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Overview of the present status of the European and American rocket activities in the field of materials sciences

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Abstract. The present overview will take into account both the qualities and the defects of the past programmes, and of the present hardware development studies and will try to define what will be the future interest of those rockets activities when compared with the manned spacecraft systems such as Spacelab, or with the automatic stations such as the ones that will be launched by the new Ariane system.

Keywords. Sounding rockets; microgravity; materials science; rocket, ariane system.

1. Introduction

Materials science research under microgravity conditions was initiated by NASA in the late sixties. Initially these activities were rather technology-oriented, and experiments were conceived to solve anticipated problems pertaining to spacecraft repair, or construction of structures in space. Attention was focused on the influence of gravity on processes involving liquids, or gases, and on the potential of weightlessness for processing of materials. Experiments were conducted during Apollo, Skylab, and ASTP missions. Later on, a larger programme was initiated by NASA to conduct materials science and bioprocessing experiments under microgravity conditions, using the Shuttle, the improvement of those activities being considered as closely bound to the development of larger laboratories, allowing crew participation, and longer times of microgravity. Today the US activities span from an intensive ground-based research programme over the Space Processing Application Rocket Programme (SPAR with 9 launches todate), to experiment preparation for Shuttle.

Even though the ultimate goal of the NASA materials processing in space programme is always to develop commercial interest in using space for production, the activities today centre more conservatively about conducting research to further our understanding of materials science and materials processing in general, and concomitantly, to further, and improve, materials processing on earth.

After the decision by Europeans to develop and to provide the Spacelab facility for use in the US Space Shuttle, similar activities have been spurred in Europe as well. At this time (1973), there was in Europe great enthusiasm about the speculated advantages that were bound to the Spacelab capabilities and looked to be obtained from its *shirt sleeves environment*. This enthusiasm allowed ESA to select in 1977 from more than 120 initial proposals, a total of 37 materials sciences experiments for the first Spacelab mission.

But at the same time, it appeared that both the characteristics of large manned space systems and their influence on microgravity levels were not as evidently favourable as initially previewed. It appeared clearly that the many activities of the crew, joined to the multidisciplinary aspect of the missions, and to the lack of priority of the MS discipline, would probably be the source of many problems ; the microgravity levels would be less than initially calculated and the costs would be higher due to the many constraints of safety that ought to be accommodated. Although the balance was still very favourable to the Spacelab philosophy, Germany decided to initiate in cooperation with Sweden a Sounding Rocket programme, TEXUS (technological experiments under microgravity conditions). Sweden provided the launch site and facilities and one of the TEXUS experiment modules was developed in Sweden, and carried Swedish experiments. Two TEXUS rockets have been launched todate. Meanwhile, the FSLP situation was still degrading due mainly to the successive delays of the mission (which is now scheduled in 1983), and to the increasing overall cost of both the hardware and the experiments. But the philosophy also underwent a significant development. Many unpredicted, and yet unexplained, behaviours of the initial programmes demonstrated clearly the need for more than a few isolated space experiments. Thus, in the US, and in the European programmes, alternative easier means to experiment under microgravity conditions (such as drop towers, aircraft and sounding rockets) have thus far been considered, mainly to provide support for Shuttle/Spacelab experiments, to bridge the gap between ASTP and the Shuttle, and to attempt to precise some surprising results of the initial programmes. Today, considerable experience has been gained with experimentation on sounding rockets, a total of 90 experiments having been carried out in both the SPAR and the TEXUS programmes. Even though little information is available, identical efforts were made in the USSR and in Japan to assess the potential of microgravity environment for materials processing, space experiments being carried out with sounding rockets. Thus, the merits of experimentation with sounding rockets can be assessed more realistically today.

