PECULIARITIES OF SPACE DEBRIS PRODUCTION IN DIFFERENT TYPES OF ORBITAL BREAKUPS.

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ABSTRACT

The paper investigates the orbital breakups as a major source of space debris production. Different types of breakups under the influence of nonuniform internal loadings are regarded caused by internal explosions or hypervelocity collisions with debris particles. The worked out new thermodynamic criterion of destruction based on the critical value of energy dissipation in irreversible transformations makes it possible to determine the number and fluxes of fragments formed in breakups. The comparative analysis shows that distribution functions of the number of fragments versus mass have extrema strongly depending on peculiarities of breakup scenario that can produce essential difference from forecasts given by the accepted fragmentation models. Breakups caused by chemical explosions or hypervelocity particles impacting pressurized vessels produce different fluxes of fragments.

1. INTRODUCTION

Since the time the first Sputnik was launched on October 4, 1957 the space activity of the mankind generated a great amount of orbital debris, i. e. manmade objects and their fragments launched into space, inactive at nowadays and not serving a useful purpose any more [1-4]. The number of "trackable" debris particles (larger than 10 *cm*) has been increasing since the beginning of regular space flights and now reaches 7900 objects with the total mass $2{,}2\cdot 10^6$ *kg*. The objects of dimensions $1\div10$ *cm* contain separating construction elements and fragments of the spacecrafts generated as a result of explosions or collisions. Their number reaches 17000 that is 0,5% of the amount of debris and the mass $\approx 10^3$ *kg*. The number of particles of $0{,}1\div1$ *cm* originated as a result of orbital explosions and collisions of spasecrafts reaches 3500000 objects. The last statistical estimates made in [31] give an order of magnitude higher values for the number of untrackable objects: 110 000 for the objects of $1\div10$ *cm* size, and 35 bln. for the $0{,}1\div1$ *cm* objects. All those objects remain in orbits for periods of sufficient duration to become a hazard to space activity [5-6].

The description of debris evolution and the determination of the amount of space debris in elliptical orbits needs adequate modeling of the major sources of debris production and consumption: in-orbit explosions, hypervelocity collisions, operational debris separation, slowing down of fragments captured by the atmosphere [7-12].

Operational debris originates mostly in separations of satellites and last stages of rocket-carriers and the mean rate of its production is assumed to be 4 objects per launch [7], that gives about 500 objects per year. The same amount of fragments can appear in one orbital breakup being the result of an explosion.

Thus fragmentations of satellites due to different reasons and mostly explositions of the upper stages are supposed to give the most essential contribution to the space debris production [13]. It was only in 1981 when Don Kessler, NASA-JSC was able to correlate space debris from satellite breakups recorded by NORAD/ADCOM to upper stages of rocket carriers left on orbit after completion of their mission [14]. Since 1969 up to 1981, ten cases of breakup of Delta second stages left in orbit after mission took place [15]. The duration of stay of the vehicles in orbit before the explosion varied from 1 day up to 5 years.

One of the most probable potential causes of orbital breakups is fuel and oxidizer tanks overpressurization and fracture of the common bulkhead that would allow mixing and ignition of the residual propellants that would most probably result in an explosion [13-15, 19].

Theoretical and experimental investigations of breakups of fuel tanks shown that the results of breakups: number, masses and velocities of fragments - strongly depend on the peculiarities of the process of energy release inside the tank [16-18].

The other probable potential causes of orbital breakups are hypervelocity impacts on pressurized compartments and chemical explosions. Gas-filled and fluid-filled vessels show different behavior in breakups caused by collisions and internal loadings.

The aim of the present investigation is to create physical and mathematical models of breakups able to describe peculiarities of the fragmentation phenomena for different breakup scenario and to determine the number, mass and velocity of fragments.

The present paper contains the description of the physical model of breakup events (section 2). The detailed mathematical models of energy release in internal chemical explosions, dynamical loading, deforming, accumulation of damages and breakup of thin-walled structures are described in [16, 17, 20-25]. The results of fragmentation for different scenario of energy release and comparisons with the experiments are discussed in sections 3-5.

2. PHYSICAL MODEL OF BREAKUP PROCESSES

On regarding different possible breakup scenario one can come to the following classification of breakup types.

1. Breakups due to chemical explosions. Breakups of this type result from internal loading due to chemical energy release inside the structures.
2. Breakups due to overpressurization - occur in gradual uniform loading of the closed containments resulting from physical changes of the internal media: heating, evaporation, etc.
3. Breakups due to collisions - occur in incidental loading of the structure resulting from the transformation of the kinetic energy of the impactor.

Each type of breakups also has a variety of possible scenario. Chemical energy release in premixed combustible materials contacting the spacecraft structure can take place in two modes: deflagration (or slow combustion) and detonation (or quick-going process when the rate of reaction zone propagation has the order of kilometers per second) [20, 21]. The rates of wall loadings and maximal loads differ several orders of magnitude for deflagration and detonation resulting in different fragmentation patterns, masses, velocities of fragments [22].

The nonpremixed combustible systems (hypergolic propellants) reacting in an oscillating diffusion mode [16], produce nonuniform wall loading resulting in formation of a very wide spectrum of fragments distribution versus mass with several extrema.

Collisions of pressurized vessels with hypervelocity particles can result in different breakup scenario for fluid-filled and gas-filled containments.

