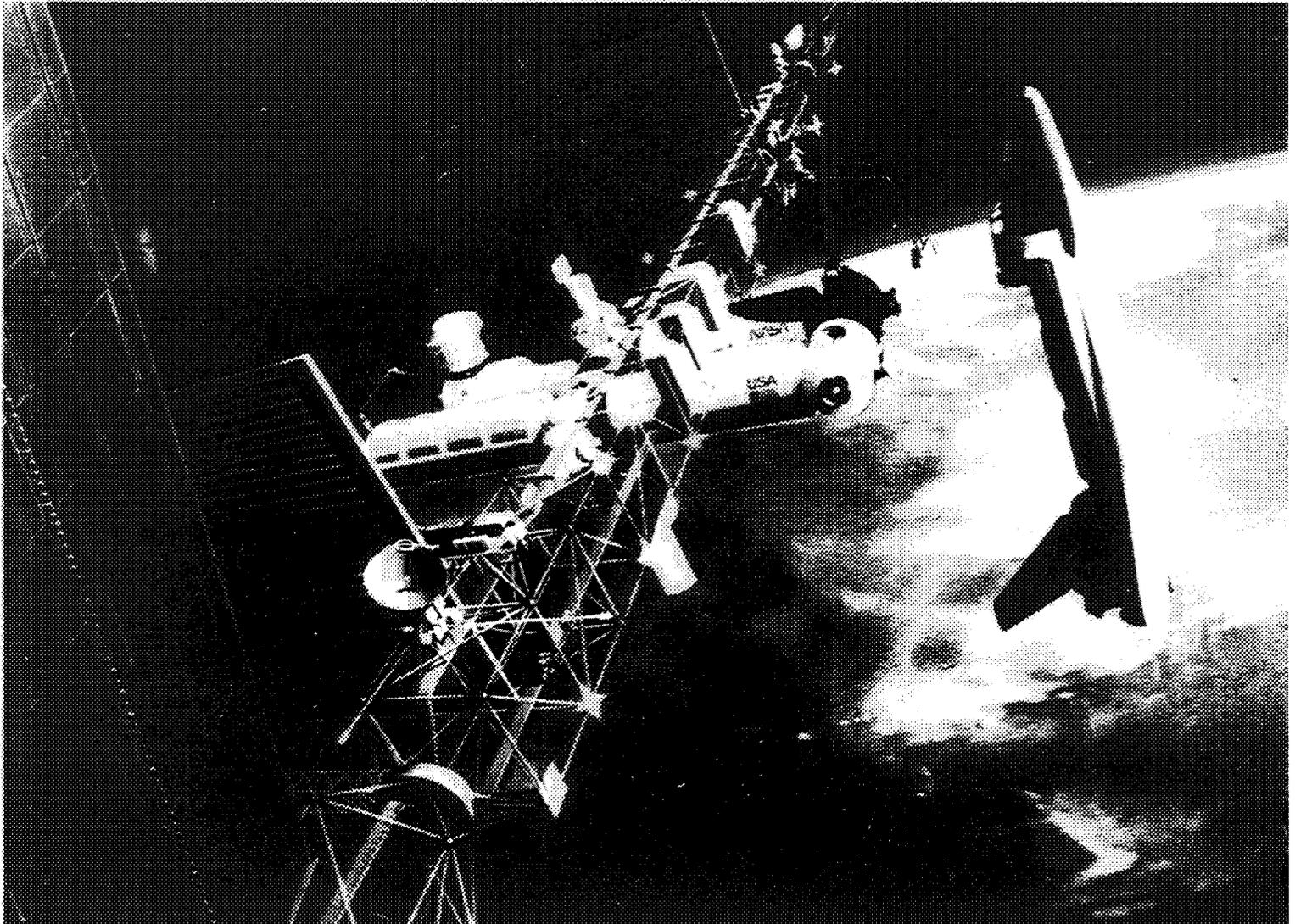


NASA-TM-103663

# CONCEPTUAL DESIGN FOR THE SPACE STATION FREEDOM FLUID PHYSICS/DYNAMICS FACILITY

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# Conceptual Design for the Space Station Freedom Fluid Physics/Dynamics Facility

**NASA**  
National Aeronautics and  
Space Administration

Lewis Research Center  
Cleveland, Ohio 44135



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## Summary

A study team at NASA's Lewis Research Center has been conducting a definition study and preparing a conceptual design for a fluid science facility, which will be located in the Space Station Freedom's U.S. Laboratory module. This modular, user-friendly facility, called the Fluid Physics/Dynamics Facility, will be available for use by industry, academic, and government research communities in the late-1990's. The Facility will support research experiments studying the properties and behavior of fluid systems in a reduced gravity environment.

This document was initially prepared as an advance hand-out for reviewers at the Fluid Physics/Dynamics Facility Assessment Workshop held at Lewis on January 24 and 25, 1990. It covers the background, current status, and future activities of the Lewis Project Study Team effort.

## Introduction

In the late 1990's, a new, unique national laboratory will become available for use by industry, academic, and government research communities. At that time, all the many elements that make up the Space Station Freedom are scheduled to become operational, including NASA's United States Laboratory (USL) module. This laboratory will be unique, because for the first time a permanently manned, multiuser facility in low-Earth orbit will provide a long-duration microgravity environment, along with essential supporting laboratory services. Because of restricted payload capacities and capabilities, these supporting services, taken for granted in Earth-bound laboratories, historically have been difficult to provide for long-duration flights in space. The principal services to be provided include electrical power, communication and data services, consumable fluid supplies, venting, and waste disposal. Of course, the one service or condition not readily obtainable in Earth-bound laboratories is the reduced-gravity environment, which cannot be duplicated or even approximated for any appreciable length of time on Earth. With the near absence of gravity on Freedom, research can be conducted with reduced buoyancy forces, hydrostatic pressure, and sedimentation.

NASA, its contractors, and its international partners are all working toward the common goal of achieving an operational space station. While this effort is proceeding, a parallel effort

is beginning in order to be ready at that time to make immediate and effective use of the space station's capabilities. NASA's Office of Space Science and Application is currently involved in a program to provide research capability by developing experiment hardware and facilities. As part of this program, the NASA Lewis Research Center was selected to be the lead center in the definition study and conceptual design phase of a Fluid Physics/Dynamics Facility (FP/DF) for Space Station Freedom. This document outlines the status of that effort and describes the capabilities of the proposed fluids facility. A list of definitions is given in appendix A; appendix B lists the FP/DF design assumptions and constraints; appendix C provides operational flow diagrams for the two representative experiments on which the FP/DF design is based; and appendix D lists principal contributors to this report.

A study team, made up of members of the Lewis Engineering Directorate and its support service contractors, has been working on the definition study and conceptual design for the proposed facility. The objective of this study is to assess the feasibility, effectiveness, and benefits to potential users, of a modular, multiuser facility for fluid physics science and applications experiments on S.S. Freedom. The study will determine the philosophy or mode of accommodating fluid physics experiments on Freedom and will propose a plan for the development of the appropriate FP/DF hardware.

There are several facets to the future successful development of the FP/DF, as described in this document. The first and most important of these is a positive assessment by the potential user community. Toward this end, the Lewis Project Study Team has sought comments and recommendations from all interested parties. The Fluids Physics/Dynamics Facility Assessment Workshop, held at Lewis in January 1990, was an effort to seek potential user-community involvement.

## Project History

Approval to begin this study was received from NASA Headquarters in June 1987. A Joint Cooperative Agreement outlined the objectives of the study and provided a baseline facility concept. This same agreement listed five tasks to be performed by the study team: (1) requirements definition, (2) trade studies, (3) concept design, (4) development plan, and (5) assessment of the concept and plan. In August 1987, a study team was assembled and the task was started. The

study team is composed of members from the three divisions of the Lewis Engineering Directorate and additional members provided by support service contractors. Two other key persons in the project organization are the Lewis Space Experiments Division (SED) Project Manager, who provides the overall project plan, budget, and schedule management, and the SED Facility Project Scientist, who assists the study team in meeting the science objectives.

### Requirements Definition

To begin the requirements-definition task, the Facility Project Scientist provided the study team with a reference experiment list, which represented candidate experiments of the kinds that might be performed in the FP/DF. The list covered a wide range of experiments and provided a broad range of conditions and requirements. In some cases, these experiments were previously flown space experiments; others had not flown but their engineering studies had been completed; and still others were conceptual experiments representing an idea of how an experiment might be done. The following are titles in the current reference experiment list:

- (1) Surface-Tension-Induced Instabilities and Flows
- (2) Surface-Tension-Induced Convection
- (3) Free-Surface Phenomena
- (4) Immersed Bubble/Droplet Dynamics and Interactions
- (5) Thermal- and Double-Diffusive Natural Convection
- (6) Multiphase Flow
- (7) First-Order Phase Transitions

- (8) Chemical Vapor Deposition
- (9) Thermal-Gradient Effects on Entry-Flow Development
- (10) Quantification of Fluid Phenomena That Occur During Solidification
- (11) Fluids Mixtures, Heat, and Mass Transfer

In a series of in-person meetings and in teleconferences with advocates of each of the experiments on the above list, the study team collected user-specific experimental requirements. Concurrently, the study team determined the proposed capabilities of the various USL module systems. The team has also been tracking the development of such systems as the data management system (DMS), the electric power distribution systems (EPDS), and the process materials management system (PMMS) as each of these evolves towards a preliminary design review.

The user requirements and the USL-module capabilities have now been summarized and tabulated by the study team in an experimental-requirements database. The information in this database, which is electronically stored in Lotus 1-2-3 files, consists of eight major sections: general information, electric-power distribution, instrumentation and data acquisition, electric controls, mechanical fluid systems, mechanical structures, environmental requirements, and timelines.

### Conceptual Design

Following the requirements-definition phase, the study team proceeded to the conceptual-design task. A modular

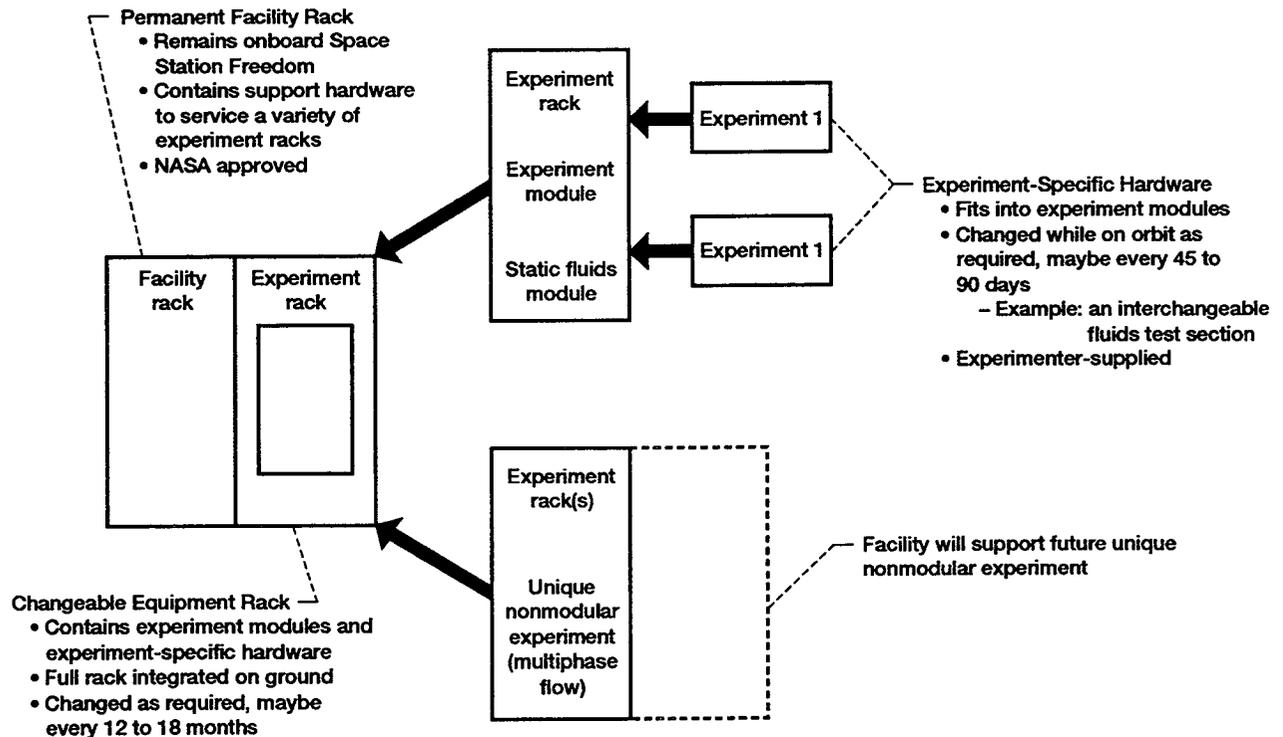


Figure 1.—Fluid Physics/Dynamic Facility modular concept.

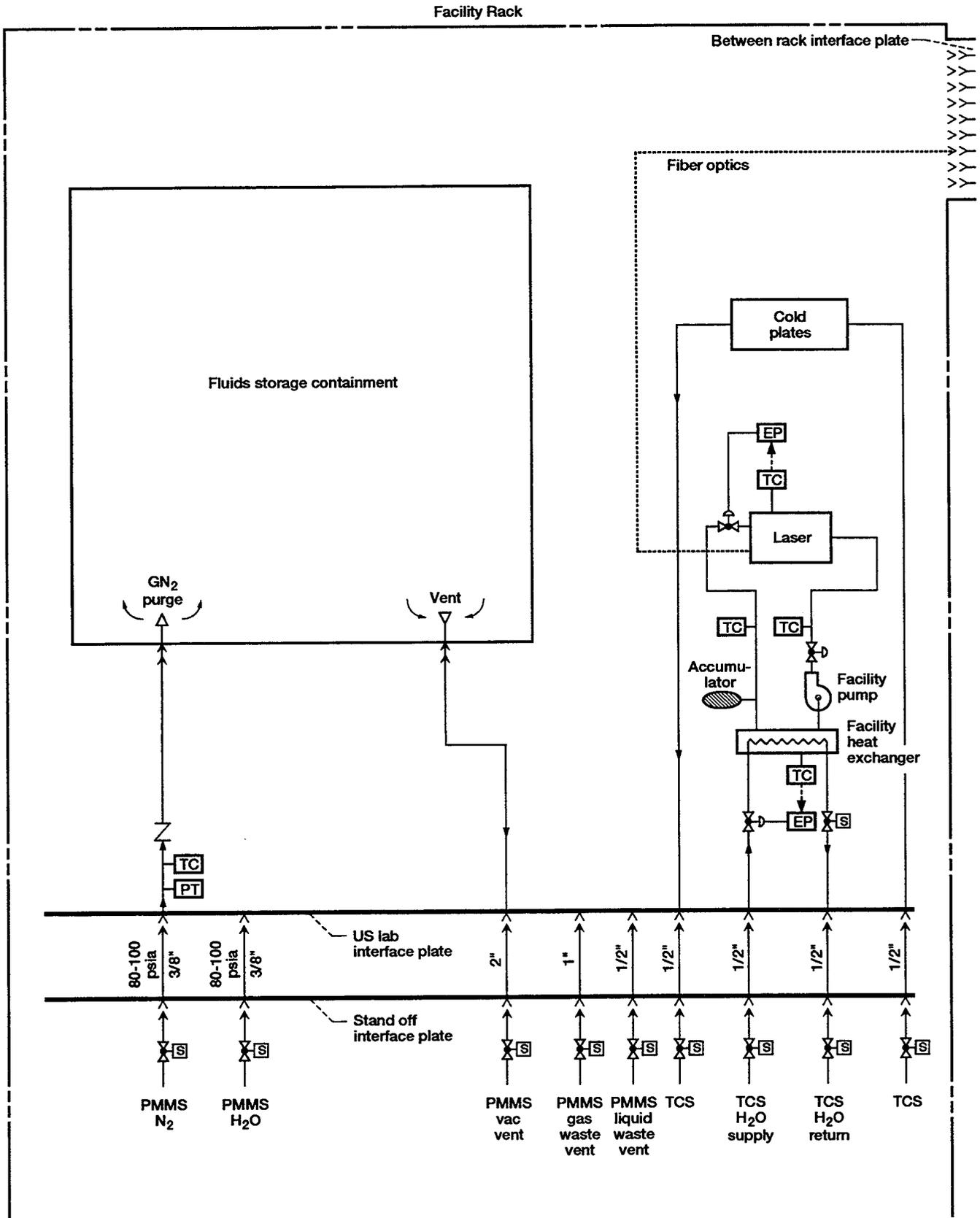


Figure 2.—Conceptual schematic diagram, Surface-Tension-Induced Convection Experiment.

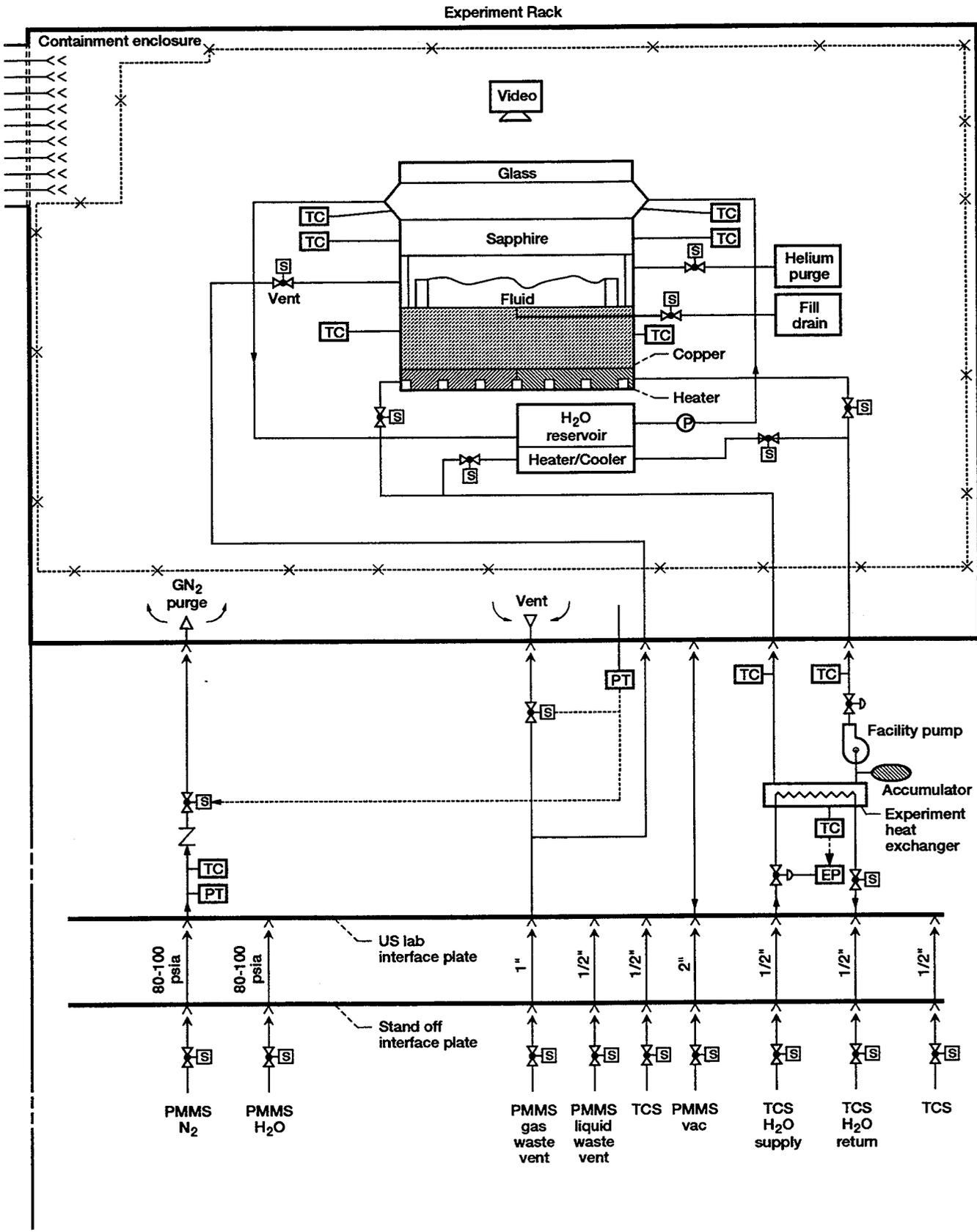


Figure 2—Concluded.

approach was pursued, in which the FP/DF would occupy two or more Freedom Station equipment racks. One of these racks was designated the facility rack, and the other(s), the experiment rack(s). This concept is pictured in figure 1. The facility rack, shown on the left, will be the permanent part of the FP/DF, housing those support systems identified by the study team as being required to support potential users. These support systems will be covered in detail in the section **Facility Description by System or Function**. The facility rack will remain onboard Freedom Station for as long as the use of the FP/DF can be justified; however, this does not preclude occasional changeout of this rack for upgrade or enhancement purposes.