The duration of residual accelerations ($< 10^{-4}$ g) during the coasting phase of the rocket was typically 260 seconds in the SPAR programme and 380 seconds in the TEXUS programme. The *g*-quality compares favourably with the *g*-levels and *g*-jitter to be expected for the manned space Shuttle with its life support systems, crew activities, etc... Rocket experiments are much cheaper (figure 1), and have less stringent safety requirements, than experiments for Shuttle missions ; rocket missions need shorter preparation time, and can be tailored to satisfy specific needs. At last, many rocket equipments may be re-used without any major modification in the planned long-duration automatic missions that will constitute the essential part of the future of MS activities in space. The manned missions will be reserved rapidly to very specific investigations, and they have thus to be considered as some kind of parenthesis in the history of MS in space. It looks so to be more sensible to orientate immediately the greatest number of hardware studies towards automatic modes, of which rockets equipments may be considered as representative precursors.

Since many of the questions posed with regard to microgravity materials research can be answered without long range planning, and long range obligations, by

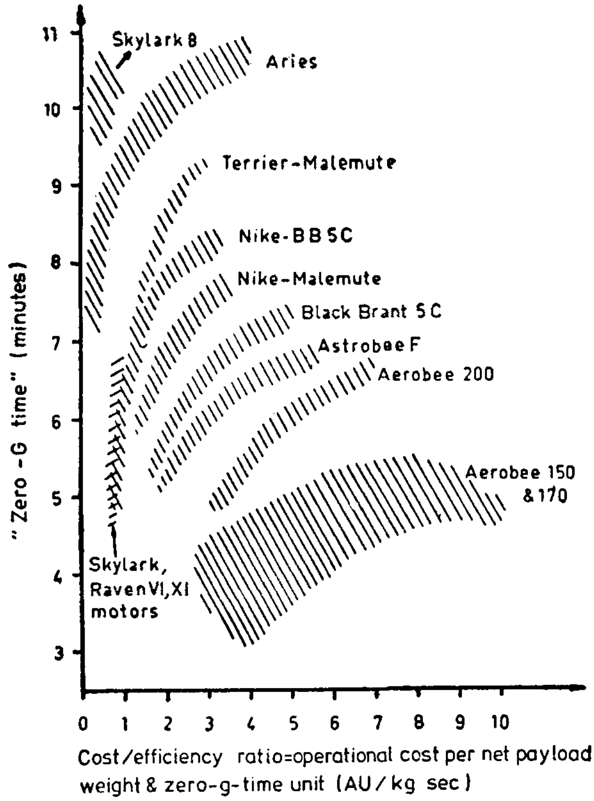

Figure 1. Cost/efficiency ratio per payload weight (1 A.U. = 1·35 U.S. $).

using sounding rockets, such experimentations should be considered, not only as a means of support for future Spacelab missions, but rather, as a means to conduct microgravity research, parallel, and complementary, to these missions.

This overview will not discuss any longer the scientific objectives that may be achieved by using rockets.

What is only important is that not even 15% of all the desirable objectives of materials sciences in space would result in difficulty to resolve problems, if it would be necessary to accommodate them in rocket flights. The existence of such a low percentage greatly increases the potential interest of short duration microgravity experimentation.

But, it must be pointed out again that they are mainly pure basic research studies that may be so accommodated !

2. Apparatus available for experimentation on rockets

2.1. *SPAR programmes*

Black Brant VC Rockets with solid propellant single-stage motor are employed in the NASA Space Processing Application Rocket Programme. Nine payloads

(SPAR I to IX) have been launched since 1975, the duration of the coasting phase with residual accelerations $< 10^{-4}$ g being 4 to 5 minutes. (A Nike-boosted configuration will be available in case of heavier payloads, or requirement of longer duration of the microgravity period.) The SPAR payload configuration consists of interchangeable experiment modules, measurement module, experiment support module, ogive recovery assembly system, despin system, payload destruct system, vehicle monitoring telemetry system, and rate control system. The experiment support module is a central service module containing a central power pac', the science payload telemetry system and timers. The measurement module contains a system of accelerometers capable of measuring accelerations with a detection limit of $\pm 1 \cdot 10^{-5}$ g in the 3 directions. The measurement module also contains sensors for temperature, pressure, vibration and shock.

