

## LIQUID COLUMN STABILITY - EXPERIMENT 1 ES-331 -

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### ABSTRACT

Results of Exp. 1-ES-331: "Floating Zone Stability in Zero Gravity", performed aboard Spacelab 1, are presented. The objective was to form a long cylindrical liquid bridge (~10 cm), between two solid coaxial discs, to study the surface deformation and inner liquid motion resulting from the application of several mechanical disturbances (rotation, vibration, stretching, etc).

Keywords: liquid bridge, microgravity, capillarity, interface, wetting, rotation, vibration, liquid handling.

### 1. INTRODUCTION

The beginning of the Floating Zone Project at Madrid (Universidad Politécnica) dates back to July 1974, when Prof. Da Riva answered an ESA Call for Ideas for Spacelab experiments, suggesting a detailed analysis of the stability of floating liquid bridges (Ref. 1). In June 1976 the formal Experiment Proposal was submitted. During that and the following year the Fluid Physics Module (FPM) was designed and developed (initially at Madrid and finally by FIAT-CR under Italian founding) to accommodate the requirements of six research teams from five European countries (Refs. 2 & 3).

At Madrid, the effort was initially concentrated on the preparation of this experiment, but by 1979, the continuous delays on the Spacelab (SL-1) launch gave way to a much broader research area, tilting the main effort towards ground simulation by means of a Plateau Tank Facility (PTF, Ref. 4) and opening other flight opportunities: in 1981 a related experiment was proposed for the TEXUS program.

The balance to date for the flight trials has been gloomy, but ground research has been most fruitful. Problems faced in SL-1 curtailed most of the quantitative information expected, and the TEXUS 10 experiment was aborted before take off. Fortunately, availability of well trained scientists aboard Spacelab and extra crew time were used to great advantage, and a lot of valuable information was gathered.

### 2. STATUS BEFORE FLIGHT

Design of the FPM for SL-1 was frozen in 1977, the apparatus presented in 1979 and tests started in 1980. The Payload Specialists (PSs) and Principal Investigators (PIs), during those four years (up to the launch), had regular training sessions with an engineering model, and several weak points were early realized, although management difficulties entangled the solution of those deficiencies among which the poor visualization system stands out.

A lot of FPM deficiencies came from its premature development, when the severity of the envisaged operating environment was judged to be so high, that little more than a clockwork sequence (to be abandoned at the first trouble) was the design baseline. That philosophy contrasts highly with the always dreamed of, and finally obtained, resourceful Spacelab capabilities, where the investigators on ground are in direct contact with their colleague on board through ambient TV plus experiment-dedicated TV links, where most common laboratory ancillaries are at hand, and where, quite soon, workshop facilities will be available. Indeed, a rather different operating environment to a deaf, blind, isolated, unidirectional clockwork operation.

Meanwhile, expertise was gained in simulation of fractional gravity in an equal density bath with immiscible liquids, using the PTF, which proved to be a key factor in mastering liquid management, interface and internal motion visualization and data analysis. Control of the gravity level with this arrangement is easy (not so with Spacelab or TEXUS), may serve to detect gravity thresholds and helps to create an insight into conditions of weightlessness.

In 1982, a videofilm was produced showing what was expected for Exp. 331 from Spacelab 1. A silicone oil 20 times more viscous than water ( $\nu = 20$  cs) was used at that time (for availability reasons) though one of 5 cs and another of 100 cs were to be used on SL-1. The discs supporting the liquid column were solid cylinders made of methacrylate, painted black to enhance visualization, which differs greatly from the discs used in the FPM, where the working surface (of 40 mm $\phi$ ) protruded just 0.5 mm from a background plate, all metallic. The simulation of Exp. 331 was nearly complete, except for the distortions caused by the outer bath

viscosity and inertia, and the impossibility to excite centrifugal instabilities in the interface between isodense liquids.

At a later stage, the possibility was offered to investigators using the FPM to be able to interact with the PS through the voice loop during execution of their experiments, which was most enthusiastically welcomed. Quite differently from other crew activities, the evolution of FPM experiments can be evaluated on the spot, and that opened the way to continuous feedback from the investigators on ground. Unfortunately, the investigators' training on voice loop usage, with all little noises from the FPM being high fidelity clues to follow the steps by ear, have proved most unrealistic for this first flight, where the crew kept the microphones closed most of the time to get rid of background noise.

