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"Fluid Space Aspects in Space Processing"

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FLUID SCIENCE ASPECTS
IN SPACE PROCESSING

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Lectures Notes for the ICTP Workshop on Space Physics: Materials in Microgravity

1. INTRODUCTION

Processing in Space can be categorized according to the motivations, the type and location in Space of the laboratory or of the Facility, the materials to be processed and to their utilization. A possible summary is represented in Table 1 where different Space environments are defined.

The term "Space" denotes, in our context, a Microgravity Environment (MGE), like that existing on orbiting platforms. "Processing" is referred to the obtainment of better (or unique) products for utilization on earth of materials that are originally available on earth.

Space platforms or Laboratories show different capabilities in performing Space Processing; limitations with respect to the ground facilities of the different types of platforms, manned and unmanned Laboratories, are illustrated in Table II.

2. SPACE PROCESSING EXPERIMENTS

In order to ascertain the feasibility of new Space processes (that is the aim of this first phase of Space utilization) a number of experiments have been performed and are being designed. These experiments can be categorized as

A) Basic Experiments B) Fluid dynamic Studies in simulated MS Facilities C) Exploratory Experiments on the MGE effects on Material Processing D) New Space Processes; they are listed in this somehow logical order in Table III.

Surprisingly enough the chronological order of the experiments performed until now did not follow the logical "brick building" process (in which an adeguate knowledge of the basic phenomena precedes the applicative phase) but is almost reversed with respect to the order appearing in Table III.

The reason for this trend was that the suppression (or strong reduction) of segregation, natural convection and buoyancy forces associated to the MGE made people hope that processing in Space could immediately solve a number of problems encountered in ground processing and that new or better materials could be immediately manufactored in Space.

Furthemore the great expenses involved in Space experimentation suggested to skip the time consuming basic experimentation in the MGE that would have given the necessary support in properly designing the experiments.

Experiments of the C) and D) category were performed on the available platforms (Rockets, Skylab, Salyut, Spacelab) but quite often the expectations were not as anticipated, mainly because the drastic reduction of the gravity forces did not necessarily imply quiescent conditions of the liquid specimens: the forces that exist on ground and in a MGE and that are typically dominated by gravity on ground, themselves dominate in a MGE and give rise to new and unexpected flow fields.

These preliminary and somehow surprising results (some of which are briefly illustrated in the next Section) suggested to perform a number of basic experiments and simulated MGE experiments that have given great impulse to the understanding of the role of gravity in typical earth process, and hopefully may also lead to better ground processes. In fact the possibility of separating the gravitational effects, by operating in an environment in which these effects are negligible, has advanced the understanding of the role of gravity in material processing and one may hope to be eventually able of controlling these forces to ameliorate the materials produced on Earth.

The facilities that are playing a major role in this phase of the Space experimentation are those that simulate MS conditions by employing low temperature, transparent liquids. The idea is to utilize liquids, methodologies, diagnostic instrumentation, thermodynamic conditions and data handling that are typically encountered in fluidynamic experiments; these conditions allow to study the phenomena which occurr during the experiment itself and not after the experiment has been terminated (as it is typically done when performing examination of solidified specimens); this procedure yields a more direct appreciation of the roles played by different parameters and avoids speculations on the possible correlations between causes and effects.

The difficulty in the design and in the preparation of the experiments is the accomplishment of a meaningful simulation of the different processes by means of different liquids, different boundary conditions and different scales. Accurate analyses of the processes to be simulated and the correct definition of the pertinent simulation parameters (or characteristic numbers) are essential for achieving at least a partial simulation of the most relevant phenomena.

Typical Space processes that may be simulated in Fluidynamic facilities are illustrated at point B) in Table III.

3. EFFECTS OF THE MGE IN SPACE PROCESSINGS

The figures 1-14 (taken from Ref. 1) try to compare what happens on ground with what is expected to occurr in a MGE due to the suppression of the gravity forces.

The figures are self-explanatory.

Illustrations 1-6 show a number of typical examples of what are the expectable advantages for material processing in a MGE.

The benefits that are likely to occurr in Space in solution growth, in electrophoresis are shown in Fig. 7-8. Substantial improvements are also expected in the measurement of diffusion coefficients (fig. 9) and in the establishment of conditions that allow basic studies to be performed (e g. diffusion flame (fig 10).

The last figures show the substantial difference in the behaviour of liquids in a MGE. Hydrostatic behaviour of contained are liquids illustrated in figs 11 12. Similarly one would be able to levitate very large drops of melts by e m. or by acoustic forces for an efficient containerless processing. Hydrodynamics behaviour in two typical situations (floating zone simulation and boiling) is reported in figs. 13 and 14.