When developing experiment apparatus for use in the SPAR programme, NASA could build on experience gained in earlier manned missions, since many of the design criteria such as minimum weight, minimum volume and power consumption, autonomous operation, automatic recording of data, etc. were similar for apparatus to be used on rockets.

The apparatus used for these early investigations was designed to minimize astronaut involvement, data were recorded on film or tape and samples were returned to earth for analysis. Examples of these first hardware developments for materials research are the multipurpose electric-furnace, the heat flow and convection demonstration unit, and the electrophoretic separation systems, that were easily adapted to rocket flights.

As mentioned already, the heart of a SPAR payload is the central service module which includes central power pack, science payload telemetry systems and timers : modules for SPAR were constructed both in house at NASA-MSFC and by various experimenters and industries. In total a pool of very diverisfied equipment has now been built up, which provides the means to do a wide variety of experiments under microgravity conditions.

2.1a. *General purpose rocket furnace* (*A-5*): The general purpose rocket furnace provides three thermally independent cavities for melting and resolidifying experiment samples in microgravity. Each cavity can be designed to provide either isothermal and gradient temperature profiles as required.

The samples are contained in a cartridge specifically designed for isothermal/gradient temperature profiles and cooling mechanisms, sealed with a suitable atmosphere and mounted in the heating cavity. Operating temperature : 100 to 1100° C.

2.1b. *Low temperature water quench furnace* (*A-6*): This apparatus provides the capability to melt and water quench molten samples in microgravity. It is a device consisting of a hemispherical housing which contains the cooling water, and a cylindrical section which contains the heater and material samples. Maximum temperature: 800° C.

2.1c. *Directional solidification furnace* (*A-7*): This apparatus is used to individually melt up to four different material samples and cool each of them with water in a manner to promote directional solidification, *i.e.*, each sample may have its own unique processing conditions, depending upon the materials being worked with. Maximum temperature : 1600° C.

2.1d. *Electromagnetic levitation furnace* (*A*-8) : This apparatus is a furnace for melting and solidifying metals in microgravity. The technique allows rapid, radiative cooling and solidification of the specimen. Also pyrometric observation of the specimen surface without interference from a container or from hot oven walls can be accomplished.

The specimen to be melted is suspended in the electromagnetic field of a cusp coil and is heated and melted by induction heating from the coil's electromagnetic field. An active servo positioning system maintains the electrically conductive specimen in the centre of the coil system against acceleration during flight and damps oscillations of the specimen in the coil system. Maximum temperature : 1300° C.

2.1e. *Crystallization processing apparatus* (*A*-9): This apparatus has the capability of carrying out both melting and crystallization of seven experiment samples under a variety of controlled solidification conditions in microgravity. Maximum temperature 180° C.

2·1f. *Dendrite remelting or polycrystalline solidification apparatus* (*A*-10) : This is a relatively simple apparatus consisting of a cuvette assembly, containing a thermoelectric cooler for cooling a plexiglass cuvette, backlighting, and a camera to record observations within the cuvette.

2.1g. *Apparatus to observe thermal migration of bubbles and their interaction with solidification interfaces* (*A*-11) : This apparatus has the capability to establish a predetermined temperature gradient along the length of the specimen, freeze the specimens at a predetermined rate in microgravity, photographically record the progress of the solidification front and the motion of any bubbles, and provide a record of the specimens. Maximum temperature 250° C.

2.1h. *Apparatus for heating and cooling for epitaxial growth of single-crystal films* (*A*-12) : This apparatus permits the growing of crystals, using the liquid phase epitaxy (LPE) method, which consists of bringing a substrate crystal into brief contact with a melt or molten solution near its melting point.

2·1i. *Apparatus for heating and cooling for comparative alloy solidification* (*A*-13) ; It is a furnace associated with a helium gas quench system. It is designed for study of comparative solidification of alloys in microgravity. Maximum temperature 750° C.