Generally the breakups are classified due to their "intensity" i. e. the number of fragments versus mass distribution function as "high-intensity explosions", "low-intensity explosions" and "collisions". This classification mostly deals with available empirical formulae for fragments production modeling [11, 26] and does not reflect the physics of the fragmentation phenomena. Different fragmentation scenario we discussed can produce a greater variety of fragments distribution functions. Besides as it was discovered in [27] the existing models for fragments distribution cannot describe adequately the peculiarities of the real breakup events. Below we shall give a brief description of models for several breakup scenario.

The overall variety of in-orbit breakups contain the following characteristic stages:

1) energy release and loading of the structural elements of the satellite;
2) dynamical deforming of the structure and accumulation of damages;
3) destruction of walls, cracks' growth, fragments formation and dispersion.

2.1 The model for the energy release

The internal loading of the structure can take place due to chemical energy release (deflagration and/or detonation) or due to kinetic energy transformation in hypervelocity collisions.

In case of chemical explosion the reactants (in propellants tanks, for example) can be in different phases: liquid, gaseous, solid. Thus the mathematical model for multiphase chemically reacting media should be applied.

In case of hypervelocity collision the fragmentation of the impactor and the satellite's structures in the collision zone gives birth to the formation of a cloud of small hypervelocity fragments entering the pressurized gas- or fluid-filled containments. The rapid slowing down (and possible combustion in the oxygen containing atmosphere) of those fragments brings to the localized energy release inside the containment similar to an explosion. Then the dynamics of the internal wall loading depends on the density of the released energy and compression waves propagation and reflections inside the containment.

Those processes of energy release and "point blasts" can be also described with the help of the mathematical model for the multiphase chemically reacting flows [28, 29].

2.2 The model for the dynamical deforming of walls

The mathematical models for the dynamical deforming of walls of containments under the influence of internal loading were described in [16, 17, 23-25]. The walls of containments can be of a multilayer composite structure thus the multiphase models are also preferable to describe the process and evaluate the accumulation of damages. The materials of the walls can be regarded as an elastoviscoplastic media [16, 17] or thermoviscoelastic [25]. The governing system of equations for the axisymmetrical problem of dynamical deforming of thermoviscoelastic composite shell [25, 30] enables us to determine the growth of elastic energy and mechanical dissipation in the shell in dynamical deforming.

2.3 Fragmentation models

We used the thermodynamic criteria of destruction based on the critical value of the dissipation in irreversible transformations: viscous dissipation, accumulation of damages in tension, shear and delamination. As soon as the destruction criterion is satisfied: $D \geq D_*$, a breakup of a shell takes place [16, 17, 30]. The number of fragments obtained in a shell breakup can be found from the balance of the elastic energy accumulated by the shell by the time of breakup and work necessary for the cracks formation. The elastic energy accumulated by the time of breakup t_* in an arbitrary section of the shell with an area S_α and thickness h can be determined by the formula:

$$E = \iint\limits_{S_\alpha} E_* \rho_0 h \cdot dS \, .$$

This energy is spent to form cracks (free surfaces) around fragments:

$$E \cdot k_E = N_{0\alpha} \int_0^{\infty} \gamma h p(s) f(s) ds ,$$

where γ is the specific energy consumed for formation of a free surface unit, *p(s)* is the semiperimeter of a fragment of area *S*, $k_E (0 < k_E \leq 1)$ is the coefficient of the elastic energy consumption, *f(s)* - the density of fragments distribution, $N_{0\alpha}$ - the number of fragments formed in breakup of the α-section of the shell.

Thus one comes to the following formula:

$$N_{0\alpha} \int_{S_{\min}}^{S_{\max}} \left(p - \frac{\rho_0 E_{*\alpha} k_E}{\gamma} S \right) f(s) ds = 0 .$$

On introducing a dimensionless coefficient of shape $k = s / p^2$ and keeping in mind that the shape coefficient can change within the limits $0 < k \leq \frac{1}{\pi}$ one can obtain some restrictions for the smallest possible area of fragments within the regarded section

$$S_{\min}^{\alpha} = \pi \left(\frac{\gamma}{\rho_0 E_{*\alpha} k_E} \right)^2 .$$

Final velocities of fragments can be determined solving the following equations:

$$m_j \frac{d\vec{v}_j}{dt} = -h s_j \left. \frac{\partial p}{\partial r} \right|_{r=x} - \frac{c_d}{2} S \rho \left| \vec{v}_j - \vec{u} \right| (\vec{v}_j - \vec{u}) ,$$

$$\frac{dx_j}{dt} = \vec{v}_j ,$$

where

$$S = s_j \cos\alpha + \left(h + \frac{l_j^2}{4 r_0} \right) l_j \sin\alpha ; \quad c_d = c_d(\alpha, f_j),$$

$$f_j = l_j^2 / s_j, \; m_j = \rho_s h s_j ,$$

m_j is the mass of a fragment, $\vec{v}$ - fragment's velocity, $\vec{u}$ - velocity of gas, s_j - area of the surface (one side), *h* - fragment's thickness, c_d - the drag coefficient, *S* - the effective area facing the flow, α is the angle of the orientation, l_j is the characteristic size of a fragment, *f* is the shape coefficient, r_0 - the curvature radius of fragments. The initial conditions for the equation are the following:

$$t=0; \quad \vec{v}_j = \vec{v}_{j*}; \quad x = r_{0j} ,$$

where $\vec{v}_{j*}$ is the velocity of the shell just before the breakup.

3. FRAGMENTATION OF SHELLS IN UNIFORM LOADING

A breakup of a cylindrical thin walled containment was regarded caused by an explosion of hydrogen-oxygen mixture filling the containment. The parameters of the mixture and the containment were chosen corresponding with that for the experiments described in [18].