Most of the expectations proven to be correct for a number of experiments; for instance: 1) the strong reduction in hydrostatic pressure allowed the formation of floating zones about 50 times larger than those obtainable on earth at the same conditions (experiments performed in the Fluid Physics Module in the FSL1) (fig. 13), 2) the lack of buoyancy forces discouraged

sedimentation and separation processes of solid particles in compounds (experiments performed in Texus and MAUS experimensts) (Fig 4) and 3) the absence of strong thermal natural convection allowed to grow protein crystals much bigger than those grown on earth (FSL1 experiment) (Fig 7).

On the other hand expectations were not met for other classes of experiments in which the gravitational buoyancy forces on earth played a dominant role that masked the effect of the other forces (e g. surface tension); when, in the MGE, these forces took over, entirely new conditions were established that sometimes did not result in an advantage of operating in a MGE.

Two typical examples will be presented that elucidate this point and show also the reasons that motivate the recent trend of performing basic fluidynamic experiments in Space aiming at a deeper understanding of the roles of the different forces.

The first example is the floating zone process that could be substantially improved by the establishment of larger liquid bridges and by the suppression of the convective motions in the melt during the solidification phase.

Texus experiments (TEM 04) and FSL1 (FPM) have shown that it is possible, as expected from a hydrostatic point of view, to establish liquid bridge many times larger than those on ground (see Fig 13).

However motions were created by surface tension unbalance in the liquid (Marangoni flows). In Fig 15 the flow field induced in a simulated floating zone (1.8 cm long) flown on Texus 9 rocket flight is shown (the picture shows the tracers position during the film exposure time) these large convective motions, caused by surface temperature gradients, were not initially expected to occurr and have triggered the interest of the scientific community, now engaged in performing a number of interesting experiments with the aim of controlling the Marangoni flows and of setting up experimental conditions favourable for the Material Processing.

The second instance is also related to surface tension forces becoming dominant in a MGE. As illustrated in Fig 4 one would expect that cooling through a miscibility gap alloys (A+B) would create small inclusion of A dispersed in the matrix B, thus allowing a more uniform and a more isotropic composite alloy to be formed. In absence of sedimentation the growing process of the drops A (Ostwald ripening, wetting actions with the crucible) are rather slow compared with the solidification process. However, again, a somewhat unexpected phenomena occurred leading to large phases separation.

Fig 16, that reports a number of experiments performed on Apollo-Soyuz and on rockets, shows a dramatic example of the difference between the expectation and the reality.

What happen is a substantial separation of phases (Pb-Zn; Zn-Bi; Al-In) apparently due to the migration of drops caused by surface tension unbalance induced at the drops interfaces by temperature and concentration non uniformities. Typically the liquid drops "swims" in the liquid matrix towards the lower surface tension sites (different concentration and/or temperature). This phenomena is so relevant in Space processing that many basic experiments in a MGE are being proposed and specific Fluid Dynamic Facilities are being developedto study the motions of intrusions in liquid matrix.

The above mentioned instances point out at the importance of a complete understanding of the liquid behaviour in a MGE. This can be obtained only by means of a number of basic experiments that are performed by methodologies and experimental equipment in use in Fluidynamics. In practice the experiments must be simulated with the use of different substances (e g.

transparent liquids) at different temperature (much lower than those encountered in melting and solidification processes) in order to allow the typical fluidynamic diagnostic equipment to be used. However the processes of interest can only be partially simulated; the relevant simulation parameters (or characteristic numbers) for each class of experiments must be known and their values in the simulated fluidynamic experiments must be the same as those in the experiments to be simulated.

Typical basic experiments that are receiving a great interest to day are:

- Surface tension induced flows in floating zones, levitating drops, open boat melts (Marangoni flows)

- Heat and mass transfer in liquids exhibiting a miscibility gap (separation processes, drop growth, motion and coalescence of drops)

- Heat and mass transfer in solidification processes (solution growth, vapour growth)

In conclusion one may distinguish four different motivations for the Facilities that have been utilized so far for Space experiments:

A) Investigating basic phenomena with ad-hoc or with multiusers Facilities

B) Studying Space processing phenomena by appropriate simulation Facilities

C) Processing in Space with basically a small scale replica of same Earth facilities and look at the ameliorations induced by MGE

D) New processes in Space

Again the B) type facilities proved to be necessary to gap A and C type facilities. They may be looked at either as a step "forward" from the A type facilities (towards applications) or a step "backward" from C type facilities (towards basic studies).

4 THE ROLE OF FLUIDYNAMICS IN SPACE PROCESSING PHENOMENA

To understand the role of fluidynamics in Space Processing one must single out the g dependent terms, in the momentum equation that governs the motion of the liquid phase, and compare them with those which are independent of the g level (pressure, surface tension, inertia). The zero g conditions are recovered in the limits when the first term vanish with respect to the second ones.

