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COMBUSTION AND STRUCTURE FORMATION IN SHS PROCESSES UNDER MICROGRAVITY CONDITIONS (SHS Plans for Microgravity Experiments)

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This paper outlines ISMAN suggestions for the joint NASA-RSA project "Combustion and Structure formation in SHS Processes under Microgravity Conditions". The basic ideas of this work naturally follow from our almost 30-year experience in the field of SHS [refs. 1 and 2]. As a matter of fact, we have already obtained some results in the following two directions closely related to the microgravity problem.

One is the studies on SHS processes in the field of centrifugal forces conducted by the group of Prof. Yukhvid [refs. 3 and 4]. These studies aimed at the intensification of gravity-sensitive SHS processes in multicomponent highly caloric systems forming melts at high overloads (up to 2000 g). In other words, these studies had the objectives that are inverse to those in the microgravity studies. Basically, the following results have been obtained. Combustion velocity U was found to increase with increasing overload $n=a/g$ (Fig.1). This was explained by the gravity-induced impregnation of the melt formed in the combustion zone into the mixture of starting reactants. This intensifies the longitudinal mass transfer in the combustion wave, thus elevating the burning velocity. Combustion yields two- or multicomponent melts. Within these melts, the gravity-sensitive processes also take place. In the gravitation field, heavy products precipitate whereas light fractions come to the surface: the so-called phase separation takes place. In experiments, the extent of phase separation η_{ph} is normally measured (Fig.2). In some systems, two ultimate limiting cases can be observed -- complete phase separation and and its complete absence. Within the intermediate range, the functionally gradient structures are formed. Overload intensifies the process of phase separation (Fig.3). In the absence of phase separation, the cast composite materials are formed. The higher is the difference between the density of constituent components, the more diffucult is to obtain cast composite materials even under the conditions of normal gravity. In view of this, microgravity may turn out to be the only tool to obtain these materials (Fig. 4).

The second group of results directly relates to the microgravity problem and the project under consideration. These experiments played the important role in establishing links between SHS and microgravity. In 1990, Prof. Shteinberg and his coworkers [ref. 5] carried out the first SHS experiments on the board of the plane during its parabolic flight: the microgravity conditions were sustained for 30 s. The experiment aimed at obtaining a foam material and its retention in the absence of gravity-induced damage of foam. The data obtained were promising: under the microgravity conditions, we obtained the foam titanium carbide with a porosity of 97% (Fig.5). Another important result is that homogeneous porous materials can be obtained only under the microgravity conditions (Fig.6). This was the only our work on microgravity. However, it turned out to be the first one that stimulated further interest in SHS microgravity studies.

Of great importance is a proper selection of the systems to be studied. This can predetermine a success of the project as a whole. For this reason, preliminary screening of numerous known systems seems to be necessary to perform. Some systems that may turn out suitable are listed in Table I, although some others can be found in the course of further studies. In investigating the processes of foam formation, the use will be made of gasifying agents.

Table 1. Systems to be studied

Synthesis of foam materials	Synthesis of fine-grained composites
foam carbides: Ti-C; Zr-C; Ti-Ni-C; Ti-Fe-C foam borides: Ti-B; Zr-B; Ti-Ni-B; Ti-Fe-B foam silicides: Ti-Si foam nitrides: multicomponent mixtures yielding nitrides foam intermetallics: Ni-Al; Co-Al; Ni-Co-Al; Ti-Ni-C; Ni-Al-B-Ti foam composites: Cr_2O_3-TiO_2-Fe_2O_3-Al-C; FeO-Al-C; NiO	Wo_3-Al; MoO_3-Al; Nb_2O_3-Al; Ni-Al-Ti-C; FeO-Al-C; Cr_2O_3-TiO_2-Fe_2O_3-Al-C

The experimental setup for first experiments is presented in Fig.7. The main point here is the angle between the vectors of combustion velocity and force of gravity. The most important cases: (1) these vectors coincide, (2) the vectors are opposite, and (3) they are oriented normally. In spite of the fact that the project has not been officially approved, we have carried out some preliminary experiments. (Table 2).