Scientific training on the FPM was scarce, both for PSs and PIs. More than a year before flight, the FPM engineering model was not available for liquid management, fluid visualization, etc., being used instead to exercise interfacing and timelining. In fact, the flight unit has never been seen by this research team. The in-house developed PTF, initially aimed just as a mechanical replica of the FPM (a kind of FPM users model), was soon diverted to more profitable research endeavours than FPM simulations (Refs. 5 & 6).

The only time the investigators had the opportunity to perform FPM tests at their premises (not with the full FPM but with only the working discs) they managed to get short bridges 5 or 6 mm high (well anchored at the disc edges) by manual operation in an improvised set up, although the cumbersome visual access discouraged a detailed testing on anchoring capability (it was just verified that the antiwetting paint did help to control the spreading). In any case, disc design, early dictated by conflicting multiuser requirements, was reckoned to be the main possible source of trouble. A small edge jump, metallic discs and a creeping liquid was a dreadful combination. Hopes were then blindly laid in the applied coating, the so called "anti-spread barrier".

Detailed procedures, a sample of which may be seen in Fig. 1, were mastered by the crew, and the presence of the investigator at the Payload Operation Control Center (POCC) was intended mainly for contingency planning and resources recovery, should problems arise in other disciplines.

A summary description of the foreseen trials for SL-1 is shown in Table 1.

### 3. EXPERIMENT EXECUTION

Exp. 331 was the last in the sequence for the FPM, due to a high risk of contaminating the test chamber in some uncontrolled liquid column breakage. This situation could be good (more time for both PS and PI to gain experience) or bad (less time and opportunities to try again). Thanks to the mission extension, both were taken for advantage.

In a previous experiment that used a common feeding disc (Exp. 327) a most fearsome problem appeared: when trying to fill the zone, the silicone oil did not get anchored at the disc edge but overflowed it. In our Step 2.2 (see Fig. 1) this possibility

STEP AT	ACTION	COMMENT
	REM: Enter from phase 0. Follow sequence 0-A-B in the diagram	
	Separate discs without injection	
2.1 FPM	FP position (mm) 022.5 RES position (mm) 022.5 FP speed (mm/s) .999 RES speed (mm/s) .999	
	Translation	START 33s from 0 to A.
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	Inject at constant separation	Inject a cylindrical volume
2.2 FPM	FP position (mm) 022.5 RES position (mm) 017.4 FP speed (mm/s) .999 RES speed (mm/s) .140	Spread, grow, touch and spread Avoid jet detachment
	(*)	
	Mode	CINE
	Frames	170
	Camera	START 34s.
	Translation	START 31s. From A to B.
	✓force perfect attachment.	
	Small cylindrical cone formed:	
	IF NOT: Liquid overflow at FP edge! Recovery, clean and try again.	

Fig.1. Extract from the flight procedures for Exp. 331 on SL-1.

Table 1. Preflight experiment description.

1. <u>Preparation</u>	Installation of film (2000 frames), of liquid reservoir (silicone oil with tracers) and working discs (40 mm $\phi$ ).
2. <u>Forming the zone</u>	Liquid injection from the reservoir through a concentric hole on one disc, to form a bridge attached at the edges of the 40 mm $\phi$ discs, and filling to get a long column.
3. <u>Axial oscillation</u>	Impose a small amplitude oscillation to one of the discs to find the first natural frequencies. Look at standing waves.
4. <u>Single rotation</u>	Sudden spin up of one disc. Vortex rings would slowly extend from there to the opposite disc. Look at liquid angle at the corner.
5. <u>Counter rotation</u>	Two similar cell patterns with vortex rings, more intense near the discs, should develop. Look at free shear layer.
6. <u>Isorotation</u>	Solid body rotation of the liquid will be increased until the stability limit is exceeded and transition to C-mode or amphora shapes takes place, stopping rotation before bridge disruption.
7. <u>Disalignment</u>	Isorotation is tried as above, but the influence of discs disalignment on stability is sought.
8. <u>Breaking</u>	Two well-controlled bridge ruptures, following quasistatic evolutions, foreseen. First, a cylindrical stretching would surpass the critical limit $L/D=\pi$ . After merging the drops, another disruption would take place by liquid removal at constant disc separation.
9. <u>Recovery</u>	Finally, as much liquid as possible is sucked back to the reservoir, to not allowing any air bubble to get in, for the oil to be reused in other experiments.
10. <u>Termination</u>	Clean everything and save the exposed film and discs.

was considered and the straightforward advice of "recover, clean and try again" given. This happening is quite common in ground simulation, and was exercised by the crew in the early trainings (later trainings were dry rehearsals). The big trouble is that space labs lack the common washing basin used for that purpose on ground (liquid handling without gravity help is the subject of this and many other studies).