The Fig.1 shows one of the test cases for the fragmentation event in the form of a diagram of total number of fragments of different masses originating as a result of a breakup of a cylindric shell caused by detonation of hydrogen-oxygen mixture inside.

The calculated diagram corresponds to experiment ESOC-2 [18]. The initial conditions were the following: the tank radius r = 30 *cm*, length 75 *cm*, wall thickness h = 0,5 *mm*, density ρ = 2700 kg/m^3, heat capacity c_v = 924,3 $J/kg{\cdot}K$, volume extendibility α_v = $6{,}72 \cdot 10^{-5} K^{-1}$, shifting module μ = 27 *GPa*, elasticity limit J_{max} = 0,68 *GPa*, energy per breach square unit γ = 100 kJ/m^2, exponential parameter Λ = 0,5. Comparison of the theoretical and experimental results shows that for the part of spectrum containing large fragments the coincidence is rather fine. A slight difference for small fragments (theory gives a larger number than the experiment) can be explained by the fact that in the experiment not all the fragments were collected. It is mentioned in [18] that for the test case ESOC-2 the lost mass was about 1,3% of the total mass of the shell that equals to about 20*g*. The existing difference of mass for small fragments between theoretical and experimental results is much less than this value.

Different modes of energy release processes were regarded: deflagration, detonation and deflagration to detonation transition process [20, 21]. In the last case an overdriven detonation wave can appear, producing very high rates of loading in reflection [22].

The results of numerical modeling show that the breakup process, the number and mass distribution of fragments, and their velocities differ greatly depending on the combustion mode (rate of energy release) inside the tank and this dependence is not monotonous. For the lowest (deflagration) and highest (detonation) rates of energy release the number of fragments is less than for the medium rate of energy release: i. e. deflagration to detonation transition. Maximal fragments' velocities and the time before the breakup for those three cases are illustrated by the following table.

Parameter	Deflagration	Transition process	Detonation
breakup time (ms)	7017	4272	1029
maximal velocity (m/s)	900	2500	1000

This dependence of breakup characteristics on the rate of the energy release inside the fuel tank is too large to be neglected.

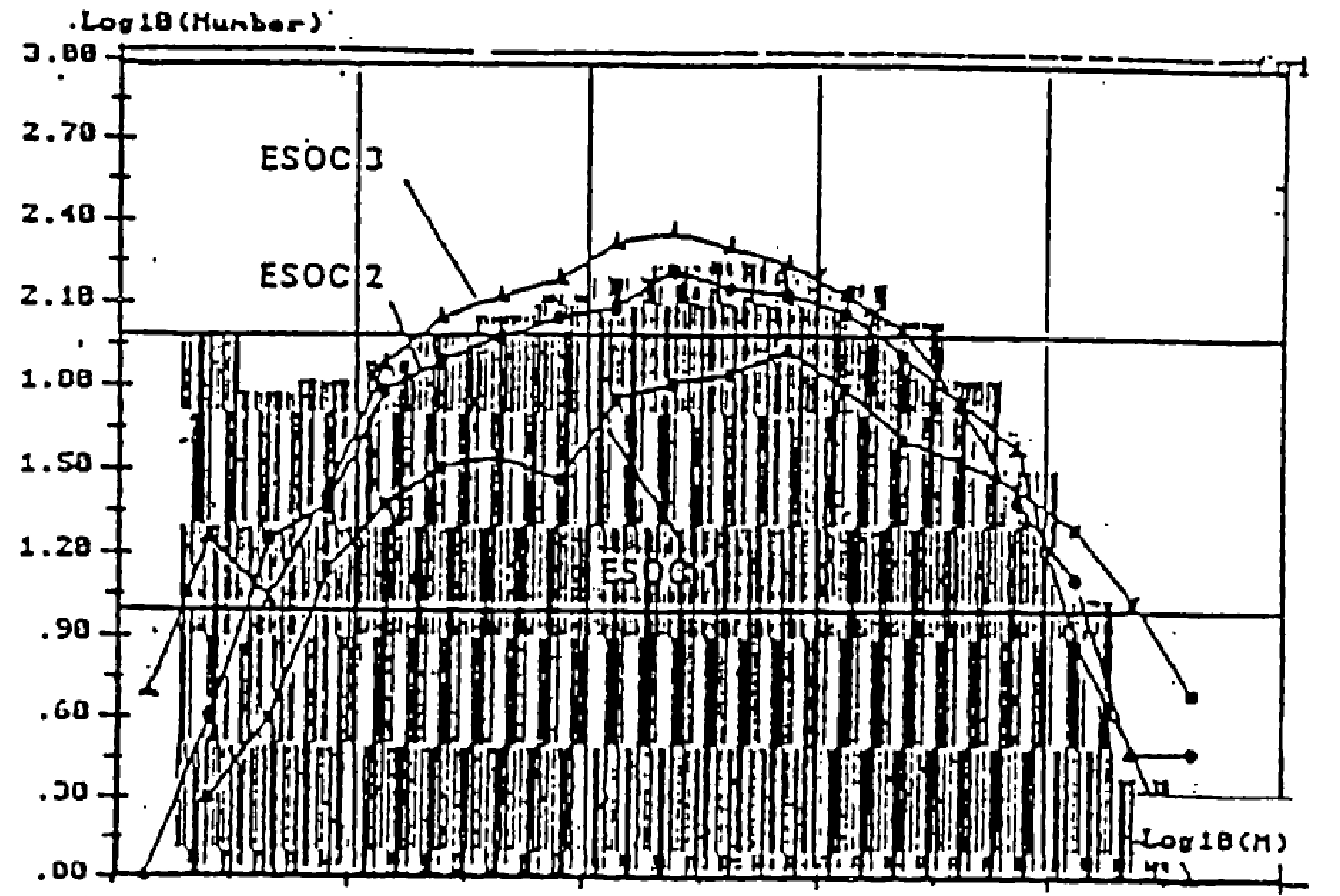

Fig.1. Number of fragments in breakup: diagram-theory; curves-experiment.