Adjacent to the facility rack will be an interchangeable experiment rack. This experiment rack will contain experiment modules, experiment-specific hardware, and a minimum amount of support hardware. An experiment module is defined as that hardware to be used, in conjunction with facility-rack support systems, to perform (1) a class of experiments or (2) a single unique experiment in the conceptual-design process: in this case, the experiment module for a class of experiments, a static fluids experiment, and an experiment module for a unique multiphase flow experiment. Detailed discussions of these two experiments are provided in the **Fluids Experiment Concept Designs and Operations Scenarios** section of this report.

After establishing a conceptual design, the study team identified a number of static experiments that could be done with some modification to the experiment hardware; this is typified by the Immersed Bubble/Droplet Dynamics and Interactions experiment. The study team also showed how a unique experiment could be handled with the concepts for a multiphase flow experiment. The multipurpose aspect derives from the variety of experiment-specific hardware modules that would be used within the static-fluids experiment module. An example of experiment-specific hardware is a set of test chambers, each representing a different fluids experiment. Each of these test chambers would have additional associated hardware that would be unique to the experiment, such as camera or laser optics, heaters, experiment-specific computer software, and instrumentation.

The experiment rack, including its FP/DF support hardware, experiment module, and one experiment-specific hardware module, is expected to be integrated on the ground and transported via the Freedom logistics module to Freedom Station. Exchanges of entire experiment racks such as this might be expected to occur every 12 to 18 months. The concept design also allows on-orbit changeout of experiment-specific hardware modules. These changeouts might be expected to occur every 45 to 90 days.

The FP/DF is being designed to support unique non-modular experiments such as multiphase flow. The design admits the possibility that an experiment rack might be larger than one Freedom Station rack.

As part of the conceptual design effort, the study team generated a series of conceptual schematic diagrams, one for each of the experiments on the reference-experiment list. Figure 2 is one such diagram; it shows the Surface-Tension-Induced Convection Experiment. These figures are basically mechanical fluid diagrams that show both the facility and experiment racks, along with major pieces of equipment in each. On the schematic, at the bottom of each rack, USL module services are shown. The changeable parts of the experiment rack, the experiment modules and experiment-specific hardware, are shown within the dashed and crossed line.

### **Facility Assumptions and Constraints**

There are certain constraints to the design of the support systems that are included in the FP/DF. These constraints come from several sources: the USL module and S.S. Freedom Program safety requirements; the USL module capabilities and requirements; Freedom Station operations and logistic requirements and capabilities; and program funding and schedules. Other constraints were imposed by certain assumptions that had to be made by the study team during the FP/DF conceptual design phase because specific information was lacking on USL module systems and S.S. Freedom Program operations that are in their early design phase. These assumptions are listed with the design to which they apply and are summarized in appendix B.

## **Facility Description by System or Function**

### **General Facility Layout**

One of the primary considerations in the conceptual design of the FP/DF has been the emphasis on user needs for the research that will be conducted in it. Because the exact experiments that will utilize the FP/DF in years to come are unknown, it has been structured so that the maximum possible volume and payload weight are reserved for experiment-specific hardware.

As mentioned in the **Introduction**, the FP/DF will reside in two adjacent racks in the module, as shown in figure 3. One rack will house most of the facility-support hardware, and the other rack will contain some facility-support hardware, the experiment module, and experiment-specific hardware. This two-rack concept, selected as a result of a trade study, was chosen for the following reasons: it maximizes the volume that will be reoriented with the quasi-steady acceleration vector; and integration and de-integration of experiment-specific hardware will require less work if the equipment is located in one rack. Another benefit of the concept is that the facility support rack can remain on Freedom Station for extended periods of time, and only the experiment rack need be returned to Earth for experiment-module changeout. One additional benefit of using a full rack for the

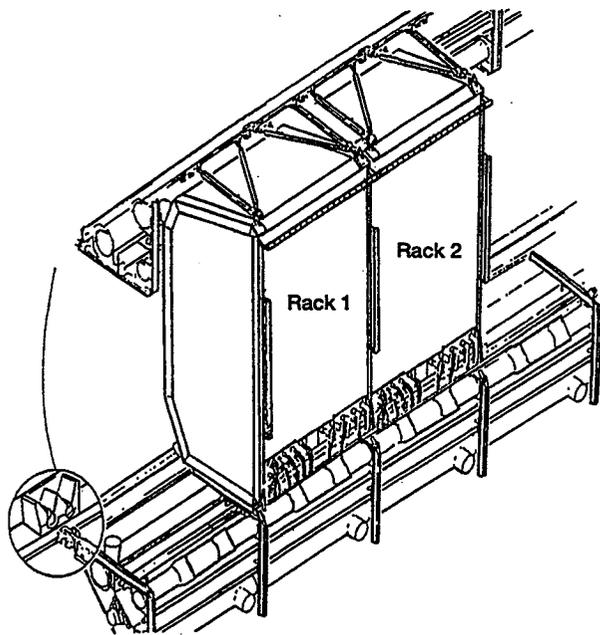


Figure 3.—S.S. Freedom standard racks.

facility is that some storage volume is available within the facility for storing hardware, such as test cells and test fluid reservoirs, which could be changed out, as required, during an experiment.

### Space Station Freedom Program Requirements

**Experiment racks.**—The USL standard equipment racks are being supplied for the FP/DF by the S.S. Freedom Program. Since only one rack can be brought into the USL module at a time because of the size of the hatch leading into the module, the two racks comprising the FP/DF must be put together in the module on orbit. These program-supplied racks may not be structurally modified by the users, and the primary rack structure may not be removed during an on-orbit installation. The S.S. Freedom Program will be using some of the rack volume for program-supplied hardware. The bottom 25.4 cm (10 in.) of the rack are reserved for the multiplexer-demultiplexer (MDM), standard data processor (SDP), power converter and protection assembly, and the Freedom Station interface panel. The back 10 cm (4 in.) are reserved for piping of the avionics air-cooling and the thermal-control systems. Figure 4 shows the dimensions of the remaining available working envelope and the volume devoted to the rack user. If the facility were to be designed for installation into any of the three other space laboratories, a slightly smaller (8.8 percent less volume) international payload rack would result.

**Payload weight restrictions.**—The S.S. Freedom Program has specified a maximum payload weight range between 400 and 700 kg per USL standard equipment rack. The higher end of the payload weight range will require additional rack-support braces, which will be supplied by the S.S. Freedom

Program. If the rack payload design weight were to exceed the maximum allowed, the additional equipment above the weight limit could be delivered into orbit independently and integrated into the rack on orbit. The maximum payload weight is specified because the racks are used as support for the hardware during transport to and from Freedom Station via the space shuttle. The weight of the S.S. Freedom Program-supplied hardware that resides in the racks is included in the payload weight calculations. For an international exchange rack, the maximum payload weight is 400 kg.

**Rack integration sequence.**—The integration of both the FP/DF hardware into the facility rack and the initial experiment into the experiment rack will be done on Earth. The two integrated racks will arrive on orbit by means of a pressurized logistics module, a cylindrically shaped payload that fits into the space shuttle cargo bay. On arrival at S.S. Freedom, the logistics module will be linked with Freedom Station, and the racks will be transported one at a time into the USL module. The racks will be attached to the USL module by means of a pin-latching mechanism on the upper back edge and on two of the bottom edges of the rack. Flexible hoses and cables that connect the standoff interface plate to the Freedom Station interface plate will provide fluid and electrical connections from the station to the Facility. An important feature of the racks is that they are designed to be tilted out—pivoting about the lower front attachment point to allow access to the module's inner wall (see fig. 5). This access is necessary in order to clean the back shell or to repair any damage that might be caused by a meteoroid or debris striking the module. The flexible connections between the racks and the module allow the pivoting motion without breaking any connections.

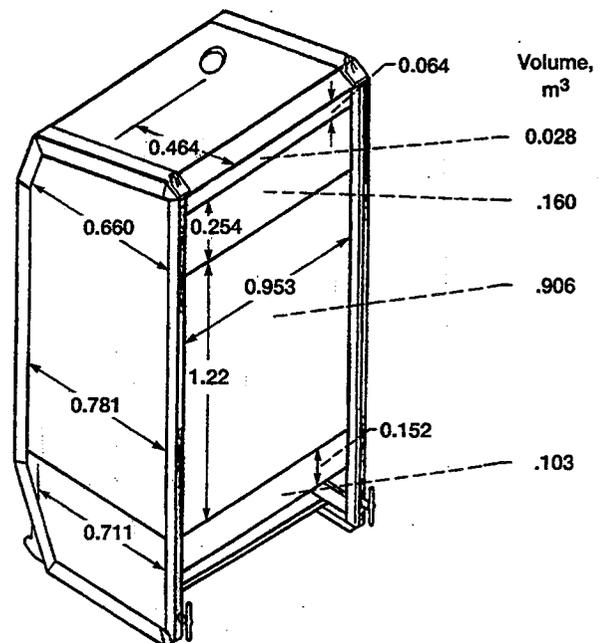


Figure 4.—Working envelope of standard rack.

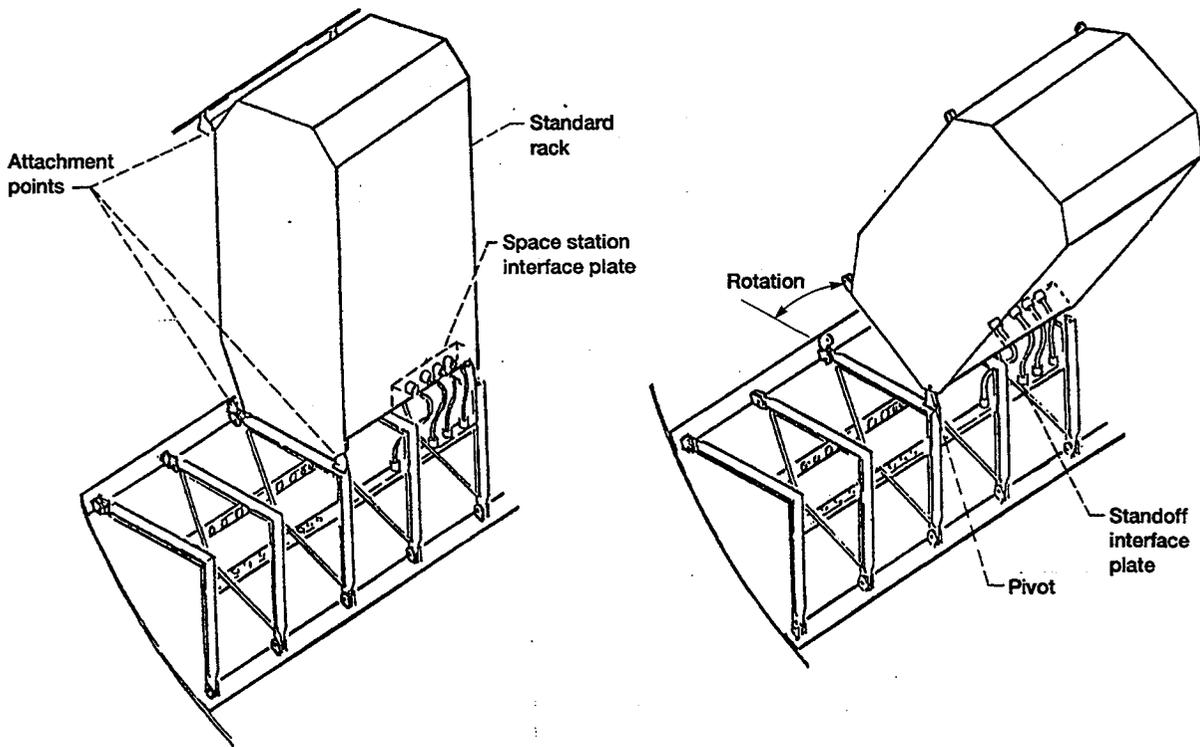


Figure 5.—Pivot feature of standard rack for access.

**Experiment changeout procedure.**—Because the FP/DF is a multiuser facility, experiment and/or experiment-module changeout is an important aspect in its design. An assumption was made, based on the difficult operations involved in hardware exchange, that a changeout of an experiment module will require de-integrating and then integrating a full rack. This assumption led to the decision to integrate the new experiment module into an S.S. Freedom rack while it was on the ground, and then to transport the rack to Freedom via the space shuttle. The on-orbit integration between the facility rack and the experiment rack would then be the same as the initial Facility integration into the module. Alternatively, if only an experiment changeout within a previously installed experiment module is required, this operation could be performed on orbit.

**Safety containment levels.**—The S.S. Freedom safety program requires that any material that could contaminate the USL module atmosphere and cause harm to the crew must be double-fault tolerant. In other words, the system must remain safe after two failures (i.e., triple contained). Because the use of toxic and/or combustible test fluids within the FP/DF is being considered, many of the experiments will probably require a double-fault tolerant design. The actual decision about whether a certain test fluid requires a double-fault tolerant system will depend on the quantity and type of fluid. On the basis of a trade study, a decision was made to provide two of the three required levels by enclosing the necessary experiment-specific hardware within a containment enclosure in the experiment rack. The pressure maintained within the

enclosure will be lower than the pressure within the USL module, thereby eliminating the possibility that any test fluid from the experiment module might escape into the USL module atmosphere through a small leak in the enclosure. The three safety containment levels are the experiment module, the negative pressure, and the containment enclosure. In the event that the experiment being conducted within the experiment module did not require double-fault containment, the enclosure could be removed; also, in some situations the experimenter might want to furnish all the required containment layers.

**Microgravity environment on Freedom Station.**—Much concern has been expressed by the fluids science community about the microgravity levels that will actually be present on Freedom Station (calling the environment in space “zero-g” is a misnomer). The S.S. Freedom Program is currently in the process of defining the microgravity requirements that will be imposed on the designers of the station. The present design documents have no firm microgravity requirements, but a design-requirements change request has been submitted. The following brief discussion describes the anticipated microgravity environment on the Freedom Station. Note that these are preliminary results and will change with any change in the design of Freedom Station.

The microgravity environment on Freedom has been divided into three general categories of disturbances: quasi-steady, oscillating, and transient. Quasi-steady accelerations are essentially constant disturbances that can be characterized by their magnitude and direction. Disturbances with frequencies

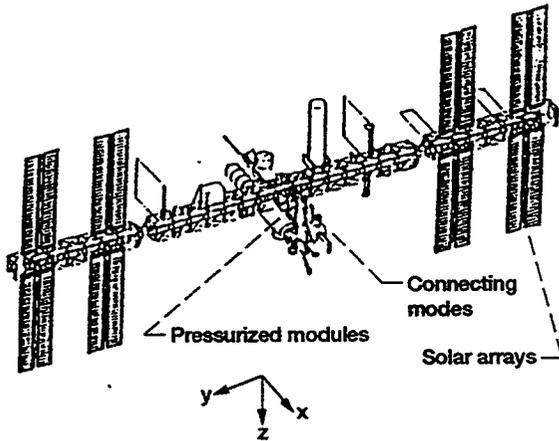
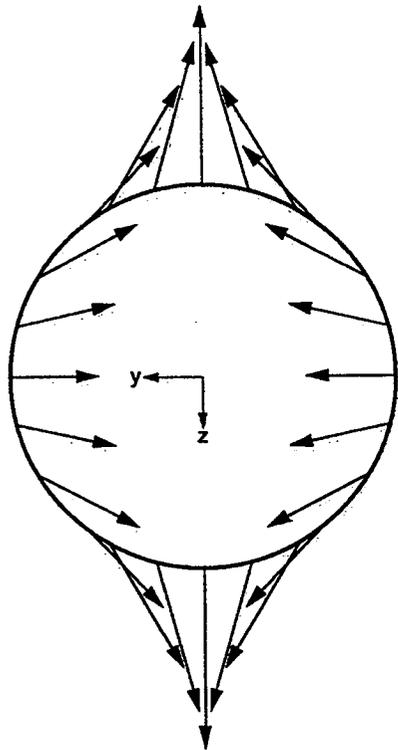


Figure 6.—S.S. Freedom gravity-gradient field.

less than 0.001 Hz are included in this category. Higher-frequency disturbances (greater than 0.001 Hz) are categorized as oscillating disturbances; they, too, can be characterized by their magnitude and frequency. Transient accelerations are disturbances due to impulsive and/or random forces. The following section contains a brief discussion of the causes of the different disturbances and an estimation of the levels of such that could be present on Freedom.

**Quasi-steady acceleration.**—The dominant factors contributing to the magnitude and the direction of the quasi-steady acceleration vector are the gravity gradient, rotational acceleration, and the atmospheric drag. The gravity gradient is due to the difference in the gravity force experienced by a

point located away from Freedom's center of gravity, and its magnitude and direction depend on the location of the point with respect to Freedom's center of gravity. At the center of gravity, there is no gravity-gradient term that contributes to the quasi-steady acceleration. The gravity-gradient field experienced by an object orbiting the Earth is shown in figure 6. The z-axis is pointing toward the Earth, and the y-axis is along Freedom's truss structure. The acceleration sensed by a point away from the center of gravity is opposite in direction to the gravity-gradient field.

The rotational acceleration term has two components—centripetal and tangential. The centripetal component results from the angular velocity, which is caused by Freedom rotating about its center of gravity during an orbit. The direction of this component is toward Freedom's center of gravity. The tangential component is due to the angular acceleration about Freedom's center of gravity and is nominally equal to zero. Because of the pitch rate changes, however, tangential accelerations do contribute to the quasi-steady acceleration vector.

Atmospheric drag, which is due to atmospheric friction, is directed opposite to the Freedom Station velocity vector. Factors that affect this component include atmospheric density, Freedom's velocity, Freedom's projected area in the velocity direction, and Freedom's mass. The atmospheric density changes as a result of geomagnetic activity, solar flux levels, and various daily effects. Freedom's velocity will change with orbital altitude, and the frontal area will vary with the repositioning of moving equipment, such as the solar panels.

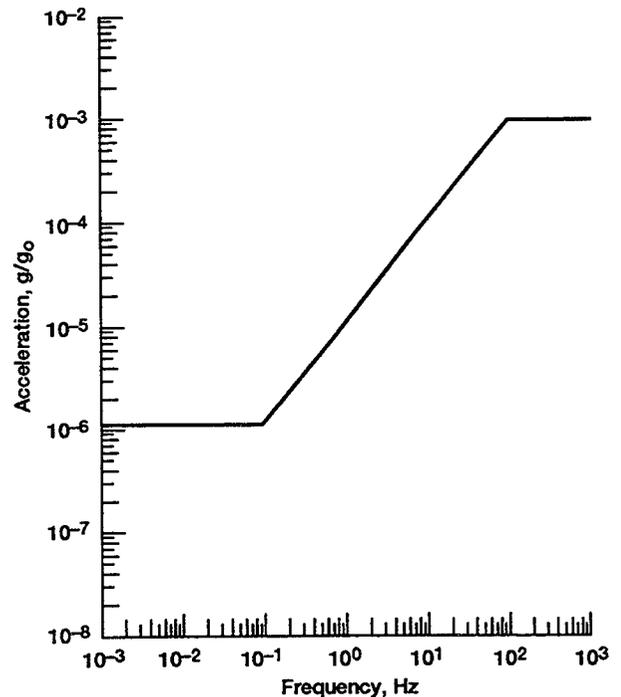


Figure 7.—Proposed acceleration requirements for oscillatory disturbances.

The gravity gradient, rotational accelerations, and atmospheric drag combine to produce a quasi-steady acceleration vector that varies in magnitude and direction with its location in Freedom. The magnitude of the quasi-steady vector is expected to range between  $10^{-6}$  and  $10^{-5} g/g_0$ , where  $g_0$  is the standard gravitational acceleration on Earth. The direction of the quasi-steady vector will not only change with its location on the station, but it will also change with Freedom's orbital location around the Earth. The largest angular change between the direction of the local orbital average quasi-steady vector at any two experiment rack locations over all the labs is approximately  $112^\circ$ . In the experiment racks of the USL, this average vector changes a maximum of  $37.5^\circ$ . Over one orbit, the largest change in the instantaneous quasi-steady vector for one experiment rack is  $\pm 13^\circ$ .

**Oscillatory accelerations.**—Oscillatory, or periodic, accelerations are characterized by their magnitude and frequency.

These disturbances are mainly due to rotating machinery, repetitive crew activities, and structurally induced modes. The oscillatory acceleration levels on Freedom are very hard to predict because they depend on individual component design. The microgravity change request proposes that the maximum acceptable acceleration magnitudes between 0.001 and 1000 Hz be those shown in figure 7. Indications are that these requirements will not be approved, but will serve as a design guide only. This is cause for concern because if no requirements are approved, the microgravity environment may be significantly higher than the proposed levels.

**Transient accelerations.**—Impulsive disturbances that are the result of crew activity, thruster firing, venting, orbiter docking, and turning equipment on and off cause transient acceleration. The effects of transient disturbances on the fluids experiments can be minimized by scheduling the critical cycles of such experiments during quiet periods.