When Exp. 331 was approached, the same fatality happened: the liquid went over the disc edge. The effort was then concentrated on a systematic search for the cause of this misbehaviour. First, a possible interaction of the spreading process over the disc surface with the anchoring at the edge was identified: the rate of feeding ( $0.8 \text{ cm}^3/\text{s}$ ), although slow enough to prevent jet detachment at the exit of the  $6 \text{ mm}$  feeding pipe, was large enough to create a flooding wave that jumped over the small edge barrier. An antiwetting coating had been also applied to the outer corona of the working disc, but it could not cope with the spreading wave either.

Then followed carefully controlled manual injection trials, where liquid anchoring at the disc edge was achieved and a large liquid drop obtained. Slowly growing the drop, a maximum liquid angle at the edge was found around  $70^\circ$  to  $80^\circ$ , beyond which the oil swiftly overflowed (with the nominal injection rate, the spreading wave jumped over the edge with a smaller angle; some  $20^\circ$  or  $30^\circ$ ). Moreover, it was judged that the influence of the antispread coating on this apparently limiting value was to allow some  $10^\circ$  increase in that angle before the surge. If one thinks of the burden and time consumption being implied by this scientific troubleshooting in relation to the time allotted, the experiment outcome could already be judged as highly positive. But there were many more accomplishments to follow.

The second time slot (Exp. 331 had two 100-minute slots allotted) was spent further trying to gain insight in the anomalies found that hindered any progress in the nominal operation of Exp. 331. First, another feeding rate limit that had been considered during FPM design, namely the maximum injection speed that does not cause liquid detachment at the exit (forming a jet) was investigated. Results are presented in Fig. 2.

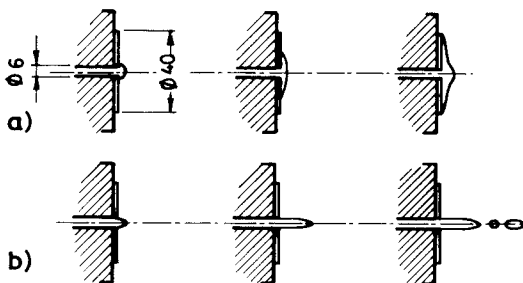


Fig. 2. In a short trial, the jet detachment speed was found to lay between  $3.5$  and  $4.0 \text{ cm}^3/\text{s}$  for a feeding hole of  $6 \text{ mm}$ .

Second, the possibility to grow cylindrical bridges without going through an initial drop, was tried, filling the small gap between the discs brought to proximity ( $7.5 \text{ mm}$ ). A cylindrical bridge was obtained, and stretched up to  $10 \text{ mm}$ , but then the

overspreading took place (and with these small gaps, visual access in the present FPM is really obstructed).

Last, the difference in behaviour due to the fact that one end plate was in aluminium and the other in stainless steel, was studied, spinning the rear disc once a bridge was formed, but no apparent difference was found. Change of liquid viscosity from  $5$  to  $100 \text{ cs}$  did not produce any improvement.

Because of the high appeal and easy replanning of FPM experiments, the announcement of a full extra mission day boosted a renewed interest among FPM investigators. As for recovery of the nominal procedures for Exp. 331, the only way out was to change the working liquid or the working discs, but both solutions were difficult to implement in this first, crowded, multidisciplinary mission. Although liquid replacement in a small container was successfully accomplished by a PS (it was seen in live TV) for one of the FPM investigators (Exp. 330), disc replacement was the option finally taken for Exp. 331. Instructions were given to the PS to dismount a piece of equipment from another FPM experiment (Exp. 339) and glue it to the feeding disc to have a new working surface.

Unfortunately, the real dimensions of the piece to be used, did not correspond to the documentation on the ground and a misunderstanding followed. The PS, relying more on his perfect knowledge of the goals of the experiment (where cylindrical columns were a must) than on what he heard via the voice loop (sometimes quite noisy), put piece A (see Fig. 3b) that did match in diameter with the intended rear disc borrowed from Exp. 329 (Fig. 3b-c), instead of piece B (Fig. 3c) that was the target selected by the investigator on the ground.