To elucidate this point let us write the momentum Bulk and interface equations in typical simplified conditions

Bulk equations

$$\underline{\nabla} P_H = \rho_o \underline{g}$$

$$\rho_o \frac{D\underline{V}}{Dt} + \underline{\nabla}(p - P_H) = (\rho - \rho_o)\underline{g} + \mu \nabla^2 \underline{V}$$

Interface equations

$$\sigma K + \delta\{p + 2\mu \, \underline{\nabla}_t \cdot \underline{V}_t\} = 0$$

$$\mu \frac{\partial \underline{V}_t}{\partial n} = \underline{\nabla}\sigma$$

where δ denotes the jump condition across the interface (i.e. the difference of expressions between the two sides of the interface), P_H is the hydrostatic pressure, subscript o denotes conditions at T=To, subscripts t,n denote component tangential and normal to the interface respectively, K is the interface curvature, σ is the surface tension.

Let us consider the quite common instance in which one wants to establish, during the process, diffusion controlled conditions or, equivalently, to eliminate convective motions in the liquid phase. In order to do that one should simply set up conditions at which all the driving forces appearing in the momentum equations (responsible of convective motions) vanish.

Apart from the wetting and spreading actions on solid surfaces and from the pressure terms, the driving forces appearing in the momentum equations are:

A) In the bulk (buoyancy) $(\rho - \rho_o)\underline{g} = [\rho_T(T - T_o) + \rho_c(c - c_o)]\underline{g}$

B) On the Interface (Marangoni)

$$\underline{\nabla}\sigma = \sigma_T \underline{\nabla} T + \sigma_c \underline{\nabla} c$$

It is therefore obvious that for liquid solutions in the absence of any liquid-liquid or liquid-vapour interfaces, vanishing values of the g-level imply vanishingly small driving forces (and vanishing convective motions) even in presence of concentration and temperature non uniformities.

Viceversa, when fluid-fluid interfaces are present, then the driving forces, induced by concentration and temperature non uniformities, do exist even for vanishingly small g levels and become predominant.

This is the reason, for instance, of the large convective motions (Marangoni flows) that were found in a number of space processing experiment (as reported in the previous section).

One of the first results of the space sperimentation is the understanding of the role played by the g forces during material processing (on ground and in a MGE); these first results should precedes the implementation to Space and to ground Material Processing. The final goal of all these experimentation is to take advantage either of the absence of the g forces (in MGE) or of the presence of the g forces (on ground) for ameliorating the products.

REFERENCES

1. R. Monti: "Space, an extension of a Ground Laboratory" Techno System - Eurosat "Microgravity Sciences Presentation" Ottawa - Oslo - Copenaghen - September 1982

2. DFVLR "Preliminary Scientific Results of micro-g Research Programme" - December 1983

TABLE I

SPACE PROCESSING SUMMARY

MOTIVATION	LOCATION OF THE FACILITY IN SPACE	RAW MATERIAL AVAILABILITY	PRODUCTS UTILIZATION
High Added Cost	Spacecrafts	Earth	Earth
Materials	Space Stations	Earth	Earth
Construction in Space	Space Station Artificial or Natural Satellites (e.g. Moon)	Earth	Space
		Space environment	Space
Survival in Space	Space Station Planets	Earth or Space environment	Space Space
Mining in Space	Space Station	Space environment	Space
	Moon	(moon, asteroids)	Al, Si, Ti, Precious Ca, Fe

TABLE II

Space, an Extension of Ground Laboratories

CHARACTERISTICS OF GROUND AND SPACE LABORATORIES EXPERIMENTS

	Ground Laboratory	Space Laboratory			
	Manned	Unmanned		Manned	
				Man on-board	Man on ground (Remote Control)
MISSION DURATION	No limitations	Very short (minutes) (Rockets)	Very long (months) (Retrievable Carrier)	Days (SPACELAB)	No limitations
Main Limitations	UNLIMITED ● TIME ● POWER ● ENERGY ● VOLUME ● MASS ● DATA HANDLING	LIMITED ● ENERGY ● VOLUME ● MASS	LIMITED ● POWER ● DATA HANDLING	LIMITED ● POWER ● MASS ● VOLUME	LIMITED ● POWER ● DATA HANDLING

TABLE III

TYPICAL EXPERIMENTS AIMED TO SUPPORT SPACE PROCESSING

A) Basic Experiments	- Free Convection - Fluid Management Problems - Liquid bridge - Interface Phenomena - Thermodiffusion and diffusion Coefficient measurements - Reaction Kinetics - Combustion phenomena
B) Fluid dynamics Studies in simulated MS facilities	- Low T melts - Intrusions management - Solidification fronts - Miscibility gap phenomena - Drop growth and coalescence - Electrophoresis
C) Exploratory experiments on MGE effects on Material Processing	- Crystal Growth (melts, solution, vapour) - Immiscibile Alloys - Monotectic and eutectics - Floating zone refiming - Undercooling
D) New Space Processes	- Skin Technology - Containerless Processing - Bubble reinforced materials - Composite with oriented fibers - Emulsions solidification

