exploitation of the longitudinal central channel. This channel serves for inserting the detonating cord, wires for electric initiation, or detonation tube in the case of non-electric initiation, which are fixed in opposite direction in the hole for the detonator in the booster body. Thanks to this method of fixation of electric wires (or detonating cord or tube, as the case may be) it is possible to easily and safely carry the non-adjusted charges to the bottom of borehole.


**Figure 1.** Booster charge KIMPRIME – appearance, consumer packaging (left), detail of the central channel in cross-section in dismantled charge (right).

**Parameters of KIMPRIME $\phi$ 50 mm charges**

| | |
|---|---|
| **Dimensions:** | |
| diameter | 50 mm |
| length | 350 mm |
| longitudinal hole | 10-10.8 mm, cone |
| opening for initiator | 7.85 mm |
| **Material:** | |
| explosive | TNT, from demilitarized ammunition, cast |
| booster element | A IX-1 (from demilitarized ammunition) – compressed or Np 10 – compressed |
| sealing | paraffin |
| covering | plastic (PE) tube + lids |
| **Mass:** | |
| total | 960-970 g |
| booster element | 20 g |
| sealing | *ca* 10 g |

This otherwise elegant and reliable solution was accompanied by a problem consisting in the questionable determination of velocity of detonation of these (unsealed) charges by means of the classic method – in the START/STOP system using an electronic chronometer (a modified method B according to standard ČSN 66 80 66 [1]). The measurement with help of ionization sensors often failed from the very beginning of the experiments due to the STOP sensor failing to connect the circuit. This led to a hypothesis of potential negative effect of the central channel that made itself felt in the measurement by the so-called "channel effect".

# Theory

### Channel effect

According to the generally accepted definitions [2], the internal channel effect consists in an interaction of shock-compressed air in front of the face of propagating detonation wave with the surface of the explosive in the channel (Figure 2).

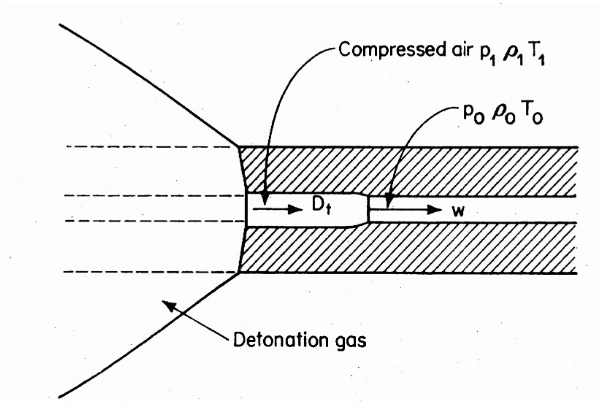


**Figure 2.** Scheme of principle of function of internal channel effect (taken from [2])

It is presumed that the precursory action of shock-compressed air markedly affects the basic properties of the explosive, which subsequently makes itself felt in their detonation parameters. These include above all the initial density of explosive, where it is assumed that the action of pre-compression can lead as far as reaching the densities close to the theoretical maximum density (TMD) – the density of single crystal. In the case of brisant explosives, this fact helps to fulfill the basic condition for achieving the circumstances enabling a detonation transformation of the explosive and exploitation of its energy in regimes near to the ideal ones – with the corresponding maximum effects.

The fact that the detonation parameters measured – above all the velocity of detonation – in some cases markedly surpassed the maximum theoretical limit was interpreted by a "pre-initiation" (not specified in any more detail) of the explosive at the inner surface of channel by the action of high pressure and temperature at the face of propagating shock wave. This "pre-initiation" should subsequently enable the propagation of detonation wave up to the observed super-ideal velocities observed with some cast explosives (TNT, TNT/TETRYL, picric acid), moreover, without any obvious dependence on the general (initiation) sensitivity of the explosive [3].

# Experimental

**Measurement of detonation velocities of KIMPRIME**

For the investigation of detonation course of the booster charges KIMPRIME studied, we adopted the method of continuous recording of the course of detonation wave using a HANDITRAP apparatus (MREL, Canada) [4]. The electronic record of the resistance changes of measuring probe (with the frequency of 1 MHz in the sampling), which were shortened by the propagating detonation wave depending on time, enables getting a good idea of the course – the uniformity – of the detonation along the whole length of the charge examined.

