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Compression Process of Pore inside Explosive Charge in a Warhead under Launching Load

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ABSTRACT

In this paper, the compression process of the pore inside explosive charge in a warhead under launching load is simulated and its influence on premature explosion is discussed. The relationship between the pore compression, distortion, and the form of 'igniting hot spot' has been established. The analysis of result indicates that the stress wave in the explosive charge developed due to launching load is a key factor in the pore compression process. The volume change of the pore, which is related to its original volume, is a major factor affecting the form of 'ignition hot spot'. It appears that a specific size of the pore may not lead to the premature explosion of explosive charge in a warhead under launching load. The quantitative relationship between the dangerous size range of the pore and the launching load is a core research subject of warhead safety during launching. With this objective, numerical computing was undertaken to assess the pore's distortion parameter inside the explosive charge of a warhead, and generate database for warhead safety under launching load.

Keywords: Thermobaric warhead, numerical computing, dynamical response

1. INTRODUCTION

The pore inside the explosive charge in a warhead is a major factor of premature non-expected explosion during launching. The distortion and compress procession of a pore under launching load are important for the safety of warhead launching.

As the research on warhead launching safety is imperfect, the premature explosion of warhead during launching may occasionally occur, which may lead to disastrous loss of property and casualties. Gengguang[1] pointed out that the pores inside the explosive charge in a warhead are the essential factors for premature explosion during launching, and the pores may form 'igniting hot spot' under launching load, which may lead to explosion. Tarver[2] also pointed out that explosive would be ignited under shock load when the mechanical energy of shock load is transformed into the heat energy. The pores inside the explosive charge and their compression process under launching load are the core issues in the research on premature explosion of warhead. The major research approach is using an exciter, a small load instrument, to check explosive charge safety and to simulate shock load in launching. The test results have shown that the pore inside the explosive charge is a key factor influencing the safety of explosive charge during launching.

Some researchers used thermo-kinetics and chemical reaction kinetics to numerically compute the growth of 'igniting hot spot'. Jette[3] presented the relationships between the pores inside the explosive charges and shock igniting characteristic through experiments. The research result showed that, for some explosive charges with pores of certain size, the stronger impact may not lead to detonation but the weaker impact may lead to detonation in certain cases[3]. The effect of pore size for B-explosive under launching loading evaluated by applying numerical computing approaches and experiments are reported by Katayama[4] and Kubota[5], *et al.* The logarithm relationship between the critical size of pores and the explosive charge diameter was determined. Shah[6] presented that the burst process always begins at the edge of 'igniting hot spot', and heat exchange characteristic of explosive material has remarkable effect on the igniting sensitivity. Gruau[7], *et al.* have undertaken safety analyses of plastic-bonded explosives (PBX). Major results are the use of a concrete-like constitutive law for the PBX and an efficient implementation of ignition criterion. Fang[8] presented an analytical model for volumetric absorption, heating, and ignition of energetic solids, which provides more flexibility than the numerical solution in understanding the energy absorption and ignition mechanism of energetic solids. In earlier paper[9], a model for the coupled property of warhead shell and charge was presented, which brought out the effect of instantaneous void creation between the warhead shell and the charge during launching and its propagation by numerical simulation.

Thermobaric explosive charge is a mixture of solid and liquid. Its chemical and physical characteristics are significantly different from that of the traditional solid explosives. Thermobaric explosive charge has a disadvantage

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that the pores get easily incorporated during filling in warhead shell by vibration process[10].

The experiment in which the compression process of the pores under shock load was investigated can not be applied for thermobaric explosive charge, as the size of pore is small, its volume change during launching is difficult to be measured in the experiment. For example, positioning a transducer in a pore of 0.2 cm radius inside the thermobaric explosive charge is very difficult. However, pore size change during launching can be simulated by numerical computing easily, in which the original pore size and the pore position can be set up randomly. It may provide a means to predict the influence of pore size and position in explosive charge on the safety during launching.

The shock load acts first on the bottom of warhead during launching and produces stress wave in the explosive charge. It spreads through the charge, from the bottom to the top of the warhead. When the stress wave passes through the pore, it is envisaged to get compressed and distorted, resulting distortion of pore[11]. The volume of the pore will get reduced leading to heating up of gas inside the pore and form the 'igniting hot spot'. As the temperature in the hot spot reaches a critical value, the premature explosion will result. The possibility of premature explosion depends on the relationship between the pore compression process and launching load.