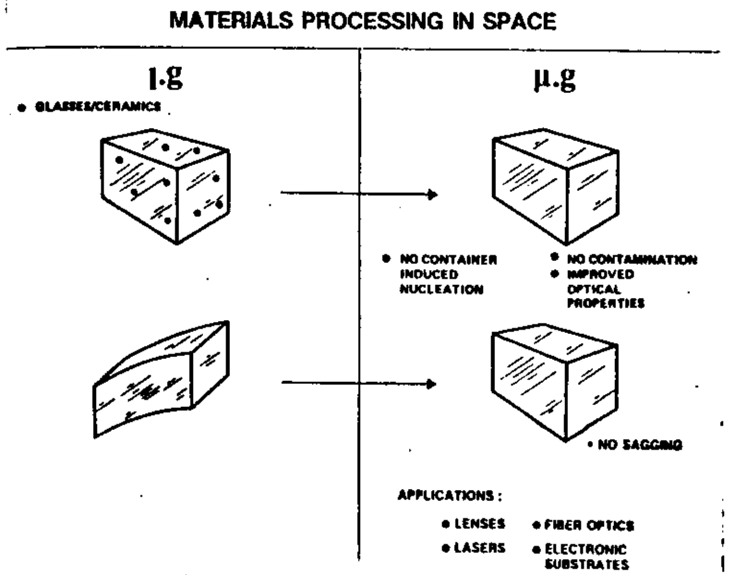


Fig. 1

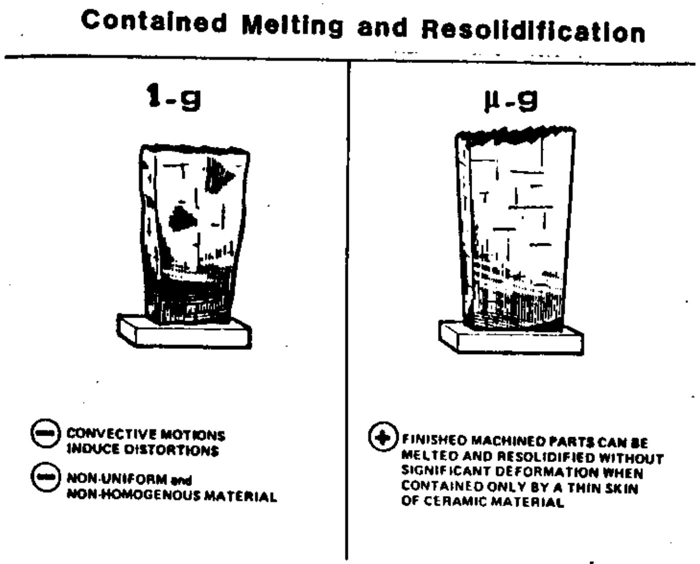


Fig. 2

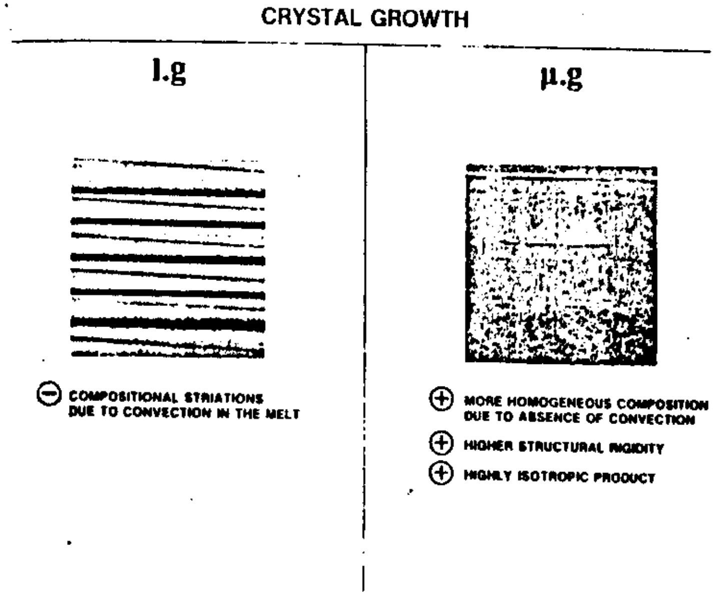


Fig. 3

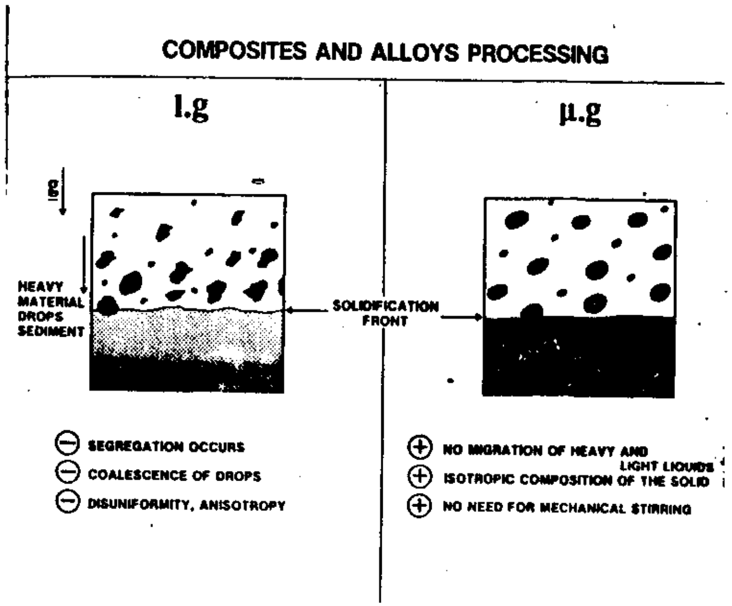


Fig. 4

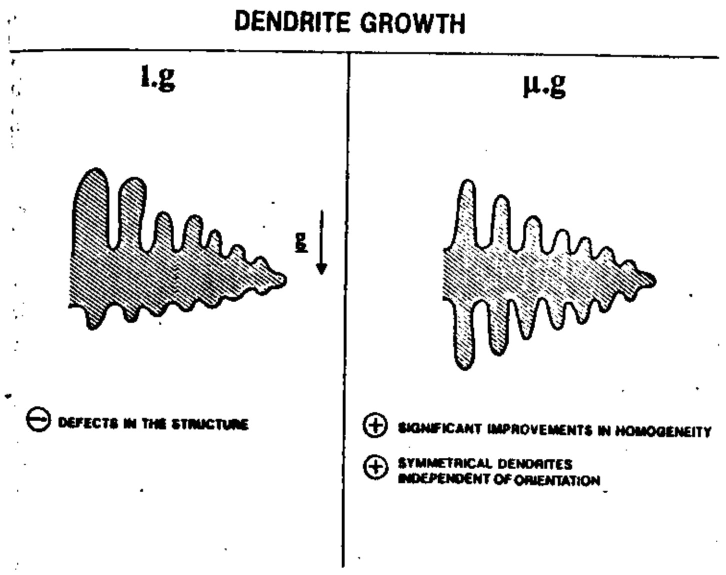