The obtained and evaluated graphical time dependence of change of resistance/trajectory unambiguously showed an instable and non-ideal course of detonation of unsealed charges KIMPRIME (see Figure 3).

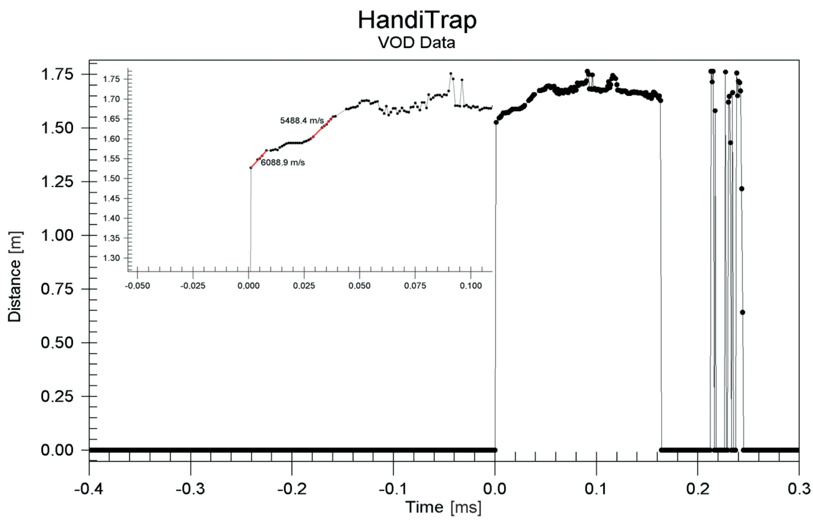


**Figure 3.** Course of distance/time dependence with a charge with failing detonation – the detail in picture shows an adapted and evaluated recording.

From the recording presented in Figure 3 it is possible to see the development of the detonation which, according to the values of velocity of detonation observed, did not (not even in the beginning phase) reach the values corresponding with the used densities and layers of the explosive. It is obvious that the detonation process very soon showed a tendency to oscillate, and after the second, third of the charge one cannot speak about proceeding detonation any more (not even in non-ideal regimes). The recording rather indicates a deflagration process, which can also be documented by the fine residues of non-reacted explosive scattered in wider surroundings (protection walls of testing gallery).

The presumed influence of channel effect under the given conditions (cast tritol with low thickness of layer-wall) can unequivocally manifest itself just by the disintegration of the charge without detonation. This very well corresponds with the absence of the STOP signal during discontinuous measurement of velocity of detonation with help of ionization sensors. Critical in this context is the low sensitivity of cast TNT to initiation by compression wave (~ 9 GPa [5]) – it is calculated with a more distinct participation of micro-mechanism of initiation [6]. Other critical factors are the low strength and high fragility of cast TNT and especially the relatively high value of critical diameter (the value given for cast TNT with the density of 1.62 g $cm^{-3}$ is 26.9 mm! [7]). Thus, the layer of *ca* 20 mm, which forms the thickness of wall around the channel (with the overall diameter of charge 50 mm), can really represent a limit for unsealed charge even if a high-quality booster element is applied (compressed PETN or RDX in this case).

**Technological solution to channel effect in VOD measurements**

The technological solution proper to the problems of VOD measurements, which follows from operation of the channel effect, is very simple. It consists in elimination of the longitudinal hole, which can be realized by its filling-sealing with suitable inert material, *e.g.* sand.

The measurements of the charges modified in this way provide typical (correct) VOD recordings (see Figure 4).