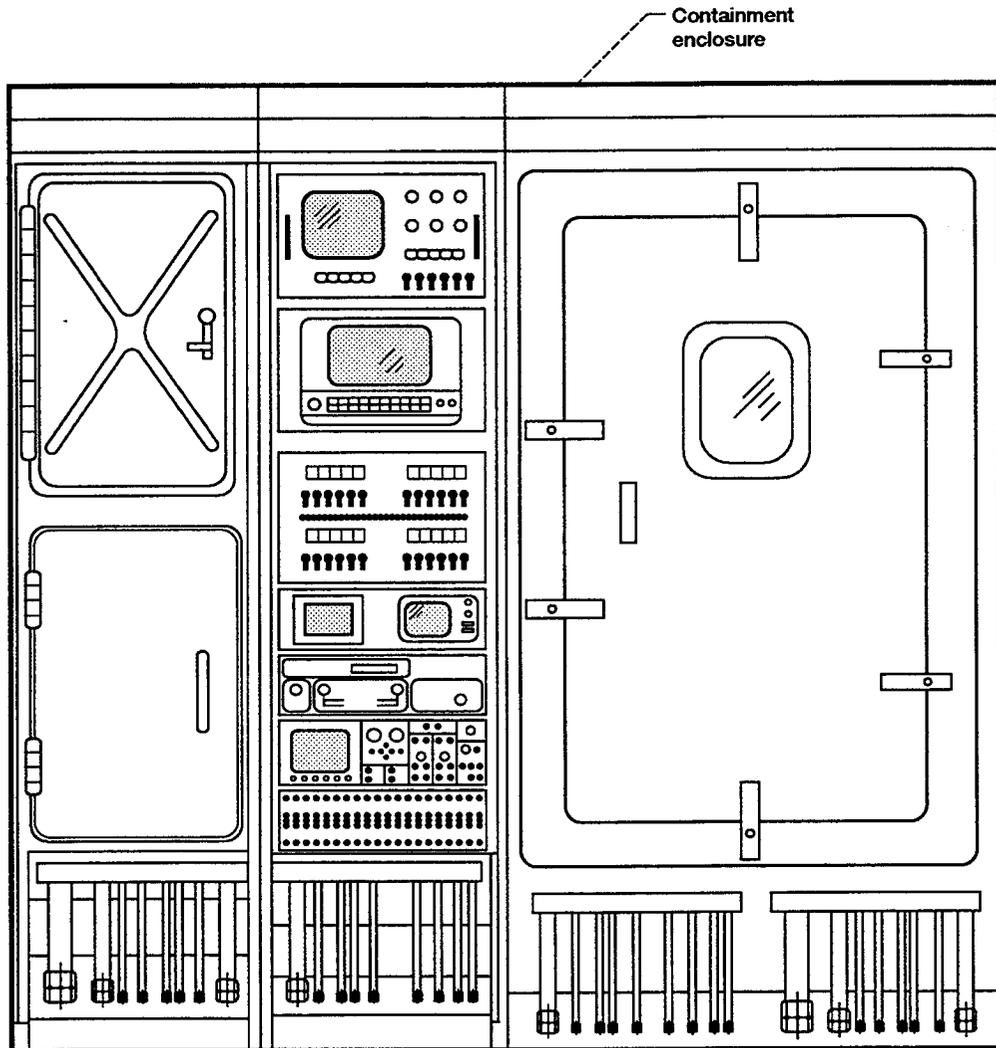


Figure 8.—Front view of Fluid Physics/Dynamics Facility.

- ① Image processing unit
- ② Diagnostic illumination module
- ③ Facility status panel
- ④ Electrical power distribution assembly
- ⑤ Multiplexer/demultiplexer
- ⑥ Video control unit
- ⑦ Portable multipurpose application console
- ⑧ Standard data processor
- ⑨ Lab interface plate
- ⑩ Power converter/protection assembly
- ⑪ Chemical storage
- ⑫ General storage
- ⑬ Acceleration measurement electronics

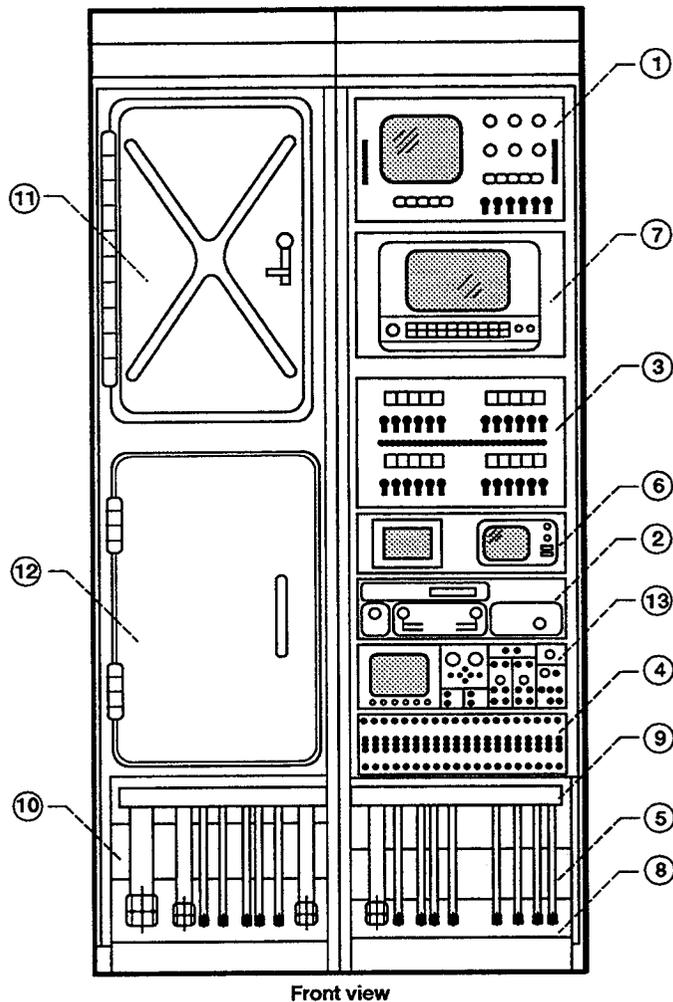


Figure 9.—Proposed facility-rack components.

### Facility Configuration

The overall layout of the FP/DF is shown in figure 8. The layout of the FP/DF stresses the modular design. All of the electronic hardware in the facility rack reside in separate boxes that could easily be replaced if necessary. A rack center support is included in the facility rack to aid in mounting standard 19-in.-wide electronic boxes. These components will be mounted on rails for ease of installation and replacement. The experiment module and experiment-specific hardware are located within the experiment safety containment enclosure. A changeout of an experiment will require exchanging hardware within the enclosure but little, if any, changing of hardware in the facility rack. A labeled drawing of the facility rack is shown in figure 9. The study team decided, on the basis of the reference experiments and input from researchers, which services would be supplied by the FP/DF. Note that the actual sizes of the components are unknown at this time, but the envelope in which the actual hardware will reside has been approximated.

**Experiment containment enclosure.**—As mentioned previously, the experiment containment enclosure will provide two of the three safety containment levels required to protect the USL module atmosphere from a test-fluid leak. The main function of the enclosure will be to keep the atmosphere within it isolated from that of the USL module by maintaining a pressure that is slightly negative with respect to the module pressure.

The enclosure (see fig. 10) has been sized to conform to the user envelope within the rack. Some space has been left for fluid supply piping at the bottom of the rack outside the enclosure. The external dimensions of the enclosure are approximately 90.2 cm wide by 73.0 cm deep by 143.0 cm high (35.5 by 28.7 by 56.3 in.). The top 0.1 m<sup>3</sup> (3.4 ft<sup>3</sup>) of the enclosure has been reserved for the Facility-supplied fill-and-drain system. The decision to locate the fill-and-drain system inside the enclosure was made because the system's design will depend on the experiment and bringing the system's piping across the between-rack interface would be impractical. In

addition, the fill-and-drain system may require triple containment for some proposed test fluids.

The enclosure has a large door on the front to allow easy access to the experiment hardware. An adapter plate will be available on the front of the enclosure door to attach a portable glovebox, which may be needed for some hardware changeout operations. In addition, the window will allow the crew to view the hardware. The preliminary material selected for the enclosure is 6061-T6 aluminum; it is weldable and has a high resistance to stress-corrosion cracking. The enclosure has been designed for a maximum pressure differential of 2 psi and has a usable internal volume of approximately  $0.69 \text{ m}^3$  ( $24.0 \text{ ft}^3$ ) devoted to experiment-specific hardware. The enclosure weighs approximately 100 kg, which leaves 600 kg for the remaining hardware in the experiment rack. Figure 10 shows additional design features of the enclosure.

**With quasi-steady acceleration-vector alignment system.**—Current plans are to assign Freedom payloads to an experiment rack location no earlier than 2 years before flight. This does not allow sufficient time to orient the experiment with respect to the vector and lock it in place. If the rack assignments were allocated earlier in the design process and the FP/DF's position were determined to be permanent, then the direction of the quasi-steady vector at the Facility location could be characterized, and the experiments could be hard-mounted in a specified orientation with respect to this vector.

Approximately one-half of the 11 reference experiments require the experiment test cell to have a specific orientation with respect to the quasi-steady acceleration vector. As previ-

ously mentioned, the direction of this vector not only varies drastically with the experiment's location on Freedom, but it also changes over an orbit. Therefore, the FP/DF is providing a vector-alignment system with which a specific orientation can be obtained. The system consists of a rotating frame, used as a mount for the test cell, and its related diagnostic equipment. This frame can be oriented in any possible vector direction; that is, the test cell can be oriented in any direction in three-dimensional space. The main reason for including the alignment system as a Facility support system is that the location of the FP/DF within the USL module has not been determined. Moreover, one of the reference experiments requires, as a controlled science parameter, that orientation of the test cell be varied. This will be possible with the alignment system.

The alignment system consists of a cubic rotating frame within the containment enclosure (fig. 11). The outer frame is 39.1 cm (15.4 in) on all sides. Standard holes will be provided in the frame for mounting experiment-specific hardware. In order to orient this frame in any direction, a full sphere of clearance is necessary. The largest sphere that can fit into the containment enclosure is 0.68 m (26.8 in.) in diameter, corresponding to the 0.68-m interior depth of the enclosure. The frame will have two axes of rotation, through which every orientation can be achieved. The volume available inside the alignment frame is  $0.06 \text{ m}^3$  ( $2.1 \text{ ft}^3$ ). Because the actual clearance volume required for the rotating frame is a sphere, the hardware mounted in the frame can extend outside the frame until it reaches the edge

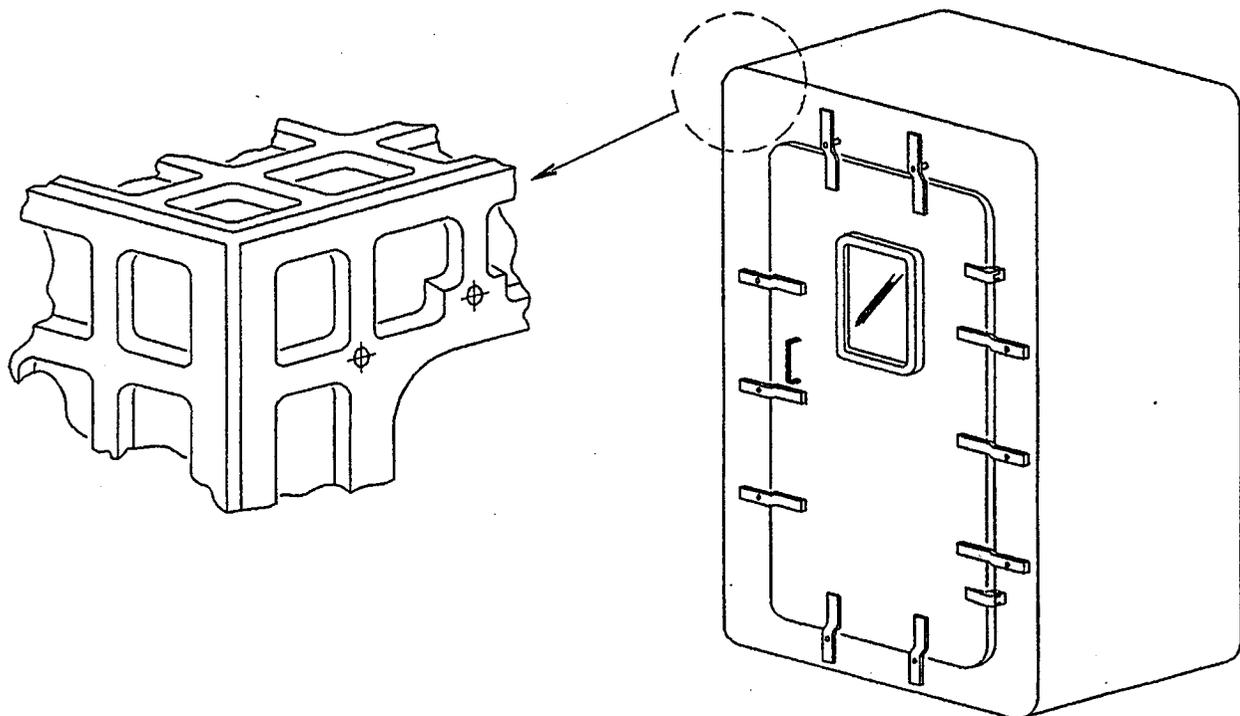


Figure 10.—Experiment containment enclosure.

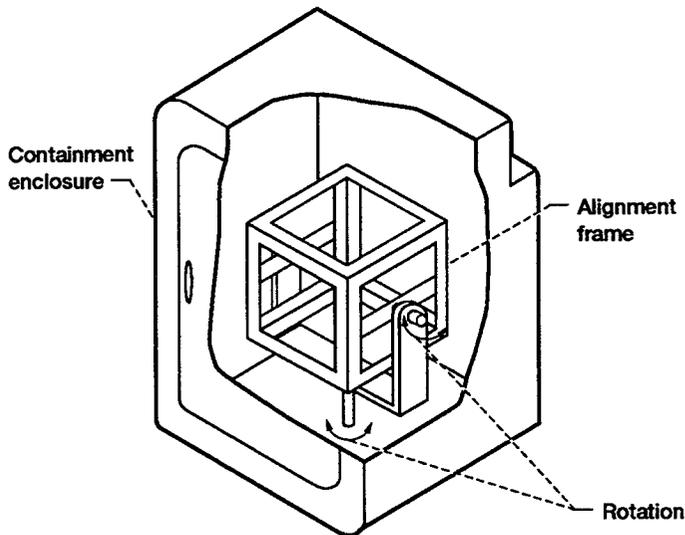


Figure 11.—Quasi-steady-acceleration alignment system.

of this sphere. Since some of this volume will be required for the alignment-frame hardware, the volume available for mounting experiment-specific hardware on the rotation alignment frame will be approximately  $0.15 \text{ m}^3$  ( $5.2 \text{ ft}^3$ ). The Facility-supplied accelerometer heads will also be located on the alignment frame since the heads must be mounted near the test cell.

The frame can be oriented on the ground after the Facility has been assigned a location in the USL module, or it can be reoriented after it arrives on Freedom. This option is necessary because experiment-specific hardware changeout might require the frame to be oriented in a certain position (i.e., one of the faces of the frame located parallel to the front of the rack). A programmable realignment system with manual backup would be the most advantageous design. The direction of the quasi-steady acceleration vector and the “home” position needed for changeout procedures could be programmed into the system. The locally mounted accelerometers could be used to fine-tune the direction of the vector, whose direction could be input to two microprocessor-controlled, rotational-drive mechanisms.

The quasi-steady acceleration alignment system will not provide exact alignment with the vector at all times during an orbit because of the orbital change in the vector direction. For the least desirable experiment rack location, the orientation could be off by a maximum of  $\pm 13^\circ$ . Substantially improved accuracy can be obtained by requesting certain preferred rack locations that have a more stable acceleration vector. Even the best rack locations have a change in direction on the order of  $\pm 4^\circ$ . If such accuracy does not meet the science requirements of an experiment, an active pointing system will be necessary. This would require a more complex design than the baseline design for the FP/DF. A feedback control system between the accelerometers on the frame and the alignment control would be necessary. The design

would have to ensure that the pointing system would not impart its own accelerations on the test fluids.

Because of the relatively small volume that can be oriented with the quasi-steady vector, only items whose alignment is critical should be located on the frame. The test cell and its associated hardware, such as thermoelectric heaters and coolers, heat exchangers, bubble deployers, and cartridge heaters, *must* be located on the frame. In addition, all diagnostic equipment that requires a critical orientation with respect to the test cell (such as video-camera heads, film cameras, and laser heads) must also be mounted on the frame. Other support equipment, such as the fill-and-drain system and storage reservoirs, can be located off the rotating frame, but must still remain within the experiment-specific volume inside the containment enclosure. The volume available off the frame, but still within the enclosure, is approximately  $0.46 \text{ m}^3$  ( $16.4 \text{ ft}^3$ ).

In order to increase the size of the alignment frame, some restrictions on the orientation of the frame could be applied. (Recall that the frame has been designed so that it can be oriented along any vector.) The actual maximum change in the direction of the quasi-steady vector for the racks located in the USL module is  $37.5^\circ$ . By taking into account the direction of the acceleration vector at each experiment rack location in the USL and the orientation necessary to perform experiment hardware changeout in each of these racks, a more detailed design of the alignment system could be produced. Such a design, however, would restrict the Facility to installation into the USL module only.

**Without quasi-steady acceleration-vector alignment system.**—A major disadvantage of the quasi-steady acceleration-vector alignment system is the small volume available for the test cell, diagnostics, and other related hardware. This could have an impact on the design of the experiments that will be conducted within the FP/DF. If the FP/DF did not provide this support system, the volume available for experiment-specific hardware would be approximately  $0.69 \text{ m}^3$  ( $24.0 \text{ ft}^3$ ). Although a significant percentage of the reference experiments requested a specific vector orientation, many of the researchers were uncertain about the

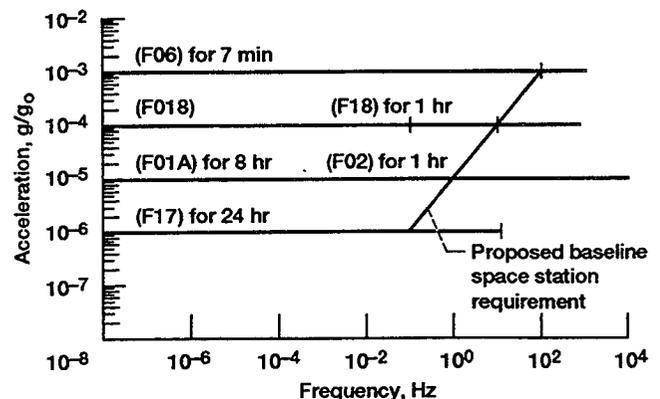


Figure 12.—Acceleration requirements for reference experiments.

effect that the quasi-steady vector direction would have on the experiments. Clearly, the direction of Earth's gravity has a significant effect on the outcome of an experiment, but when gravity is in the  $10^{-5} g/g_0$  range, its effects on the experiments are unknown.

**Oscillatory-vibration isolation.**—The effects of oscillatory vibrations on experiments are unknown, and complications arise when one considers such effects. Oscillatory accelerations are also of concern to the fluids science community. In figure 12 the maximum allowable vibration levels for the reference experiments are plotted with respect to the proposed Freedom design requirements. In general, it seems that lower frequency vibrations have a more detrimental effect on fluids than do higher frequency disturbances, because of the viscous nature of most fluids. Analytical studies are being conducted to learn more about the sensitivity of certain fundamental fluid experiments to oscillatory and impulse excitations. Even if Freedom guaranteed these vibration levels, some form of vibration isolation would still be required, because the Freedom vibration levels exceed the maximum allowed by science experiments.

The method of vibration isolation that would be employed is directly related to the frequency of the vibration against which the experiment is being isolated. Higher frequency vibrations can be isolated by using conventional passive-isolation techniques, such as rubber mounts. Lower frequency vibrations can be isolated only by using active-isolation techniques, such as electromagnetic isolators. Passive isolation cannot be used for low-frequency disturbances because low-stiffness passive isolators are unavailable and because large strokes are necessary. The frequency threshold at which active-isolation techniques must be used is unknown at this time.

A passive-isolation system will be incorporated into the Facility. This decision was prompted by the potentially severe impact that active-isolation methods could have on the Facility; it implies that only higher frequency vibrations can be isolated. The following is a brief discussion of the passive-isolation design and a summary of the possible effects that an active-isolation method could have on the Facility design.

**Passive vibration isolation.**—The present concept is to passively isolate from the rest of the Facility the quasi-steady-acceleration alignment frame and its associated mounted experiment-specific hardware. Thus, only the critical components, such as the fluid-filled test cell, would be isolated. In order to achieve isolation at the lowest possible frequency, any connection that crosses the interface must be as flexible as possible; the design goal is to minimize the overall spring stiffness that crosses this interface. Thus, the horizontal rotational joint shown in figure 11 will be passively isolated from the remaining alignment structure by using some type of a flexible mount. All other connections, such as electrical wires and fluid tubes, must be designed with the lowest possible spring stiffness. Such methods as

separating the individual wires in electrical cables and coiling the wires to resemble large-diameter compression and extension springs will aid in achieving the lowest isolation frequency. Fluid transfer could be accomplished by using flexible tubing or soft, nonmetallic hoses. In any case, during transport to and from Freedom, the hardware will need to be locked in place to avoid damage.