Fig. 5

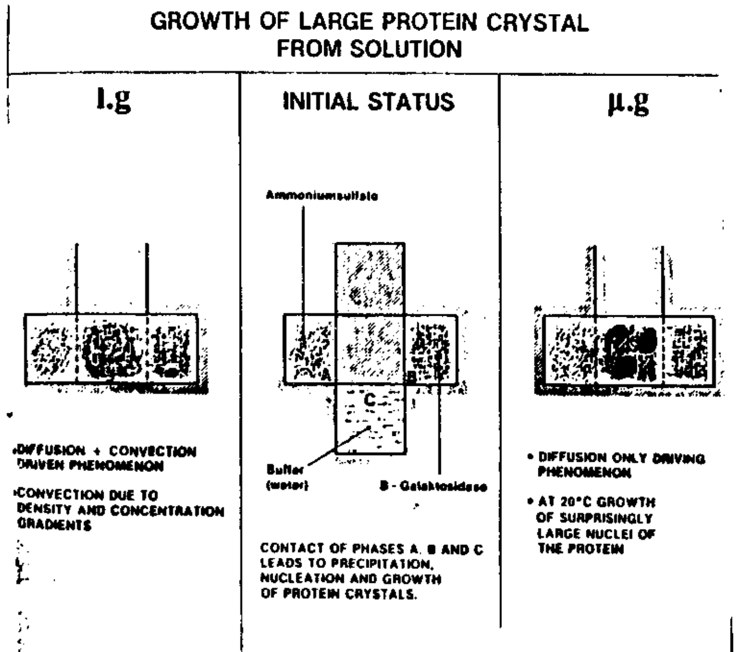


Fig. 7

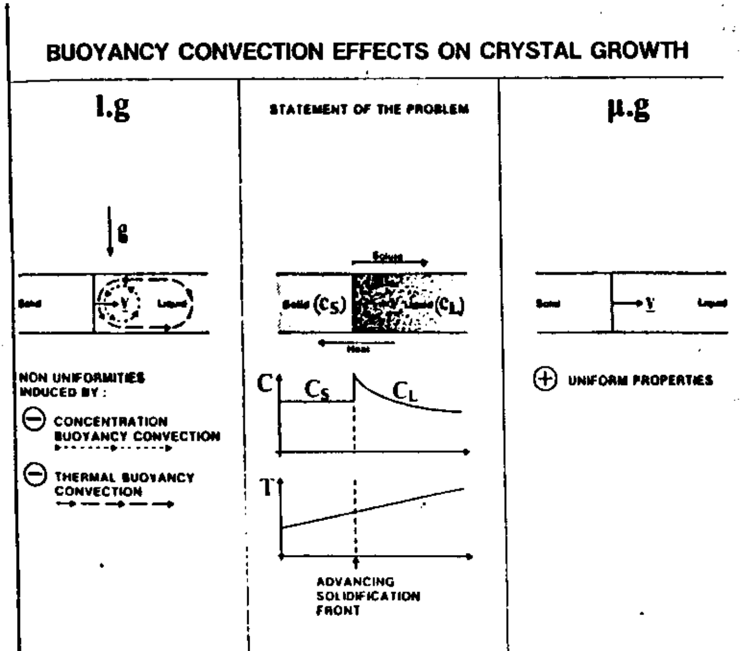


Fig. 6

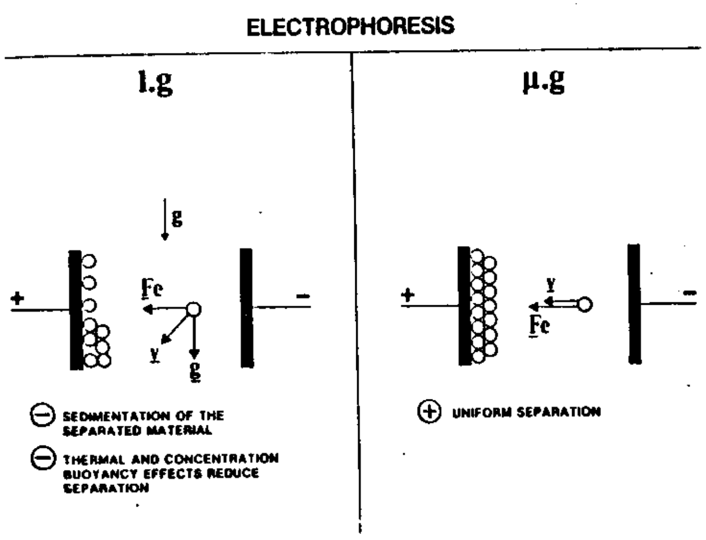


Fig. 8

EVALUATION OF DIFFUSION COEFFICIENT OF LIQUID METALS