Table 2. Same preliminary results

System	$U\downarrow g\downarrow$		$U\uparrow g\downarrow$		$U\leftarrow g\downarrow$	
	U, cm/s	$\frac{\Delta l}{l}$	*U*, cm/s	$\frac{\Delta l}{l}$	*U*, cm/s	$\frac{\Delta l}{l}$
Ti+C	0.60	6	0.60	7	0.60	4
Fe_2O+Al+Al_2O_3	0.45	2	–	–	0.20	1
Ni+Al	3.20	1	3.20	1	2.20	1

For the Ti+C system, the sample elongation was found to be orientation-dependent. The maximum (7-fold) elongation was achieved in the case of opposite orientation. At normal orientation, the elongation never ecxeeded a value of four.

Another possibility is the dependence of combustion velocity on the angle between the *U* and *g* vectors found in the Fe_2O_3+Al+Al_2O_3 system. Burning velosity is largest when the angle is equal to zero and smoothly decrease with increasing angle. Quite different behavior is observed for the Ni+Al system. Minimum burning velosity is obtained when sample is oriented horisontally. Even these preliminary results seem to be fairly promising

Fig.8 shows the experimental setup for the study of combustion mechanisms under high overload (n = 2-10). This is a centrifugal machine (up to 10g) specially designed for a given project. Its manufacturing will get started immediately after real financial support. Special attention was paid to provide a possibility of experiments at both positive and negative overloads. Centrifugal studies are needed for the extrapolation of the data to be obtained to the microgravity conditions. Our approach -- the use of positive and negative overloads -- allows us to reduce the extrapolation problem to the interpolation one, thus making the solution more reliable. An expected result is illustrated in Fig. 9. It cannot be ruled out that, under the antigravity conditions (negative overload), SHS may turn out promising and competitive in solving some special problems.

Expected behavior of various SHS systems at gravity and microgravity conditions is illustrated in Table 3. Some effects have already been discussed above.

Table 3. Behavior of SHS systems at microgravity conditions (preliminary data)

Characterization of SHS system	Behavior at normal gravity	Expected behavior at microgravity conditions	Microgravity applications
1. Solid flame	Weak effects at high overload	No effects	–
2. Melted reactants, solid product	Effect of centrifugal impregnation	Purely conductive combustion of melts	–
3. Melted reactants, liquid (melted) multiphase product	The same as for Item 2.	The same as for Item 2.	
	Coalescence of drops, phase separation in melt	No drop coalescence and phase separation in melt, formation of fine-grained materials	Producting of cast fine-grained heterogeneous materials
	Melt shaping	Controlled shape formation (by the forces of surface tension), spheroid products	Producting of cast spheres
4. Partial gasification of components with melt in the combustion zone; added gasifying agents	Sample elongation, pore formation	Formation of highly porous materials	Synthesis of foam materials on the spacecraft board for *in situ* applications

In this context, we have selected the following two problems: (1) the formation of pores and foam and (2) the formation of fine-grained pore-free materials upon crystallization of multicomponent melts as well as the related microgravity effects.

Objectives of the Project:

1. Fundamental studies
   - Dynamics and mechanism of the gravity, "antigravity", and microgravity effects on the combustion and structure formation in SHS systems during the formation of pores and foam in the combustion wave
   - Formation of fine-grained structures upon crystallization of multicomponent melts
2. Research and Development
   - Synthesis of foam materials (borides, carbides, nitrides, silicides, intermetallics, and composites) on the spacecraft board for *in situ* applications
   - Preparation of cast fine-grained composites

Principal Stages

1st Stage: Laboratory-Scale Experiments

1.1. Selection of the systems to be studied by screening

1.2. The effects of the charge composition, charge structure, and environment on the SHS parameters under the conditions of gravity ($U\downarrow g\downarrow$; $U\uparrow g\downarrow$; $U\leftarrow g\downarrow$)

1.3. Centrifugal studies at $n=a/g=\pm 10$ followed by the interpolation to microgravity conditions

1.4. Model experiments with elementary heterogeneous cells

1.5. Mathematical modeling of combustion and structure formation at microgravity conditions

1.6. Detailed studies on the properties and structure of selected SHS products prepared under optimum conditions

1.7. Designing the reactors for space experiments

2nd Stage: Experiments at Artificial Microgravity -- to check the data obtained at Stage 1.

3rd Stage: Experiments at Natural Microgravity (on the board of spacecraft)

In conclusion, I would like to note that we found the points of mutual interest with Prof. Moore of the Colorado School of Mines in the SHS+microgravity problem and agreed to unify our efforts. Partially, the above tasks are to be solved within the frame of another project that has no special financial support. I believe that this cooperation will be useful for the project under consideration. I would like to note that we are open for cooperation with all those who are interested in.

