Assessing the possible consequences of Starship explosion above the launch pad

Yu. I. Lobanovsky

Since then I never pay attention to anything by "experts". I calculate everything myself.
R. Feynman

Summary

This work shows that in an unfavorable development of events, a process of self-oscillations of Pogo type that arises and spontaneously goes out at the start can lead to explosion of Starship above the launch pad. Based on analysis of thermobaric weapon effects, data characterizing the destruction from the shock wave for five known large and very large explosions, as well as information on the destruction caused by the blast of giant Soviet N1 rocket at Baikonur Cosmodrome, estimates of the energy of this explosion, as well as Starship explosion during start were made. All this made it possible to determine the levels of possible destruction in the settlements and cities of Cameron County, Texas and Matamoros Municipality, Mexico, closest to the starting position of Starship, as well as possible number of wounded there.

Key words: Pogo, self-oscillations, accident, Starship, thermobaric weapon, nuclear explosion, shock wave, pressure, destruction

Symbol list

a, b and c – empirical coefficients in Sadovsky's formula
c – speed of sound
E – explosion energy
E_e – calculated explosion energy
f_e – own frequency of rocket hull
f_n – frequency of hydroacoustic oscillations
H – explosion height
L – length
L_{eq} – equivalent length of the oscillatory circuit
p – pressure
Δp – pressure drop at front of the shock wave
R – radius
α – oxidizer excess coefficient
ξ – reduced radius

I. Introduction

Papers [1 – 3] describe the causes of explosions that occurred with both stages of Starship stack during its second flight (IFT-2). It was shown there that both explosions, which led to the destruction of these stages, occurred due to self-oscillations of Pogo type, which arose as a result of the interaction with elastic vibrations of the body and of hydroacoustic oscillations in the oxygen supply lines to the engines. Elastic vibrations affect the movement of the object in which they originated, so traces appear on the graph of its acceleration in the form of a sharp change in this parameter. These peaks and dips in acceleration were noticeable during IFT-2 in the periods preceding the explosion of the second stage [3], but before the explosion of the first stage they were invisible due to the fact that the stage performed sharp maneuvers that completely erased traces of any other influences on it flight path [2].

II. The appearance of Pogo type self-oscillations in the initial phase of Starship acceleration

Moreover, even in video of IFT-2 in the window demonstrating the object's flight speed [4], its sharp fluctuations are noticeable in a period of time from approximately 5 to 20 seconds from the moment of launch. This is also confirmed by the acceleration graph shown in Fig. 1. Sections of the acceleration trajectory of Starship stack in both the first (IFT-1) and the second (IFT-2) test flights are shown here, up to the 160th second, so that the launch section can be shown on a larger scale.

In Fig. 1 (see [5]), a comparison was made over time (in seconds) of four Starship parameters in two flights, namely: rocket acceleration (in cm/s2), speed (in m/s), altitude (in hundreds of meters), as well as direct (horizontal) flight range (also in hundreds of meters). Data related to the second flight (IFT-2) is displayed with thick lines, and data related to the first flight (IFT-1) is displayed with thin lines. Acceleration is shown with yellow curves, speed with blue lines, altitude with olive lines, and range with purple lines.

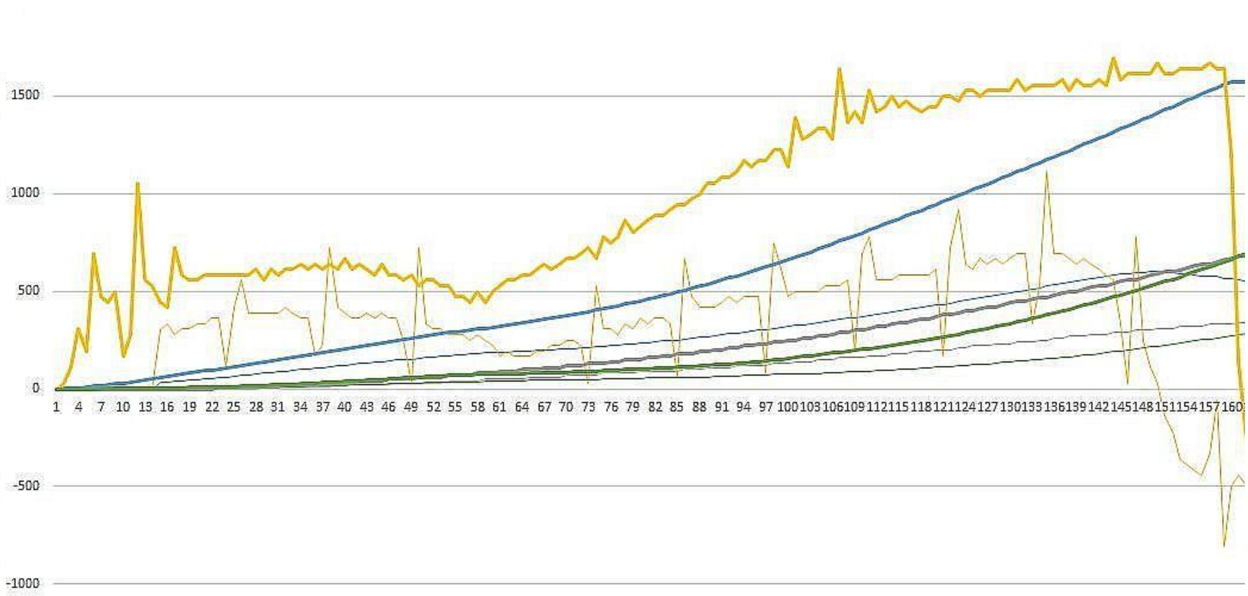

Fig. 1 – Acceleration, speed, altitude and range of Starship stacks in the first and second flights [5]

We are now only interested in the acceleration of the rocket vehicle in the second flight – this is the thick yellow line. From the 4 second mark, the smooth and rapid increase in the acceleration of the rocket stops, and up to the 19th second its sharp fluctuations are observed, more or less similar to those observed in the first flight, and their scale far exceeds anything that can be seen further on the acceleration graph on the second flight. But these fluctuations stopped as quickly as they began.

The most natural explanation for such sudden changes in acceleration is the occurrence of self-oscillations of Pogo type in Starship stack, the envelope of which is shown in Fig. 1 as section of the acceleration graph at the start. In paper [1], an estimate was given for the frequency of own elastic vibrations of stack hull – f_e = 11.5 – 12.5 Hz. In order for Pogo type process to occur, it is necessary that the frequency of hydroacoustic oscillations f_n in any of the two types of fuel lines feeding the rocket engines be close to this value or a multiple of it. For variants of the geometry of these lines, previously presented in [1], the frequency of hydroacoustic disturbances in the oxygen path when Raptor-2 engines operate at nominal mode can be in the range fe = 9.7 – 11.0 Hz, see Table 1, and they, in general, are outside the elastic frequency range.