The next series of numerical experiments was devoted to testing the so-called similarity parameters for breakup of fuel tanks [18]. The similarity parameter was supposed to be $p_0 r_0/h = A = const.$ It was supposed in [18] that for the constant values of similarity parameters the number of fragments and their final velocities remained constant and masses of large fragments grew up proportionally to the growth of the volume of a shell's material.

The results of calculations for the case similar to ESOC-2 but with proportionally increased radial dimensions of the shell and thickness: $r_0 = 120$ *cm*, $h = 2$ *mm*. This increase of dimensions of the tank preserves the similarity parameter A constant. The results have shown that the number of fragments increased nearly an order of magnitude contrary to predictions [18]. The increase of final velocity was more than 20%. The volume of the shell material increased 16 times, but the mass of largest fragments contrary increase only 8-9 times.

Thus the results show that there cannot exist similarity parameters for such a complicated phenomena as breakup of a fuel tank and scaling of model tanks is a very difficult procedure. To apply the results of model experiments to the real fuel tank it is necessary to make use of general theoretical models and not simple scaling parameters.

4. BREAKUPS CAUSED BY NONUNIFORM LOADING

Most of explosions in space are not that producing uniform loading on the construction elements. Some of explosions were caused by accidental mixing of hypergolic components in fuel tanks of the second stages that had been in orbit for significant periods of time [13-15]. The conditions arose because first stage systems shut down on fuel or oxidizer depletion. Performance reserves are all in the second stage. The failure of the bulkhead brings to mixing and ignition of propellants. The energy release in breakup is not consistently related to residual propellant mass but to the mass of mixture of self-igniting components in an unknown pattern of dispersal within the tank formed after the breakup of the bulkhead. This type of combustion studied in [16] brings to nonuniform and sometimes oscillating loadings of the structure.

The fragmentation scenario in nonuniform loading can differ from that in uniform loadings. The breakup can start in the zones of maximal loadings where the breakup criterion is satisfied, and then cracks can develop in less loaded zones. This second stage of breakup can be initiated by the cracks coming from the damaged zone. Thus the less loaded zones (wherein the accumulated elastic energy E_α^* is smaller) form the larger fragments in breakup. Nonuniformities in internal loading can lead to different spectra of mass distribution of fragments.

Numerical investigations of wall-loading and breakup in diffusive combustion inside the tanks were carried out for the cylindrical tank of 1m diameter and 1*m* length with the walls 2*mm* thick and a coaxial orifice in the bulkhead 25*cm* radius [16]. The breakup took place when dissipation in one of the sections overcame the critical value D^* determined in independent experiments on spallation. The total number of fragments versus mass distribution function is shown in Fig.2. The corresponding velocities distributions are shown in Fig.3 in the form of the plots for maximal, mean and minimal velocities.

It is seen from Fig.2 that the plot of number of fragments versus mass distribution has two maxima and one of them for the large fragments that is an essential difference from the distribution (Fig.1) obtained for symmetrical loading by detonation. Large fragments were formed in the less loaded zones and small fragments were formed in the zones of high density of the accumulated elastic energy E^*.

The fragments velocity distributions (Fig.3) show that the mean velocity for large fragments is less than that for the smaller ones. Final velocity for the very small fragments does not depend on mass and is practically constant that is in a good agreement with the velocity distributions [11]. The decrease of velocity for large fragments took place due to the fact that in nonuniform loading the less loaded zones accumulated less elastic energy and less kinetic energy. Those zones could produce only large fragments in breakup.

The cumulative flux of fragments for the regarded case is shown in Fig.4a (curve 2). For comparative purposes Fig.4a contains also the cumulative flux of fragments formed in breakup of the same vessel in uniform loading by the detonation of hydrogen-oxygen mixture (curve 1). The difference in cumulative fluxes for the explosions of one and the same energetic equivalent is due to different modes of energy release and different loading patterns. Fig.4b contains the comparison of the cumulative number of fragments detected in orbital breakup with the EVOLVE model predictions [27]. The qualitative comparison with Fig.4a shows that the breakup having taken place was rather one caused by nonuniform loading in combustion than a high intensity explosion.

5. FRAGMENTATIONS CAUSED BY HYPERVELOCITY COLLISIONS

Fragmentation of a gas-filled or fluid-filled containment in hypervelocity collision has several characteristic stages. The first stage is fragmentation of the impactor and the wall in the collision zone and formation of a hypervelocity jet of small fragments penetrating inside the containment. Formation of cracks (and petals) in the collision zone do not usually bring to a breakup of the containment at the present stage. The hypervelocity fragments cloud forms a shock wave in the media, filling the containment. In case of a highly compressible media (gas) the edges of the hole in the wall (or petals) are deformed inside the containment, in case of a low compressibility of the media (fluid) the edges of the hole are bulging out.