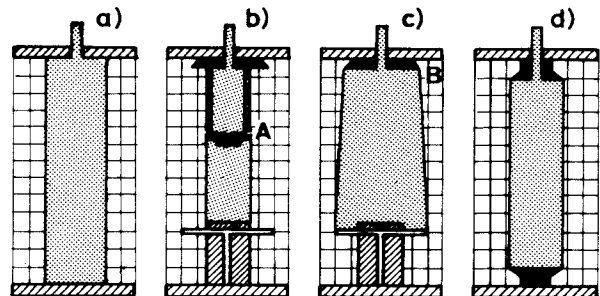


Fig. 3. a) Nominal configuration foreseen for Exp. 331 on SL-1 ( $40 \text{ mm}$  protruding discs). b) Cylindrical bridges obtained on SL-1. c) Conical bridges obtained on SL-1. d) Configuration to be used in SL-D1. The background grid (in cm) was not present in SL-1.

With the configuration sketched in Fig. 3b, cylindrical liquid columns  $30 \text{ mm}$  by  $52 \text{ mm}$  long ( $L/D=1.7$ ) were realized. That was the maximum disc separation allowed by the FPM with this arrangement. Isorotation was applied to the discs, first at  $5 \text{ rpm}$  and then rising suddenly to  $10 \text{ rpm}$ . Some small bubbles ( $\sim 2 \text{ mm}$ ) accidentally found in the oil, helped to follow the sequence on the TV recording (the illumination used for TV did not allow the smaller solid tracers ( $\sim 0.06 \text{ mm}$ ) to show up). After the sudden jump of disc rotation from  $5$  to  $10 \text{ rpm}$ , the bubbles close to them were spun up in a couple of turns, showing a small centrifugal drift outwards.

After that, the speed was suddenly increased from 10 to 15 rpm, and in the second turn a definite C-mode deformation was apparent. The PS, having been warned not to allow for a C-mode breaking, and being out of contact, quickly slowed down to 5 rpm, which immediately ended the deformation, creating a secondary flow from the discs to the liquid interior, dragging all bubbles to the midplane between discs. A calmer look at the video recording clearly indicates that the deformed shape was stable, rotating synchronously with the discs. Theory predicts the instability to occur at 21 rpm, and a possible explanation of the facts is that there must be some threshold in rotation speed (here 12 rpm), associated to the 2 mm eccentricity of the glued appendage, that triggers C-mode deformation, which would eventually grow with applied speed until breaking at some limit below the 21 rpm upper limit that would apply in absence of any eccentricity.

It must be mentioned that the liquid was slowly leaking out of the column through the thread in the improvised working edge (Fig. 3b), which was apparent after a while by a small necking of the column. Some liquid was then added to regain a cylindrical shape (bubbles can be seen pushed towards the rear disc again). The spinup sequence was repeated with a smaller step, but when C-mode rotation developed at 12 rpm, the leaking increased. At 14 rpm it was quite appreciable, and a smooth breaking, symmetric, as expected for liquid removal at this slenderness, took place. The satellite drop formed, drifted along the axis towards the rear disc. The leaking through the front plate edge seemed to stop, leaving a big drop of almost 90° angle at the edge, but the drop shaking at the rear disc caused the liquid to detach from the 30 mm $\phi$  edge, overflowing to the 60 mm $\phi$  outer rim.

After several hours using the front plate shown in Fig. 3b (for both Exp. 331 and 327) a live TV connection allowed the PIs to realise the misunderstanding and to redirect the PS to try piece B (Fig. 3c) which, although by now known to be of the wrong dimensions, at least had a sharp edge.

With the configuration of Fig. 3c, the maximum allowable length of 96 mm (for this set up) was easily achieved, and almost all Exp. 331 steps exercised: axial vibration was excited (Fig. 4) and C-mode deformation (Fig. 5) obtained, although lack of data (some TV scenes have lately been gathered by chance by the investigators), and the preliminary status of a workable theory for this new configuration (Refs. 7-9), are a source of continuous delays in the effort to make a sound analysis of the available images.

A summary of the trials performed in flight is presented in Table 2.

#### 4. AFTER FLIGHT

It had been long protested that post-flight data retrieval had not received proper attention, but it was thought that real-time data acquisition (with simultaneous data display and printout) would be enough. For contingencies, play back support from ESA, for all conceivable scientific and housekeeping data, was taken for granted.