In this study, the numerical computing was used to simulate the dynamic process of pore volume change under launching load. The stress, displacement, and moving velocity around the pore with time was obtained. The work has established a database for the research on temperature change in the pore in an explosive charge under compression.

2. COMPRESSING MECHANISM OF PORE

The launching load increases from minimum at time of ignition and reaches the maximum value. The warhead accelerates gradually along the launcher tube. Once the warhead is out of the tube, the launching load diminishes rapidly (Fig. 1). To gain the real launching load curve, one must take into consideration the propellant characteristic, propellant charge configuration in the chamber, and warhead aerodynamics characteristic. It can be seen from Fig. 2, that the peak of launching load is at the end of raise stage. The increasing load in the raise stage produces stress wave spreading from the bottom to the top of warhead. The stress wave gets reflected at the top of warhead and propagates towards warhead bottom. At this moment, the

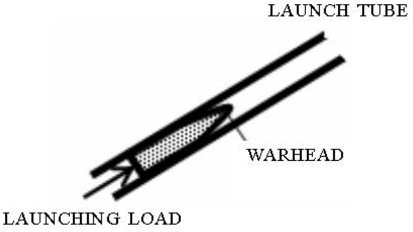

Figure 1. Launching process.

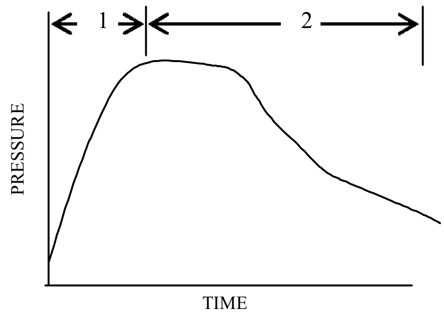

Figure 2. Launching load pattern.

warhead begins to move macroscopically, leading to the inertia force inside the explosive charge of warhead. There, the forces acting on the explosive charge in warhead during launching are of two types: (a) force due to stress wave and (b) force due to inertia. In the stress wave stage, the stress wave spreads from the bottom to the top of explosive charge in warhead, so the stress near the bottom is maximum and decreases gradually from the bottom to the top. In the inertia action stage, the inertia stress near bottom is also maximum. Thus, the explosive charge near the bottom of warhead experiences the maximum stress and premature explosion is most likely to get initiated in this region and thereby to be investigated for launching safety of warhead.

In the inertia force action stage, there is

$$p_s A = (A_e h\rho + m_s)a \tag{1}$$

where, p_s is launching load per unit area on the bottom of warhead in the inertia stage: A is cross-section area of column warhead; A_e is cross-section area of column explosive charge in warhead; h is explosive charge length in warhead ρ is explosive charge density; $\rho = 1470$ kg/m^3 for thermobaric explosive; m_s is warhead shell mass, a is acceleration of warhead during launching.

The length of shell is larger than explosive charge. That is

$$h_s > h$$

where, h_s is the length of the shell. For cylindrical shell and column explosive charge, approximately $m_s = (A - A_e)h_s\rho_s$. Obviously, there is

$$m_s > (A - A_e)h\rho_s > (A - A_e)h\rho \tag{2}$$

where, ρ_s is density of metal shell. Warhead shell is usually made of metal, taken as $\rho_s = 7800$ kg/m^3.

From Eqns (1) and (2), the stress on the bottom of explosive charge column can be expressed as

$$ah\rho = \frac{p_i A}{A_e h\rho + m_s} h\rho < p_i \tag{3}$$

For a warhead during launch, movement equation is

$$p_s A_w = am_w$$

where, A_w is bottom section area of warhead, $A_w = \pi\,(r_e + \delta)^2$; r_e is radius of column charge; δ is thickness of shell wall of warhead; m_w is mass of warhead. In practice, there is always

$$\delta < 0.2 r_e$$

For the explosive charge inside of warhead, movement equation is

$$p_i A_e = a m_e$$

where, m_e is mass of explosive charge filled in the warhead; $A_e = \pi r_e^2$.