Acknowlegments

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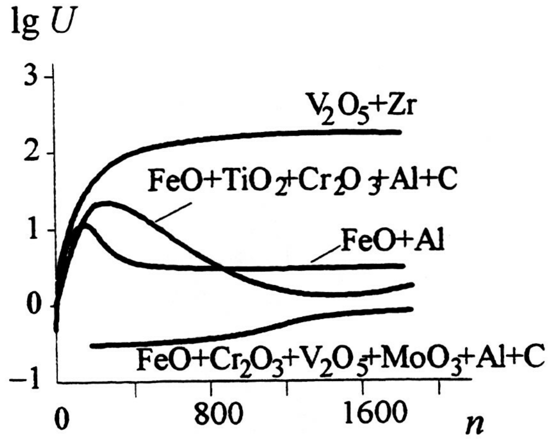

Figure 1. Combustion of SHS systems of gravity overload (some results)

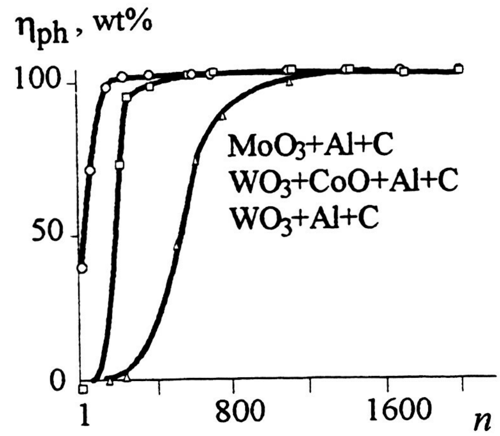

Figure 2. Effects of overload on phase separation

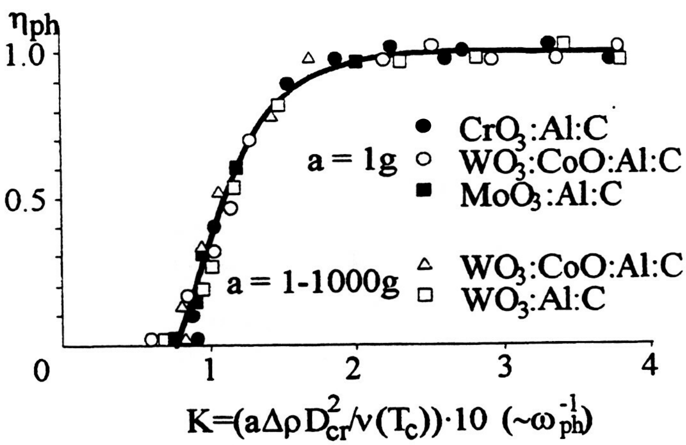

Figure 3. Generalized curve of phase separation

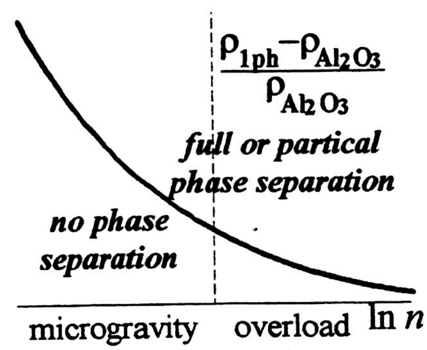

Figure 4. Expected microgravity effect

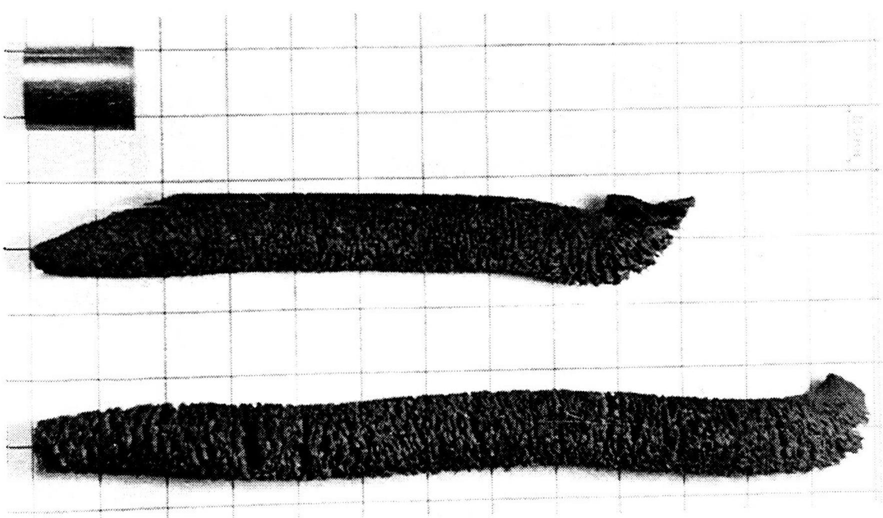

Figure 5. Photograph of samples.