The following is an example of a possible isolation scenario. Suppose there is a disturbance from Freedom that has a magnitude of  $10^{-4} g/g_0$  and a frequency of 10 Hz. Further, assume the isolated hardware weighs 100 lbs, and the maximum allowable acceleration that can be input to the experiment is  $10^{-5} g/g_0$ . If damping is assumed to be negligible, the natural frequency of the system can be calculated as 3 Hz, which requires a spring rate of 93 lb/in. If the input frequency is changed to 0.4 Hz, the natural frequency of the system would be 0.12 Hz, with a spring rate of 0.15 lb/in. Providing an isolated system with a spring rate of 0.15 lb/in. would be very difficult to achieve, because a single electrical wire could have a spring rate of this magnitude. However, the spring rate of 93 lb/in. could be achieved.

**Active vibration isolation.**—Active-isolation methods for space applications are being investigated in other space-experiment projects. The main advantage of an active-isolation system is its ability to alter its stiffness and damping, thereby immediately decreasing the magnitude of a disturbance transmitted to the isolated system. Active systems utilize a motion or position sensor and an accelerometer feed-forward control loop to counteract a mechanical disturbance. This minimizes the resulting motion of the isolated system. A current method of stiffness and damping control that is being investigated uses electromagnetics to provide an isolated system magnetically suspended between electrically controlled magnets. This technique might make possible the isolation of vibrations down to around 0.01 Hz.

For actively isolated experiments, the connections between the Facility and the experiment would have to be strictly controlled. In order to compensate for the stiffness of the connections, the electromagnetic isolators could simulate a negative stiffness to essentially negate the connection. In order to write an algorithm to counteract the stiffness, a well-characterized connection will be very important. If the force-deflection response curve for the connection were nonlinear or if it changed with time, the algorithm could easily become unmanageable. If isolation at very low frequency levels were required, it is possible that no physical connections would be allowed across the isolation interface; then, the experiment would require total physical isolation from the Facility. This restriction would severely affect the noncontacting transfer of power, laser light, data, and control signals to and from the experiment; in addition, temperature control for the experiment would be more complex. The following is a brief discussion of noncontacting transfers.

In order to provide power to the isolated experiment, either the isolated system will have to provide its own power or a

method to transmit the power across the isolation "gap" will be required. Because of the relatively large power requirements and since only a small volume can be isolated, a self-contained power system does not seem to be a viable option. Therefore, a noncontacting method to transmit power across a gap would be necessary. A gap distance of about 2.5 cm would be required to isolate to around the 0.01-Hz level. A noncontact power transformer consists of both primary and secondary windings around a soft-iron core; the secondary winding is separated completely from the core by a gap. A 1-kW prototype with a 0.7-cm gap has been built and successfully tested; larger power transmission may be possible by scaling up this configuration or by using multiple units. Using noncontact transformers has some disadvantages, however. First, the electromagnetic fields that are produced could leak into the surrounding area and affect other electronics and, potentially, disturb the experiment. Second, this method requires a small gap distance; therefore, any minor control system failure in maintaining the gap could damage the power-transfer equipment. Last, any increase in the gap size would increase the field leakage into the surrounding area and decrease power transfer efficiency; thus, because of the transfer losses across the isolation gap, more power would be required to power an experiment.

Transferring the Facility-supplied laser light across the isolation gap would also be a difficult procedure, owing to the relative motion between the Facility and the isolated experiment. The laser light cannot be directed across the gap because the light would not remain focused on a specific location on the experiment. Currently, no method has been identified that will collect the moving light beam and refocus it to a stationary point. The alternative to transmitting the light beam across the gap is to locate the laser source on the isolated system.

Transferring data and control signals across the isolation gap is another area of concern. For the active-vibration-isolation design, the experiment-specific hardware on the isolation system could be controlled by a local controller that resides on the alignment frame. This controller would communicate with the Facility computer by using a pair of opposing transceiver units to transmit across the isolation gap; one transceiver would be located on the alignment frame and the other directly across the air gap. Each transceiver would consist of a light-emitting-diode (LED) transmitter and a photo-detector receiver. Transceivers with data rates up to 200 Mbps are a well-established technology, and off-the-shelf equipment is available. The use of a lens and collimator would ensure that the signal will traverse the air gap properly.

The present thermal control concept for the Facility involves using thermoelectric heaters and coolers in combination with heat exchangers. If the problem of transferring power to the isolation system is solved, the use of thermoelectric devices would still be conceivable. Transferring the heat exchanger cooling fluid across the gap would be prohibited; however, one possible design solution would be to use

forced convective cooling. Cooling fins could be attached to the thermoelectric devices, and a fan could be mounted within the containment enclosure to blow cooling, PMMS-supplied, pressurized nitrogen across the fins. The heated nitrogen would then be circulated into a radiator-type heat exchanger. However, such a device would remove only a limited amount of heat from the experiment; in addition, a high nitrogen flow rate could disrupt the isolation system.

**Between-rack interfaces.**—Interfaces between the two racks will be required because the experiment will be housed in one rack and the control hardware will reside in an adjacent rack. The number of interconnections between the racks will be minimized in order to decrease the time required to integrate the two racks. The design of the Facility has limited the between-rack interfaces to electrical lines only. The interconnections include the Facility electrical bus, fiber-optic cables for the diagnostic illumination system, and cables for the video system. Some generic ports will be provided for experiment-specific connections. The experiment will interface with these systems on the inside of the containment enclosure wall.

**Facility-supplied storage.**—The FP/DF will require local storage for many items pertaining to the assembly, preparation, operation, disassembly, and cleanup work associated with running a typical fluids experiment. It is anticipated that a portion of the facility rack will be used as a storage area. The facility-rack storage area will be divided into two storage lockers: the chemical-storage locker and the general-storage locker. Fluids, gases, and solids will be contained and kept in the chemical-storage locker until needed for experiment use. The volume devoted to storage is about 0.59 m<sup>3</sup> (21.0 ft<sup>3</sup>), which is one-half of a rack; half of this volume has been assigned to general storage and half to chemical storage. When the experiments become better defined, the actual sizes of the storage areas can be specified. Additional storage will be available in the logistics module of Space Station Freedom. The general-storage locker will contain hardware items secured in place with quick-release mechanisms (e.g., Velcro) and fitted clip-in slots. The following types of items are expected to be stored within the general-storage locker:

- Special-purpose tools
- Spare fill-and-drain system hoses and parts
- Video-system accessories (tape media, lenses, cleaning set, etc.)
- Laser-system accessories
- Experiment-specific items (e.g., test cell/chamber)
- FP/DF cleaning supplies
- Spare electronic cards
- Light bulbs

The chemical-storage locker will be located above the general-storage locker within the facility rack. A fire- and leak-detection system on the chemical-storage locker front panel will alert crew members to locker interior conditions. It will also send status information through the MDM's to the Freedom data management system (DMS) network. Other

support systems for the locker include lighting and atmosphere control. Since the locker will contain hazardous materials, some of which could require triple containment, the design will be similar to the design of the containment enclosure. The outer wall of the locker will be one safety level; a negative pressure, the second; and the bottle containment of the hazardous material, the third. Tanks, bottles, reservoirs, and containers will be secured in the chemical-storage locker by locking-release retention techniques. The portable glovebox will be compatible with, and used for, transfers in and out of the chemical-storage locker.

Some of the chemicals expected to be stored are the following:

Liquids	Gases	Solids
- Freon	- helium	- aluminum oxide
- silicone oil	- argon	particles
- methanol	- carbon	- silicon dioxide
- water	dioxide	wafers
- glycerin		

For some experiments, a complete storage-locker change-out might be advantageous when an experiment changeout is performed. In addition, the storage lockers could be removed if an experiment requires extra volume in the facility rack for experiment-specific equipment.

**Experiment-specific hardware changeout.**—Since the test-cell geometry and the test fluids vary in many of the reference experiments, changeout of experiment-specific hardware will be necessary. This will be one of the most difficult tasks that the crew will perform on the FP/DF. All connections to the test cell must be disconnected prior to changeout. The electrical connections will be made by electrical pin connectors. The fluid connections will be zero-leakage,

quick-disconnect fittings. Because loose fluid may be present during the changeout procedure, the use of a portable glovebox might be required. The glovebox, which will be an S.S. Freedom Program-supplied device, will be designed as a standard piece of equipment that can interface with any experiment rack. It will be attached to the front of the containment enclosure, as shown in figure 13. Two problems that the portable-glovebox designers will need to address are visibility and accessibility. Although the hemispherical end of the glovebox will be made of an optically clear material, it will be difficult to see what you are doing inside the rack. In addition, because of the large size of the enclosure and the relatively small size of the glovebox, it will not be possible to reach all areas within the enclosure. If a major leak should occur, the experiment rack might have to be brought back to Earth for cleaning. An alternate design option features a free-form, disposable glovebox that would eliminate the access problems of a solid-box design.

### Electrical Systems

**Electric power distribution.**—The USL module will provide users with 120-V dc power at the bottom of each rack within the module. The function of the electrical power distribution system (EPDS) will be to distribute this power to the various loads in both the facility and experiment racks. This system must also provide circuit protection, monitoring, and voltage and frequency conversion for loads requiring power other than 120 V dc.

**Background:** The known subassemblies that make up the FP/DF fall into two categories: (1) clearly defined functional boxes such as video and diagnostic assemblies; and (2) the more diffused functions such as solenoid-valve assemblies and instrument transducers. For equipment that is designed specifically for S.S. Freedom use, 120 V dc will be specified as the operational input-voltage requirement. For the diffused subsystems, because of the large selection of suitable flight-verified hardware available and because of design familiarity with this hardware, the preferred voltage will be 28 V dc. One or more 120- to -28-V dc-to-dc converters will be part of the EPDS.

All equipment located within the USL module must be able to withstand depressurization (nonoperating) and repressurization without presenting a reliability or safety hazard. Although this requirement does not preclude the use of commercial equipment, it does require that the design, testing, and verification of commercial equipment be rigorous, to ensure meeting the requirement for vacuum-condition survivability without rupture, leakage, or other degradation that could cause a hazardous condition to occur. Commercial designs and parts rarely are of the quality needed for off-the-shelf application to space environments. For these reasons, this conceptual design has assumed that only military-specification parts rated for operation in a space environment will be used.

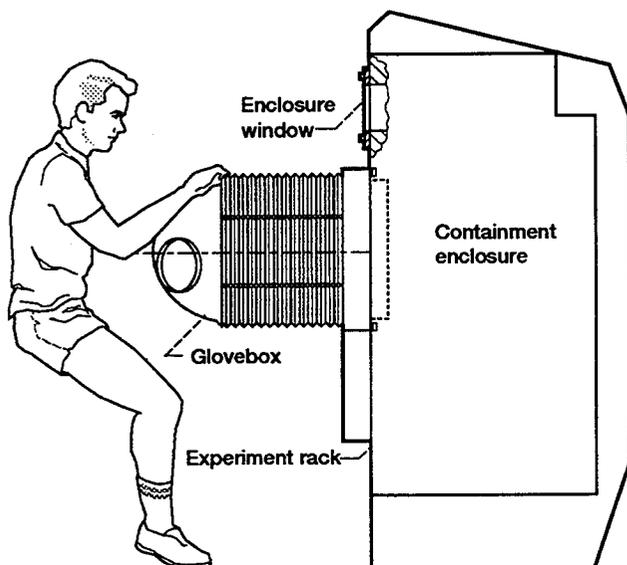


Figure 13.—Portable glovebox concept.

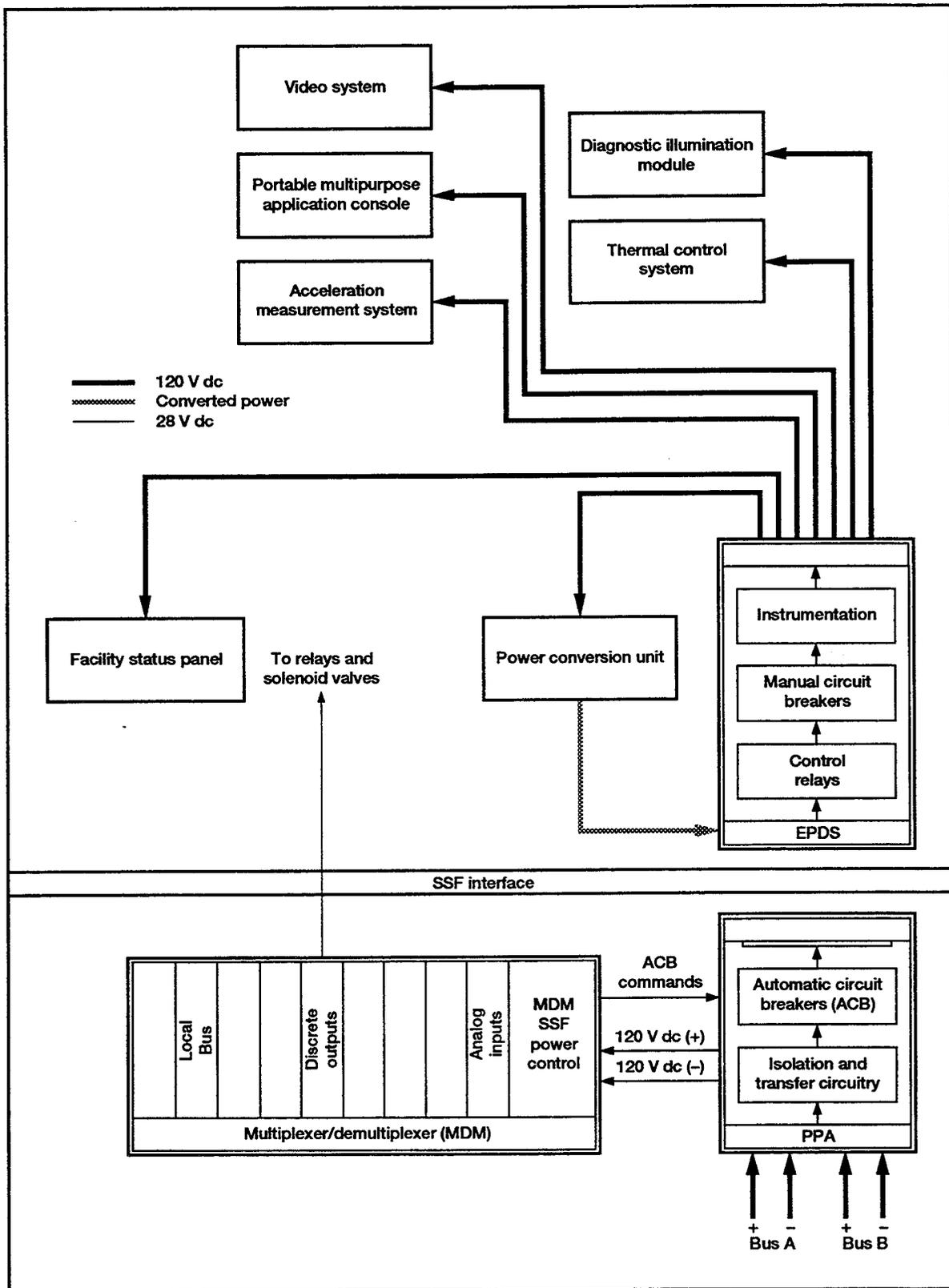


Figure 14.—Facility rack electrical power distribution system.

Since most electrical power consumed is ultimately converted into heat, close attention will have to be paid to the thermal control schemes employed to keep the facility and experiment racks within the cooling-capacity limits available. Additional studies will be required to generate an integrated philosophy of power control, distribution, and thermal impacts. Such an approach will be necessary to achieve efficient packaging and operation of the facility and experiment racks. Some of the considerations of this evolving strategy are as follows:

(1) The use of any voltage other than the USL module-supplied 120 V dc will require the use of power converters within the Facility. Since power converters are typically only about 80-percent efficient, they are inherently wasteful of the limited power resource. Although power conversion is essential, multiple conversions are to be avoided.

(2) The co-location of power converters with high power users is required so that the heat generated by the converter can be controlled by the same means that cools the device being powered.

(3) Power conversion for required dc logic levels should be done by small dc-to-dc converters located on or close to using boards. This will give better regulation, electromagnetic compatibility (EMC) control, and isolation than will a larger unit serving many boards. Although some loss of volumetric or weight efficiency may be incurred in this approach, power levels should be small and electrical efficiencies high.

(4) Power conversion for such heavy motors as might drive a compressor will require soft-start and current-limiting circuitry to limit the stalled rotor current at startup. Tentatively, such motors are assumed to be 400-Hz, three-phase ac input, but tradeoff studies will be required for each application.

(5) Within the facility and experiment racks, power distribution and protection should take place at the 120-V dc level.

Concern for the health and well being of the Freedom Station crew affects the conceptual design in many ways. Numerous safety reviews will be required to prove the inherent safety of the FP/DF systems. Although safety guidelines are not yet available for the USL module, rules for the Space Transportation System (space shuttle) can be assumed to be the level that is minimally acceptable. Two rules in particular must be considered even at this preliminary stage of electrical system design: (1) loss of input power at any time shall not cause any hazardous condition to exist that would violate the basic safety requirements placed on the FP/DF or the experiment, and (2) a loss of cooling or heating at any time shall not cause any hazardous condition to exist that would violate the basic safety requirements placed on the FP/DF or the experiment. These requirements are referred to as the fail-safe conditions, and for the operation of the FP/DF they must be

considered essential to the design of hardware and software. Such capabilities will be verified by safety board review. From the electrical system viewpoint, the conceptual design assumes that the FP/DF can attain a fail-safe condition without the use of electrical power.

*System design:* Figures 14 and 15 show the block diagram of the Facility EPDS. The EPDS consists of wiring, cables, coaxial lines, connectors, disconnects, dc-to-dc converters, circuit protective devices, switches, insulation protection, and power supplies. All electrical power distribution, signal routing, and electrical interface interconnections are provided by the EPDS. Since grounding-path and equipment-bonding resistance are also electrical parameters, these are also part of the electrical system, along with the shielding or filtering necessary to meet electromagnetic compatibility requirements. Experiment-specific hardware, such as thermal-electric heaters and coolers, fans, and lights, will use electrical power under the direction of the control system. These are not shown here other than as power directed from the EPDS.

The EPDS provides the FP/DF with the capability to isolate itself from Freedom Station and to distribute electrical power within the racks. Each rack will contain an EPDS, consisting of four components: power relays, manual circuit breakers, power instrumentation, and a bus interface. As shown in figure 16, 120-V dc power is brought into the EPDS through the Freedom Station interface. The S.S. Freedom-supplied power is then branched into individual circuits, each consisting of a power relay, a manual circuit breaker, and required instrumentation. Power distribution is controlled via discrete outputs from the appropriate rack MDM to the associated power relay. The output of the power relay is fed through a manual circuit breaker, which is switched at the front panel of the rack. Tripping the circuit breaker provides a manual override of MDM commands, thereby preventing inadvertent energizing of the circuit. During controlled sequences, the circuit breakers will be closed to provide overcurrent protection to the circuit. Each branch will also contain power instrumentation, details of which are still to be determined. Instrumentation and breaker-position information will be fed to the MDM through a local bus interface.