2.1j. *Acoustic levitator, three axis* (*A*-14) : This apparatus permits a liquid specimen to be positioned and manipulated without contact. Manipulations include rotation, oscillation, and fission. The oscillation and rotation could be used to stir the liquid, as well as centre gas bubbles in the liquid drop.

Forces and torques on the liquid are generated by the radiation pressure of acoustic standing waves excited within a chamber. Ambient temperature only.

2.1k. *Acoustic levitator, single axis* (*A*-15): It is a high temperature furnace facility in which containerless melting and cooling of specimens can be performed, as the specimen is positioned by means of a weak acoustic field. Maximum temperature 1600° C.

2.1l. *Apparatus for precision temperature control for dendrite solidification at small supercooling* (*A*-16): This apparatus will permit observation of dendrite solidification at precisely controlled temperatures; 57·5 ± 0·001° C. A camera will record the progress of dendrite solidification within the test chamber.

2.1m. *Apparatus for gradient heating for glass fining* (*A*-17): This apparatus will provide data on the thermal fining of glasses. A camera will record bubble arrays and the interaction of bubbles within the sample. Maximum temperature 850° C.

2.1n. *Polymer reactor* (*A*-18): This apparatus is a four-chamber polymer reactor to be flown in the near future. The polymer reactor is monitored by measuring the change in volume during the chemical reaction.

2.2. *TEXUS programme*

In the German TEXUS programme, Skylark 7 rockets, with a Goldfinch II C first stage, and a Raven XI second stage, are used. Four payloads have been launched from December 1977 to May 1981. Microgravity times were approximately 380 sec. The science payload consists of presently 5 experiment modules, one of the modules, being a Swedish module from the Swedish Space Corporation. The remaining payload consists of an ogive recovery system assembly, a rate control system, a yoyo despin system, and an instrumentation module with accelerometers and telemetry systems.

Autonomous experiment modules were developed which could be separately integrated and tested. Consequently, the modules had separate structures, power supplies, telemetry interfaces, and experiment timers. As far as possible standaridized components like structure elements, power supply, telemetry interface, timers and signal conditioners were used for different modules.

The mechanical concept is basically the same for all modules; The outer skin of the rocket provides the basic structural support. Individual sections are linked together by Radax connections. There are two experiment platforms in each section connected to the skin through shock absorbers. The experiment apparatus is mounted on the upper platform, the power supply under the lower platform, electronics and data interface are mounted between.

The electrical circuitry was designed for decentralized operation. Consequently, a failure in one system does not affect performance of other modules. All high power circuits are separated from housekeeping and regulation circuitry by inverters, or optocouplers, which is advantageous with respect to noise suppression in signal lines. All furnaces are powered by separate battery packages.

The modules for TEXUS-I and II were designed and constructed by ERNO. Exceptions are the Swedish mirror and gradient furnace module, which was built by the Swedish Space Corporation, and the acoustic levitation device; This one-axis acoustic levitator for operation at variable temperature conditions was developed by Battelle Institute, Frankfurt.

Experiment modules can be refurnished and used in successive launches. The apparatus used in the TEXUS-I mission was reused in following TEXUS, either simply refurbished or modified.

2.2a. *Multipurpose furnace* (*TEM*-01): This equipment consists of four thermally independent furnaces. Each furnace has a cylindrical heating cavity, there is an isothermal region in the central section of the furnace cavities. The heating element of each individual furnace can be regulated and programmed separately, so that different thermal profiles with different heat-up cycles and soak periods can be programmed individually for each furnace. Maximum temperature: 1450° C.

2.2b. *Isothermal furnace with acoustic levitation system* (*TEM*-02)

— *Isothermal furnace*

The furnace consists of a quartz tube with resistance heater, it was designed to provide isothermal conditions in the centre section. Maximum temperature 800° C.

— *Acoustic levitation system*

The acoustic levitation system consists of an ultrasonic transducer and a reflector, with the quartz furnace tube as resonator volume. Maximum temperature 800° C.