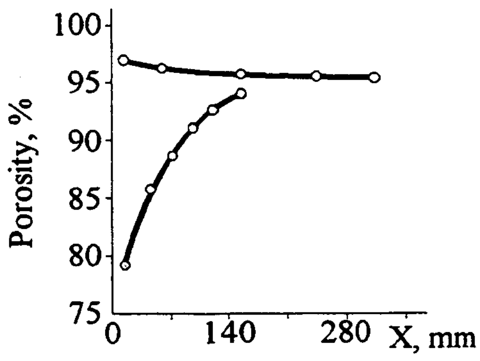

Figure 6. Porosity distribution along the sample length after combustion

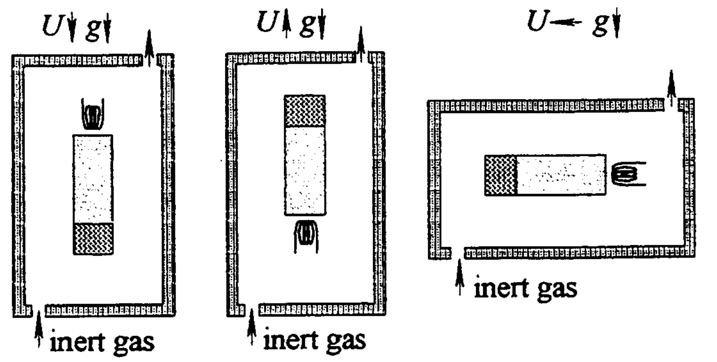

Figure 7. Experimental setup for testing the system to be studied

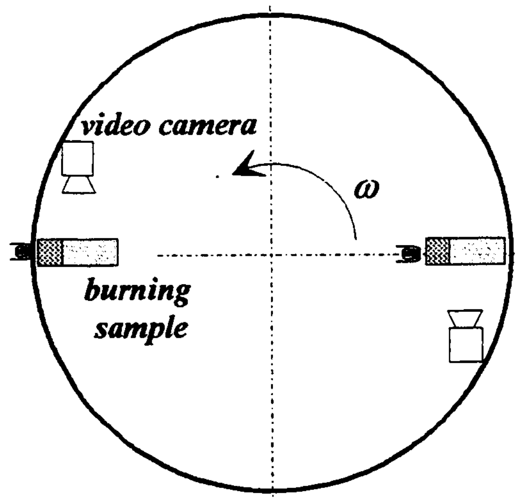

Figure 8. Schematic diagram of centrifugal experiment

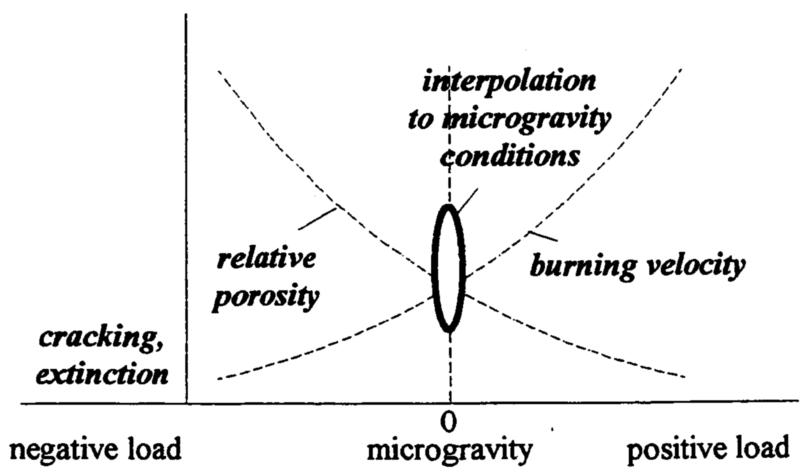

Figure 9. Expected results