Therefore, $A_w < 1.2 \quad \pi r_e^2 = 1.2 A_e$.

In practice, for the warhead shell made of steel

$$m_w > 2 m_e$$

According to the above analysis, one gets

$$\frac{p_s}{p_i} = \frac{m_w}{m_e}\frac{A_e}{A_m} > \frac{2m_e}{m_e}\frac{A_e}{A_w} > \frac{2}{1.2} > 1$$

That is, the inertia stress p_i is less than impact load p_s per unit area on the bottom of warhead during launching process. From Eqn (3), one gets

$$a h \rho = \frac{p_i A}{A_e h \rho + m_s} h \rho < p_i < p_s \tag{4}$$

The above formula implies that the impact load on the warhead's bottom in the inertia force action stage is less than that in the stress wave action stage, therefore, it is the primary factor affecting launching safety of warhead.

The increasing instantaneous temperature inside the pore is expected to be the primary cause of premature explosion of explosive charge in the warhead[12]. The increase in instantaneous temperature of the pore being compressed and distorted could be estimated by numerical computing. The instantaneous temperature inside the pore may be given by the expression[11]

$$T = \frac{pv}{c_v(\gamma - 1)} \tag{5}$$

where, p is the instantaneous pressure inside pore v is the instantaneous specific volume of pore c_v is the specific heat of medium inside pore; and γ is the adiabatic exponent of medium inside pore.

The gas states equation is

$$p v^{\gamma} = p_0 v_0^{\gamma} \tag{6}$$

where, p_0 is the initial pressure inside pore; and v_0 is the initial specific volume inside pore. v_0 and v may be obtained from relations:

$$v_0 = \frac{1}{\rho_0} \qquad v = \frac{V}{V_0 \rho_0}$$

where, V_0 is the initial volume of pore; V is the instantaneous volume of pore. From Eqns (5), (6) and (7), one gets

$$T = \frac{(V_0 / V)^{\gamma - 1}}{c_v(\gamma - 1)\rho_0} \tag{8}$$

From Eqn (8), it can be inferred that the instantaneous temperature inside pore relates to the ratio of the instantaneous volume to the initial volume of pore. It is obvious that the smaller the pore is, the faster is the temperature rise in the process of compressing. But in fact, under launching load, the moving velocity relates to the size of pore. However, it is a complex issue. In the object, numerical computing was adopted to investigate the distortion process of pore under stress wave.

3. NUMERICAL COMPUTING MODEL AND PARAMETERS

For the warhead shell and explosive charge, the basic equations used for computing are:

$$\frac{\partial \rho_1}{\partial t} + div(\rho_1 v_1) = 0 \tag{9}$$

$$\rho_1 \frac{Dv_1}{Dt} = div A \tag{10}$$

$$\rho_1 \frac{De_1}{Dt} = \rho_1 h_1 - div q + A_{ik} \dot{e}_{ik} \tag{11}$$

where, ρ_1 is the material density; v_1 is the velocity of particle; A is the stress; e_1 is the internal heat per unit mass; h_1 is the released heat in unit time per unit mass medium; and q is the thermal flux.

Considering, the gas inside the pore as continuous medium, the basic equations in computing are:

$$\frac{\partial \rho_2}{\partial t} + div(\rho_2 v_2) = 0 \tag{12}$$

$$\rho_2 \frac{Dv_2}{Dt} = \rho_2 b - grad P \tag{13}$$

$$\rho_2 \frac{De_2}{Dt} = \rho_2 h_2 + k \nabla^2 T - P div v_2 \tag{14}$$

where, ρ_2 is the density of gas in pore; v_2 is the velocity of particle in gas medium; b is the body load per unit mass of medium; P is gas pressure; e_2 is the internal energy per unit mass of medium; h_2 is the released heat per unit time in unit mass of medium; k is the heat exchange parameter; and T is the temperature of the medium in the pore.

The gas inside pore is combination of air and volatile gas from thermobaric explosive charge. As the gas pressure inside the pore is not too high, it may be dealt with as ideal gas and the state equation of ideal gas is given as

$$P = n \rho_2 R T \tag{15}$$

where, n is mol number of gas; R is gas constant.

At the interface between the pore and the explosive charge, one has

$$v_1 = v_2 \tag{16}$$

The friction coefficient was taken as 0.4 for the explosive charge and the shell of warhead.