The cloud of small fragments slows down very rapidly due to the drag forces. The deceleration for fragments is proportional to $1/r_0$ and grows up with the decrease of a characteristic size r_0. On slowing down the cloud the convertion of its kinetic energy into the internal energy of the surrounding gas (or fluid) takes place. The rapid increase of the density of energy in a small volume inside the containment is similar to that for the local explosion. The energy release gives birth to diverging blast waves inside the containment that reflect from the walls (Fig. 5 a, b) thus producing nonuniform loading. The loading pattern is somehow similar to that in reflected detonation waves but the fragmentation scenario can be different for the same energy equivalent. The concentrated energy release causes blast waves of higher intensity than the detonation wave. Thus the wall being more close to the blast point exercises higher loading and gives birth to a large number of small fragments. The breakup of the wall causes the pressure drop and the rarefaction waves going inside the containment, overtaking the blast wave and lowering down its intensity. Thus the far wall will be much less loaded and will give birth to large fragments.

This is not the case for the detonation wave propagating inside the containment as the rarefaction waves from the depressurization zones will never overtake the detonation wave and never decrease its intensity. Hence the "point blast" energy release produces a more wide spectrum of fragments than the detonation wave loading.

In case of a fluid-filled containment an overheated expanding gaseous cloud is being formed in the zone of fragments deceleration due to the concentrated energy release. The expansion of the gas-vapour cloud brings to a formation of a diverging shock wave. Reflections of shock waves in fluids from elastic walls take place in the form of the rarefaction waves that brings to the formation of the cavitation zones near the walls. The collapse of those zones usually results in breakup of the walls. The succession of the processes of internal loading of the fluid-filled containment: energy release in deceleration of fragments, gas-vapour cloud formation and expansion, blast wave propagation, reflection from an elastic shell, cavitation and collapse of cavities - can be described making use of the mathematical models for dynamics of multiphase media accounting for chemical and physical transformations [29].

6. CONCLUSIONS

The worked out mathematical models enable to create a universal approach to orbital breakups modeling. The results for fragments distribution functions and velocities qualitatively coincide with the existing models for different types of breakups and are in a good quantitative agreement with the experimental observations.

Being based on the physical principles, the created breakup models enable to solve inverse problems: to determine the possible breakup scenario using the data of fragments distribution and velocities.

The investigations show, that:

1) number, mass and velocity distributions of fragments depend not only on the total energy of explosion but have a strong nonlinear dependence on the scenario of energy release;
2) there is no unique similarity parameter for the problem, thus simple upscaling of the experiments is impossible.

7. RECOMMENDATIONS AND FUTURE RESEARCH NEEDS

A more detailed modeling of the fragmentation and/or damages in hypervelocity collisions of debris particles with pressurized gas-filled or fluid-filled vessels accounting for the peculiarities of kinetic energy transformation into the energy of blast waves' internal loading is necessary. The creation of a closed form model for the process will make it possible to have an adequate physical description of the peculiarities of one of important fragmentation scenario. Besides the solutions of the inverse problems enable to classify the reasons of the breakups having taken place.

The physical and mathematical models for hypervelocity impact on pressurized structures will be very useful in evaluation of potential damages of space vehicles in collisions with debris particles which turn to the more and more probable.

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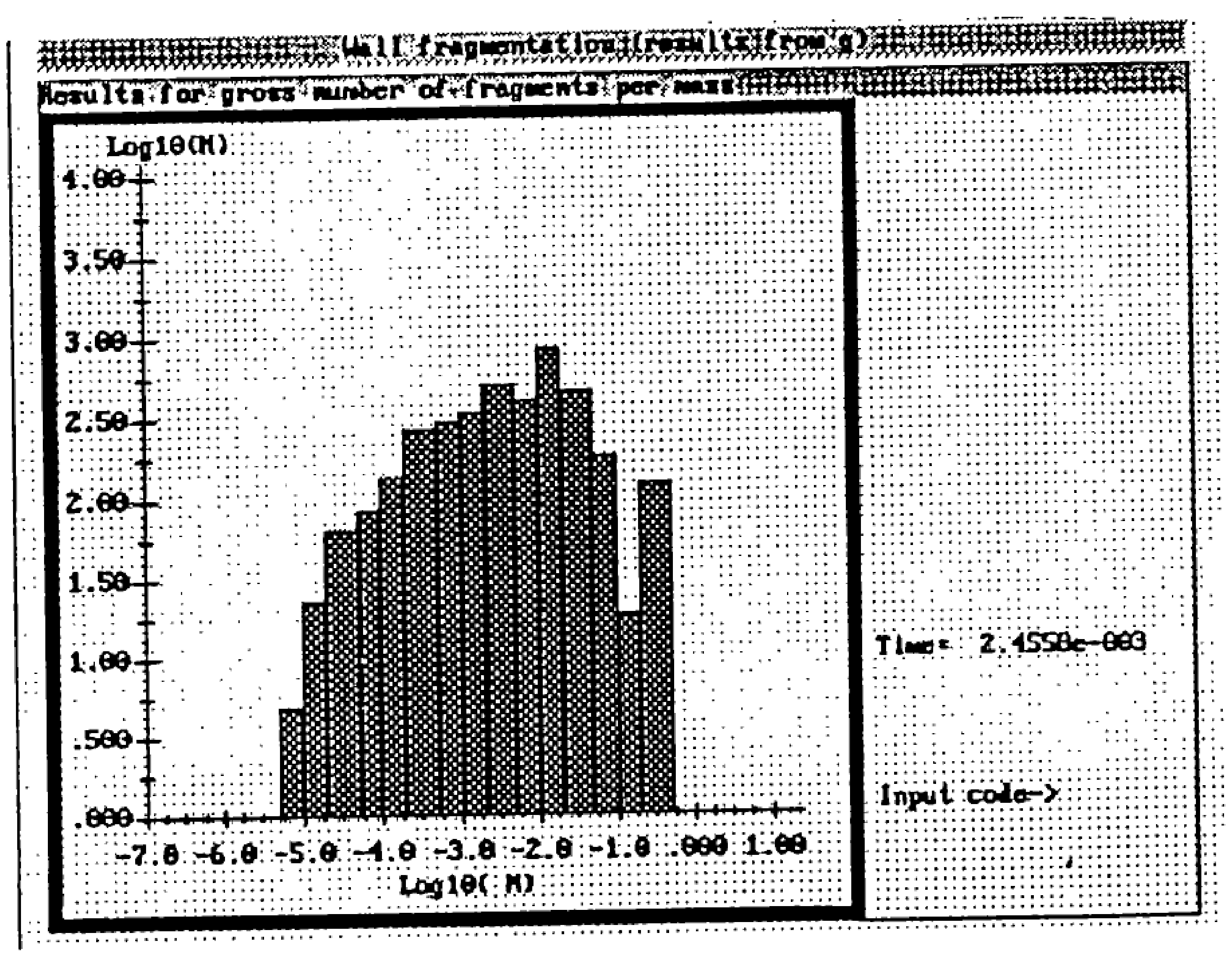