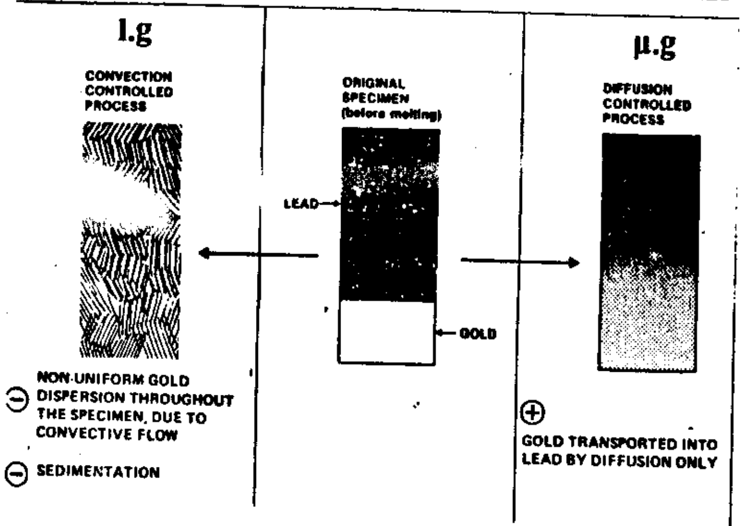


Fig. 9

DIFFUSION FLAME STUDY

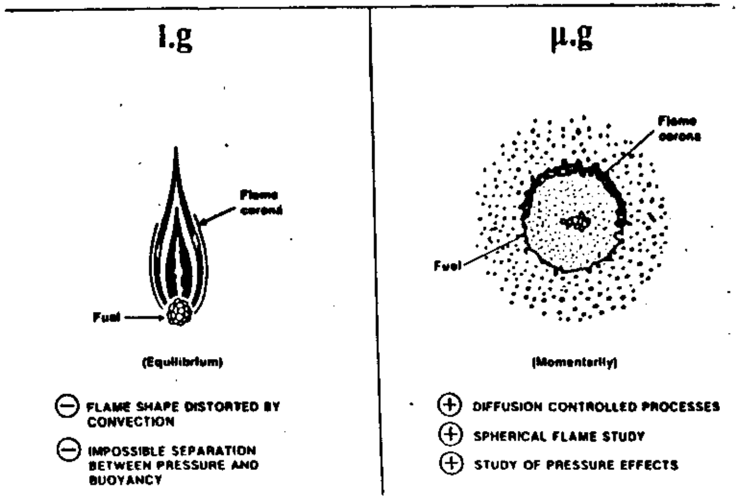


Fig. 10

HYDROSTATIC CONFIGURATION OF LIQUIDS IN MICROGRAVITY INSIDE THE SPHERICAL CONTAINER (50 % FULL)