Table 1

Rocket Stage Engine	**p_2/p_1**	**L_1 (m)**	**L_2 (m)**	**L_3 (m)**	**L_{eq} (m)**	**f_n (Hz)**
c = 930 m/s						
Starship Super Heavy Raptor-2	170	0.30	3.00	3.30	19.6	11.9
	135				17.5	13.3
	170	0.35		3.35	21.2	11.0
	135				18.9	**12.3**
	170	0.40		3.40	22.6	10.3
	135				20.2	**11.5**
	170	0.45		3.45	24.0	9.70
	135				21.4	10.9

Table 1 uses the following notations: c is speed of sound in liquid cryogenic oxygen, p_2/p_1 is degree of pressure increase in the oxygen pump of Raptor-2 engine, L_1 is length of the oxygen path from the pump to the gas generator, L_2 is length of the oxygen path from the tank to the pump, L_3 is their sum, L_{eq} is the effective length of the oscillatory circuit, that is, the length that corresponds to the frequency of oscillations that occur in it in the absence of a pump, f_n is the frequency of hydroacoustic oscillations of liquid oxygen.

The degree of pressure increase in the oxygen pump of Raptor-2 engine at the nominal operating mode is $p_2/p_1 \approx 170$. However, at the start, the engines don't reach this operating mode immediately. Moreover, apparently, due to the fact that autogenous pressurization of fuel tanks is produced in Starship (that is, combustion products from the engine gas generators are supplied to the tanks), achieving the nominal pressure in the tanks before the engines reach maximum thrust requires some time for the engines to operate at intermediate mode. And the time of this process here is noticeably longer than, for example, it was for Saturn V rocket. At least judging by Figure 1, reaching the nominal thrust of Starship engines, ensuring its overload during a vertical launch of at least 5 – 5.5 m/s^2 at in the absence of oscillations, would have occurred approximately at the 10th second of the flight time countdown, or at the 12th second from the moment of launch of the central engines and the inner ring engines [4], while the length of this interval for Saturn V rocket was only 1.5 – 2 seconds [6].

At the final stage of time interval for gaining full thrust of Raptor-2 engines, the pressure in their main combustion chamber increases to the nominal value. At the same time, the pressure drop across the oxygen pump increases to the nominal value – parameter that greatly influences on hydroacoustic oscillations frequency in the oxygen line. And the lower this drop, the higher the frequency of oscillations (see Table 1). For the first time, signs of Pogo phenomenon occurred at approximately the 4th second of flight when the system acceleration was 2.5 – 3 m/s^2, and stopped at the 22nd second, when the acceleration of the device was at least 6.5 m/s^2. Thus, even taking into account mass of rocket decreasing, the appearance of Pogo occurred at a thrust of about 0.8 of the nominal (taking into account ~ 10 m/s^2 gravitational acceleration). This mode corresponds to a pressure drop across the oxygen pump of about 135, which increases the dynamics of hydroacoustic oscillations by about 12 %, see Table 1.

In this case, this frequency may be close to the frequency of elastic vibrations of the rocket hull, which should cause the appearance and growth of Pogo. However, an increase in engine thrust and pressure in its main combustion chamber soon leads to a divergence of frequencies, and Pogo spontaneously goes out. Thus, such a model explains both the occurrence of these self-oscillations and their termination. This process, fortunately, simply doesn't have time to develop to a dangerous or even catastrophic level, which happened twice during IFT-2 later.

However, there remains the potential possibility that in a different, unfavorable development of events, the process of self-oscillations of Pogo type may have time to do this. For example, if the pressurization system of an oxygen tank for some reason increases the pressure in it by 20 – 25 %, then even at the nominal operating mode of the engines, the conditions in the oxygen supply lines will be such that Pogo will develop until the destruction of the rocket, which in such cases, it is usually accompanied by an explosion. Another dangerous option is making changes to the design of the first stage – Super Heavy, leading to changes in the length of its fuel lines, which will also change the frequencies of hydroacoustic oscillations. In addition, there must be many other random causes, which are almost impossible to predict in advance.

In this regard, it seems appropriate to assess the consequences of an explosion of Starship stack over launch pad, since due to the reasons described above, there is nothing impossible in such an explosion.

III. Formulas used in calculating the explosions consequences and energy estimations of two giant rockets blasts

The main damaging factor of the air explosion, which is expected to occur if the process of Pogo type self-oscillations in the first 20 – 25 seconds of Starship flight comes to its natural catastrophic conclusion, will be a shock wave. The excess pressure at its front Δp is a fairly adequate indicator of its ability to fracture. Of course, reflections and re-reflections of the shock wave, as well as blocking it with obstacles, can greatly affect its impact in the case of very rough terrain and in buildings consisting of durable concrete structures, but as a first approximation, to which we will limit ourselves, this simplest generalized indicator gives a good idea of what to expect from this explosion.

The pressure drop at the front of the shock wave Δp is determined primarily by the energy released during the explosion E and the distance R from the center of the explosion to the point in space under consideration. And for a sufficiently intense shock wave (~ $\Delta p \geq 1$ Pa) a self-similar parameter can be constructed from these two quantities, reduced radius ξ

$$\xi = RE_e^{-\frac{1}{3}}, \tag{1}$$

which determines the dependence of Δp on energy and distance (E_e is the calculated explosion energy, as it is related to the nominal energy E, described below). In addition, for high-altitude explosions, the pressure at the shock wave front is also affected by its height due to a decrease in ambient pressure. But in the case we are considering, the heights of the explosion are such that this influence can be neglected.

To estimate the excess pressure Δp as a first approximation, it is convenient to use the so-called Sadovsky's formula. It is an interpolation using the parameter ξ of experimental data and a proven and widely known method for determining excess pressure on a wave from an explosion [7]:

$$\Delta p = a\xi^{-1} + b\xi^{-2} + c\xi^{-3}, \tag{2}$$

where a, b and c are empirical coefficients determined for a point explosion of TNT.

In such a model for assessing the consequences of an explosion, it is necessary to distinguish between ground and air explosions. In an air explosion (when the distance from the epicenter of the explosion is much less than its height), its energy is distributed throughout all space, and in formula (1) the calculated energy of a chemical explosion is equal to its nominal value: $E_e = E$. In a ground explosion, its energy is distributed in a hemisphere, bounded below by a solid surface, and $E_e = 2E$. In a nuclear explosion, only about half of the energy under the conditions under consideration is converted into shock wave energy, therefore, in an air nuclear explosion, $E_e = ½ E$, and in a ground nuclear explosion, $E_e = E$.