But the cumbersome development of Exp. 331, completely off the nominal sequence, originated the following end-of-flight miserable status: the in-

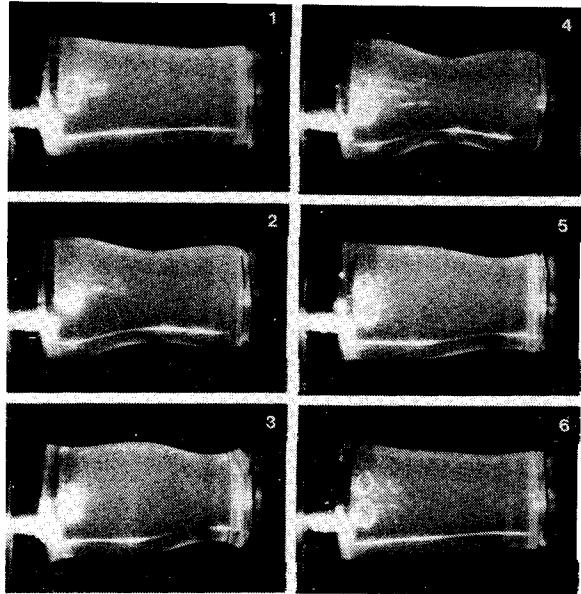


Fig. 4. Axial vibration at 0.4 Hz (0.5 mm amplitude) of a liquid bridge anchored to discs of 51 & 60 mm $\phi$ , showing consecutive frames at 1 fps.

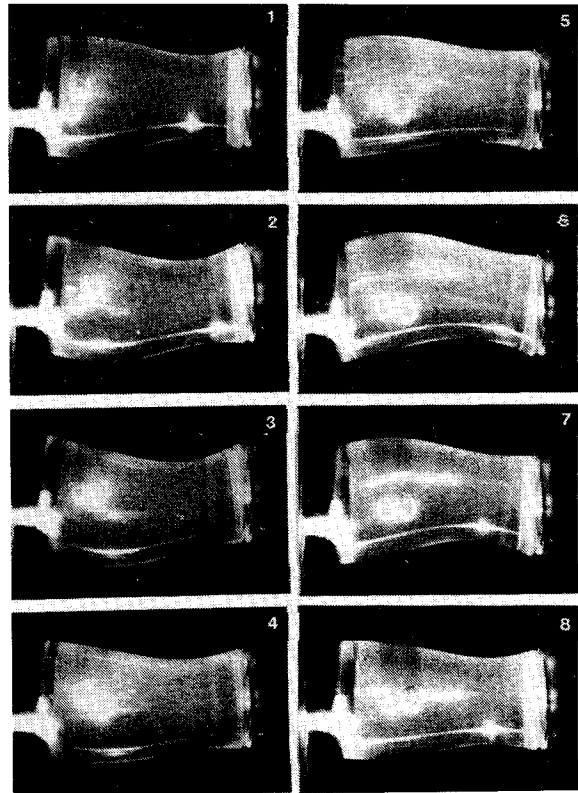


Fig. 5. C-mode deformation during isorotation at 7 rpm. Consecutive frames at 1 fps.

Table 2. Chronological summary of trials performed aboard Spacelab 1 for Exp. 331.

<u>Trial name</u>	<u>Time<sup>a</sup></u>	<u>Geometry</u>	<u>Liquid</u>	<u>Recording</u>	<u>Comments</u>
Nominal	4/01:10 - 05:30	40/40	DMS-5-T	Film A	Drop formation, overspreading at disc edge Short free-edged bridges.
Retry nominal	5/07:45 - 08:45	40/40	DMS-5-T	Film A	Unlogged. Small bridge rupture by spreading
Emerging jet	6/13:09 -	40	DMS-100-T	Film B	Critical jet speed about 0.45 mm/s.
Short cylinder	-	40/40	DMS-100-T	Film B	Up to 10 mm long bridges obtained
Rear drop	- 14:38	40/40	DMS-100-T	Film B	Overspreading by rotation.
Screwed edge	8/04:00 - 07:50	30/30	DMS-5-T	Film B	Cylindrical columns 52 mm long. Vibration and rotation applied. C-mode deformation recorded. Liquid was slowly leaking.
Unequal discs	8/09:00 - 11:00	50/60	DMS-5-T	Film A	Good anchoring at the edges of unequal discs. Vibration, rotation and C-mode. Without ground contact.