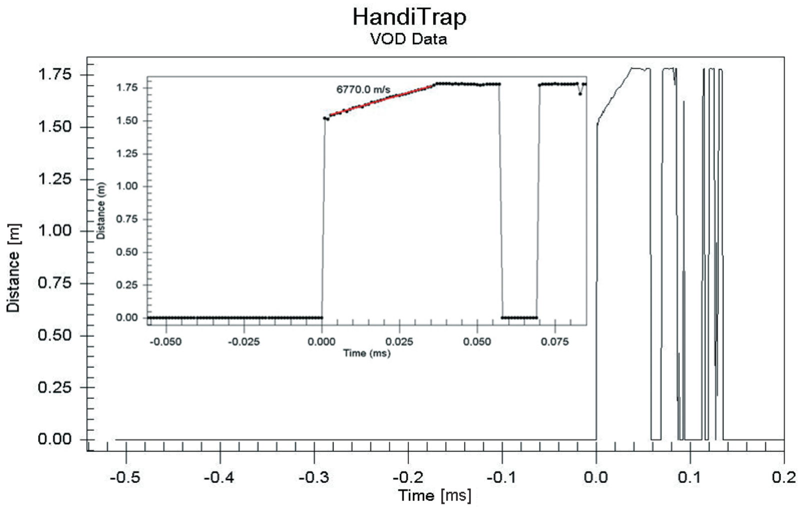


**Figure 4.** Evaluation of continuous measurement of KIMPRIME charge: typical correct recording of measurement with help of HANDITRAP.

Nevertheless, the found value of stable velocity of detonation, ~ 6800 m $s^{-1}$ for a charge of *ca* 1.6 g $cm^{-3}$ density, indicates a detonation that is not in a perfectly ideal regime, which can most probably be ascribed to the low thickness of layer of the detonating explosive.

However, it is important to bear in mind that, with regard to the fact that the KIMPRIME charges are designed as boosters for industrial explosives in bore holes, on no account should the results of their testing without corresponding sealing be competently interpreted in connection with their factual practical applicability.

The found deviations of the detonation process with KIMPRIME charges represented a significant motivation for attempts at investigation of obvious participation of channel effect with help of numerical simulation.

The geometrical configuration of charge (its inner channel) unequivocally predetermines that here the jet of cumulated products of detonation can and will be formed, and this will be reflected in a certain way in the behavior of the charge during the detonation. The close connection between cumulation and channel effect has already been described [8]. The experience gained at DTTX from the studies of cumulation of gaseous products of detonation [9, 10, 11] made it possible to successfully predict the mechanism of formation of cumulative jet of detonation products and their interaction with the charge, *i. e.* its manifestation in the channel effect. Hence, the chief aim of the simulation experiments carried out was to prove (and/or correct) the anticipated operation of cumulative effect in the case of the inner channel effect in the charges studied.

## Numerical modeling

The modern testing methods, adopting continuously improved technology of measurement and apparatus, significantly extend the possibilities of study of detonation processes. Especially useful is the fact that the results are obtained distinctly faster and are more reliable. However, an unavoidable role is still played by the tests making use of visualization means, as it can be shown by studies carried out in the cognate area – the outer channel effect [16].

### Simulation experiments

The experiment studied was simulated by the calculation code **LS-DYNA 3D** [12] in the system **ANSYS** [13].

The overall geometry of simulated experiment is depicted in Figure 5. In the numerical simulations, only one quarter of real geometry was simulated with respect to the cylinder symmetry of the problem (see Figure 6). This reduction made it possible to adopt a larger number of elements of the problem and, hence, to obtain a more precise description of spreading detonation wave through the charge modeled.

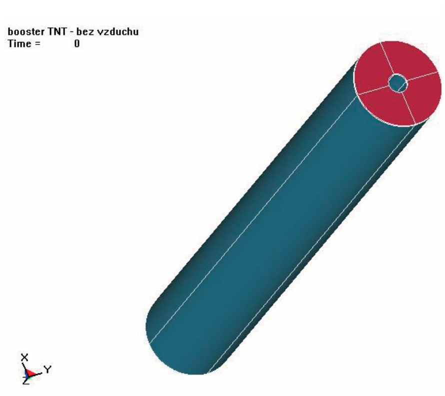


**Figure 5.** Global geometry of system.

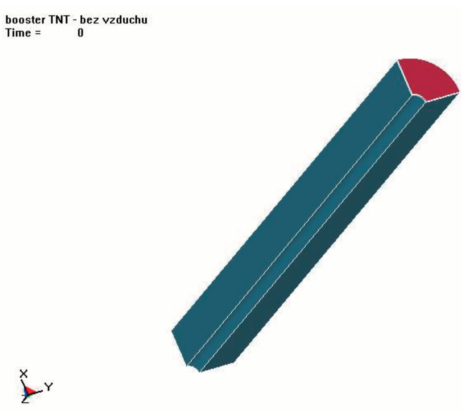


**Figure 6.** Real geometry of solution – 1/4 segment.

The calculation model used can briefly be characterized as follows:

- the calculations were carried out by the calculation program **LS-DYNA3D Code, ver. 950e**;
- three-dimensional (3D) elements of the brick type were adopted (8 nodes, one-point integration, rigidity regulation of non-stabilities of the "hourglass" type)
- number of finite elements of the model: **303072**;
- number of nodes: **280800**;
- the calculation was carried out with one quarter of the real geometry of system with the respective boundary conditions of symmetry;
- important simplifications:
  - the calculations were carried out with the presumption of the experiment performed in vacuum;
  - ideal initiation of the explosive over the entire surface of the lower face (the x-y plane) of the charge.