Let us now estimate the energy that could be released during the explosion of Starship at the starting section of the trajectory. The mass of fuel in its first stage is about 3.4 kt, and in the second stage it is approximately 1.2 kt, that is, only about 4.6 kt [8]. The ratio of the components – methane and oxygen is 1:3.6 [9] (despite the fact that the stoichiometric ratio for this pair of fuel and oxidizer is 1:4.0, that is, the oxidizer excess coefficient $\alpha = 0.90$), so the total amount in the rocket at the start should be about 1.0 kt of methane. With specific energies of TNT – 4.18 MJ/kg and methane – 50.2 MJ/kg, the TNT equivalent of this amount of fuel is 12.0 kt. However, at least in the main explosion, it seems that only methane from the first stage, which begins to collapse due to the occurrence of Pogo, can be involved. In addition, the oxygen from its tank will be enough to burn only 0.9 of the available amount of methane, and the oxygen in the surrounding air is unlikely to have time to significantly influence the combustion reaction of the resulting methane-oxygen mixture. In addition, from Fig. 1 we can conclude that by 20 – 25 seconds of flight, when, presumably, conditions for an explosion could have arisen, about 10 % of the fuel had already turned into jet gases. As a result, the TNT equivalent of the explosion of the first stage of Super Heavy at 20 – 25 seconds of flight at an altitude of 1 – 1.5 km can be estimated as E = 7.0 – 7.2 kt, which, taking into account the fact that during a nuclear explosion half of the explosion energy is converted into shock wave energy, according to this impact would be about 90 % of the nuclear explosion in Hiroshima with a nominal energy of $E = 16 \pm 2$ kt [10].

This appears to be close to the maximum estimate of the amount of Starship propellant energy that could be converted into explosion energy. But we will try to resolve this issue as thoroughly as possible now. To do this, it is necessary to consider the closest analogue to the hypothetical event we are studying, and for it to perform all the manipulations associated with calculations in a completely similar way.

As is known, on July 3, 1969, during the second launch of Soviet lunar rocket N1, in the first 12 seconds of flight, a cascade failure of 29 of its engines occurred, and the only engine remaining in operation turned it across, and at the 23rd second it fell flat from its launch position from a height about 100 m and exploded. "As a result of the largest explosion in the history of rocketry, the launch pad was practically destroyed, and the second launch pad located nearby was severely damaged" [11]. It makes sense to compare the consequences of that long-ago explosion with what would be expected from the explosion of Starship above its launch position.

The fuel mass of N1 rocket in its first stage was 1.75 kt, and in total – 2.43 kt [11] with the ratio of the components – kerosene and oxygen in its NK-15/NK-33 engines – 1: 2.62, while the excess oxidizer coefficient turned out to be equal to $\alpha = 0.769$ [12]. Therefore, in the first stage there was 0.48 kt of fuel out of a total amount of 0.67 kt (0.68 kt according to other sources), but the combustion of only 0.37 kt of kerosene from the first stage tanks was provided by the oxygen available there. The specific heat of kerosene combustion is 42.9 MJ/kg, and the maximum possible TNT equivalent of the explosion of its fuel is E = 6.9 – 7.0 kt. Taking into account all the factors described above when estimating the explosion energy of the Starship system, the energy of this explosion can be similarly estimated as $E \approx 3.5$ kt, that is, about half the energy of the maximum possible explosion, as well as half of the explosion energy of Starship calculated above.

The spread of available estimates of the explosion energy of N1 from various sources (see, for example, [13, 14]) is so large – from 0.25 kt to 7 kt – that in itself indicates the absolute impossibility of relying on them. In order to achieve the goals stated in the work, it is necessary to build a transparent, reliable and based on dependable experimental data procedure for determining the energy released during such explosions of large rockets.

Essentially, these explosions are similar to what can be observed during the operation of thermobaric weapon: first, small amount of a conventional solid explosive destroys a canister containing a flammable substance, it is sprayed into the air, and in the resulting cloud of aerosol after ~ 150 milliseconds a second small explosive amount a detonation wave is created [15]. Such ammunition usually uses flammable substances such as ethylene oxide with a specific heat of combustion of about 30 MJ/kg, and then from the characteristics of the well-known ODAB-9000 aerial bomb (mass of explosives is 7.1 tons, TNT equivalent is 44 tons) [16] it follows that in its explosion detonates about 85 % of the flammable substance.

Large missiles have a mass of fuel that is 1.5 – 2 orders of magnitude greater, but the time it takes to create an explosives cloud is usually several seconds, that is also 1.5 orders of magnitude longer than that of thermobaric weapon. In addition, in the cases we are considering, the mixing of fuel occurs mainly not with atmospheric air, but with cryogenic oxygen rapidly evaporating during a fire that has already begun in the rocket, which should sharply increase the rate of mixing of the cloud components. Therefore, an explosion involving about 50 % of the fuel from the rocket tanks opened by the initial explosions seems quite possible. Moreover, even the source [13] mentions an assessment of a rocket stage explosion with the detonation of 60 % of all the fuel contained in it. In this case, a fire that occurs when engines are destroyed can cause detonation of emergency detonation systems, which will create a detonation wave in a cloud of propellant components.

So estimates of the explosion energy of N1 and Starship rockets at launch with a TNT equivalent of 3.5 kt and 7.0 kt, respectively, can be taken into consideration for further analysis.

IV. Determining the distances from epicenter of a possible explosion at SpaceX launch site to the nearest settlements, as well as similar distances at Baikonur Cosmodrome

In order to understand what consequences the shock wave from the supposed explosion of Starship at the launch site could lead to in some of the closest settlements in Cameron County, Texas, using the resource https://www.google.com/maps we will determine the distances from the launch position before them.

Fig. 2 – Distance from start to Boca Chica

Fig. 2 shows that the distance to the outskirts of the residential area of the nearest settlement with a small number of inhabitants, Boca Chica, is 2.75 km, and to the center of Port Isabel, the nearest town with a population of about 5 thousand people [17], is 10 km, see Fig. 3.

Fig. 3 – Distance from start to Port Isabel

The center of the largest city in the county, Brownsville, with a population of about 190 thousand residents [18], is approximately 32.5 km from the starting position. Immediately across the Rio Grande River lies the even larger Mexican city of Matamoros, where 540 thousand people live [19], and the distance to its center is approximately 37 km, see fig. 4.