Fig.2. Number of fragments distribution in breakup caused by nonuniform loading

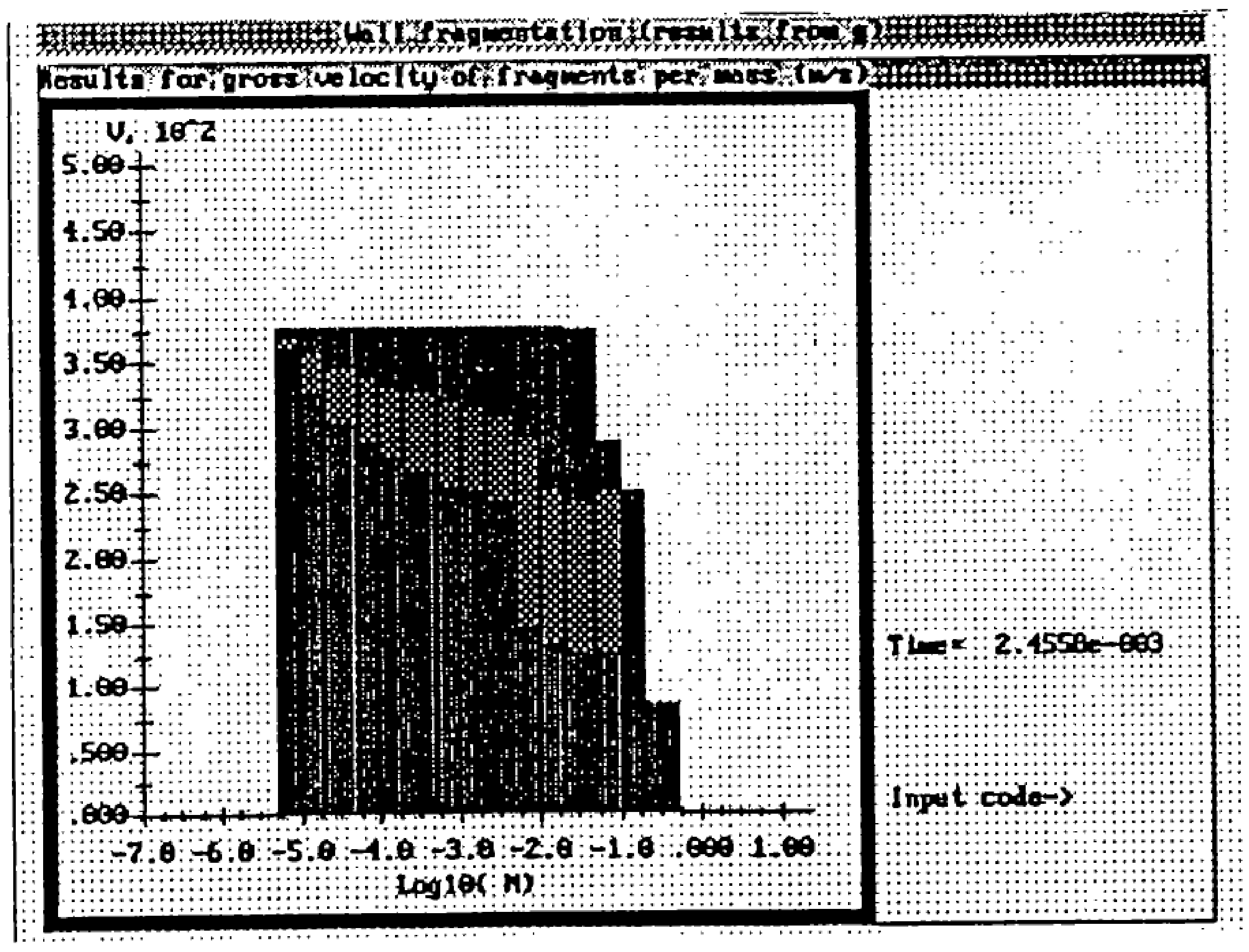

Fig.3. Maximal, minimal and mean velocities of fragments in breakup caused by nonuniform loading