*Facility capabilities:* The EPDS will be designed to provide the power needed by the identified FP/DF support system equipment and by the anticipated experiment-specific hardware that was identified in the experimental-requirements database. Currently, the facility rack is expected to require 6 kW of 120-V dc power, whereas the experiment rack will have 3 kW of 120-V dc power. Bulk dc-to-dc conversion of 120 V to 28 V will be provided through the Freedom Station interface or by a power conversion unit within the racks. In either case, the 28-V dc power will be routed through the EPDS to the required loads. Other

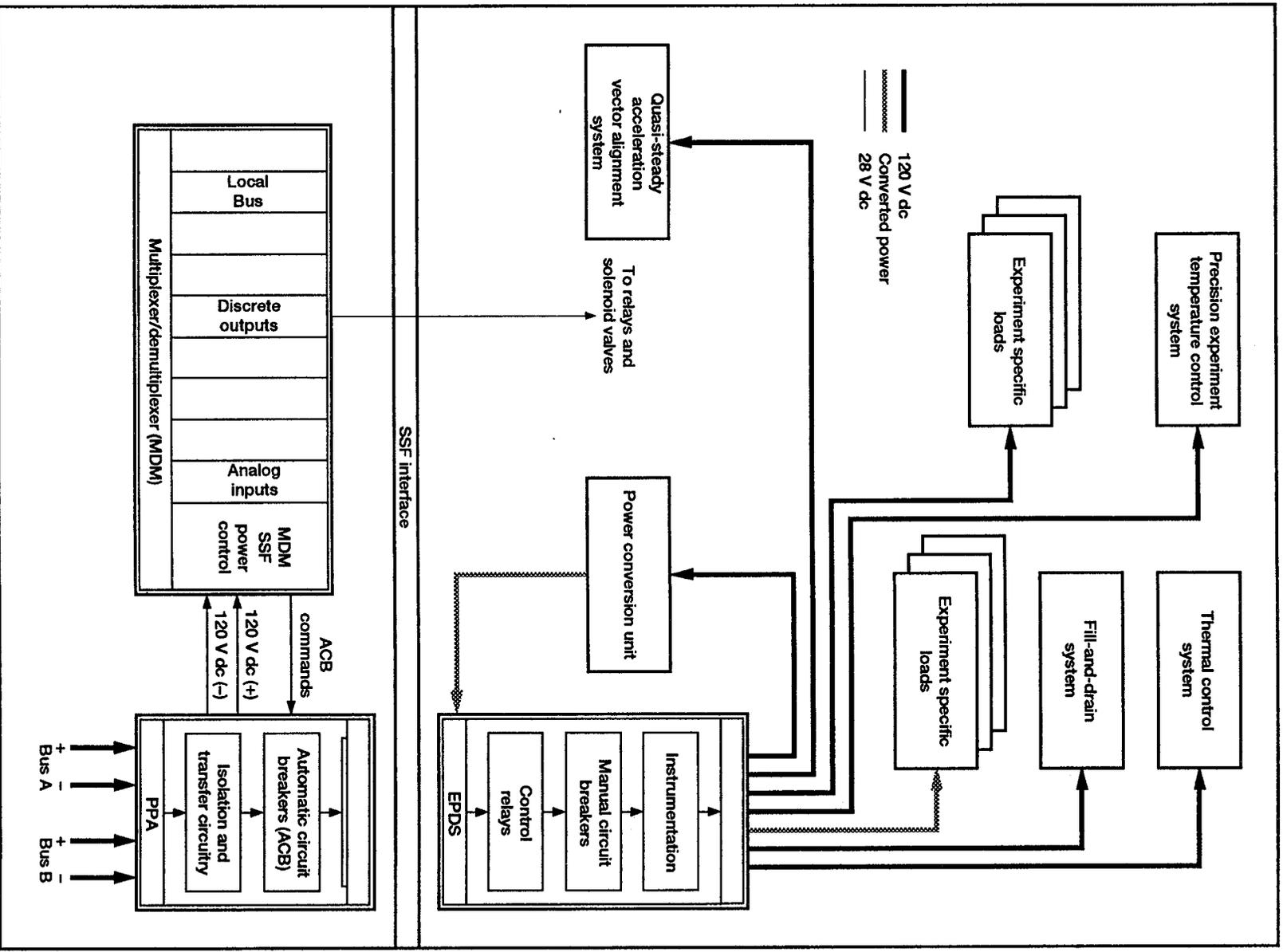


Figure 15.—Experiment rack electrical power distribution system.

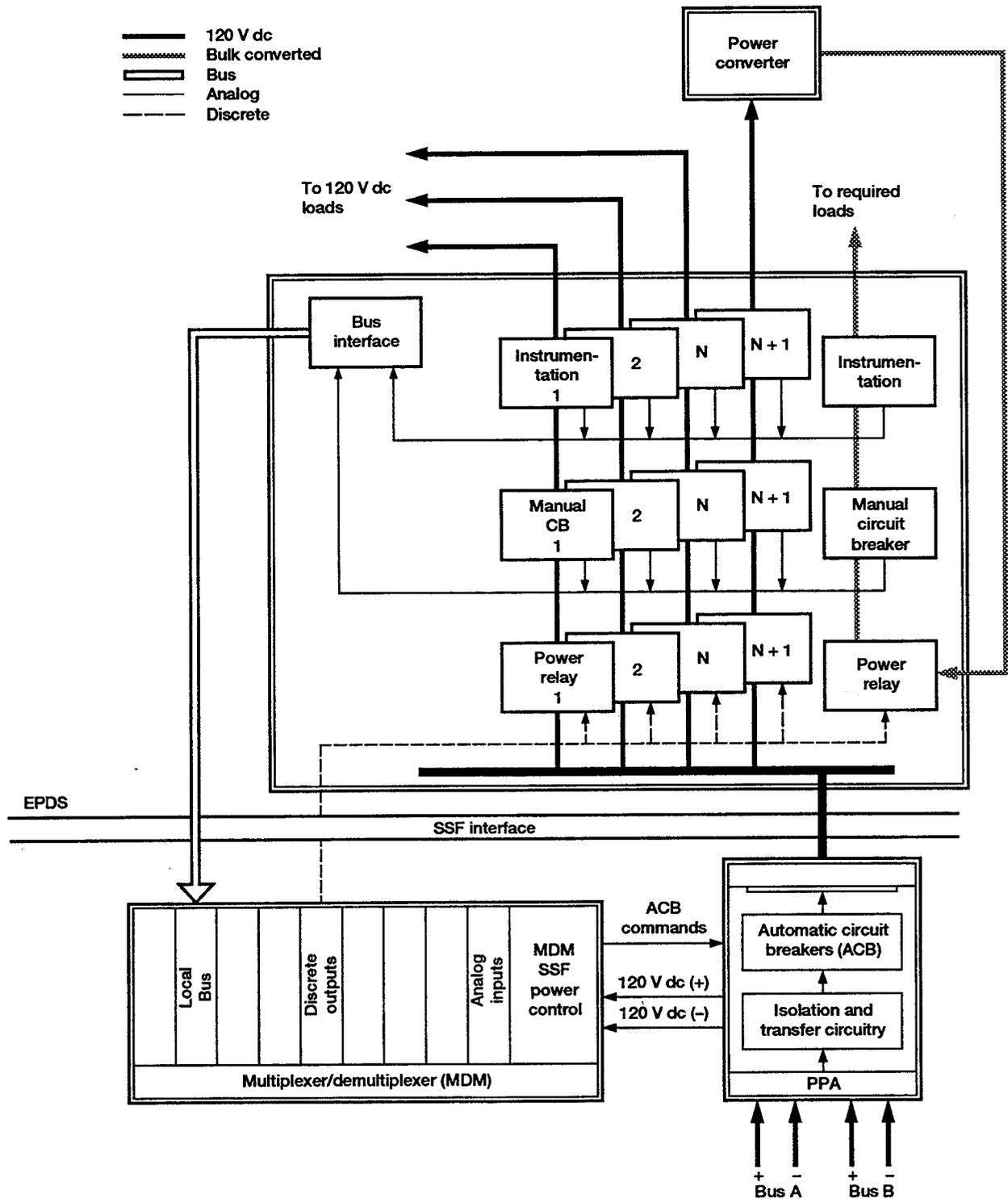


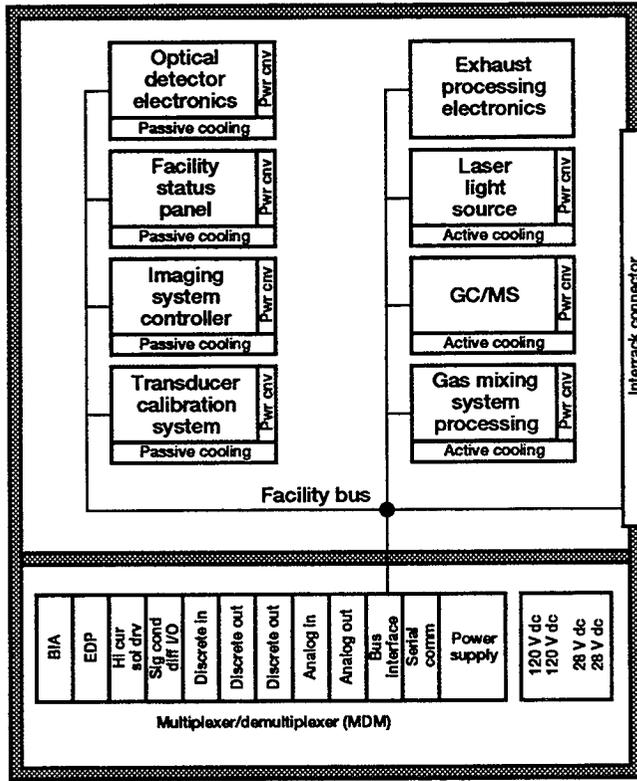
Figure 16.—FP/DF electrical power distribution system.

conversions, such as to 400 Hz, will be supplied as required. Elements peculiar to a facility or experiment that is designed for multiuser fluid physics experiments include the following items, which were found to be common to many of the experiments reviewed during the definition study phase:

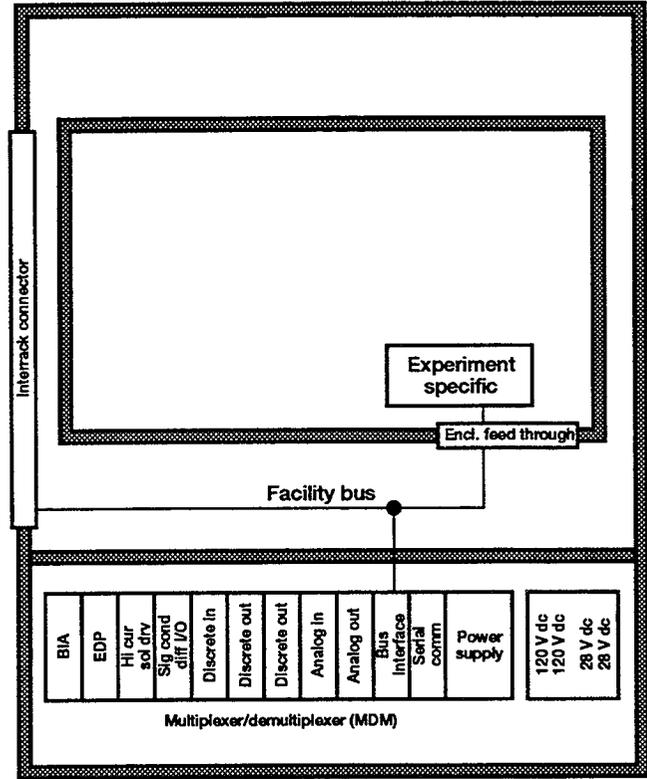
(1) *Heaters.* Electrical heaters used will be of two general types: open-loop controlled heaters, wherein power is applied and heat is produced until the power is removed; and closed-loop controlled heaters, wherein the heater is controlled by some means of feedback such as a thermostat,

BIA = Bus interface adapter  
 EDP = Embedded data processor  
 PWR CONV = Power converter  
 Serial comm = Serial commutator

Encl feed thru = Enclosure feed through  
 GC/MS = Gas chromatograph/mass spectrometer  
 Hi cur sol drv = High current solenoid drive  
 Sig cond dif I/O = Signal conditioner differential input/output



Facility rack - Fluid Physics/Dynamic Facility



Experiment rack - Fluid Physics/Dynamic Facility

Figure 17.—FP/DF computer system.

thermal switch, proportional controller, or computer software. The preferred voltage for heater loads is the USL module-supplied 120 V dc. A special case of heater control might be one in which the thermal output of a heater is a parameter of an experiment. In such a case, the power would require a closely regulated voltage source; this would preclude running these heaters directly on the program-supplied power source. The experiment-specific heater power control would reside in the experiment rack.

(2) *Illumination.* Illumination within the experiment test chamber will be required during the setup and removal phases in most fluids experiments. Aircraft-type 28-V, 20-W minifloodlamps have been used successfully and are proposed for this application.

(3) *Solenoid valves.* Solenoid-operated valves will be the nonlatching type and will require coil-excitation power continuously during operation; they will be cooled by the avionics air-cooling system. The preferred operating voltage for solenoid valves will be 28 V dc.

(4) *Lasers.* The use of lasers in this Facility, especially a master-laser light source for use by a laser diagnostic system, is discussed in the section on Diagnostic Systems. Future

advancements in laser technology will determine the power required by such a laser light source. At this point in the FP/DF conceptual design, the study team is taking a worst-case approach and is allocating 250 W of 120-V dc power for this purpose.

(5) *Motors.* Motors rated at 1/16 hp or less will be powered by 28 V dc. Because of the capacitive energy storage in the dc supply, no special startup circuitry will be required. Such motors will be sealed and will be operated with an intermittent duty factor of less than 10 percent. Heat produced by these small motors will be conducted away by their mechanical mounting and, ultimately, by the avionics air cooling. Motors with ratings greater than 1/16 hp must be evaluated to determine the proper supply voltage and frequency for the intended purpose. Compressors and other devices with heavy motor-starting loads will probably be run on 400 Hz and, thus, will require a power converter to convert from 120 V dc. Such a converter will also include a special motor-starting circuit in order to stay within Freedom Station load-limit requirements. The larger motors and small, continuous-duty motors will probably have to be dc-brushless or 400-Hz polyphase types, and may require active cooling to keep within the avionics air-cooling capacity for the Facility.

(6) *Computer.* The computer that the Facility will use for data acquisition and control will have the same hardware as that being designed and built for the S.S. Freedom DMS. This hardware is expected to be specified to operate on 120 V dc and provide the necessary power conversion to operate its analog and discrete input/output (I/O) cards.

*Computer system.*—The FP/DF computer system (fig. 17) will be based on S.S. Freedom data-management system (DMS) hardware and software. The FP/DF computer system will be a node on the S.S. Freedom network through which data and commands will flow. The S.S. Freedom Program is expected to provide most of the basic hardware and software, including networking boards, processor boards, some selected I/O boards, and appropriate software to run these boards. Most of the operations of the FP/DF will be managed through the element control workstation (ECWS), which is a centralized workstation in the USL module that contains displays, a keyboard, and other I/O devices. Experiment runs will usually be automated, with the ECWS used to initiate and monitor the experiment. The DMS will handle all of the data storage and data downlink for the FP/DF, with the possible exception of some video data. Automation will be an important factor in experiment operations. Even though a mission specialist will be invaluable for sample preparation, sample retrieval, and data analysis, a computer-controlled timeline is usually the most effective way to run a test. Telescience will allow a principal investigator (PI) on the ground to monitor experiment conditions in real time, and possibly, to change process parameters as necessary. Procedures to enable telescience are being investigated separately at Lewis.

*System design:* The FP/DF computer system will consist of two MDM's, each composed of an embedded data processor (EDP), an I/O control unit, assorted I/O cards, and an FP/DF local bus card. An MDM will be located in the bottom of both the experiment and facility racks. About half of the I/O resources of the MDM will be dedicated to S.S. Freedom-unique requirements such as fire detection and suppression, and power control. The remainder will be used for Facility or experiment control and instrumentation.

The processor board, known as an EDP, has a 32-bit Intel 80386 microprocessor with 4 MB of memory and is capable of 4 MIPS (million instructions per second). It has an internal IBM microchannel architecture and an external Intel Multibus II interface. The rationale for these choices was a desire to use state-of-the-art, off-the-shelf technology in order to provide a lower overall cost and to allow users to develop experiment-specific hardware with available technology.

The data acquisition section of the system will consist of an I/O control unit and an assortment of I/O boards that include the following: temperature inputs, pressure inputs, analog voltage inputs, analog voltage outputs, discrete inputs and outputs, valve and solenoid drivers, and a serial digital bus. User-unique boards could also be accommodated. Some experiments may need higher accuracy and/or a higher

sampling rate; for these, new boards would have to be developed. The I/O control unit acts as an I/O processor for the EDP. It can take a list of channels, acquire the data from the specific boards, and send the data back to the EDP. This removes the burden of low-level I/O processing from the EDP. The I/O control unit also has built-in monitoring and self-testing features to ensure proper operation.

The FP/DF local bus will be used to communicate with most subsystems and will be connected to all appropriate devices in the experiment and facility racks, including experiment-specific devices. Most of the subsystems will contain enough intelligence to receive and interpret commands from the FP/DF local bus, and thus be able to relieve the FP/DF computer of the low-level processing necessary to accomplish some of the subsystems functions. The FP/DF local bus will be either an IEEE-488 or Military Standard 1553 bus; since both of these are command and response protocols, this implies that there is one bus master (controller) that allocates bus resources to all of the devices. In this case, the MDM in the facility rack would be the bus master.

The mission specialist will do most of the interacting with the computer system at the ECWS, where there will be keyboards, "mouse"-like devices, video displays, voice communications, and other devices to operate the FP/DF. The specialist will be able to send commands to the FP/DF, to monitor experiment parameters by displaying data from the FP/DF, and to display video from a camera monitoring the experiment. A portable computer unit that can be located at the FP/DF, if required by a particular operation, will also be available. And a status display panel will show the FP/DF health status in case there should be a problem with the communications.

There will be three paths for data to flow from the FP/DF: a 1-Mb/sec local bus, a 10-Mb/sec local area network, and a 100-Mb/sec high-rate link. The local bus will be either an IEEE 802.4 standard, which is a 1-Mb/sec (10-Mb bandwidth) balanced protocol, or a Mil. Std. 1553 bus. The local bus will deliver commands to the FP/DF and will transmit status and housekeeping data to a user at the ECWS or to mass storage. The 10-Mb/sec network is a fiber-distributed data interface (FDDI) protocol. It has a 10-Mb/sec throughput with 100-Mb bandwidth. This network could be used for some video data transmission. The 100-Mb/sec high-rate link is a fiber-optic link that connects through a patch panel directly into the communication system. This will be used mainly by the high-resolution, high-frame-rate video system to downlink experiment image data.

*System capabilities:* The FP/DF computer will contain the major portion of the software and will exercise overall control of the FP/DF and experiment racks by receiving and acting on commands from the mission specialist via the ECWS. If the computer received a new set of operating parameters for an experiment, it would set up the facility hardware for these new conditions and then send on the remaining parameters to the experiment-rack computer. The facility- and experiment-rack

MDM's will be able to communicate via the FP/DF local bus, which will be connected inside the rack. The configuration of the facility computer will not change from experiment to experiment, since the facility rack should not change much from one experiment to the next.

The experiment-rack computer will be responsible for interfacing with the experiment-specific hardware and will be able to adapt to the changing needs of each experiment by utilizing modular signal conditioners. The computer will receive commands from the facility-rack MDM, but it will send out data by using the network. The processing capability of the experiment computer can be augmented if an experiment has a unique requirement. This would be accomplished through the use of another EDP, which could reside in the same box.

The FP/DF-computer software will consist of (1) software written for the FP/DF and (2) software written for the experiment. New software will be uplinked to Freedom Station and routed through the network to the facility rack MDM. A backup copy of the software will be kept in a mass storage unit and will be available through the network.

When a new experiment is installed, the software will be the most important item to be changed. Other changeable items might include the signal conditioners, a board in the MDM, additional hardware in the MDM, and new diagnostic instruments to be connected to the FP/DF local bus; most of this changeout will be done at the Lewis Integration Center. After the hardware is installed, the new software will be loaded, and some tests will be run to ensure proper operation of the hardware and the software.

**Control system.**—The functions of the control system are to control and monitor the FP/DF experiment and to detect and take corrective action for any unsafe condition that could result in a safety hazard. The design of the control system will depend on both the operational and safety requirements

imposed on the FP/DF by the S.S. Freedom Program and the control and safety functions inherent in the DMS and EPDS. In addition, hardware being developed under the S.S. Freedom Program that will be available to users will have some effect on design of the control system. These requirements, functions, and hardware are presently being defined and/or developed, so details of the control system design are still evolving. Some basic control concepts and principles being considered are given in the following paragraphs.

The facility-rack MDM will be the master controller. Individual devices or systems, such as the fluid fill-and-drain system and the video system, will operate as self-contained slave units. Each slave-unit CPU will be programmed to provide the functions necessary for control, data acquisition, built-in test, and to some extent, safety hazards unique to that system. These smart devices will be connected to the facility-rack MDM via the FP/DF local bus.

A typical subsystem slave controller, functionally depicted in figure 18, would consist of the following elements:

- Bus interface electronics
- Multibus II backplane
- Local CPU controller
- Memory, RAM/ROM
- Built-in, self-test electronics
- Standard I/O card complement
- Unique subsystem control electronics

The software for overall experiment control and for safety maintenance will reside in the facility-rack MDM. This MDM will also send commands for specific actions to smart devices and monitor these devices for proper operation.