The calculation mesh (see the detail in Figure 7) was chosen so as to get the smallest possible elements of the system with due respecting the capacity of the available hardware – in the given model, the characteristic length of brick is 1 mm.

The description of behavior (expansion – acceleration) of explosion products of the explosives used the model by **Johnson-Wilkins-Lee** ($p_{eqs}$ is the pressure, $E$ is the inner energy, $\rho$ is specific density) in the following form:

$$p = A\cdot\left(1-\frac{\omega}{R_1}\cdot\frac{\rho}{\rho_0}\right)\cdot e^{-R_1\frac{\rho_0}{\rho}} + B\cdot\left(1-\frac{\omega}{R_2}\cdot\frac{\rho}{\rho_0}\right)\cdot e^{-R_2\frac{\rho_0}{\rho}} + \omega\cdot E\cdot\frac{\rho}{\rho_0}$$

with the following parameters of the explosive used – TNT (at TMD – according to [14]):

- velocity of detonation – **D** = 6930 m s$^{-1}$,
- Chapman-Jouguet pressure – $\mathbf{p_{CJ}}$ = 21.0 GPa.

The propagation of detonation wave in the explosive was described by the model of the so-called "burn up", which on the basis of compression of element of explosive calculates the increase in pressure by the relationship:

$$p = f\cdot p_{eqs}$$

$$f = (1 - V)/(1 - V_{CJ})$$

where: $V$ is simultaneous specific volume, $V_{CJ}$ is volume at the pressure in C-J plane. As soon as the factor $f$ is greater than 1.0, it is reset to the value of 1.0 and the whole element detonates – assumes the properties of the detonation products.

The “compression” model “burn up” proved unequivocally the most suitable for studies of similar problems, because it very well respects the propagation of detonation bound with the pressure-conditioned initiation of the respective elements, which corresponds very well with the reality.

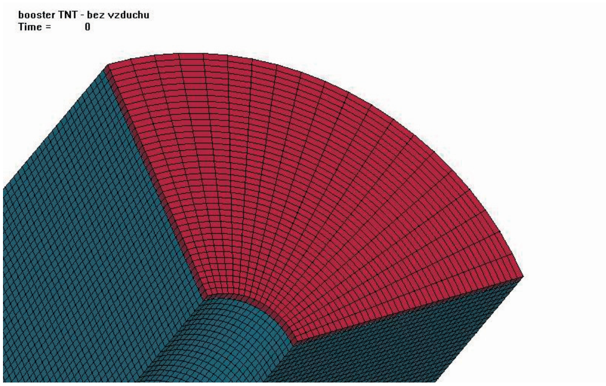


**Figure 7.** Real geometry of calculation detail of mesh.

The main result from the simulation was a realized visualization of the cumulative jet formed (see the sequence of snaps in Figure 8).

As it can be seen from Figure 8, a cumulative jet of products is formed in the inner channel. The conditions of collision of the elementary jets of products result in formation of incoherent cumulative jet, which subsequently overtakes the source detonation wave and interacts with the non-reacted explosive before its front. In the model adjusted for compression initiation of relatively low potential (an analogy with highly sensitive explosives) there takes place initiation of the explosive and subsequent propagation of detonation wave parallel to the charge axis (perpendicularly to the original detonation wave). In the model studied, where the explosive used (TNT) was relatively insensitive, the interaction of cumulated products with the explosive at the surface of the inner channel (shock wave) need not make itself felt as an initiation impulse for ideal detonation. In a limit case, we can also calculate with simple mechanical destruction of the charge.

Due to numerical instabilities connected with the extreme prolongation of elements in the center of cumulative jet, it was impossible – in the given model – to follow further behavior of the excited detonation wave and its interactions with the original detonation wave.