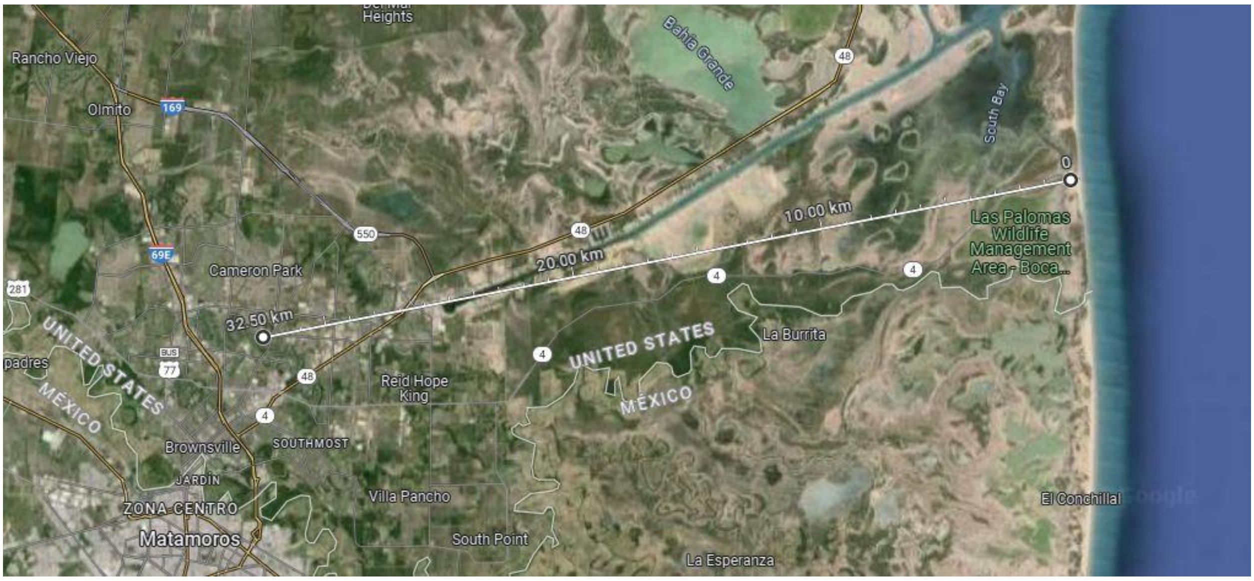

Fig. 4 – Distance from start to Brownsville

At the other end of the Earth – on the vast territory of Baikonur Cosmodrome, it was possible to find 3 points where the consequences of the explosion that occurred on July 3, 1969 at the right launch site of N1 rocket in a complex of structures called site 110 were described in one way or another, see fig. 5 [14].

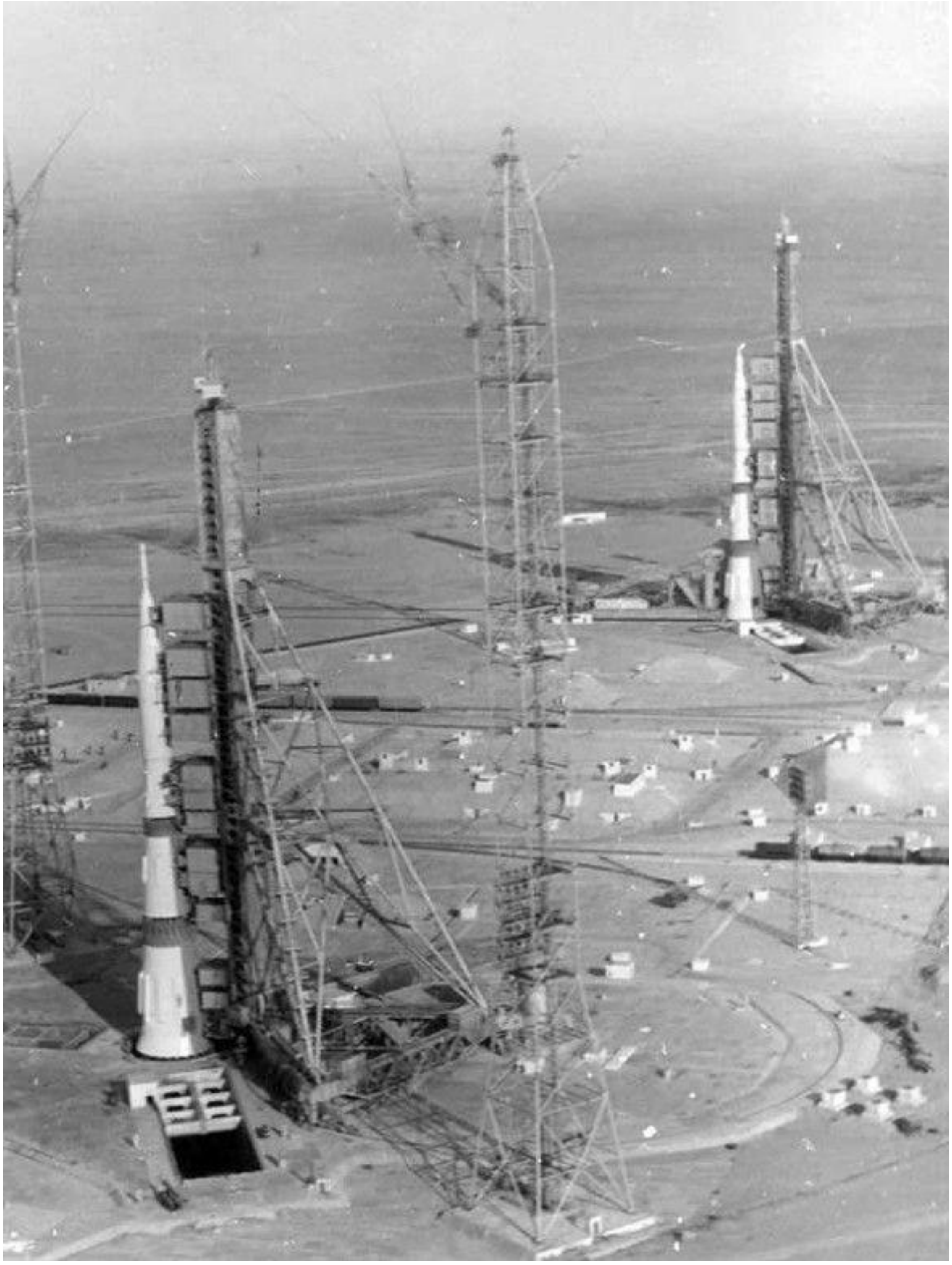

Fig. 5 – Two N1 rockets at launch positions [14]

The current state of this place can be seen in Fig. 6. The distance between the still existing but rebuilt left launch site of Soviet N1 lunar rocket and the completely destroyed right one is 1.1 km, determined using both photographs presented here, as well as other satellites photographs of site 110 after the explosion.

Fig. 6 – Distance between two former launch positions of N1 rocket – rebuilt and destroyed

In addition, there is data on broken window glass, which is the most reliable non-instrumental indicator of the shock wave intensity with a pressure drop across it in the range of ~ 0.5 – 5 kPa: in the residential area of 95th site of the cosmodrome, the center of which is located exactly in the west at a distance of about 28.8 km from the point of explosion, and in the city of Baikonur, which lies almost exactly to the south (42.3 km to the described point – "Cosmonaut" hotel), see Fig. 7.