For the warhead shell and thermobaric explosive charge, elastic-plastic material model and Hooke's law was adopted for the elastic process.

$$\dot{s}_{ij} = 2\mu\left(\dot{\varepsilon}_{ij} - \frac{1}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) + \overline{\delta}_{ij} \qquad (i, j, k = 1, 2, 3) \tag{17}$$

where, μ is the shear modulus, ε_{ij} is the strain tensor, s_{ij} is the deviatoric component of stress tensor, δ_{ij} is the Kronecker's symbol; and $\overline{\delta_{ij}}$ is the rotation correction term.

In the plastic process, Mise's yield condition and ideal plastic material model was adopted.

$$\begin{cases} \dot{e}_{ij} = \dfrac{1}{2\mu}\dot{s}_{ij} + a\dot{\lambda}s_{ij} \\ \dot{\varepsilon}_{kk} = \left(\dfrac{1-2\nu}{E}\right)\dot{\sigma}_{kk} \end{cases} \tag{18}$$

where, a = 1 in the elastic-plasticity process; a = 0 in elastic states, or under unload state; and s_{ij} is the term of plastic strain rate.

For computing, the height of warhead shell was taken as 40 cm, and the bottom thickness 2 cm. The shell was filled with thermobaric explosive. Considering the symmetry, 1/4 of the simulated warhead was considered for computation (Fig. 3).

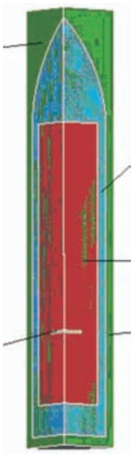

Figure 3. Compute model.

The distortion velocity of pore under launching load mostly relates to the instantaneous pressure in the pore, but seldom to the shape of pore. Therefore, the shape was assumed to be a flat cylinder. The explosive charge around the pore filled with gas was considered as uniform and continuous medium. The centre axis of cylindrical pore was superposed on that of the warhead. The diameter of cylindrical pore is taken as 2 cm and the thickness 0.2 cm. The pore is assumed to be 5 cm from the bottom of warhead.

Shell material is taken as 45 C_r steel, which is assumed to be elastic-plastic medium and the density ρ = 7.81 g/cm^3, the elasticity modulus E 230 GPa, Poisson's ratio λ= 0.3, the shear modulus G = 82 Gpa and yield limit σ = 920 MPa.

The thermobaric explosive charge was also assumed to be elastic-plastic medium of density ρ = 1.47 g/cm^3 the elasticity modulus E = 0.0474 GPa, Poisson's ratio λ = 0.48, the shear modulus G = 0.016 GPa, and the yield limit σ=7.7 MPa.

4. COMPUTATIONAL RESULTS AND ANALYSIS

The launching load in computing is shown in Fig. 4. The peak of launching load is100 MPa, and the loading rate is 40 MPa/ms.

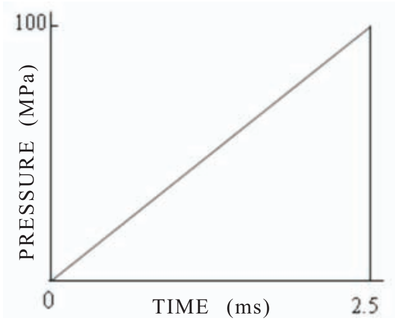

Figure 4. Launching load on the bottom of warhead.

4.1 Stress Distribution Around Pore

To study the stress distribution around the pore, selected positions (as shown in Fig. 5) were considered. The points A, B, C, D, E, F and G were on the pore border. Their X and Y coordinates are shown in Fig. 5 and Table 1.

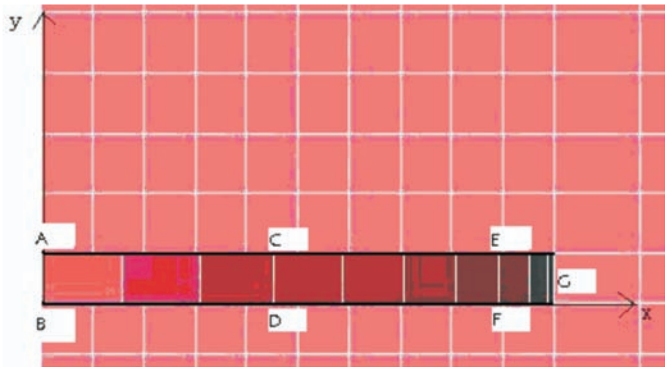

Figure 5. Points considered at the interface between pore and explosive charge.