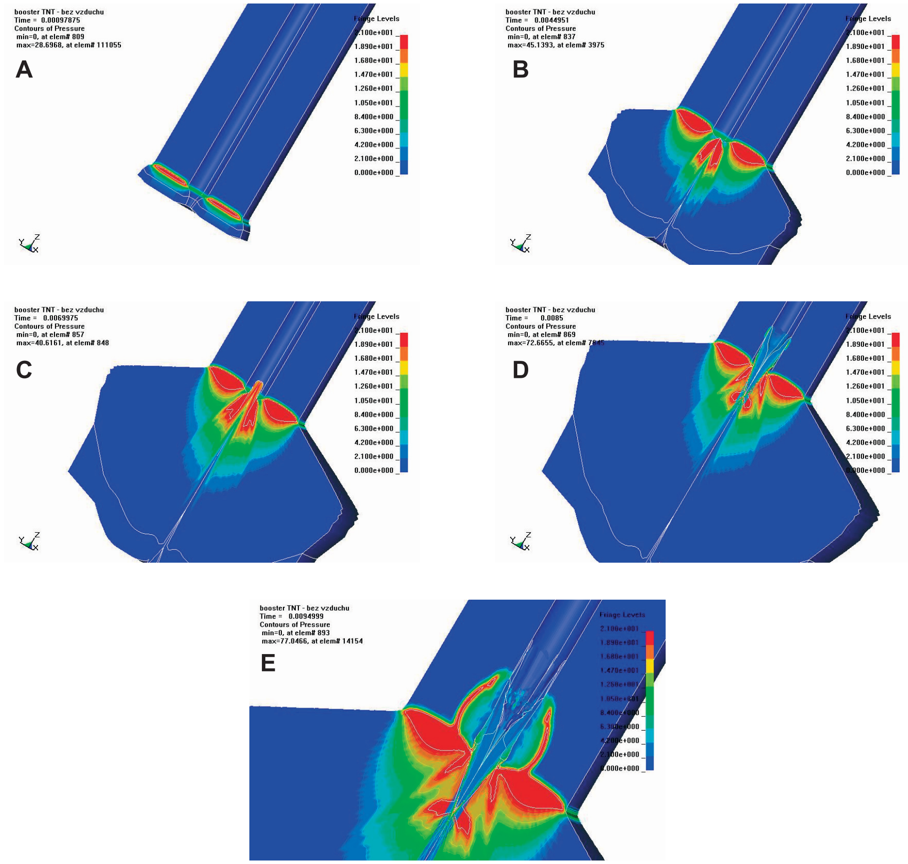


**Figure 8.** Propagation of detonation wave and formation of cumulated jet of products in inner channel – pressure profile.
A) The beginning of progression of detonation wave through the charge, time ~ 1 microsecond from initiation.
B) The beginning of formation of cumulative jet, time ~ 4.5 microseconds.
C) The cumulative jet formed begins to overtake the source detonation wave, time ~ 7 microseconds.
D) The front of non-coherent cumulative jet of products hits the channel wall, the beginning of secondary initiation, time ~ 8.5 microseconds.
E) Detail of cumulative jet formed at time ~ 8.5 microseconds, interaction of the primary and the secondary detonation waves.

Therefore, another simulation experiment was devised and realized: it started from radial toroidal initiation at the inner surface in the center of channel. The illustrative series of pictures in Figure 9 clearly show that this simulation did confirm the presumption that the shape of detonation wave during its propagation is gradually transformed from spherical into planar one (as the radius of the sphere increases), and new conditions are adjusted for formation of the next cumulative jet. Therefore, it can be presumed that the whole process can thus periodically repeat with a certain equilibrium frequency. This would also very well explain the limits of possible acceleration of detonation by means of the inner channel.