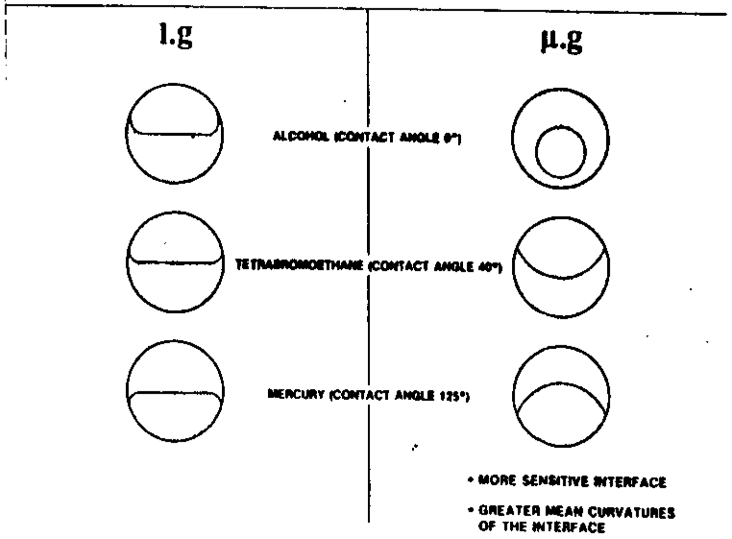


Fig. 11

STABLE CONFIGURATION OF TWO IMMISCIBLE LIQUIDS INSIDE A CONTAINER

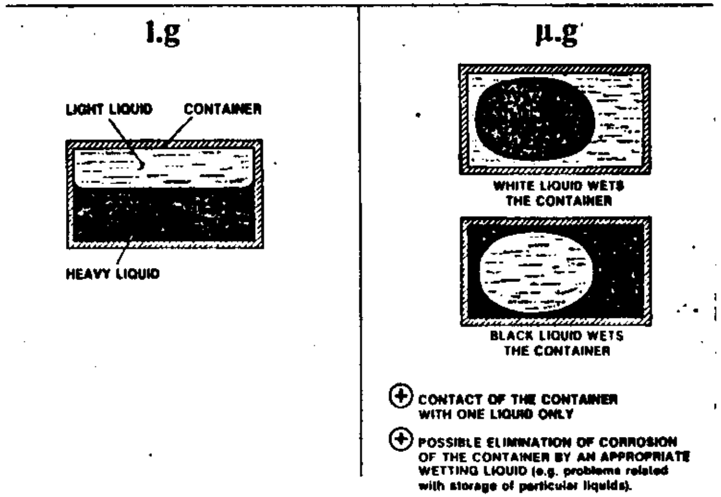


Fig. 12

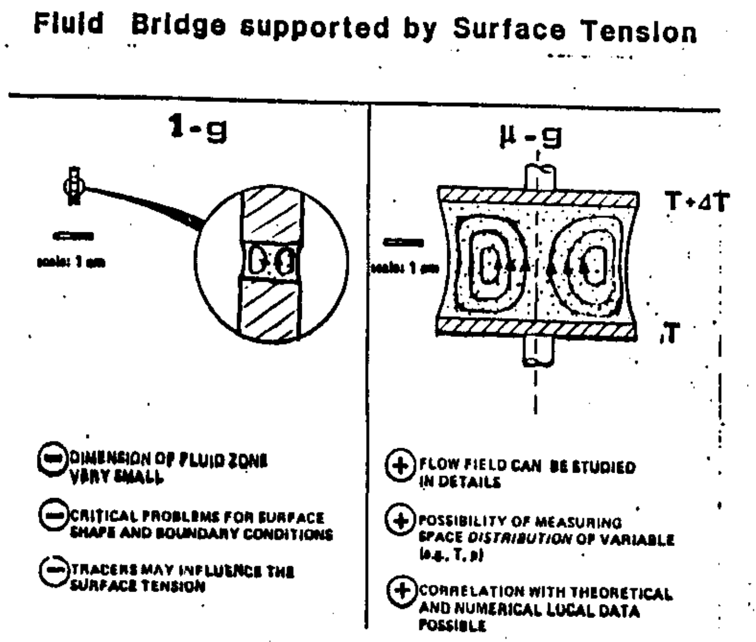


Fig. 13

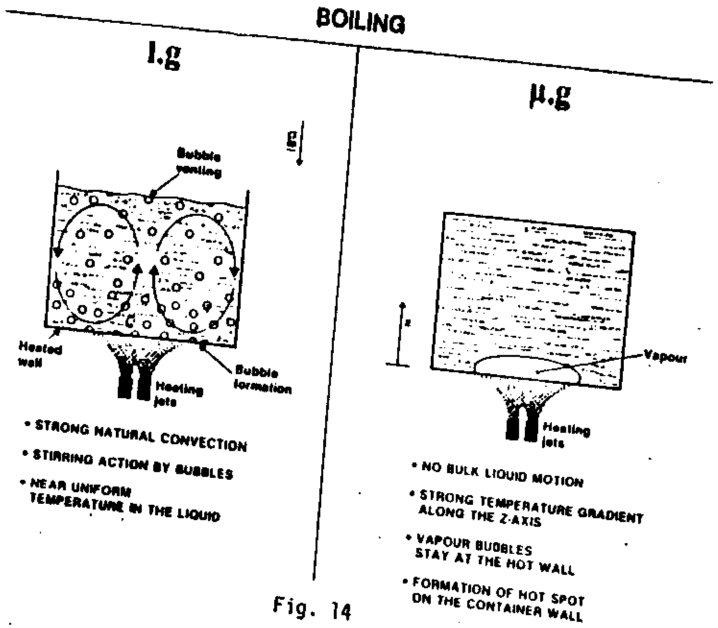


Fig. 14