Table 1. Local coordinates of given positions on the border interface

Positions	A	B	C	D	E	F	G
				(cm)			
X	0	0	1	1	1.8	1.8	2
Y	0.2	0	0.2	0	0.2	0	0.1
Z	0	0	0	0	0	0	0

The stress-time curves at different positions on the border of pore were determined by numeral computation and the data represented in Fig. 6. Table 2 shows peak stress at various positions on pore border. The computational results indicate that the stresses on the pore border decrease with increasing distance from the axis. The stress on the lower interface of pore is higher than that on the upper interface. The stress-time curves at the spots on the border also bring out a similar trend. The stress on some sections in the explosive charge decreases with the distance away from the axis.

Some of the stress values are selected from the computing results at the special positions around the pore. These positions are A_1, B_1, C_1, D_1, and E_1, the local coordinates

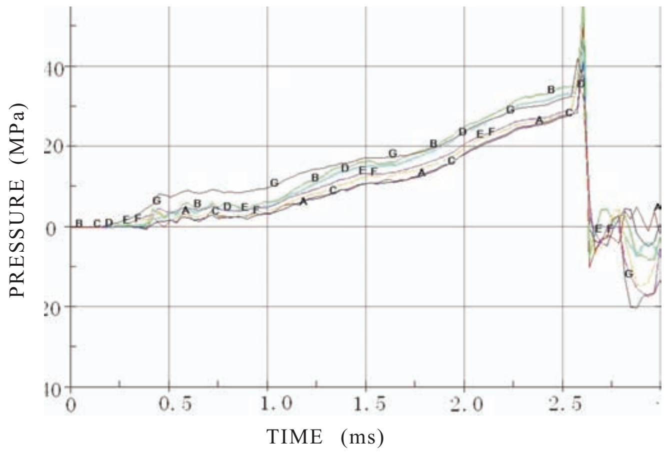

Figure 6. Stress-time curves at different positions on pore's border (A,B,C,D,E,F,G positions are responding to Table 1).

Table 2. Peak stress at various positions on pore border

Positions	A/B	C/D	E/F	G
Peak stress (MPa)	51.0/57.6	41.5/46.4	36.4/37.3	42.2

of which are compiled in Table 3. The stresses at selected positions are specified in Table 4. The estimated stress at interface of pores located at increasing distance from warhead bottom and lying on the warhead axis are plotted in Fig. 7. It was observed that the closer the pore to the bottom of warhead higher is the stress at the interface and vice versa .

Table 3. Local coordinates of given positions around pores

Positions	A_1	B_1	C_1	D_1	E_1
			(cm)		
X	0.4	0.4	1.2	1.2	2.67
Y	0.65	-0.2	0.4	-0.45	0.1
Z	0	0	0	0	0

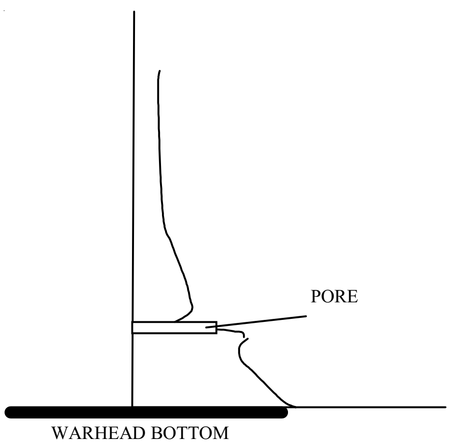

Figure 7. Estimated change in stress at different positions along warhead axis.

Table 4. Peak stress at various positions under different loads around the pores

Positions	A_1 /B_1	C_1/D_1	E_1
Peak stress (MPa)	47.0/53.2	38.2/37.5	34.4

4.2 Distortion of Pore

The pore is compressed and distorted under the stress wave under the influence of launching load. The instantaneous state of pore in the process of distortion was obtained by numerical computing. The deformation of pore under stress wave is shown in Fig. 8.