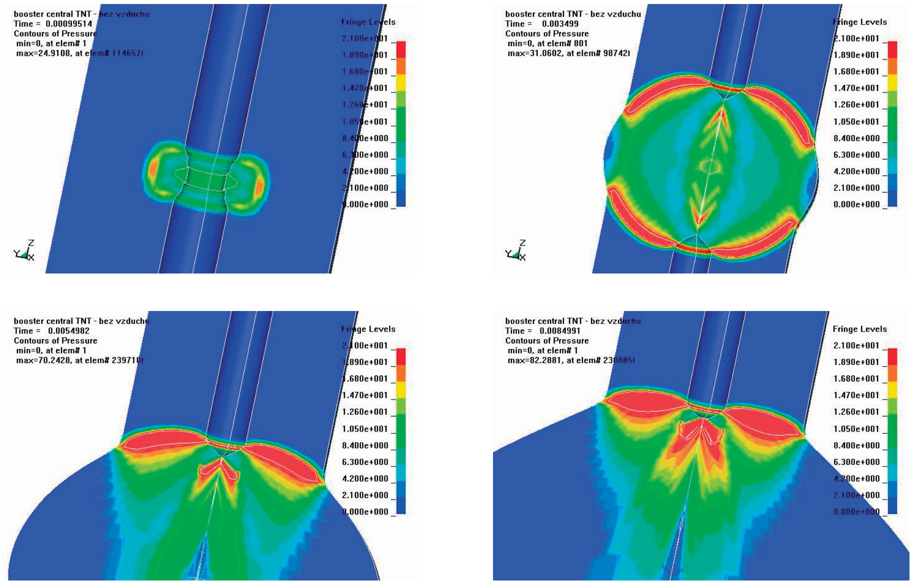


**Figure 9.** Propagation of detonation wave and formation of cumulative jet of products in inner channel during radial toroid initiation at the inner surface in the center of channel – time ~ 1 to 8.5 microseconds, pressure profile.

The described realization of simulation experiments in vacuum, *i.e.* with neglecting the effect of air on the cumulative jet in inner channel, obviously deviates from real conditions. And this simulation deviates fundamentally from the current ideas about mechanism of operation of channel effect – by means of the overtaking shock wave in compressed air. In spite of that, on the basis of experience gained from realization of other experiments connected with studies of propagation of cumulated jet of detonation products in real medium [10, 11], inclusive of the closed space – a channel [12], it is obvious that the resistance of medium – air – principally affects the propagation of cumulative jet. On the other hand, it is seen that also the cumulative jet hindered by the medium, after taking its optimum form in this medium, moves at distinctly higher velocity than are the velocities of the remaining parts of the system, inclusive of the velocity of detonation. Hence, it is possible to formulate a justified assumption that the cumulative effect is a dominant element of realization of channel effect in the sense of attaining a distinctly higher overall velocity of the detonation transformation in a system with inner channel.

However, the participation of effect of compressed air in front of the propagating detonation face and of the cumulative jet on the whole process cannot definitely be neglected. A certain guideline on the evaluation of contributions of individual components (cumulative jet and the hindering air in front of its face) can also provide the maximum resultant velocities of the cumulative jet face read from the simulation (see Figure 10), which surpass 20000 m $s^{-1}$, whereas at real conditions, analogous cases presume the maximum attained velocities of about 13000 m $s^{-1}$ [9]. On the other hand, a number of signs indicate that the precursory action of shock-compressed air will be predominant for the resulting effect. This is in accordance, above all, with the observed continuous (non-oscillating) courses of velocities of detonation as well as their absolute values, which only slightly exceed the nominal maximums.

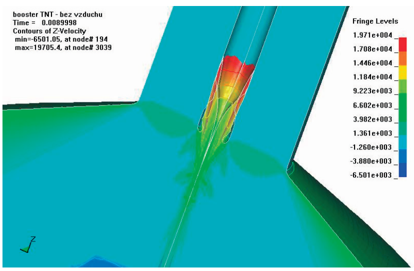


**Figure 10.** Velocity profile of cumulated jet of products in inner channel, time ~ 9 microseconds, maximum velocity *ca* 19700 m $s^{-1}$

Neither the quantification nor particular way of its realization can so far be unequivocally documented and simulated with available apparatus. The basic drawback in this respect is the absence of reliable data, which would exactly describe and define the condition and behavior of shock wave of compressed air at the given conditions. It is, of course, anticipated that this theoretically and practically interesting topic will be given intensive attention in the future, too.

A parallel interesting finding obtained from the simulation experiment is the little expected but obviously justified presumption that the inner channel effect (in contrast to the outer channel effect) can also operate in vacuum.

# Conclusion

Using the methods of numerical simulation, we examined the operation of channel effect in a particular case of detonation of charges made of cast TNT and containing a central channel. The main finding of the present study is the support given to potential way of realization of inner channel effect by means of cumulation of gaseous detonation products in combination with a precursory action of shock-compressed air in the channel.

**Acknowledgement**

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