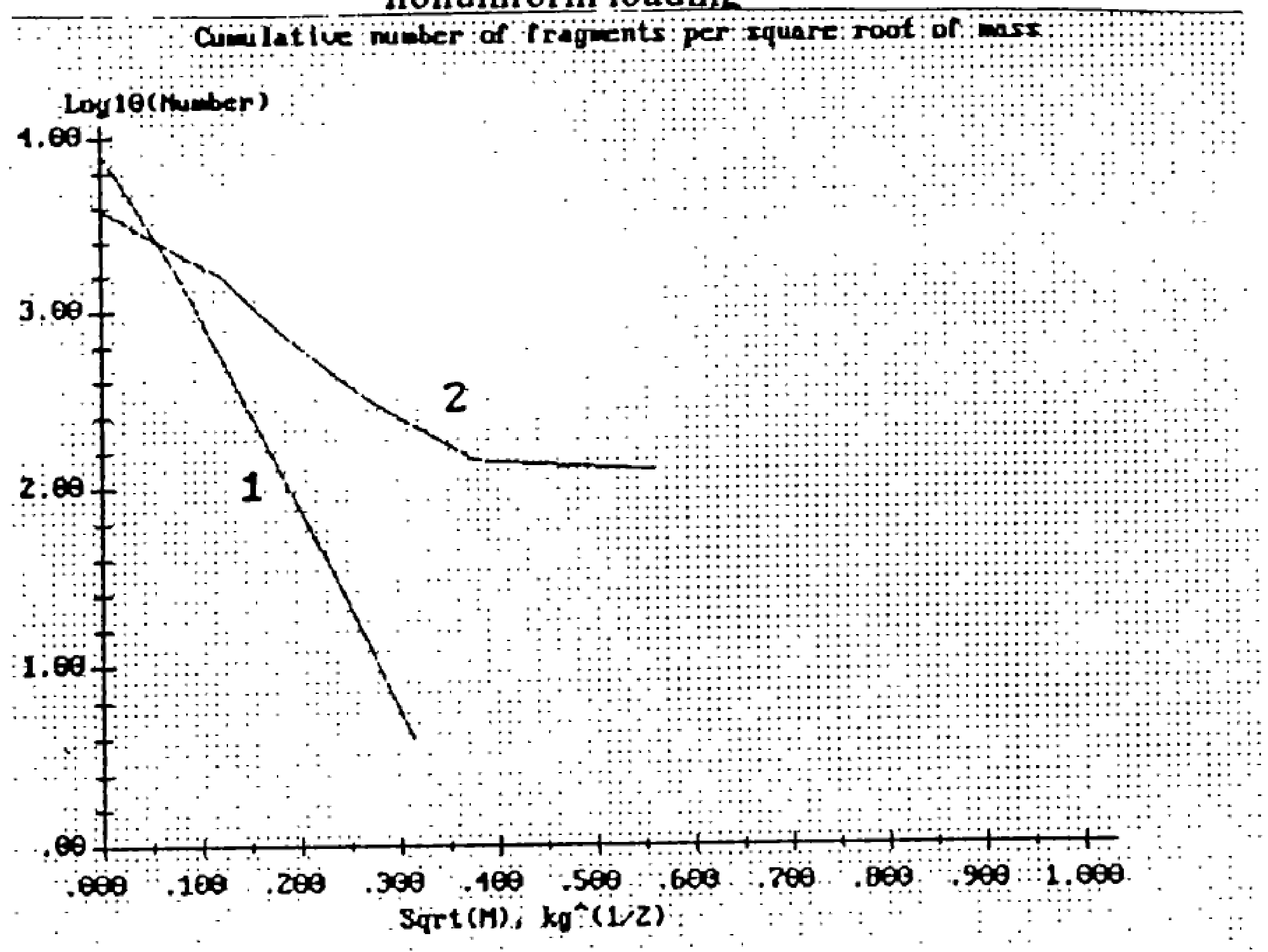

Fig.4a. Cumulative number of fragments in breakups caused by uniform (curve 1) and nonuniform (curve 2) loading