<sup>a</sup>Mission Elapsed Time from launch (MET).

investigator knew that long cylindrical columns, the key configuration for Exp. 331, had not been reached (this was point 2 of 10 in the planning shown in Table 1). Two film cassettes and some unknown video cassettes were to be analysed, but a script was lacking and there was no time correlation on the frames (a deficiency detected many years ago). The PS, forced to proceed on his own, and devoted to coping with more basic problems, was not expected to do any bookkeeping. Live TV of Exp. 331, some couple of minutes (none was previously allotted), just served to realize a misunderstanding. That was the gloomy perspective with which the investigators left Houston in December '83.

In January, the two 16 mm film cassettes, with its entangled 2000 frames each (most of them overexposed by the illumination used for the TV camera) were available. Shortly after, audio cassettes with the voice traffic were distributed. Both retrieval operations above happened directly among FPM PIs.

By the end of May '84, some video cassettes were received, but others remained astray in the pipeline and were fetched by chance. Besides, time correlation in the tapes seems unreliable.

Finally, printouts of FPM operational and house-keeping data started to pour in in July '84, but, up to now, they only trace back the early phases of Exp. 331, full of contingencies, and with little information content.

## 5. CONCLUSIONS

A couple of hours of crewtime in the maiden flight of Spacelab were allotted to perform an experiment on liquid column stability, using a newly designed multipurpose facility. Tens of other experiments from all scientific disciplines were scheduled to be operated at nearly the same time, under the close watch of their respective investigators, understandably eager to redirect available resources to the benefit of their own research. And all that being continuously overlooked by the news media. Under this perspective, the achievements here described may seem miraculous.

The scheduled investigations for Exp. 331 (Table 1) were not accomplished due to the impossibility to hold the liquid interface anchored at the nominal disc edge. In spite of that, many interesting findings can be qualitatively described that will surely help to better plan future trials.

The first lesson is that better attention must be paid to inertia forces during bridge formation. Ground simulation is misleading in this point, either because of the small scale in microsimulation, or due to the outer bath in neutral buoyancy. Feeding at  $0.8 \text{ cm}^3/\text{s}$  forced the liquid to jump over the edge of the  $40 \text{ mm}^{\phi}$  working disc.

Constrained selection of working materials (liquid, discs, cleaning aids) under severe safety rules may cause unwanted coupled behaviour that needs much ground testing. The operators faced unsurmountable difficulties in achieving a clean start.

Feeding slowly, a maximum liquid angle of  $70^\circ$  or  $80^\circ$  was achieved, what contrasts with the  $180^\circ$  easily obtained in neutral buoyancy configurations. Anchorage improvement with antispread coating was  $\sim 10^\circ$  bigger than without, much below expectations. No difference in wetting behaviour due to disc materials (aluminium, steel) or liquid viscosity (5 and 100 centistokes) was observed.

Solid tracers ( $0.3 \text{ kg m}^{-3}$  of ceramic spheres of 53 to  $74 \text{ um}^{\phi}$ ), highly visible in the thinner oil, did not show up in the thicker one (it seems they stuck to the walls).

The microgravity level was excellent: no appreciable deformation in a 10 cm liquid column. Indeed, it was Dr. Haynes's scrutiny (Exp. 327 PI) that help to discover a distortion caused by a Shuttle manoeuvre.

The silicone oil wetted everything (disc edges, antispread coating, chamber walls, crew hands and tools, the entire Spacelab) and was difficult to get ride of, significantly contributing to a dirty environment and consuming valuable time (if may take an hour to clean a  $100 \text{ cm}^3$  spill).

As regarding crew operations, an awkward access to the test chamber forced the FPM to be operated out of the MSDR rack. Even so, access to the test chamber is precarious (dim light, small opening, poor visibility, slow mechanisms). The FPM, as a facility to support long liquid bridges, needs much improvement.

Unscheduled video coverage was of an invaluable help to the investigators, allowing to share the view of the liquid, thus avoiding cumbersome image descriptions. Nominal voice link was much less worth than anticipated; pressure on the system prevented detailed scientific discussions with the crew, which were continuously interrupted for long messages and for troubleshooting other facilities.

Absence of time correlation in films, poor visualization and the script deficiencies associated with the too many changes needed to recover from failure to get the interface anchored, hinder a deeper analysis of this first experiment.

In any case, this first real-time feedback scientists-on-ground  $\rightleftharpoons$  TV  $\rightleftharpoons$  scientist-on-Spacelab, has proved most fruitful for this kind of research.

We are indebted to the SL-1 scientists, both on board and on ground, that have contributed to the outcome of this experiment, and in particular to Drs. Merbold and Lichtemberg which actually did it.

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