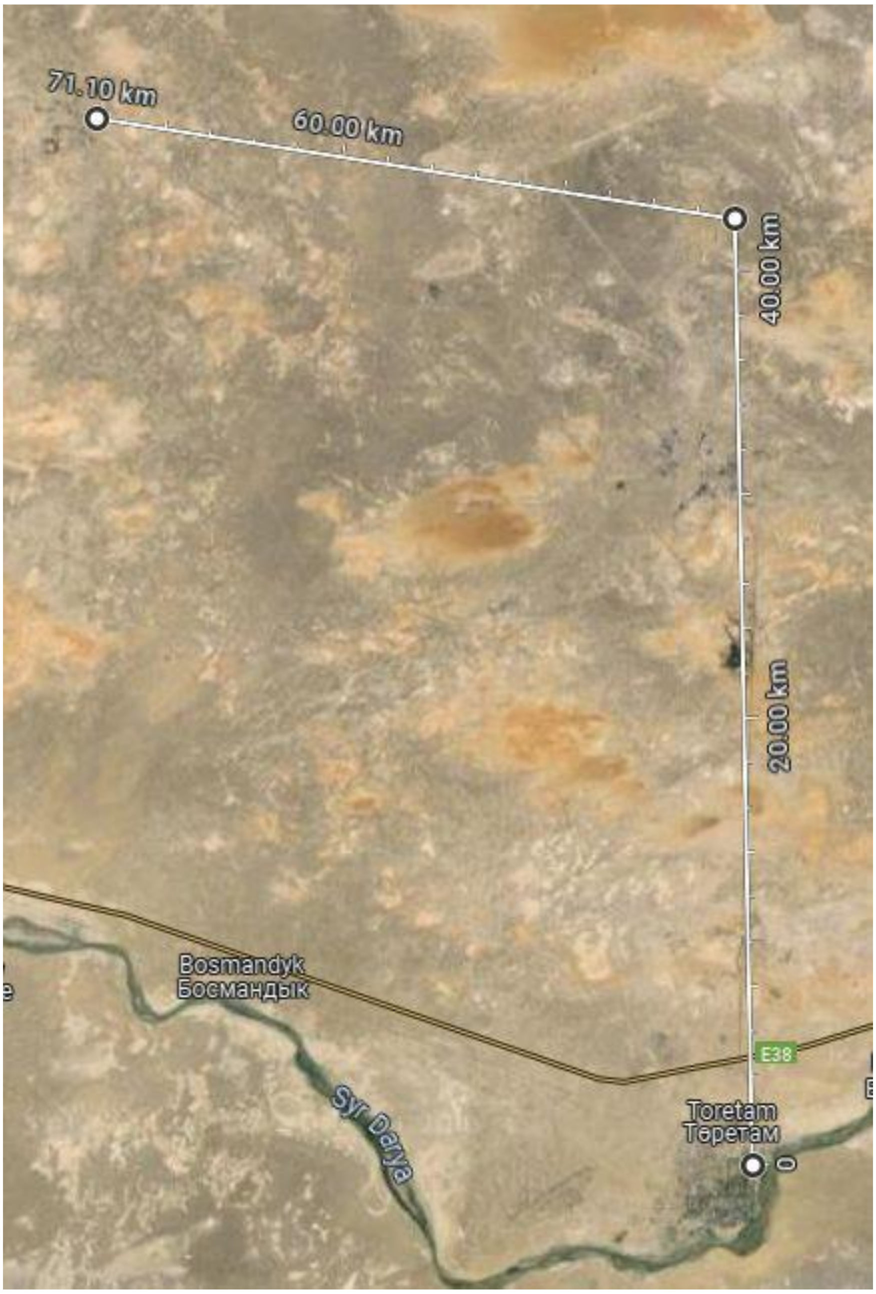

Fig. 7 – Distances between launch position of N1 rocket and the residential area of 95th site, as well as "Cosmonaut" hotel in Baikonur (Leninsk)

The data presented in this and the previous sections is sufficient to verify the described method for estimating the energy of launch vehicle explosions, as well as to assess the possible consequences of the proposed explosion of Starship for the nearest populated areas.

It should be noted that topographic conditions of both the coastal areas of Cameron County and the semi-desert in the vicinity of Baikonur Cosmodrome contribute to the accuracy of recalculation of shock wave propagation data. Both of these areas are flat plains without any natural barriers that could affect its motion. And the distances to the calculated points in Texas and Mexico and the reference points at Baikonur don’t differ too much. Moreover, given the almost indisputable fact that TNT equivalent of a possible explosion of Starship should be approximately twice that of N1, it turns out that the equivalent of destruction distances for Cameron and Matamoros districts are $2^{1/3} \sim 1.25$ times greater than for the Russian cosmodrome, and with such explosion and the same consequences, the residential area of 95th site would have to be located at a distance of about 36 km from the epicenter, which exactly corresponds to the bank of Rio Grande River between the cities of Brownsville and Matamoros. So for these cities, strictly speaking, there is no need to count anything. It’s enough just to find out what happened at 95th site of Baikonur Cosmodrome on July 3, 1969. After this, all that remains is to say that although Lord God, according to A. Einstein, is not malicious, but judging by this episode, he knows how to joke.

V. Determination of N1 rocket explosion energy

In Section III of this work, an estimate of N1 rocket explosion energy was obtained under the assumption that the main explosion, which determined the destructions from the shock wave, was caused by a mixture of the main propellant components in the amount that was in the first stage at the time of the explosion, and the limiting factor was the oxygen amount in its tanks. Under this condition, the explosion energy turns out to be around the value E = 3.5 kt TNT, which corresponds to the fact that 50 % of the fuel detonated during the explosion. However, there are other estimates, up to 0.25 kt [13]. Therefore, based on the information presented above, we will carry out calculations of three options for the value of the TNT equivalent of this explosion: 3.5 kt, 0.25 kt (detonation of ~ 3.5 % percent of the fuel), as well as its average value – 1.0 kt (detonation of ~ 15 % of the fuel). And after that we will compare the effects for the calculated levels of pressure drop on the shock wave with similar effects from several explosions described in sufficient details in the literature. Since the energy levels for the three options for describing N1 explosion under consideration differ from each other by 3.5 – 4 times for each nearest pair, then for a given point the pressure drops on the wave will differ by 1.5 – 1.6 times, which can be noticeable even without use of measuring instruments. Based on these data, we will select the option that best corresponds to the observed phenomena.