The displacements at the pore borders increase with time. The pore closes at 0.509 ms after the start of impact loading. The relative displacements on the pore borders are compiled in Table 5. The relative velocity changes on the lower and upper interfaces as a function of time can be inferred from Table 6.

From the date in Table 5, one can obtain a formula for the instantaneous volume of pore as a function of time.

$$V = 0.6283 - \frac{0.6283}{1+e^{-26.66(t-0.33)}}$$

where, V is instantaneous volume of pore (cm^3); and t is time (ms). The original volume of pore is considered as 0.6283 cm^3.

The compression and distortion processes of cylindrical pore have been simulated by numerical computing in the present work. For the pores with other shapes, the compression and distortion processes can be investigated using the

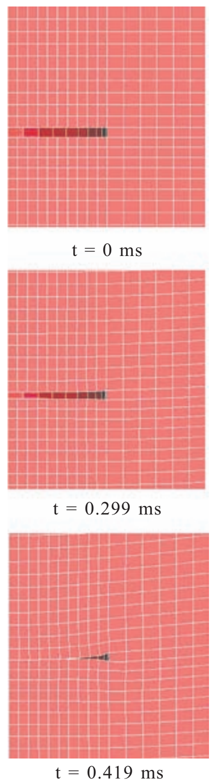

Figure 8. Pore closing process under stress wave.

Table 5. Relative displacement changes (cm) at given positions on the pore border vs time

Time (us)	200	250	300	350	400
A and B	0.0045	0.025	0.067	0.121	0.192
C and D	0.0058	0.028	0.062	0.107	0.167
E and F	0.0048	0.014	0.025	0.042	0.064

Table 6. Relative velocity changes at given positions on the pore border *vs* time

Time (ms)	0.20	0.25	0.30	0.35	0.40
			(cm/s)		
A and B	22.5	100.0	223.0	346.0	480.0
C and D	29.0	89.3	206.6	305.7	417.5
E and F	24.0	56.0	83.3	120.0	160.0

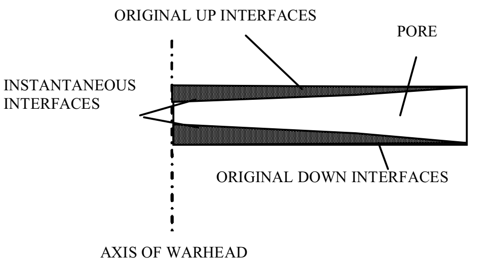

Figure 9. Instantaneous state of pore in process of distortion.

results obtained in the present study. The real volume of pore should be converted to equivalent volume. By using the equivalent volume instead of the volume of cylindrical pore, the compression and distortion processes of pores with other shapes can be obtained. If the equivalent volume of pore is the same as that in this example, their relative volume changes in compression process would be the same. The launching safety of warhead can be assessed using the relative volume change of the pore[11-12].

5. CONCLUSIONS

The launching load changes as a function of time, as the thermobaric explosive medium characteristics are highly nonlinear. The analysis results bring out that the action of stress wave from launching load is a key factor in investigating the safety of explosive charge in the warhead. The propagation of stress wave was simulated by numerical computing in the work. The instantaneous temperature in the pore in the explosive charge during compression process depends on the ratio between the instantaneous volume and the original volume of the pore. This ratio depends on the pore distortion velocity which is related to the launching load and the pore size and structure. For a given launching load, its components are different on explosive medium filled in the warhead and the pores in it, therefore, it is impossible to find out a general trend of the distortion process under stress wave from launching load. During this work, dynamical response and the distortion parameters of the pore in a cylindrical thermobaric explosive charge under influence of stress wave are obtained by numeral computation. The work provides input for the energy evolvement mechanism during launching safety of the warhead. Because the strength of the thermobaric explosive medium is very low, the pore distortion process under stress wave mostly depends on the instantaneous pressure in the pore, not its shape, it may be envisaged that the volumes of the pores with various shapes are the same and with respect to their relative volume changes to the original volumes during distortion processes are also similar. Therefore, the results obtained in the study may be used extensively.

New inputs generated by the theoretical work will be introduced and the temperature changes of gas trapped in the pores being compressed and distorted during launching will be discussed in another paper to be published.

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