2.2c. *Fluids module I* (*TEM*-06 *G*): This apparatus was designed to study convective flow at liquid-liquid interfaces. The apparatus consists of a small fluid cell with flat windows for illumination and observation.

Convective flow is observed by means of a movie camera, the contrast of the flow patterns is enhanced by a Schlieren-Optic system.

2.2d. *Fluids module II* (*TEM*-06 *E*): This module is subdivided into two separate subunits, with a separate fluid cell to perform different experiments on electrolysis. One of the cells has a movie camera adapted to it for recording of events like fluid flow made visible by tracer particles, transport of charged particles in the electrolyte, gas bubble formation and bubble behaviour, etc.

2.2c. *Mirror- and gradient furnace module* (*TEM-SSC*): This Swedish module was designed and constructed by the Swedish Space Corporation. A total of 10 elliptical reflector furnaces (mirror furnaces), and 2 gradient furnaces are incorporated in this module.

— *Mirror furnaces*

The 10 furnaces were designed to study solidification phenomena with small samples having melting temperatures below 1000° C.

— *Gradient furnaces*

These devices are designed for studies of directional solidification of samples with melting points > 1000° C.

3. Statistical study of past experiments

Todate, ninety rocket experiments have been realized in the frame of the two SPAR and TEXUS programmes and seventeen other ones will be realized without delay in the United States and in Europe.

3.1. *Success of the experiments*

This analysis concerns 84 rocket experiments and the following distribution could be adjusted :

(*a*) Objectives were largely achieved : 40 experiments (48% of all experiments).

(b) Conclusive analysis was not possible because of unpredicted behaviour : 4 experiments (5% of all experiments).

(c) Conclusive analysis was not possible because critical parameters for meaningful analysis were not obtained, nor considered : 18 experiments (21% of all experiments).

(d) Objectives were not achieved due to failure of necessary experimental conditions : 22 experiments (26% of all experiments).

From those elements it may be concluded that one half of the flown experiments were successful and that one half of the other ones would have been more conclusive with an improved background of scientific preparation.

3.2. *Utilization of the equipments*

Fourteen SPAR modules were available. Only 9 amongst these 14 were used in the SPAR I to SPAR VI flights. The module A-5 was extensively used for nine different experimental runs belonging to 7 different scientific objectives. All the other equipments were used for 1 to 6 different experimental runs belonging to no more than 2 different scientific objectives.

The situation was somewhat different with the TEXUS hardware. Four TEXUS modules were available that were all extensively used. The multipurpose furnace was used for 8 different experimental runs belonging to 7 different scientific objectives. The fluids module n° 2 was used for 4 different experimental runs belonging to 4 different experimental runs belonging to no more than 2 different scientific objectives.

These statistics were established without taking into account the number of specimens that were introduced in each experimental run. Its main merit is to demonstrate the prevailing importance of some specific equipment compared with the other ones.

3.3. *Research topics*

It is rather difficult to strike a perfect balance of the research topics which were approached in those 14 rocket programmes. Many of the proposed investigations included a serial of the individual research topics for microgravity experimentation, what increases the difficulty of a totally precise analysis. It may only be indicated that the following topics were approached rather extensively :

(i) Fluid flows due to surface tension gradients,

(ii) Dendritic growth,

(iii) Eutectic reactions,

(iv) Interactions between the inclusions within composite materials,

(v) interactions of inclusions with solid liquid interfaces,
(vi) processing and properties of artificial and *in-situ* composites,
(vii) some containerless processing technologies,
(viii) casting processes,
(ix) electrochemical processes.

There are consequently many other research topics that need an increase in the number of flight experiments and which would be worth performing.

4. Conclusions

It should first be emphasized that some microgravity experiments can be conducted on earth by using *drop-towers* allowing about 4 sec of a very good quality microgravity environment. Nevertheless a number of valuable experiments can be performed within this brief period, for example in the field of fluid physics.