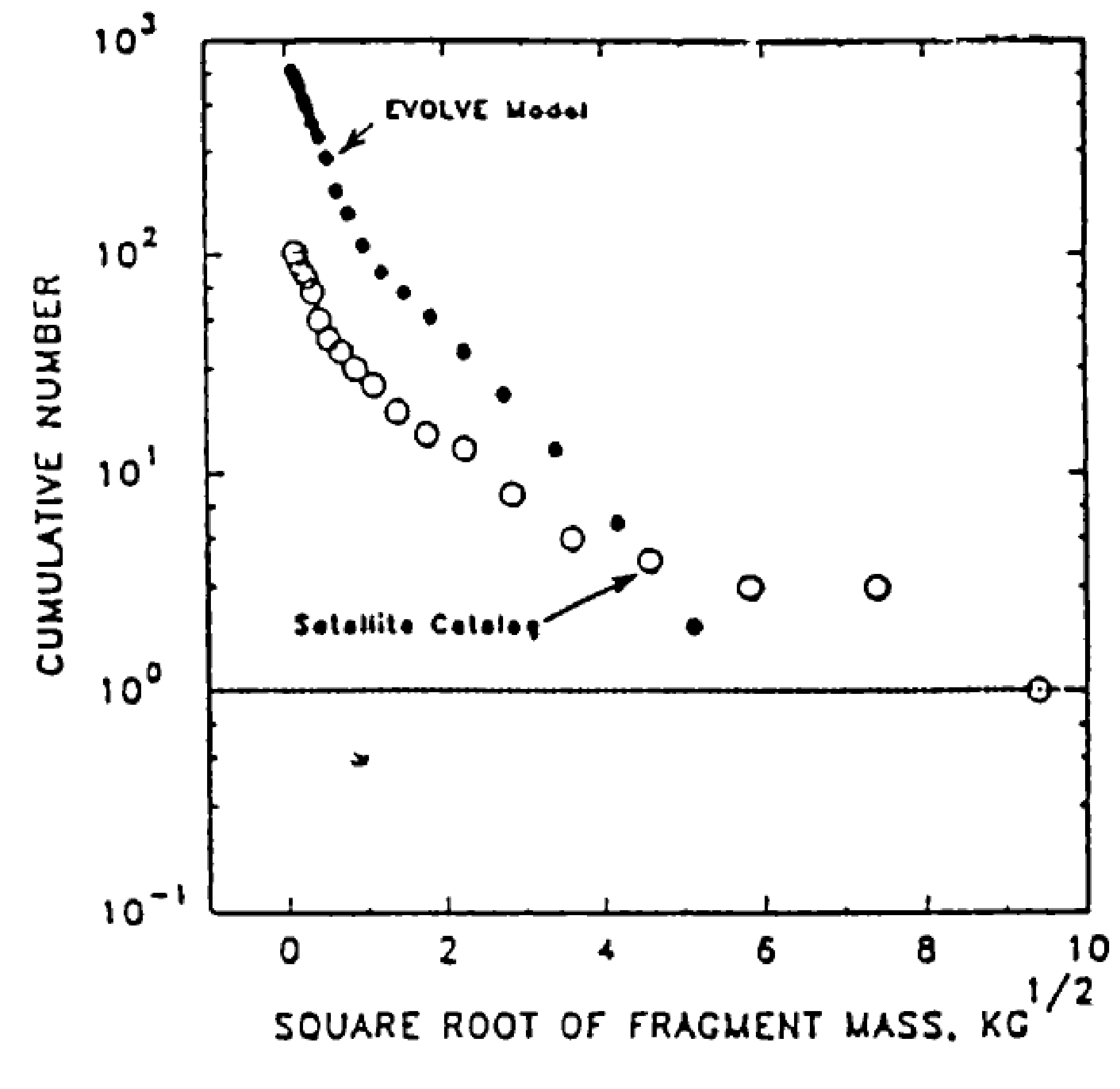

Fig.4b. Cumulative number of fragments in Nimbus 6 breakup: 0 - satellite catalogue; • - EVOLVE model

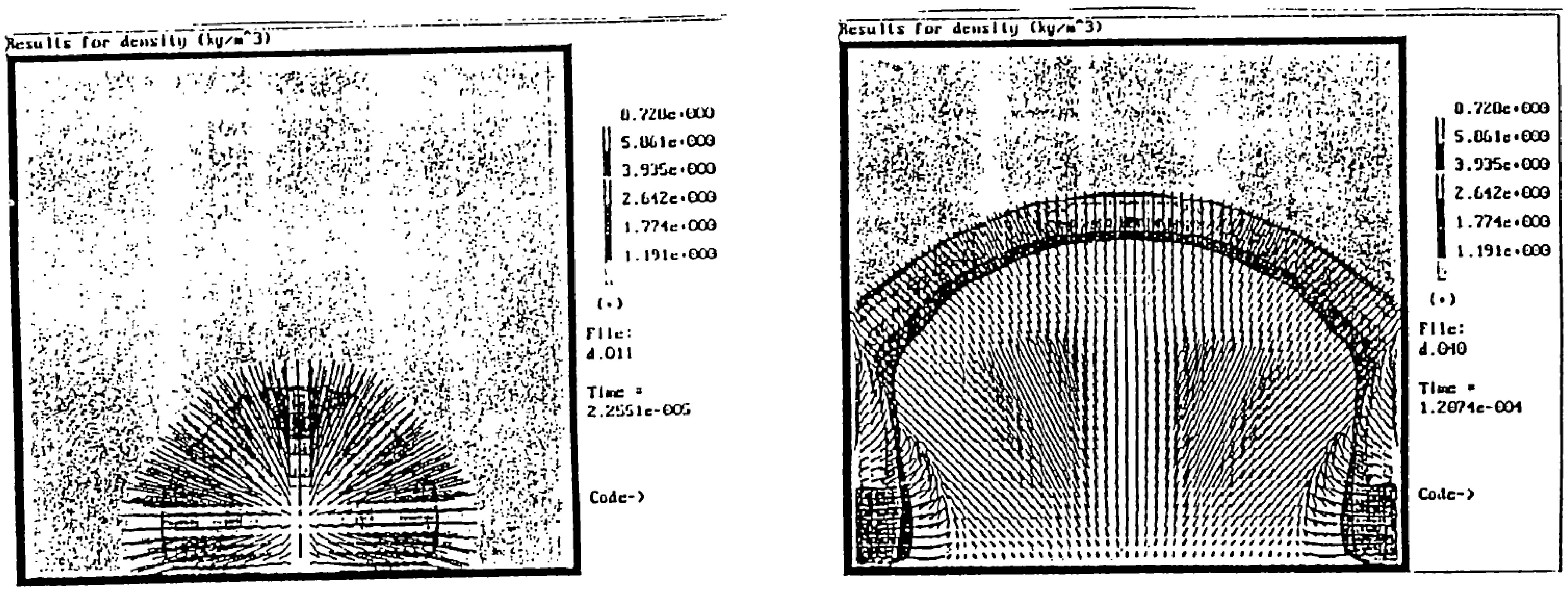

Fig.5. Sequent phases of internal loading in case of concentrated energy release. The map of tones in the upper right side of the figures shows density values in kg/m^3