Physical inhibits, provided by relays located in each power distribution and control unit (PDCU), will activate or apply power to any device or hazardous system in the FP/DF. The facility-rack MDM will be configured to allow direct computer-control of these relays by means of a discrete output card rather

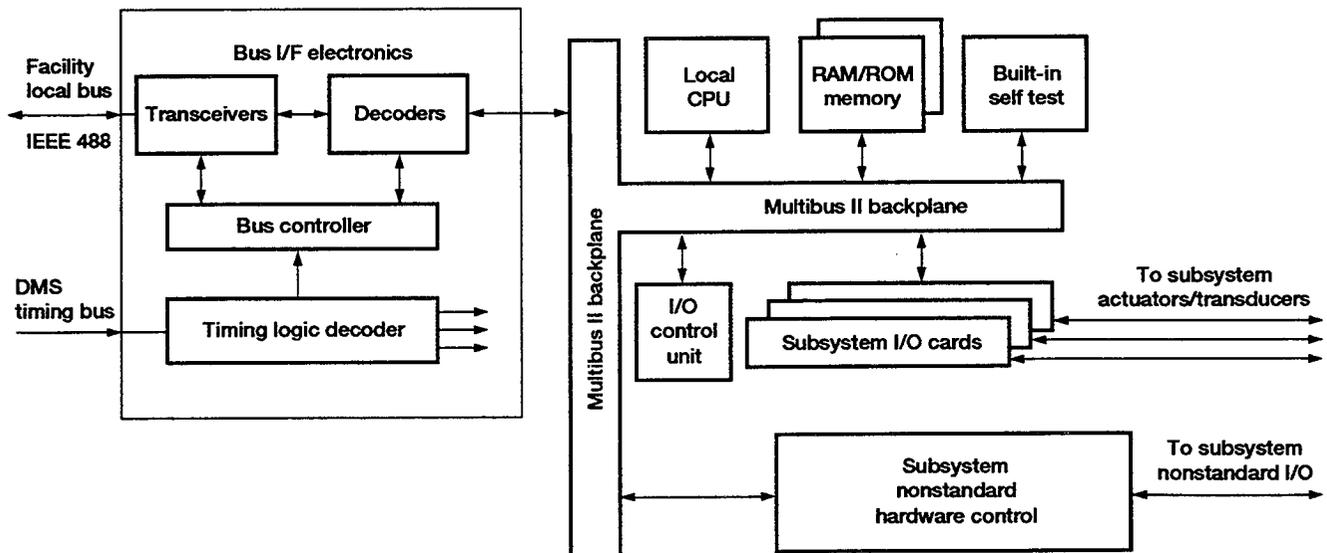


Figure 18.—Typical subsystem controller functional block diagram.

than through the FP/DF local bus; thus power control will be possible even with a local bus failure. The PDCU will also contain circuit protection and isolation hardware, as discussed in the section on electric power distribution.

In the event of an unsafe condition and/or hardware failure, the facility-rack MDM will direct all local controllers (slave units) to shut down and "safe" their system in an orderly fashion. Two emergency situations that need to be addressed are (1) requirements to shut down and "safe" the FP/DF in the event of loss of power and (2) failure of the facility-rack MDM. For the latter case, the DMS will detect the failure and remove power from the FP/DF.

A basic ground rule of the FP/DF is to return to a "safe" state on removal of power. Ideally, equipment in the FP/DF can be designed to fail-safe in the event of removal or loss of power; if it did fail-safe, no action would be required. If it did not, or if specific actions were necessary (e.g., dump waste products), circuitry and backup power to sequence through a series of operations would be required.

**Instrumentation and data acquisition system.**—The FP/DF will provide an in-place, user-friendly, easily accessible method of interfacing with many of the standard analog transducers that may be required for an experiment. The size and configuration of this proposed system has been based on the experiment requirements determined in the FP/DF requirements-definition phase.

**Assumptions and constraints:** The instrumentation and data acquisition system will use the FP/DF computer system and a series of analog and digital I/O cards (previously described) as a basis for data acquisition. If an experiment should require any transducer beyond the FP/DF support capability, the experiment will have to include experiment-specific signal conditioners. These must be compatible with the instrumentation and data acquisition system.

**System capabilities:** All analog signals, including those derived from the experiment and from the FP/DF and its support systems, will be routed through the data acquisition system to the FP/DF computer system and then to the S.S. Freedom DMS. Once in the DMS, user-selected data signals will be available for engineering unit display onboard at the ECWS, locally at the FP/DF, or on the ground after being downlinked. The experiment-instrumentation interface will be located inside the containment enclosure. Connectors or other interfacing devices will be provided so that the user can terminate experiment transducers. The types of measurements that will be accommodated, at a minimum, will include the following:

- Thermocouples, including any National Institute of Standards and Technology (formerly National Bureau of Standards)-calibrated type
- Resistance temperature devices (RTD's), including platinum ones
- Strain gage devices, including pressure transducers and flowmeters

—Frequency generating devices, including flowmeters and tachometers

In general, any transducer producing a voltage output compatible with the system voltage level will be usable with this system, as will transducers producing a digital, binary-coded decimal, or binary output.

A software development system will be provided as part of this system. This ground-based service will allow a user to program input-channel scan patterns, gains, and characteristics. Output displays, including channel selection and engineering-unit determination, will also be supported.

**Acceleration measurement system.**—Since the microgravity environment is one of the most important parameters, it is imperative that this be monitored while an experiment is being run. Currently, the S.S. Freedom Program is not planning to develop such an acceleration measurement system; therefore, the FP/DF design team plans to provide one as part of their Facility. This system would be similar to the Space Acceleration Measurement System (SAMS) that has been developed at Lewis under a separate program. Typical specifications for SAMS include a 0- to 100-Hz frequency range,  $10^{-9}$ -g resolution, 1- to 500-samples/sec (variable) sampling rate, and a triaxial sensor head.

However, some changes would be made to the present SAMS. Since the SAMS would operate in the FP/DF only during an experiment, the present data storage capacity would not be needed; the SAMS data would be handled with the rest of the experiment data. One enhancement that should be added is the capability to identify, in real time, accelerations that are outside of the experiment's operating window and to alert the experiment operators of the out-of-limits condition.

**Signal conditioning and data processing.**—Signal conditioning comprises all functions from the power source to the sensor, and from the sensor output to the analog-to-digital (A/D) converter. Among these functions are isolation, excitation, amplification, reference junctions for thermocouples, bridge completion circuitry, frequency-to-analog conversion, grounding, and shielding. In addition, data processing, such as linearization of thermocouple outputs or generation of special algorithms that are accomplished through software, can be considered signal conditioning.

Versatility will be required in order to accommodate many different kinds of sensors. Even so, there will probably be some cases where experiment-specific conditions require that the experimenter provide the necessary signal conditioning as a black box, input card, or software module. Some instruments require only a source of power and a compatible data bus for I/O. The only concerns of the FP/DF will be isolation and proper configurations of wire runs (grounding, shielding, impedance, cross-talk suppression, and mechanical considerations such as protection from stress and providing dependable connectors).

Thermocouples, if they are to meet tolerance requirements of better than  $\pm 5$  K, require a reference junction and linear-

ization of the output. The reference junction favored for this application is the isothermal reference unit (IRU), which is a passive device designed to maintain all junctions, from alloy to copper, at the same temperature while measuring this temperature with a highly accurate, stable sensor such as a resistive temperature device (RTD). The compensation can be accomplished digitally. An important advantage of the IRU is that it can be located close to the thermocouples; preferably it will be the first connector. Thereafter all wiring would be copper, thus eliminating long runs of alloy and alloy-connector parts. Also, only the designation of thermocouple type need be loaded into the computer.

For RTD's, including thermistors, the signal-conditioning requirement varies according to the way in which resistance is converted to an analog voltage. Bridge circuits are common items with respect to the bridge-completion elements. Only the wiring is different in two- and three-wire circuits; this difference is easily accommodated on input cards. Four-wire circuits require a constant current source, which is available on I/O cards.

### Thermal-Control System

The FP/DF thermal-control system rejects waste heat from the facility rack and experiment-specific hardware. The Freedom Station thermal-control system can accept a total thermal load of 29 kW. The maximum water-loop cooling available to any single rack is 15 kW. Heat is rejected from each rack by three different thermal-control subsystems: a rack-interface-heat-exchanger water-cooled loop; a cold-plate water-cooled loop; and an avionics air-cooling system. The heat-removal capacities of each thermal-control subsystem are given in table I.

TABLE I.—FLUID PHYSICS/DYNAMICS FACILITY THERMAL-CONTROL SYSTEM HEAT-REMOVAL CAPACITIES

Subsystem	Maximum heat-removal capacity per rack, W
Rack-interface water-cooled loop	8000
Cold-plate water-cooled loop	7000
Avionics air-cooling system	1500

The FP/DF will be able to actively control the flow rate and heat-removal capacity of the rack-interface heat-exchanger water-cooled loop; however, it will not be able to directly control the flow rates and heat-removal capacities of either the cold-plate water-cooled loop or the avionics air-cooling system. Additional system design parameters are given in table II.

The two water-cooled, thermal-control loops in the facility rack are shown in figure 19. This figure identifies each heat load, the associated cooling loop, and the method of heat rejection (either cold-plate or heat exchanger). The two water-cooled, thermal-control loops in the experiment rack are shown in figure 20.

TABLE II.—FLUID PHYSICS/DYNAMICS FACILITY THERMAL-CONTROL DESIGN PARAMETERS

Maximum flow rate, gal/min	
Rack-interface heat-exchanger .....	2.2
Cold-plate cooled loop .....	2.0
Heat-exchanger inlet temperature, °C	
Space station loop (minimum) .....	24
Facility loop (maximum) .....	39
Heat exchanger outlet temperature, °C	
Space station loop (maximum) .....	38
Facility loop (minimum) .....	25

The experiment-rack thermal-control system incorporates a method for precisely controlling the experiment temperature. Many reference experiments require precise thermal control of one relatively hot and one relatively cold surface; thus such controls will be standard Freedom-supplied equipment. Surface temperatures will be maintained by thermoelectric heaters and coolers. These thermoelectric devices will transfer heat to or from liquid-cooled or forced-air convection heat exchangers. Since thermoelectric heaters and coolers are heat pumps, they absorb heat from a region of low temperature and reject heat to a region of higher temperature. Their heat-pumping capacity is proportional to electric-current input. Through a microprocessor-based, feedback control circuit, precise surface-temperature control will be possible. Surface temperature uniformity will be verified and feedback to the temperature-control circuit will be provided by thermocouples embedded in the hot and cold surfaces.

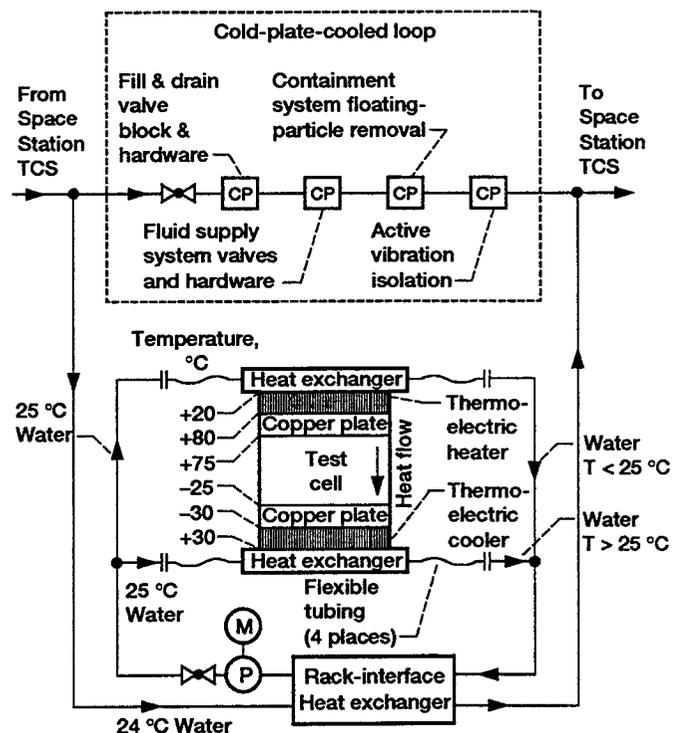


Figure 19.—Facility rack water-cooled, thermal control loops; M = motor, P = pump, CP = cold plate.

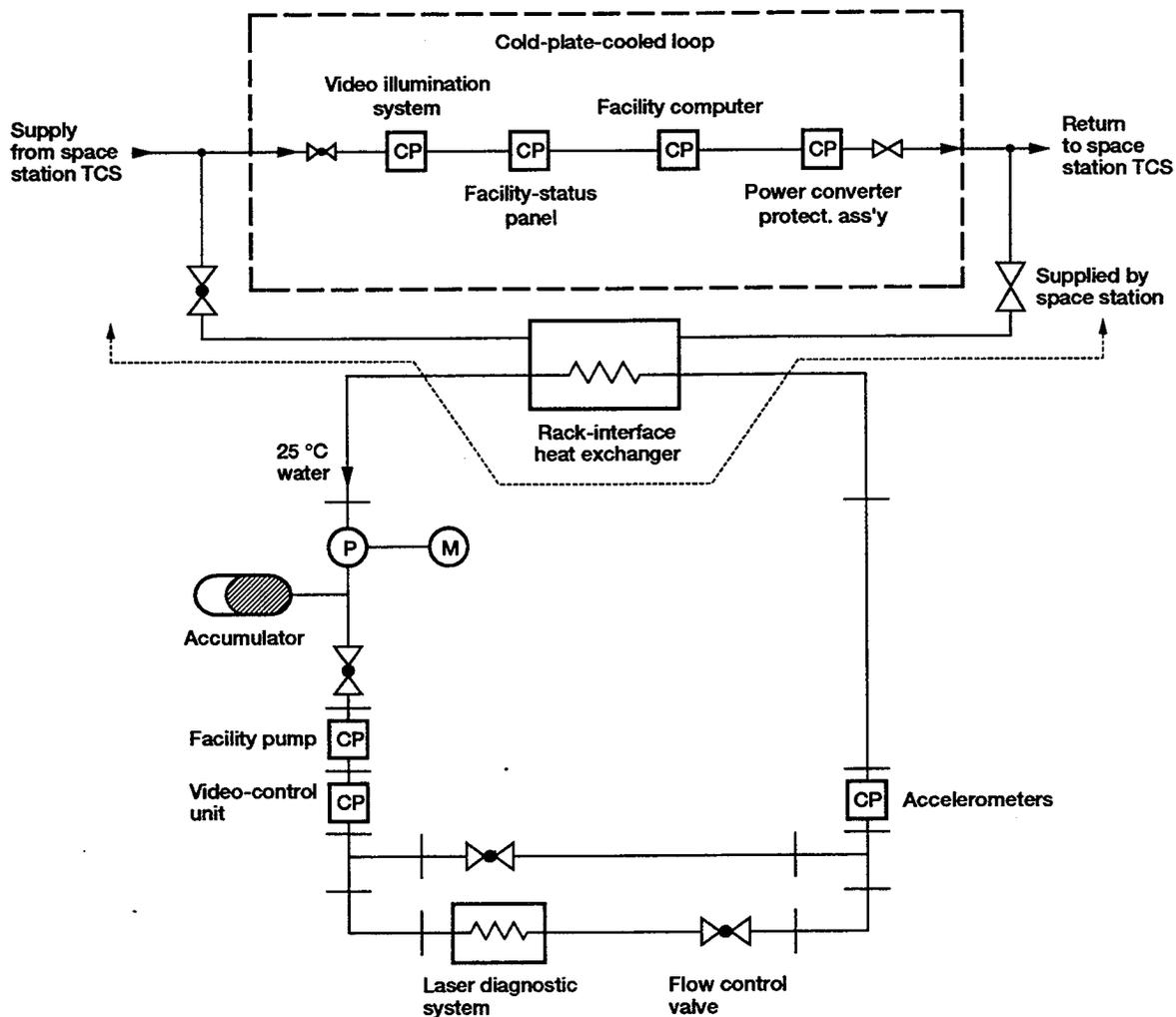


Figure 20.—Experiment rack water-cooled, thermal-control loops; P = pump, M = motor, CP = cold plates.

## Mechanical Fluid System

**Assumptions and constraints.**—The assumptions and constraints followed in preparing this conceptual design are listed in appendix B of this report.

**Description and scope.**—The mechanical fluid system consists of the (1) fill-and-drain and (2) containment-enclosure pressure control subsystems (fig. 21). The fluid system will fill and drain the experiment test chambers with the four identified liquids: water, alcohol, Freon R113, and silicone oil. The impact on the experiment from vapor bubbles entrained in the fluids with higher vapor pressure (water, alcohol, and Freon R113) will require further investigation. The facility that is planned will allow the crew to clean and flush the system when the test liquid is changed; this will require the use of a portable glove box, cleaning solvents, and other miscellaneous cleaning and flushing components that are still to be determined.

The fluid system also provides the pressure control for the containment enclosure by means of an inert nitrogen atmosphere around the experiment test chamber. Therefore, the fill-and-drain system will be located within the experiment containment enclosure (fig. 22), and the crew will need access to this during cleaning and flushing. The procedures and safety issues for crew access to the experiment through the containment enclosure have not yet been developed. Cleaning of the experiment containment enclosure, if it should become contaminated, is not within the scope of this task.

All test chambers and reservoirs (filled with the liquids to be tested) are to be furnished by the experimenter. Since the test chambers and reservoirs will not be cleaned for re-use, storage space for these and for supplies required for cleaning and flushing will be provided in the facility rack. The flexible hoses adjacent to the test chamber (see fig. 23) permit one to preferentially align the test chambers with respect to

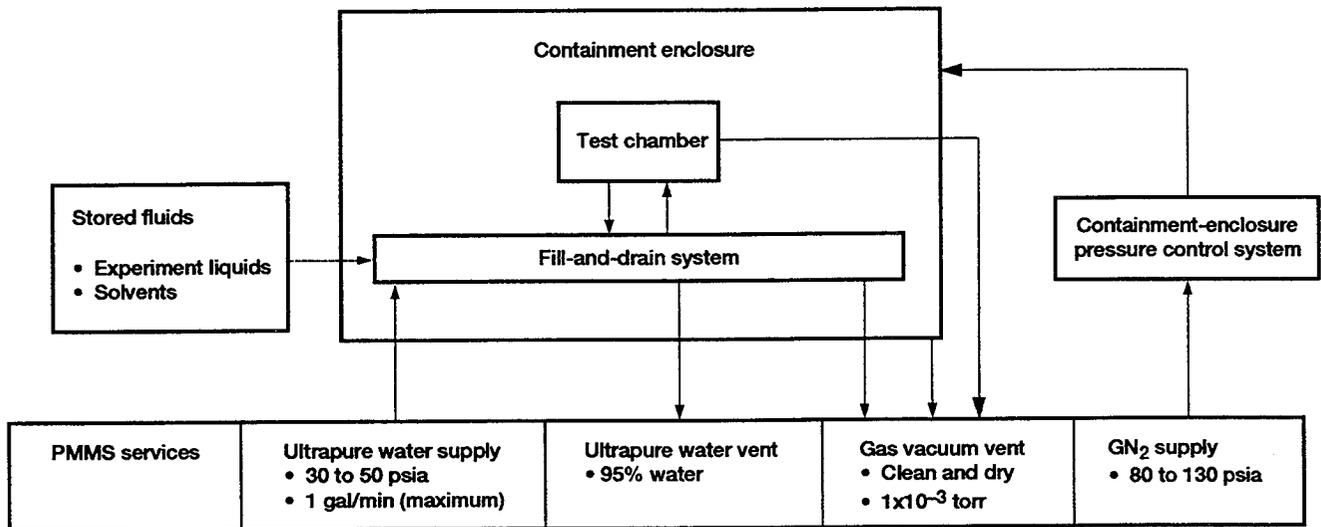


Figure 21.—Mechanical fluid systems block diagram.

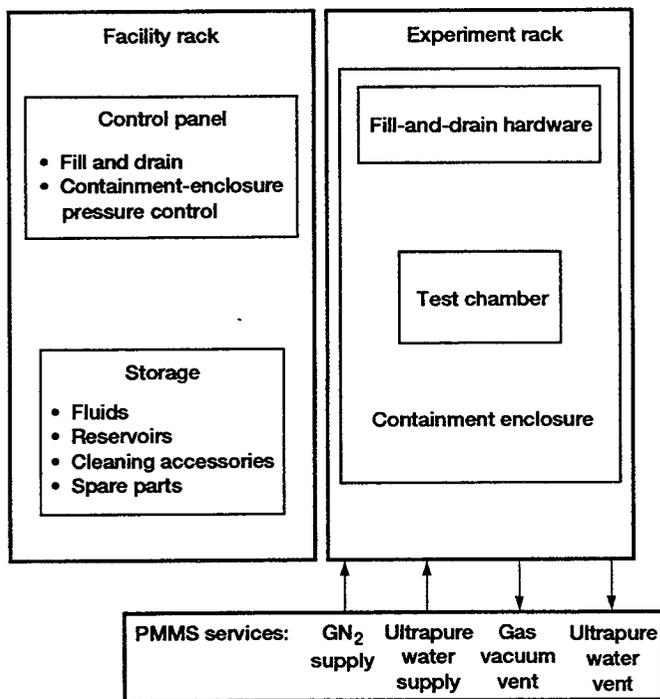


Figure 22.—Fluid systems layout in facility and experiment racks.

the direction of quasi-steady acceleration. Since the hose lengths are expected to vary for each experiment, a proposal has been made to make them a part of the experiment.

The use of the process materials management system (PMMS) ultrapure water supply, the ultrapure water vent, and the gas vacuum vent will be required for cleaning and flushing the system. The power requirements for the pump and each solenoid are approximately 50 W and 10 W, respectively.