With classical sounding-rockets, microgravity times of 6 to 10 minutes can be obtained, with payloads up to several hundred kilograms (figure 2). A much wider variety of more comfortable experiments can thus be performed during this period.

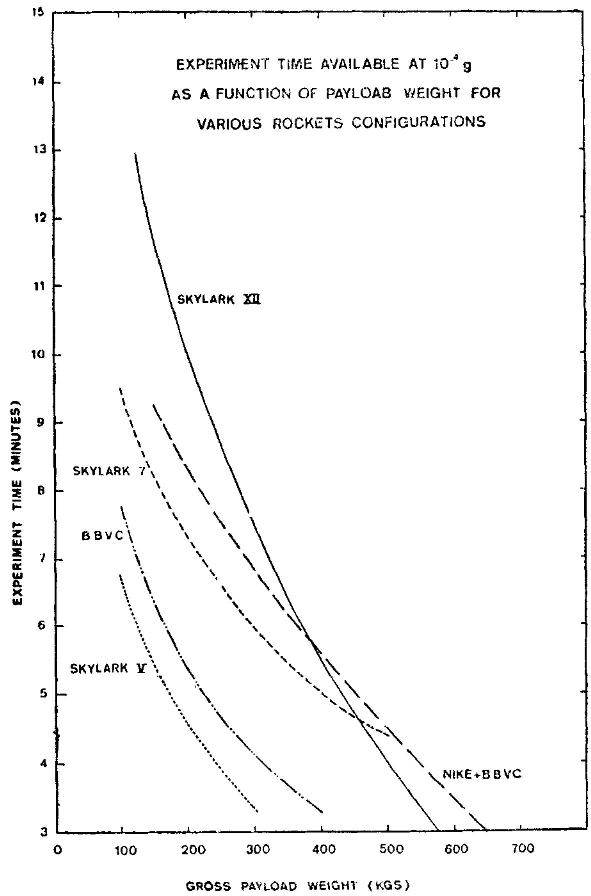

Figure 2. Experiment time available at 10^{-4} g as a function of payload weight.

Furthermore, although there are great scientific incentives to allow the payload specialist to interact directly with an experiment, a fair proportion of the proposed materials sciences experiments, could first be performed automatically, without significantly affecting their objectives and potential results.

Some of the more interesting experiments that have been realized todate were performed during rocket flights using fully automated equipments. On the other hand, from a statistical point of view, as many experiments were entirely successful in the rocket programmes as in the manned programmes.

From both these points of view, rocket experimentation may be considered as a means to help defining experiments to be carried out in more sophisticated Spacelab-type laboratories.

This procedure would allow to increase the rate of success of this reduced number of more complex, and much more expensive, experiments. Furthermore, it must be kept in mind that only about 15% of the topics of interest for microgravity experimentation do necessitate the use of long duration facilities. Thus, precursor experiments with rockets would allow precise experiment requirements in terms of hardware, and experiment parameters, that would be necessary to analyse fully, or even to prepare, any longer and more complex materials sciences experiments.

For the next five-year period it will be realistic to focus the activities on basic research topics which do not need very complicated facilities, but which require careful planning of various limited studies, and which can demonstrate both, the potentials and the limitations of materials sciences activities in space. During this first stage the necessity of large experimental systems such as Spacelab would be limited to only a fraction of all the possible basic research materials sciences topics, or to experiments that are no more considered as preliminary experiments, because they have already been extensively studied in past programmes, or finally, to any technological experiment that would be funded by its authors on a non-cooperative basis.

The consequence would be to allow other experiments that really need crew intervention, long duration, complex monitoring, and heavy facilities, to be much easier in their integration and realization, which would improve their value and efficiency. Other experiments would benefit by being prepared and flown more quickly, and more economically, and thus, by getting the opportunity to be repeated as required.