Table 2 shows the calculated values of Δp for the three explosion energy values mentioned above (H1-1, H1-2 and H1-3) at the three distances described above. Data are also given on the explosion of the first American uranium nuclear bomb Little Boy (LB) over Japanese city of Hiroshima [10], the first Soviet two-stage thermonuclear bomb RDS-37, detonated in the same Kazakh steppes [20], where 14 years later was N1 blast, as well as about the most powerful man-made explosion – the one released by the Soviet thermonuclear weapon AN602 ("Tsar Bomba" or "Kuzka's Mother") [21]. Calculations were carried out according to the method described in section III. The coefficients in formula (2) were standard: with energy in megatons and distance in kilometers, A = 0.084, B = 0.270 and C = 0.700 [7].

Table 2

<table>
<tr><th>N</th><th>Object</th><th>E (kt)</th><th>L (km)</th><th>H (km)</th><th>R (km)</th><th>Δp (kPa)</th></tr>
<tr><td>1</td><td rowspan="2">LB</td><td rowspan="2">16</td><td>0.16</td><td>0.58</td><td>0.60</td><td>83</td></tr>
<tr><td>2</td><td rowspan="4">1.10</td><td>0.10</td><td rowspan="4">1.10</td><td>42</td></tr>
<tr><td>3</td><td>N1-1</td><td>3.5</td><td rowspan="3">0.0</td><td>26</td></tr>
<tr><td>4</td><td>N1-2</td><td>1.0</td><td>14</td></tr>
<tr><td>5</td><td>N1-3</td><td>0.25</td><td>7.7</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>6</td><td>LB</td><td>16</td><td>19</td><td>0.58</td><td>19</td><td>1.2</td></tr>
<tr><td>7</td><td>RDS-37</td><td>1600</td><td>175</td><td>1.55</td><td>175</td><td>0.57</td></tr>
<tr><td>8</td><td>N1-1</td><td>3.5</td><td>28.8</td><td>0.0</td><td>28.8</td><td>0.57</td></tr>
<tr><td>9</td><td>AN602</td><td>58000</td><td>810</td><td>4.2</td><td>810</td><td>0.41</td></tr>
<tr><td>10</td><td>N1-1</td><td>3.5</td><td>42.3</td><td rowspan="5">0.0</td><td>42.3</td><td>0.39</td></tr>
<tr><td>11</td><td rowspan="2">N1-2</td><td rowspan="2">1.0</td><td>28.8</td><td>28.8</td><td>0.37</td></tr>
<tr><td>12</td><td>42.3</td><td>42.3</td><td>0.25</td></tr>
<tr><td>13</td><td rowspan="2">N1-3</td><td rowspan="2">0.25</td><td>28.8</td><td>28.8</td><td>0.23</td></tr>
<tr><td>14</td><td>42.3</td><td>42.3</td><td>0.16</td></tr>
</table>

In this table, E is the explosion energy in kilotons of TNT, L is the distance in kilometers from the epicenter of the explosion to the considered surface point, H is the height of the explosion and R is the distance from the center of the explosion in the same units of measurement, Δp is the excess pressure at the shock wave front in kilopascals.

The group of the first 5 calculated options of this table is associated with the analysis of the consequences of N1 rocket explosion in its immediate vicinity. The first calculation case, the consideration of which is necessary to determine the scale of destruction, relates to the so-called Atomic House or Genbaku Dome [10, 22]. This reinforced concrete structure turned out to be only 160 m from the epicenter of Little Boy explosion. The excess pressure of the shock wave of about 80 – 85 kPa did not completely destroy this concrete building, see Fig. 8 [22]. Standard estimates are as follows: the average destruction of earthquake-resistant buildings occurs at Δp = 80 – 120 kPa [23], and this seems to be quite consistent with the observed picture.

Fig. 8 – Atomic Bomb Dome in Hiroshima [22]

If this nuclear bomb had exploded at the right N1 launch position, then pressure drop levels at the left position would have been approximately 2 times less, see row 2 of Table 2 (for a greater similarity to the effects of point and thermobaric explosions, the bomb should would be raised above the right starting position approximately to the center of the cloud of the fuel mixture, but already at distances of more than 1 km this has practically no effect on the data obtained). Option H1-1 leads to their reduction by another 1.5 times, and in options H1-2 and H1-3 the force impact on the structures of the left starting position drops by another 2 and 3.5 times. It is stated that "the second launch pad [was] heavily damaged" [11]. However, it is also known that already on August 21, 1969, a prototype 1M1 of N1 rocket was taken to the left launch position and was filled with oxygen. Thus, the damage to the left launch site, located at a distance of about 1.1 km from the epicenter of the explosion, although it was quite significant, was completely eliminated in 7 weeks.

In this case, the force impact from the pressure drop, presented in the 3rd – 5th rows of Table 2, is described as follows: at overpressure levels of 20 – 30 kPa, complete destruction of wooden houses occurs, severe destruction of brick multi-storey buildings, average destruction of brick warehouses and panel houses, as well as slight destruction of administrative frame buildings. At 15 – 25 kPa – average destruction of low-rise brick houses. Weak destruction of wooden houses is observed at 6 – 8 kPa [23]. It is quite clear that the force effect of a pressure difference of 7 – 8 kPa, corresponding to the N1-3 option, on the steel and, mainly, buried reinforced concrete structures of the position, which was supposed to withstand the launch of such a rocket as N1, will be completely negligible, and this option should be immediately excluded from consideration. And option H1-2, the impact of a shock wave in which is between "average destruction of low-rise brick houses" and "weak destruction of wooden houses", seems very doubtful. But for now, we’ll leave them for further consideration.

Let us now move on to significantly lower pressure levels on the wave, a good indicator of which is broken window glass. Line 6 of Table 2 takes us back to Little Boy's explosion. It is known that on August 6, 1945, glass was broken in Hiroshima within a radius of at least 19 km [10]. According to calculations, this corresponds to a pressure level $\Delta p \approx 1.2$ kPa, which significantly exceeds the minimum pressure at which window glass still breaks. However, everything is explained simply – Hiroshima is located in a low-lying river delta, which is surrounded by mountains, and the Terrain Map shows that there isn’t a single direction where the shock wave could easily spread over a greater distance (see Fig. 9, where the length of the rays, leaving the epicenter of the explosion is 19 km). Therefore, this result doesn’t in any way contradict all subsequent ones, where the data were obtained for flat plains without noticeable obstacles or for vast expanses of water.