**Fill-and-drain system.**—A fill-and-drain system that is currently being designed for the Lewis Surface Tension Driven Convection Experiment (STDCE) is the baseline design for the fill-and-drain subsystem. Significant changes are required to this baseline. Since in the STDCE only one fluid (silicone oil) is used and the test chamber is not changed, cleaning and flushing are not required. For the FP/DF, four fluids have been identified as representative of the fluids that will be tested in this Facility: water, alcohol, Freon R113, and silicone oil. The system piping is small-diameter, stainless-steel tubing, which is compatible with the liquids to be used in the FP/DF. The system components and seals, however, should be investigated for compatibility with these fluids. The variable speed pump can fill a test chamber to a predetermined level, and a mechanical counter will display the number of pump revolutions, which is related to the volume pumped. The STDCE flew aboard the space shuttle in 1992; new developments in the STDCE fill-and-drain system were monitored.

The experimenter will be required to furnish (1) the test chamber, which will be unique to each experiment; (2) the liquid reservoir, filled to the extent needed for the experiment; and (3) any  $Al_2O_3$  seeding required, premixed with the liquid in the reservoir. Facility-furnished items will include (1) no-leak, quick disconnects between the test chamber and the fill-and-drain system; (2) quick disconnects leading to the fluid reservoir; and (3) storage space for the experimenter's test chambers and fluid reservoirs while they are not being used.

It will be necessary to clean and flush the system of the residual liquids when a different liquid is to be tested. To minimize unnecessary liquid changes, which would require crew involvement, PMMS services, and portable glove box

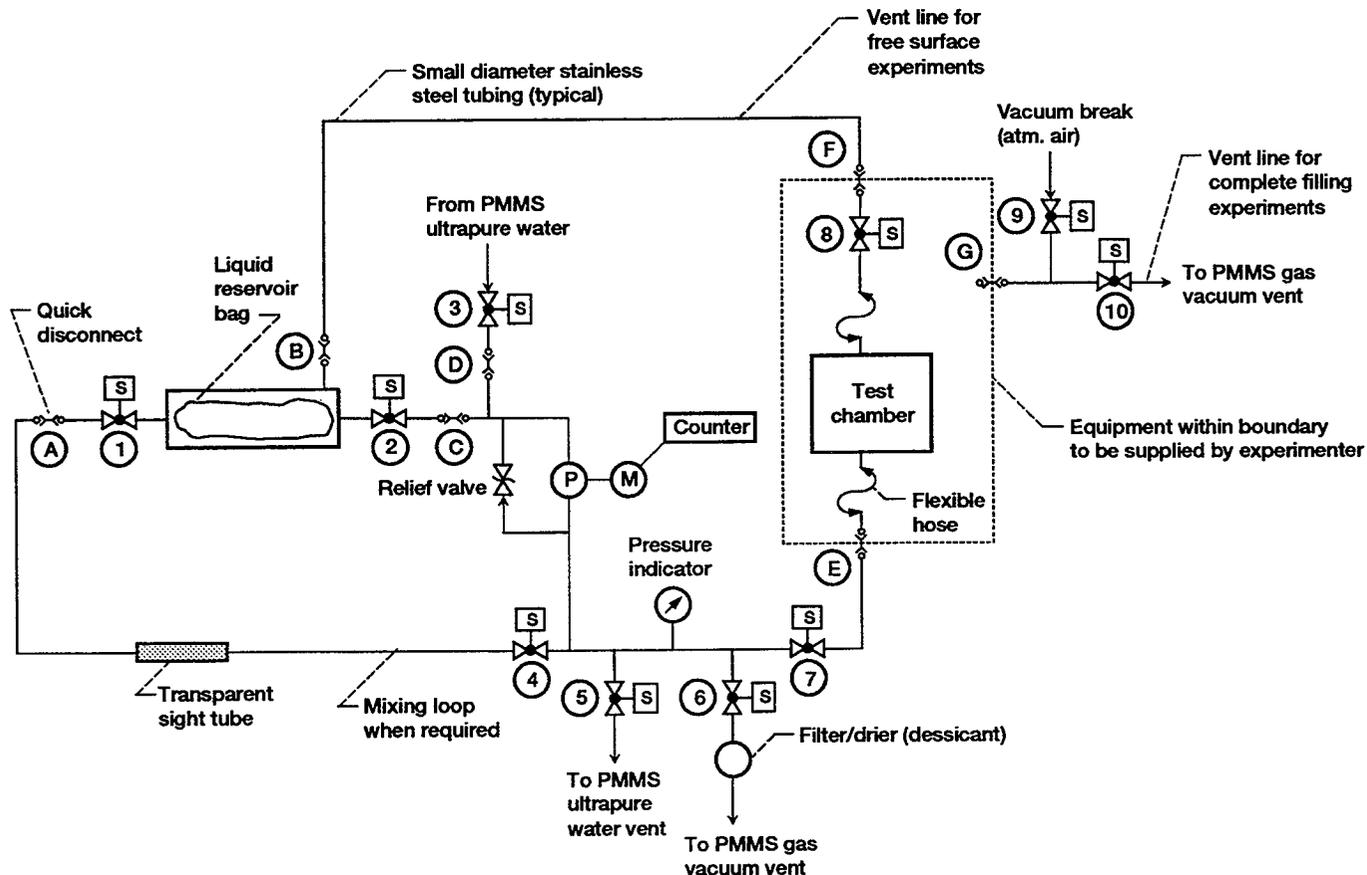


Figure 23.—Fill-and-drain system.

use, the test schedule should be well planned. Of the four liquids planned for testing, silicone oil is the only one whose removal requires a solvent; the others can be removed by evacuation. Many solvents can remove silicone oil, including alcohol, Freon, and NA500 (trichloroethane). A soap or detergent may also be suitable for this. We propose using NA500 since it is nonflammable and is widely used for cleaning purposes.

*System operation for experiments with a free surface:* The user-provided liquid reservoir is contained between valves 1 and 2 (fig. 23). The line on which valves 2, 3, 4, 5, and 7 lie will be evacuated through valve 6. With valve 6 closed, opening valve 2 will allow the fluid to fill the line accessed by valves 2, 3, 4, 5, and 7. If the pump is operating, opening valve 7 will allow liquid to fill the test chamber to the desired level; the fill rate will be slow, to prevent the entrainment of air bubbles. The air displaced by the liquid in the test chamber will flow into the annular region in the liquid reservoir. The pump can cause a predetermined amount of liquid to flow and to stop. It can also be used to withdraw fluid, so a variety of liquid levels can be achieved with the same test setup.

If a seeded liquid is to be tested, the mixing-loop line must be evacuated and the liquid circulated for a time sufficient to

achieve a uniform mix. A transparent sight-tube is provided for viewing the mixed liquid. When testing with a particular liquid is completed, the liquid will be pumped back into the reservoir; some residual liquid (to be determined) will remain in the line. The liquid reservoir and the test chamber will be removed at the quick disconnects and placed in storage. The remaining liquid (water, alcohol, or Freon R113) will be removed by flushing with the ultrapure water system. The ultrapure water will be pumped through the system and then will be returned to the ultrapure water vent. The residual water will be evacuated by the PMMS gas vacuum vent. Additional ancillary piping components (to be determined) may be required to ensure that all segments of the system are cleaned and flushed. For example, a hose can be connected from point E to point C (fig. 23) to clean and flush the main fill line.

After testing with silicone oil is completed, the silicone oil will be pumped back into the liquid reservoir. The reservoir and test chamber will be removed and placed in storage. A reservoir filled with NA500 will be installed in place of the silicone-oil reservoir. The NA500 will be pumped through the piping to clean and flush the system. It will then be pumped back into the reservoir and removed from the system. Next, the ultrapure water from the PMMS will be pumped through

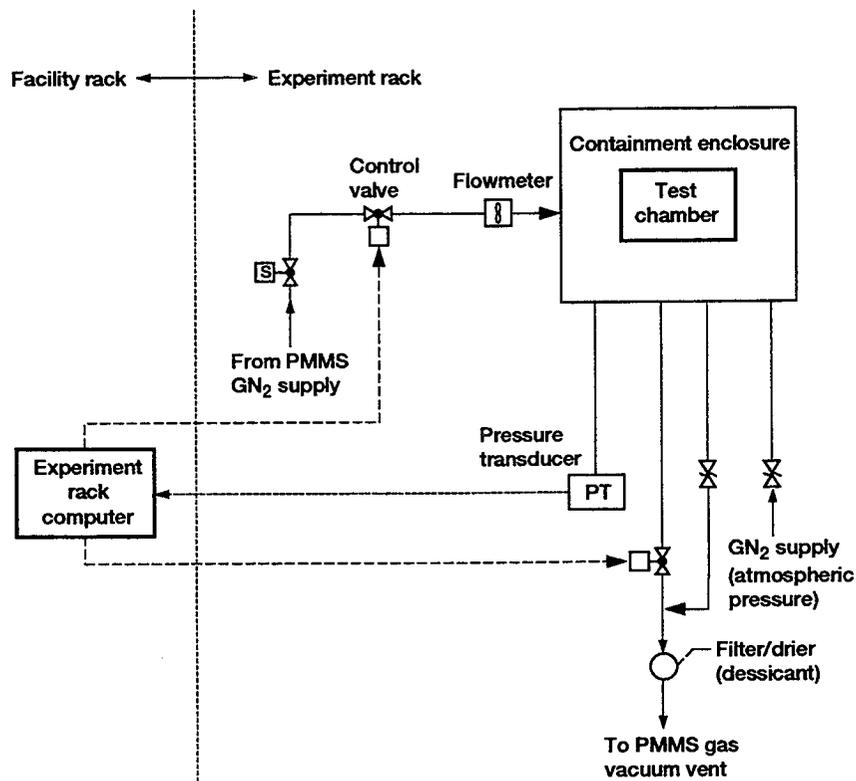


Figure 24.—Containment-enclosure pressure-control system.

the system to flush out the residual NA500. It will then be returned to the ultrapure water vent. Finally, the residual ultrapure water will be evacuated through the vacuum vent. A filter and drier (desiccant) will ensure that the gas entering the PMMS gas vacuum vent is clean and dry. This cleaning procedure could be simplified if it were permissible to evacuate the alcohol, Freon R113, and NA500 to the PMMS gas vacuum-vent system.

*System operation for experiments requiring complete filling (no free surface):* The fill procedure for experiments requiring complete filling will be similar to that for the free-surface experiments, except that evacuation of the test chamber through valve 10 (fig. 23) will be required. Valve 8 isolates the liquid reservoir and valve 9 breaks the vacuum after the test chamber is filled. Cleanup after experiments requiring complete filling will be the same as that for a free surface. No cleaning of the test chamber is proposed.

**Containment-enclosure pressure-control system.**—The pressure-control system provides one of the three levels of containment required for hazardous fluids per NHB 1700.7b. By maintaining the containment-enclosure pressure at a level below that of the USL module, any inadvertent leakage from the experiment will be vented to the PMMS gas vacuum vent and not to the USL module atmosphere. A nitrogen atmosphere within the enclosure will prevent possible combustion. For the representative experiments discussed here, the test-

chamber pressure will be equal to the USL module pressure; however, other test-chamber pressures can be considered.

*Design:* The proposed design (fig. 24) consists of nitrogen shutoff and control valves, a vent control valve, a flowmeter, a pressure transducer, and the experiment-rack computer system. A gas chromatograph will monitor the composition of the atmosphere within the enclosure. Two relief valves will protect the enclosure from excessive positive or negative pressures. A filter and dryer in the gas vacuum-vent line will dry the fluid before it enters the PMMS system.

*Operation:* Before an experiment is run, the nitrogen control valve and the vent control valve will be used to purge the containment enclosure and to reduce the pressure inside the enclosure to a level slightly lower than that of the USL module cabin; then if the test chamber should leak, liquid will enter the containment enclosure instead of the USL module. If high-vapor-pressure liquids (e.g., alcohol, water, Freon) were to leak into the test chamber, they would evaporate in the dry nitrogen atmosphere and increase the pressure in the enclosure. Such an evaporated liquid would be sensed by the gas chromatograph. This, along with the pressure-control system, would initiate a nitrogen purge, thereby venting the excess gases and vapors. If low-vapor-pressure liquids (e.g., silicone oil) leaked, they would form droplets that would cling to surfaces within the containment enclosure; therefore, methods for detecting such leaks, and procedures for entering a contaminated containment enclosure, must be developed.

## Imaging System

**Background.**—The FP/DF video system serves two purposes: to capture images for observation and analysis; and to provide image data for automated processes within the experiment. The first objective allows experimenters to learn as much as possible about the science being performed. Toward this end, the user's scientific requirements and the FP/DF engineering requirements must be known so that the imaging system will be compatible with optical diagnostic methods. Ideally, careful selection from available and proposed imaging systems, together with the use of telescience, will provide the experimenter a means to extract useful visual information and thus better understand the science.

The use of automated image processing and analysis will play a greater role in meeting scientific goals. And as the requirements for process automation increase, the data derived from images will be used in process operation and control. Such a level of automation will permit the FP/DF to accommodate a diversity of fluids experiments. It will also provide experimenters with a broad, flexible range of optical diagnostic methods.

**Assumptions and constraints.**—The operation of the imaging system will depend on careful planning and scheduling of the available S.S. Freedom resources, including electric power, data transfer, and crew time. Crew members are expected to be available to change modular camera heads and to load and unload film and imaging cassettes. However, onboard automation, together with control of experiments from the ECWS or from the ground with telescience, will minimize the use of crew members. The video-system control, located in the facility rack, will provide the hardware for these functions.

Fluids experiments require unique imaging capabilities that cover a wide range of camera operating parameters. This wide range suggests that several types of cameras will be needed. For example, an experiment may require a high-resolution, low-frame-rate camera to monitor droplet size. The same experiment may also require a lower resolution, high-frame-rate camera to record particle motion in the seeded host fluid. (e.g., see the bubble/droplet experiment in the section **Fluids Experiment.**) No single camera (and lens) meets all of these requirements. The question of which specific camera (film, standard video, or nonstandard video) and associated optics will satisfy the science requirements remains an open issue. Figure 25 shows some of the imaging systems to consider when defining the video-system requirements. Many operating and control functions are common to a number of imaging systems. A proposal has been made that these common supporting controls and electronics, including the storage and transmission of video information, be provided for all S. S. Freedom facilities. These functions would also interface with S. S. Freedom bulk storage and processing for workstations and telemetry. If these functions are not centralized, the FP/DF video system will provide them.

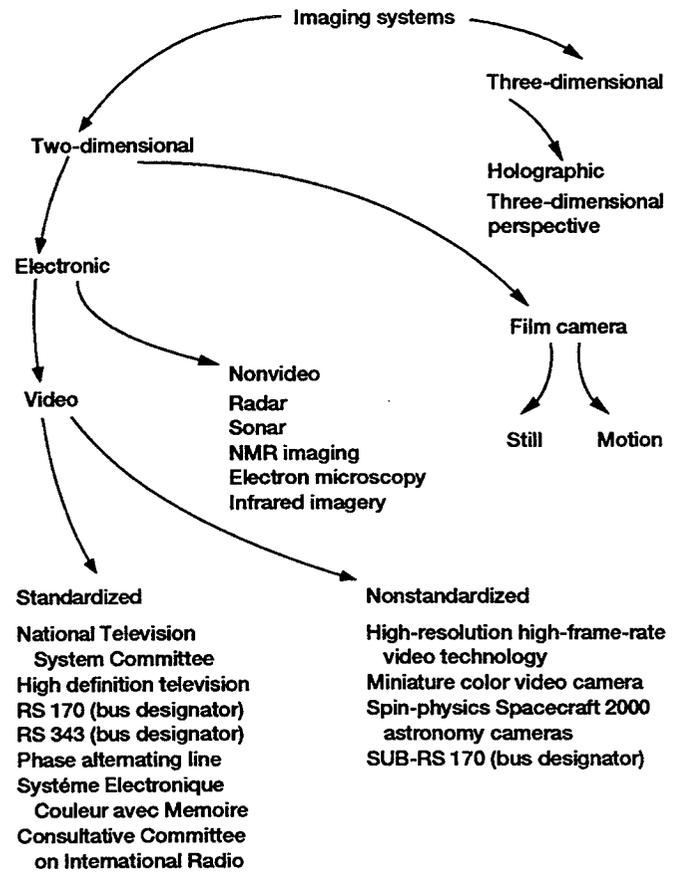


Figure 25.—Categories of possible imaging systems.

The high-rate data link, which has a data rate of 100 Mb/sec, is expected to be available to the imaging system. At best, only 75 to 100 Mb/sec of the Tracking and Data Relay Satellite System capability will actually be available for real-time (or near real-time) downlinking of all science data. The S.S. Freedom Program is expected to provide adequate data storage and data transmission for the FP/DF. Based on microgravity user requirements, requests have been made to provide 1 Tb (terabyte) of storage and a 1-Gb/sec (gigabyte) data rate.

It should be noted that the onboard video system provided by the S.S. Freedom Program is standard National Television System Committee (NTSC) video; however, many fluids experimenters desire instrumentation imaging (nonstandard video) systems. For better understanding the science, higher resolution, higher frame rates, subframing and tracking, and pretriggered imaging would offer distinct advantages over standard NTSC video. Also, as envisioned by the concept of telescience, the video system could provide the experimenter on Earth with near-real-time monitoring and interactive control of the experiment. Although film cameras can provide high resolution and high frame rates, significant amounts of film may be required, and up to 90 days could pass before the film could be returned to Earth for processing and analysis.

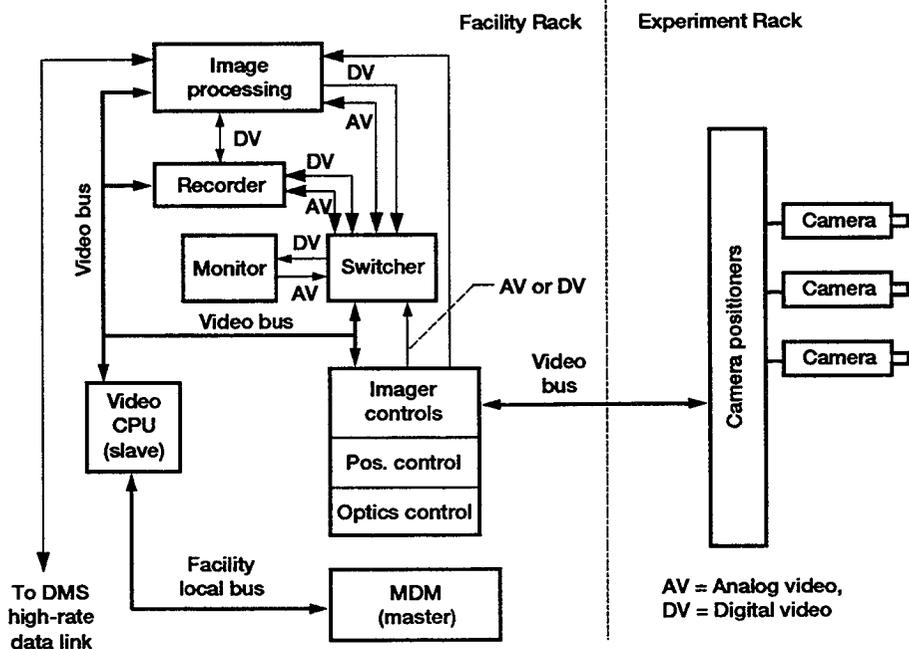


Figure 26.—Functional block diagram of video system.

**Video-system concept.**—The video system in the FP/DF has two purposes: its primary purpose is to capture images of the experiment for scientific observation and analysis; secondly, it also generates data from images and analyzes these for automated processes within the experiment. The video system provides operational support for imaging equipment in the experiment module. The signals pass between racks either over a bus or on individual cables. Figure 26 is a functional block diagram of the video system. The dark, heavy lines indicate functional communications. The thin lines indicate the passage of video signals between functions within the video system.

Two types of video signals, analog (AV) and digital (DV), will be accommodated in the system. The type of video signal will depend on the type of equipment employed and on the uses of the image. One possible case, in which images are only recorded and downlinked, may require AV signals. However, another case, wherein images are processed for automatic control, may require both AV and DV signals.

Imager controls in the facility rack will control such equipment as cameras (both film and electronic), positioners, and optics in the experiment rack. Many of these operations will configure the video system prior to experiment runs. A switcher will route video signals between the other elements of the system, and a monitor will display the video images. Hardware for digital image processing, recording, and telemetry interfaces will reside in the Facility. The FP/DF will also communicate to an S.S. Freedom high-rate data link.

Operation of the video system will be compatible with the master-slave concept of the Facility subsystem controller.

Facility control and interfaces will be through the Facility MDM. This unit will send and receive communications with the local video CPU, where system configuration, status, and operational commands will be monitored.

**Optics, cameras, and positioners.**—The FP/DF video system will provide functional support for equipment mounted within the experiment module. This equipment, including lenses, cameras (film or electronic), and positioners for imagers, mirrors, and other optical devices, will be provided for in the experiment design. This concept suggests that specific imaging equipment must be integrated into the equipment rack.