These basic studies should be oriented mainly towards the research topics for microgravity experimentation which were not studied in detail in the past. Examples are :

- Residual gravity-driven convection.
- Fluid flows due to various driving forces (instabilities of liquid meniscus, surface charges, electric, magnetic, and thermoacoustic fields etc.).
- Heat transfer properties of fluid phases.
- Critical point phenomena.
- Nucleation and maximum undercooling of melts.
- Preparation of homogeneous multiphase mixtures.
- Mixing and positioning devices.
- Preliminary floating zones studies.

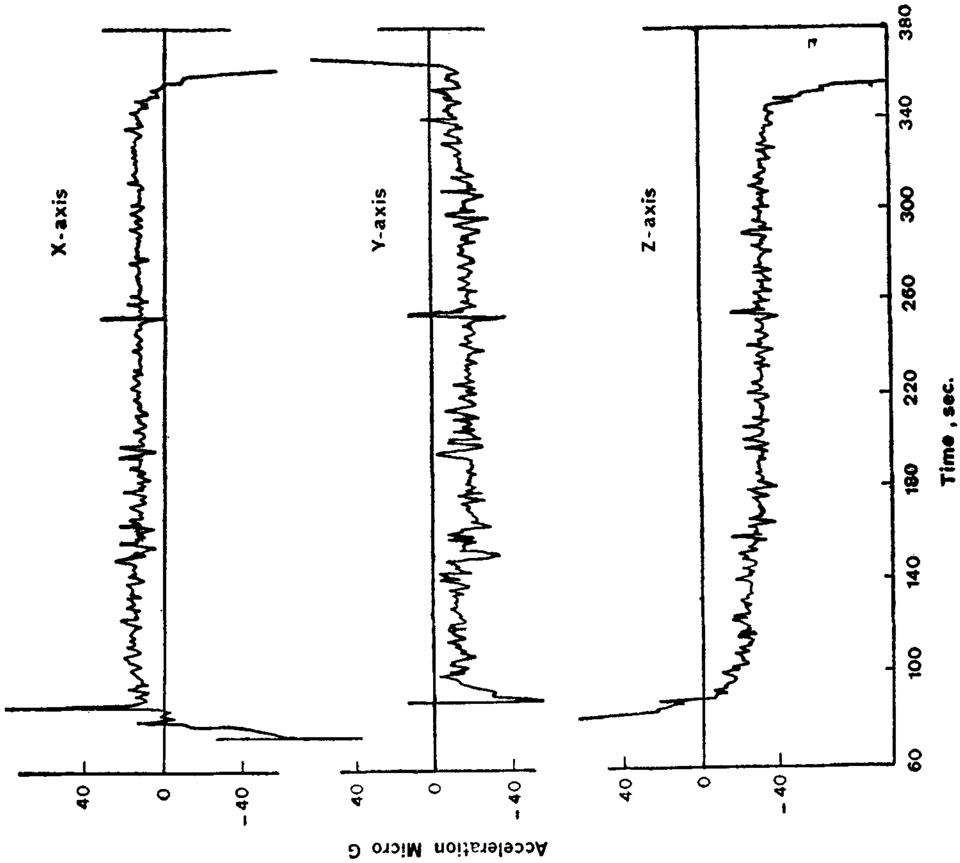

Figure 4

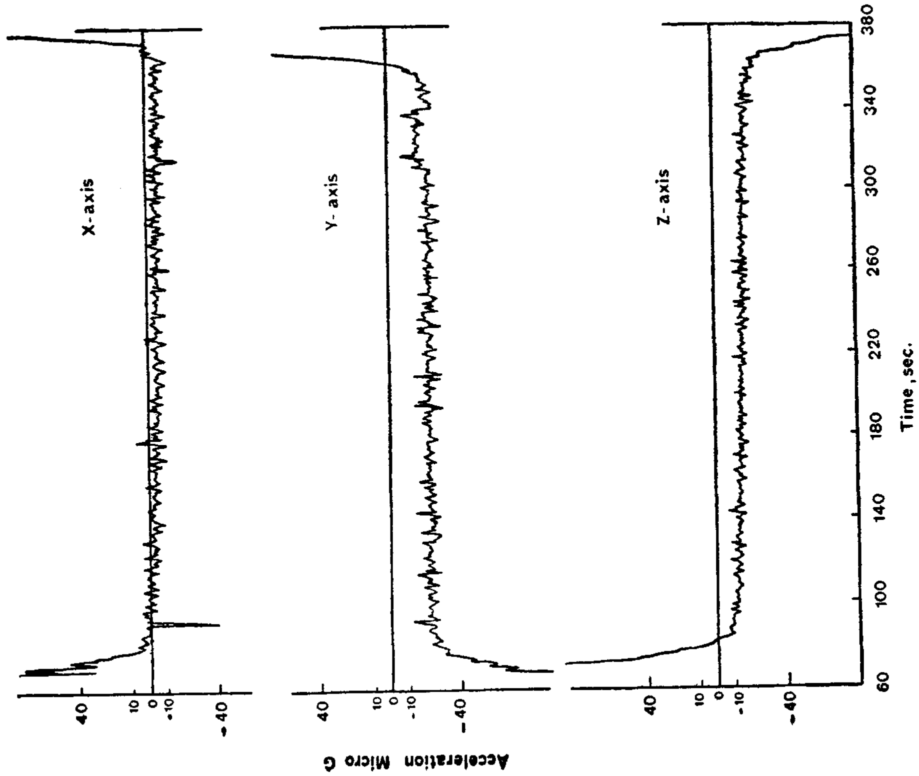

Figure 3

Figures 3, 4. Microgravity quality of SPAR I and SPAR II flights.

There are, however, some critical points that need special care when assessing the potential of sounding rocket experimentation.

At first, it is imperative to have detailed knowledge of the residual acceleration during experimentation to enable one to correlate anomalies observed in the systems under investigation, with such disturbances (figures 3–4). This would allow an experimenter to analyse basic mechanisms and behaviours, as a continuous function of *g*-level, and thus would help in introducing *g* as a separate parameter.

One of the most crucial limitations of the rocket flights results from the difficulty to control fluid flow associated with accelerations and vibrations during take-off and spinning of the payload. A systematic study of such behaviours would be useful for a better assessment of the potential of rocket experiments.

At last, it appears that a high percentage of all the planned solidification experiments could be performed in rockets, at least in a precursory fashion period. However, in many instances problems will be related to the fact that thermal and chemical steady states cannot be achieved during the time available. The basic prerequisite for a successful analysis of the results obtained is to exploit the ransient state observations, which in turn requires an understanding of the underlying physics laws.