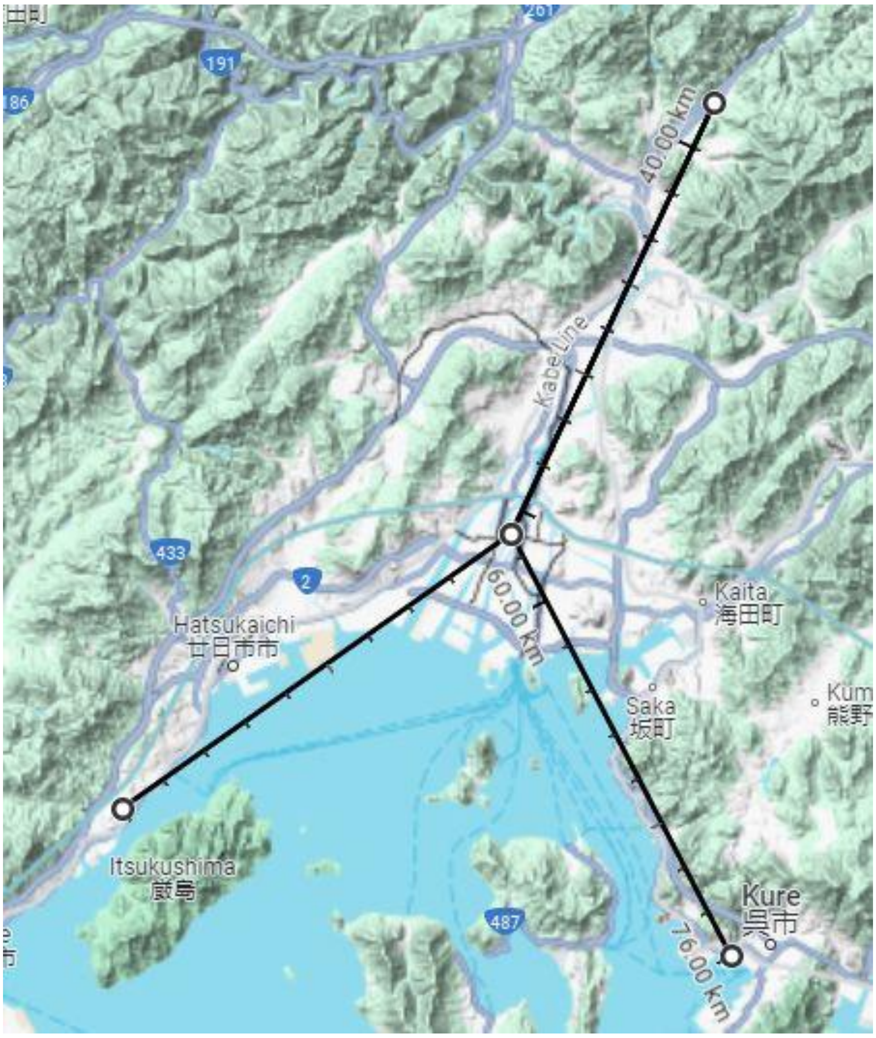

Fig. 9 – Relief in the vicinity of Hiroshima

As mentioned above, a distance of 28.8 km is the remoteness from the epicenter of N1 explosion from the residential area of cosmodrome 95th site. Four-floor houses were built there. According to the stories of veterans, their windows, located mainly on the fourth floors and directed towards the 110th site, had partially broken glass, which corresponds well with what was observed in other explosions at a pressure level of 0.5 – 0.6 kPa (see line 8 Table 2).

In paper [24], a large amount of information on the consequences of various explosions was collected from many sources. For example, line 7 of Table 2 corresponds to the explosion of RDS-37 thermonuclear bomb at the Semipalatinsk test site. Distance 175 km is the remoteness of western outskirts of Semipalatinsk (now the city of Semey). There, according to local authorities, there were broken windows and 16 wounded people asked for medical attention [24]. Line 9 is the explosion of "Tsar Bomba". Distance 810 km is the remoteness of the island and the village of Dikson. "From Dikson... the post reported that an explosion was visible, and suddenly a small air shock wave reached them, window glass cracked in several houses. A day later, the restoration party inserted all the window glass, even those that had been broken before the tests" [24]. This pressure level, about 0.4 kPa (more accurate estimates are ~ 0.35 kPa), is the lower limit of any noticeable window glass breakage recorded in nuclear test reports.

Test cosmonaut Anatoly Voronov recalled that cosmonauts were present during preparations for the second launch of N1 rocket. Late in the evening they watched its launch from "Cosmonaut" hotel: "Suddenly it flared up, we managed to run down, and at that time all the windows were broken by the shock wave" [25]. The distance between the launch position and "Cosmonaut" hotel was 42.3 km. The fact that in the hotel, according to Voronov, "all the windows were broken", at first glance seems to be an obvious exaggeration, which is typical of many testimonies about various incidents. After all, then, it would seem, a lot of glass would have been broken throughout the city, about which there is no data – broken glass isn't recorded in other places in the city. In addition, at a distance of 42.3 km from the epicenter of the maximum possible explosion (option N1-1), the pressure on the wave, according to estimates, turned out to be even 10 % lower than at Dikson on October 30, 1961, and, practically, was at the lower limit of the effect under consideration.

However, perhaps the cosmonaut was partly right in his memories. The fact is that the hotel building in plan is similar to the letter L, the inner corner of which is open to the shock wave that was then flowing from the 110th site. In addition, in this space near L-shaped building of the hotel there is another rectangular house, see fig. 10 (a straight line with a mark at the end "42.30 km" shows the direction of shock wave propagation). At pressure levels on the shock wave of ~ 0.4 kPa, its properties differ little from the properties of a sound wave, the diffraction of which by obstacles of complex shape leads to wave interference and significant pressure fluctuations in the vicinity of the obstacles, which could lead to the destruction of glass in a narrow corridor between the buildings. Something similar, but on a much larger scale, happened on the island of Novaya Zemlya after AN602 thermonuclear bomb explosion, when the village of Lagerny located in a mountain basin was completely destroyed at a moderate nominal pressure at the front of the shock wave, see below.

Fig. 10 – Top view of the hotel where glass was broken during the H1 explosion

From the data presented in Table 2 it follows that the options for the explosion on July 3, 1969, with indices H1-2 and, especially, H1-3, are unable to provide the described levels of glazing destruction at 95th site. And in the city of Baikonur, even option N1-1 turned out to be close to the lower limit of such an impact, at which destruction of glass usually occurs when they are loosely fastened or in places with special conditions where the wave can be amplified due to the interference of waves during their complex interaction with obstacles. Therefore, the TNT equivalent of N1 rocket explosion in the second flight cannot be any noticeably less than 3.5 kt, which corresponds to the detonation of ~50 % of the fuel.

VI. Estimations of pressure at shock wave front after Starship supposed explosion and demonstration of destructions at similar pressure levels from earlier explosions

From all the information presented in sections I – V of this work, it follows that the most probable value of Starship explosion energy in the first 20 – 25 seconds of flight is close to 7 kt TNT. Using the previously presented data on the distance for nearest settlements of Cameron and Matamoros districts from the launch position, using the Sadovsky's formula (1, 2) we calculate the pressure at the shock wave front in these populated areas and compare the possible destructions with those previously observed at similar pressure levels, see Table 3.