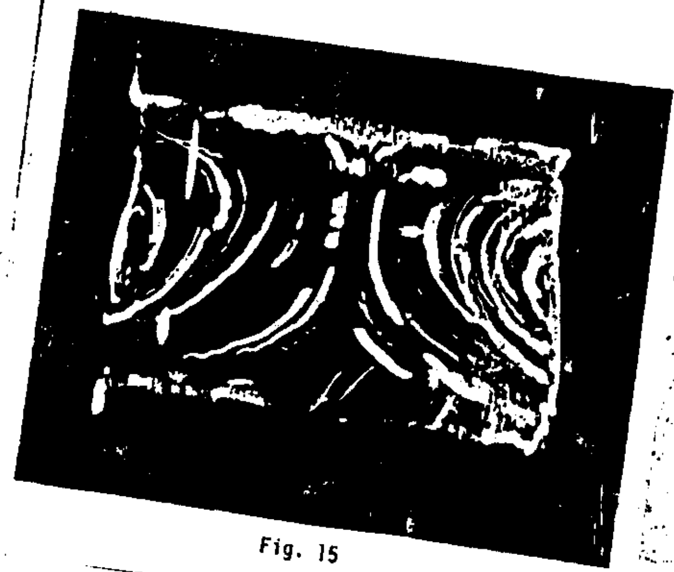
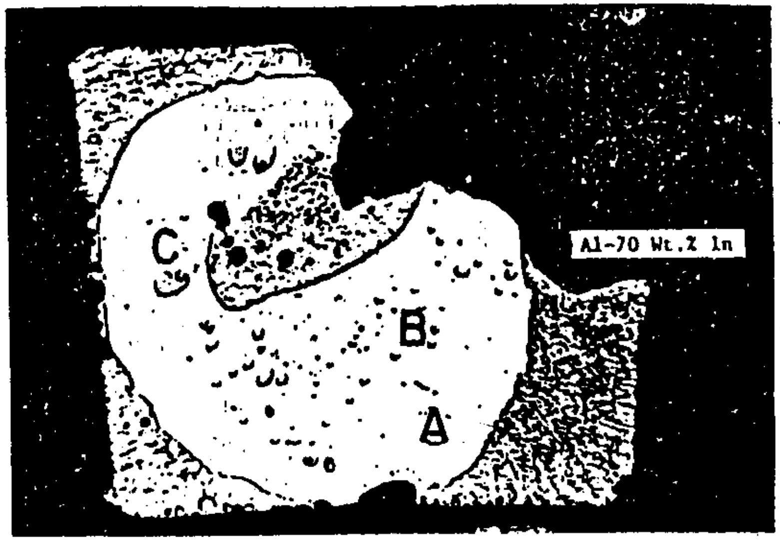


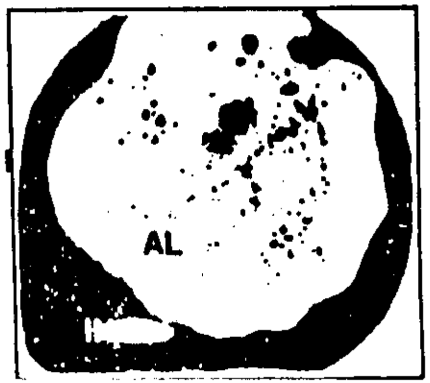
Fig. 15

Pb-Zn

Zn-Bi



Al-In



Al-In

Flight Experiments with Immiscible Alloys:

1. Ang & Lacy: ASTP
2. Fredriksson: TEXUS II
3. Gelles: SPAR II
4. Ahlborn & Löhberg: SPAR II

Fig. 16