Beyond purely scientific investigations the environment provided by rockets can also be employed to test, and develop, experiment apparatus and components, that cannot be tested thoroughly on earth.

Examples are positioning, or mixing devices, floating zone apparatus, or heat pipe furnaces.

Thus, a need exists for various microgravity facilities that would be viable for MS: Rockets are by evidence one of the most necessary facilities.

Considerable capabilities already exist in Germany and in the USA. It would be useful and desirable for all the potential investigators to get an access to those already existing programmes and equipment, what would prevent them to duplicate efforts and investments.

This is what ESA is actually trying to realize for the greatest benefit of all the European experimenters. ESA, whatever the advantges and defects of the Spacelab 1 mission, is now emphasizing to European investigators that a good programme of rocket experimentation apt to support more important space experiments, can in specific cases be of great merit.

ESA will also aid the experimenter, in case a specific need has been identified, to carry out his experiments in one of the on-going programmes. To allow that, ESA will first suggest NASA and DFVLR to increase the frequency of their flights according to the recruitment of new European, or even non-European investigators.

It is now critical to enlist the greatest number of MS experiments to be realized either with rockets or with satellites to improve the flexibility of both kinds of programmes, and also to prevent the future MS experiments from being associated—as they are in many large multidisciplinary missions—with other disciplines not oriented towards the best level of microgravity.

This will only be possible when large international programmes will include the greatest number of potential investigators.