Rows 1 and 2 of Table 3 correspond to possible destruction in the nearby small settlement of Boca Chica. The value L = 2.6 km is the distance from the epicenter of a possible explosion to large structures in the form of hangars, apparently for commercial purposes, located on the eastern outskirts of Boca Chica, and L = 2.75 km is the distance to the residential area. At such distances, the explosion is intermediate between a spherically symmetrical air explosion and a ground explosion propagating in a hemisphere, and at L = 2.6 km this estimate is within the range $7.3 < \Delta p < 9.7$ (kPa). Then the pressure at the shock wave front can be represented as $\Delta p = 8.5 \pm 1.2$ kPa at L = 2.6 km and $\Delta p = 8.0 \pm 1.15$ kPa at L = 2.75 km

Table 3

N	Object	E (kt)	L (km)	H (km)	R (km)	Δp (kPa)
1	**SH**	7.0	2.60	1.0	2.79	8.5 ± 1.2
2	**SH**	7.0	2.75	1.0	2.93	8.0 ± 1.15
3	**RDS-37**	1600	16.0	1.55	16.1	7.8
4	**AN602**	58000	53.5	4.2	53.7	7.7
5	**ChM**	57000	39.5	28.2	48.5	7.5 ± 0.5
6	**SH**	7.0	10.0	1.0	10.0	2.2
7	**Questa**	670	39.7	1.6	39.7	2.0
8	**RDS-37**	1600	54.5	1.55	54.5	1.9
9	**SH**	7.0	32.5	1.0	32.5	0.64
10	**RDS-37**	1600	175	1.55	175	0.57
11	**N1-1**	3.5	28.8	0.0	28.8	0.57
12	**SH**	7.0	37.0	1.0	37.0	0.56

Similar pressure levels were calculated at three points where there is data on destruction during the explosions of two Soviet thermonuclear bombs RDS-37 and AN602 and Chelyabinsk meteoroid (ChM) at various, much larger distances, see rows 3 – 5 of Table 3. Data on pressure for the meteoroid $\Delta p = 7.5 \pm 0.5$ kPa were obtained from ground-based measurements [26], and the energy of its explosion was calculated from these data using a more complex calculation model than the one considered here [24].

Fig. 11 – Building of Chelyabinsk zinc plant destroyed during air explosion of meteoroid on February 15, 2013 [27]

It is shown from Fig. 11 that excessive pressures on a wave of ~ 7.5 kPa can lead to fairly large-scale destruction [27]. This means that those hangars on the eastern outskirts of Boca Chica may well collapse during the incident in question. What can happen to private buildings in Boca Chica can be seen in Fig. 12 [28]. This house was located 16 km from the epicenter of RDS-37 explosion, and excessive pressure on the wave there was about 7.5 – 8 kPa.

Fig. 12 – Destruction of house on Semipalatinsk test site [28]

Another example is the complete destruction of Lagerny village, built 6 years before the testing of Tsar Bomba on the shore of Matochkin Shar Strait of Novaya Zemlya Iceland, and which was completely destroyed during testing of AN602 warhead on October 30, 1961. "Only brick pipes remained standing, and a bathhouse, built by miners back in 1959 from thick logs, on the bank of Shumilikha River" [29]. However, here the impact of the shock wave on the structures was significantly enhanced by its reflections and re-reflections due to the complex topography of the area [24], which most likely cannot take place in Boca Chica.

It is also interesting to note that the described possible incident with the explosion of Starship at low altitude is a fairly accurate model of the explosion of Chelyabinsk meteoroid with a decrease in all linear dimensions by about 20 times and, accordingly, the explosion energy by 8000 times. What is this if not the second joke of Lord God in this story that has not yet taken place?

Now let’s consider greater distances from the epicenter of the explosion, corresponding to the position of Port Isabel, which lies approximately 10 km from the launching position, see rows 6 – 8 of Table 3. It should be said that Questa is an American thermonuclear bomb was detonated on May 4, 1962 over the Pacific Ocean near Christmas Island (now Kiritimati) at a distance of 39.7 km from the airfield and camp of testers [30]. All the planes parked at the airfield, as well as the tents located nearby, were not damaged at this level of pressure on the shock wave, according to available data. But this wasn’t the case with RDS-37 explosion. At a distance of 54.5 km from the epicenter of the explosion, there was Maisky village, in which some of the 26 people injured in the explosion in this and neighboring somewhat more remote (up to 57 km) settlements were victims by glass fragments [24]. So at a level of pressure drop at a wave of $\Delta p \approx 2$ kPa, there is no significant destruction of buildings, but window glass can be broken in fairly large quantities, and many people are injured.

And the last group of estimates with a pressure drop level $\Delta p \approx 0.6$ kPa. Here we can talk practically only about the destruction of glass, and this is also only partial. Rows 10 and 11, related to Semipalatinsk (RDS-37) and the 95th site of Baikonur (H1-1), have already been given in Table 2 and described. And rows 9 and 12 describe pressure levels during a possible explosion of Starship in the cities of Brownsville and Matamoros. As can be seen from Table 3, glass breakage in Brownsville should be expected, apparently somewhat more than at 95th site of Baikonur Cosmodrome, especially during the daytime breeze blowing from the sea, which can enhance the impact of the shock wave, and Matamoros, from the point of view under consideration, is practically an analogue of 95th site, but also, apparently, until the daytime breeze blows.

Therefore, we can assume that a fairly large number of broken glass and at least several dozens of wounded are quite possible here, since ordinary residents differ from cosmodrome employees who inhabited 95th site, and they were also several thousand times less numerous there than here. And in Semipalatinsk in 1955 the population was approximately 5.5 times less than in Brousville and Matamoras, and no less than one and a half dozen wounded had to seek medical help. In Port Isabel, everything will be even worse, and Boca Chica village, apparently for the second time in its history, will be completely destroyed [32].

Conclusions

1. It was shown that the process of self-oscillations of Pogo type, which arises and goes out at the start of Starship, in the unfavorable development of events, can lead to a rocket explosion above the launch position.
2. Analysis of effect of thermobaric weapon, data characterizing the destruction from the shock wave for five previously carried out and naturally occurring large and very large explosions, as well as information about the destruction caused by the explosion of giant Soviet N1 rocket at Baikonur Cosmodrome, made it possible to determine its energy, and also estimate the energy of a possible explosion of Starship at launch.
3. From these data, levels of possible destructions were determined in the towns and cities closest to Starship launch site in Cameron County, Texas and Matamoros Municipality, Mexico, as well as the possible number of wounded there.

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Yu. I. Lobanovsky