A comprehensive set of imaging devices should be developed to meet the needs of many fluids experiments. If a unique camera, whose operation cannot be supported by the Facility video system, is employed, its supporting equipment will be housed in the experiment rack and it will be operated independently from there.

Although the need to move cameras during experiments is unlikely, position controllers can provide an effective way to align the cameras during setup. When the cameras are enclosed in the experiment rack, the crew (or automation) will be able to position cameras via remotely controlled platforms, which will be an integral part of the camera mount.

Video- and film-camera operation possess common features: imager control will allow setting of zoom, iris, and frame rate, and regulation of power and recording start and stop functions. White balance, back focus, and targeting will also be controlled; these functions may be part of the self-testing and self-calibration for cameras.

Experimenters often use mirrors to provide multiple views of an experiment. This need has been anticipated, and a remotely controlled method of placing and maintaining position of the mirrors has been included. This operation will be similar to the camera-mount control.

Signals will pass between racks either over a bus or on individual cables. All connections between experiment-rack equipment and facility-rack equipment will be kept to a minimum. Currently, common connections use either coaxial or RS-422 designs. The exact choice for these interrack connections remains an open item.

**Visual display.**—A local video monitor in the facility rack will provide views of the experiment in progress. A switcher will select the camera views. The monitor should be able to display either AV or DV signals, and it should be of sufficient resolution to permit viewing of most images. Controls to adjust the picture quality should be readily accessible on a front panel. As a minimum, a video monitor will allow observation and manual control of the imaging system.

The particular type of monitor to be supplied is an open issue. Currently, cathode ray tubes are available for space-flight use; at this time they still provide the highest quality image. They represent the most common, mature display technology. Other types of displays are under development and may provide desirable options in terms of safety, power consumption, volume, and weight.

In addition to selecting which camera to display on the monitor, the switcher will be able to combine views in various wipes, split screens, keys, and fades. These mixed video signals can be recorded for future analysis. The output of the switcher will also be routed to telemetry interfaces in the Facility MDM and to the image processing equipment. The switcher would be the logical place for an external synchronization signal that would mix video signals for video cameras in the experiment rack.

**Recording or storage.**—In the event that common storage and recording equipment is not available in the USL module, the Facility must provide it. Video may be stored in whatever format is deemed appropriate; currently, 1/2-in. formats are employed, which record analog signals. With some modification, this equipment can be used to record low-data-rate digital signals. Other possible means of storage for digital data, whether digitized video or signals from image processing and compression, include digital-tape formats, magneto-optical and optical disks, and magnetic-disk formats. The choice of a particular format will be governed by the amount of data, the type of data, and the data rates required for FP/DF operations. Because of the need for image compression, and links to telemetry as well as to other Facility systems, use of a high-data-rate, mass-storage device is likely.

**Telemetry.**—The video system will provide the proper interfaces to the Facility MDM and the S.S. Freedom high-rate data link. It is through these routes that video images are likely to be downlinked. Present S.S. Freedom operational scenarios suggest that a limited number of images will be

accommodated by the data management system, and those will largely support telescience operations, including the setting and control of imaging equipment.

**Image processing.**—The term “image processing” encompasses many functions. These include image compression, enhancement, and object recognition. Although much of the analysis and enhancement of images will be done with ground-based equipment, several functions, some for experiment automation, will require that image processing be done within the FP/DF video system.

The video system will provide a means to digitize video signals. This unit will receive input from the electronic imagers in the experiment rack and send output digital signals to other subsystems (e.g., other processors, storage devices, image processing modules, and telemetry).

For real-time operation, a special video data processor is needed. At present, the fastest image operations are done by dedicated hardware. One important function of this processor will be compression. Because of the amount of image data and the limited data rate and access of the downlink, image compression is likely to be required for many fluids experiments. Two points have been identified as suitable times for compression to occur in the image data stream: one prior to recording or storage, the other prior to downlinking.

In addition to compression algorithms, other algorithms, known also as modules, can be performed by the video data processor. These processing modules can be used to control positioners and the experiment. For example, a motion detection algorithm could align a laser sheet at the start of an experiment run. A dynamic morphology module could help control test chamber temperatures and pressures by monitoring changes in the shape of a bubble. Edge-detection and filtering are two of the other modules that may be appropriate for automation and image data reduction. The image processor could also allow comparing, switching, and combining of views, along with combining of video with ancillary data. Finally, the video system will provide signal generation, including synchronizing and internal timing signals. Also, test patterns for equipment calibration and registration may originate here.

**Video-system control.**—Video-system control will address the individual features of each of a variety of cameras. It will also link with other Facility systems through the facility rack MDM, to facilitate both automation and remote control of the system; S.S. Freedom crew members will be able to prepare, run, and monitor experiments.

Provided with a common set of imaging devices and an automated operating mode, a control panel could provide a means of configuring the imaging subsystem. For example, one could choose a recording mode to dynamic RAM or video cassette, or no recording. Also, the system could be programmed to specify which video signals would be downlinked. A means to configure data annotation for both recording and downlinking can be included. For film cameras, a very practical device for inclusion would be an indica-

tor of the amount of remaining film. A hardware enable and/or reset switch would be able to lock out the video section when it is not in use. Power to the video system will come from the facility-rack EPDS.

The video system will be controlled and configured in one of three modes: telescience, workstation, or local. In the telescience mode, the imaging system will be controlled by a ground-based experimenter. Commands issued from the ground will be displayed for the crew on the ECWS video screen. The crew will have an option to override the system manually if needed. In the workstation mode, a crew member will have access to the video system through the ECWS. For this mode, communication with the video system will take place through the facility rack MDM. Configuration settings would be made from the ECWS, yet control and communication could come from both the ground-based experimenter and the crew member, working as a team. In local mode, control of the video system could reside in a local control panel in the Facility.

The setup sequence for control functions will come from the facility-rack MDM. From the local control panel CPU, the video-equipment parameters can be automatically varied as an experiment progresses. The video system will provide status words to the facility rack MDM, which will store and provide configuration information. Built-in self-testing and self-calibration of the panel will be activated on powerup and on software request from the facility-rack MDM.

The video system will address the peculiar features of a variety of imaging devices and cameras. It will also link with other systems through the facility-rack MDM to facilitate automation and remote control of the system; provide a convenient and common interface for S.S. Freedom crew members to prepare, run, and monitor combustion experiments; and through telescience, provide ground-based investigators with the ability both to monitor and to modify experiment operation so as to optimize the scientific information acquired.

## Diagnostic System

**Background.**—The FP/DF will support experiment diagnostics by providing both imaging capabilities (discussed in a previous section) and illumination capabilities. Two light sources that would provide the flexibility to accommodate multiple diagnostic techniques have been identified: a white-light source and a laser.

The white-light source would serve as a general-purpose lighting instrument, since many imaging techniques use a camera and a front-and-back light source. A color technique, such as rainbow schlieren, would also require the spectral distribution that a white light provides.

The laser would complement the white-light source. It offers an intense, monochromatic light that, with filters, can easily be isolated from the white light. In this way, multiple diagnostic techniques can be performed concurrently. By

splitting the laser light beam, a front-and-back light source could be created. Alternatively, the laser beam could be manipulated to project a sheet of light suitable for imaging particles in a colloid. In addition, the laser's coherent light would make interferometric techniques possible.

**Hardware description.**—Both the white-light source and the diode laser are contained in a module in the facility rack. A fiber-optic-beam delivery system carries the light energy through containment structures to the experiment. A separate cable is required for each source. Experiment control of the light sources is accomplished by communication via a common bus with the facility computer.

Housing the light sources in the Facility simplifies the design of experiment racks and maximizes the volume available for experiment apparatus since the cooling and mounting of illumination hardware need not be considered by experiment designers. Mass and volume are of special concern when vibration isolation techniques are considered.

Fiber-optic cable allows the sources to be located remotely and permits flexibility in positioning the sources inside the experiment volume. Penetration of containment enclosures is made possible by the use of quick disconnects. Light from one or more laser diodes can be coupled into a fiber-optic cable, and the optical power output can be controlled by adjusting the current through the diode(s). Because the laser can be pulsed very rapidly, some high-speed camera techniques requiring a pulsed-light source that is synchronized with the frame rate could be used.

A selection of discrete frequencies from the visible red to the near IR is available with laser diodes. The laser diode can also be used to pump a solid-state-laser head, which would be coupled to the output of the fiber-optic cable. White light from a quartz-halogen light source would be transmitted through a second fiber-optic cable. In this case the experimenter could control the intensity through the bus.

The diagnostic illumination module communicates over a common bus to the facility-rack MDM. Self-diagnostics are integral to the unit so that problems can be detected and diagnosed immediately; such a capability is very important in the highly automated FP/DF environment.

## Software Systems

**Software functional description.**—The software will perform the functions of real-time control, data acquisition, computation, data processing, I/O, safety, and self-testing necessary to conduct a microgravity FP/DF experiment. The software will interface with the Freedom Station DMS.

**Assumptions and constraints.**—Two assumptions have been made relative to the software system. The first is that the Freedom Station crew will probably be minimally involved with the FP/DF and, in general, will be restricted to prestart activities (setup, etc.), emergencies, and postrun activities. A second assumption is that hardware constraints imposed on the software will be minimal. Choosing an Intel

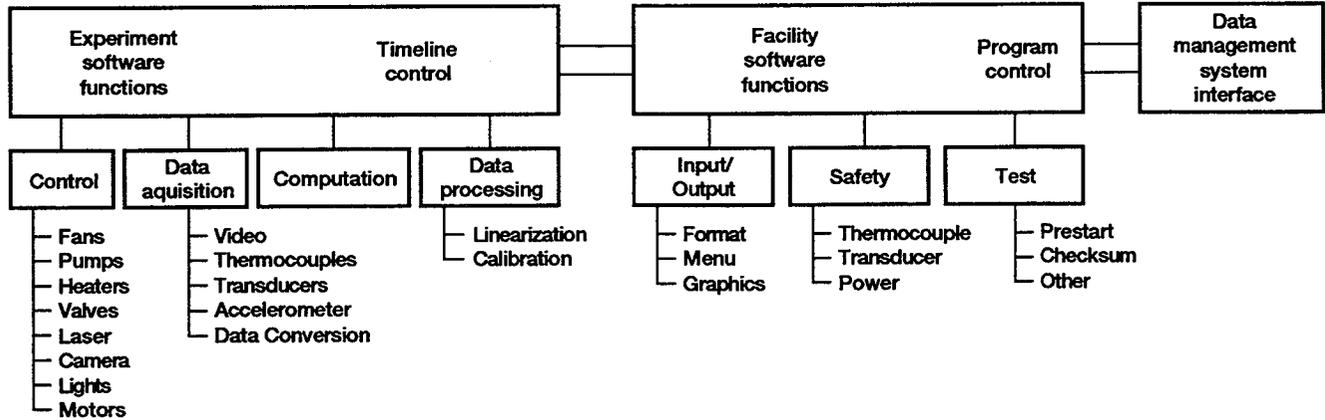


Figure 27.—Software functional requirements.

80386 microprocessor would allow considerable latitude in the design and use of a high-level language for much of the coding.

**Software functional requirements.**—For conceptual purposes, the software functions have been allocated to the facility rack, the experiment rack, and the necessary interfaces. The software functions are listed in figure 27.

**Experiment software functions:** These software functions will depend primarily on the experiment. The following functional descriptions are general and may not be required for all experiments:

(1) **Timeline control.** The timeline control function will control those devices or quantities that interact with the experiment timeline, such as the power profile.

(2) **Device control.** Devices will be controlled through the timeline control or by comparison of sensor output with preestablished values, in accordance with experiment specifications. Control may be overridden by the Facility safety function or by priority interrupt through the DMS interface.

(3) **Data acquisition.** Data-acquisition software will allow the interpretation and buffering of raw data received from the analog-to-digital converters.

(4) **Data processing.** Linearization and calibration of sensors will be accomplished by software.

(5) **Computation.** Data analysis is expected to be done by ground software. However, some quantities may have to be derived from ongoing experiment data in order to determine control parameters. The experiment software will be able to perform this function.

**Facility software functions:** The Facility software functions are expected to change very little from one experiment to another. They are as follows:

(1) **Program control.** The Facility software will have overall program control, with the exception of timeline control details. This control includes experiment start and stop, data sampling for safety tests, emergency shutdown, and other like functions.

(2) **Input/output.** The I/O function will convert data to Systeme Internationale (SI) units and format the data for onboard display. In addition, this function will have a menu

system dedicated to onboard display and limited onboard input of commands, a two-dimensional graphics system (to be determined) for onboard graphics display of data, and time-tagged video.

(3) **Safety.** The Facility safety function will compare thermocouple and pressure-transducer outputs and power level with predetermined maximum values and institute appropriate action; this action, in an emergency, may include warning messages and alarms, a memory dump to mass storage, and saving quantities that indicate an alarm condition.

(4) **Test.** The test function will include software tests, such as a prestart checksum, and prestart-device tests selectable by menu and/or by an automated runthrough.

**Software structural design.**—The design effort will be to make the software as modular as possible. A distributed-software concept will be used, as shown in figure 28.

The subsystem software modules provide the functions necessary for control and/or data acquisition unique to those subsystems. Subsystems include, but may not be limited to, the fluid supply, waste conditioning, thermal control, and optical systems. The subsystem software modules may also perform certain safety functions assigned to each. Status words will be maintained for each subsystem. The experiment modules will consist of the timeline-control module and

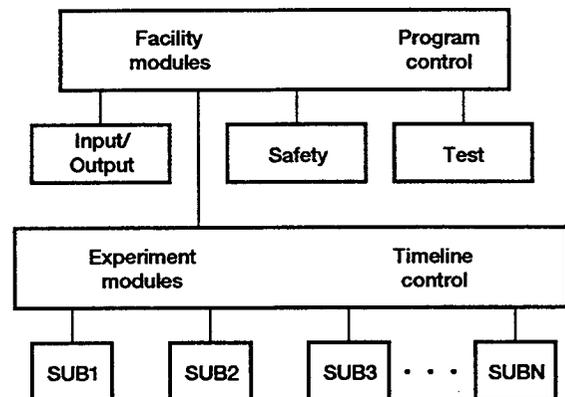


Figure 28.—Program hierarchy.

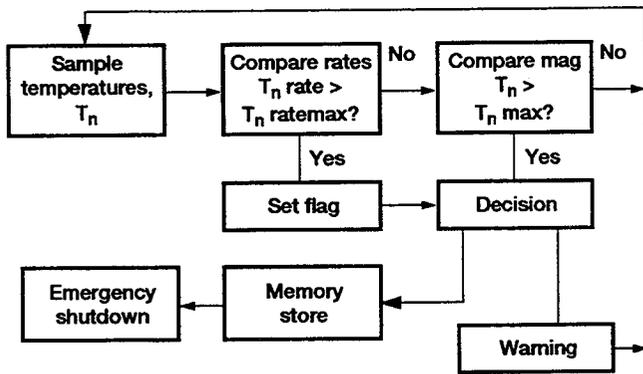


Figure 29.—Possible safety-monitoring subfunctions.

any modules necessary for functions not provided by the system modules. Embedded software will probably be used for at least some of the subsystem software modules.

The Facility software module will consist of the program control module, which will comprise the operating system, providing startup and shutdown, and the DMS interface. The Facility software module will define the environment and will control execution and safety. Modules for handling I/O, facility software safety functions, and prestart tests will be included, to complete the modularity.

Figure 29 illustrates some safety-monitoring subfunctions possible under the FP/DF safety function, namely temperature monitoring and related decision-making, and action-taking subfunctions. Although monitoring of pressure, temperature, and other parameters will also be done as part of the experiment control function, the facility safety function will set limits for these parameters by determining what is safe for the facility and meets USL requirements, independent of experiment-control considerations.

There are several advantages to using the modular software design: changes can be made with minimum impact on the rest of the software; breadboard testing of the hardware subsystem prior to integration will be facilitated; commercial and Freedom Station software packages may be utilized where applicable; and program debugging can be more easily accomplished.

**Interfaces.**—The FP/DF and experiment-software module interface will be accomplished by global declaration of variables and by argument-passing. The subsystem software interfaces will conform to subsystem software specifications (to be determined). The DMS interface will be accomplished through the network interface unit.

**USL module payload development software.**—A number of Freedom Station support services that can be of benefit in the development of FP/DF software are available or planned. A prototype DMS hardware and software kit will be available. Later, functional-equivalent units will be available for DMS interfacing evaluation and testing. A multipurpose applications console will be available for the display of experiment data and Facility status. A subset of the DMS operating system that will be compatible with the IEEE Portable Operating System Interface X can be used.

Computer-aided software engineering tools should be available for use under the software support environment (SSE). The FP/DF should be able to make use of applicable software generated by the SSE. In addition, current plans are that like processes in different facilities will be able to use software in such a manner as to avoid duplication.

Commercial, off-the-shelf software may be used as long as it is compatible with interfacing requirements and it meets quality-control and other Freedom Station requirements.

**Software lifecycle.**—The software lifecycle will consist of four phases, as shown in figure 30. Software engineering and qualification encompasses all four phases and the configuration control functions shown.

Configuration control will be maintained by a system that uses (1) engineering notebooks, (2) planning and scheduling, (3) monitoring, (4) meeting support, and (5) documentation.

**Software products.**—The following software products will be developed:

**Conceptual design document:** The conceptual design document will detail the functions to be performed by the software of the FP/DF microgravity experiment. This document will be produced for the breadboard testing and evaluation.

**Detailed design document:** The first part of the detailed design document will describe the functions to be performed by and the algorithms required for the FP/DF. The second part will describe the functions of and the algorithms for the experiment.

**Software test plan:** The software test plan will detail the tests to be performed on the software for validation and verification. These may include (a) tests with FP/DF and experiment hardware to validate the software control and data acquisition functions and (b) tests with software emulation of FP/DF and experiment hardware to validate the software safety function. All testing will be done in accordance with Freedom Station software qualification requirements.

**Executable code:** The product of the final development phase will be code compatible with the DMS interface and meet USL specifications and requirements.

**Flight-qualification documents:** All documents required for flight qualification will be produced.

**Programmers guide:** The programmers guide for an experiment will consist of the final detailed design document for that experiment.

**Users manual:** The users manual will describe the program requirements in general and the program I/O requirements in particular, including status words and messages, in a format that can be easily understood by the person who will be running the experiment.

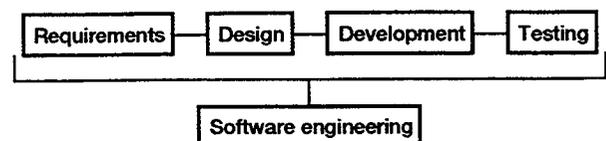


Figure 30.—Phases of the software lifecycle.

# Fluids Experiment Concept Designs and Operations Scenarios

## Immersed Bubble or Droplet Dynamics and Interactions Experiment

**Science background.**—The fundamental low-gravity phenomenon to be studied in this experiment is the thermocapillary behavior of immiscible bubbles or droplets in a uniform temperature gradient. Bubbles or droplets released into a temperature gradient will begin migrating toward the hotter end because of thermocapillary effects (fig. 31). If the surface tension change with respect to temperature ( $d\sigma/dT$ ) is assumed to be a negative quantity, the surface tension is higher at the cold end of the bubble. The interfacial fluid will then begin to migrate from the warmer toward the cooler end of the bubble. Through viscosity, the fluid motion affects the surrounding liquid layers, with the result being bubble or droplet motion toward the hot end.

In considering the mathematical formulation of the problem, two nondimensional parameters appear to control the migration velocity of the bubble: the Marangoni number  $Ma$  and the surface tension Reynolds number  $R\sigma$ . The Marangoni number is part of the energy equation describing the external temperature field and is defined as

$$Ma = (-d\sigma/dT)(dT/dz)(R^2)/(8.25 \mu\alpha)$$

where ( $d\sigma/dT$ ) is the change in surface tension with temperature (dyne/cm-°C); ( $dT/dz$ ) is the imposed temperature gradient (°C/cm);  $R$  is the bubble radius (cm);  $\mu$  is the external fluid dynamic viscosity (cP); and  $\alpha$  is the thermal diffusivity (cm<sup>2</sup>/sec).

The surface tension Reynolds number is part of the momentum equations describing the external velocity fields and is defined as

$$R\sigma = (-d\sigma/dT)(dT/dz)(R^2)/(\mu\nu)$$

where  $\nu$  is the kinematic viscosity (cm<sup>2</sup>/sec).

Other secondary, nondimensional parameters like the Weber and capillary numbers are important in describing the bubble's shape (degree of nonsphericity).

Most of the past analytical work dealt with perturbations of creeping flow and, therefore, yielded solutions valid for Marangoni and Reynolds numbers of the order of unity (or less). Balasubramaniam and Chai (ref. 1) determined motion for arbitrary  $R\sigma$ ; however,  $Ma$  had to be small. More recent work by Balasubramaniam (ref. 2) presents a solution for large Marangoni numbers. For several reasons, these latter cases (for large  $R\sigma$  and  $Ma$ ) are of particular interest for microgravity experiments. If thermocapillary effects were to dominate over gravitational effects in a one-g experiment,

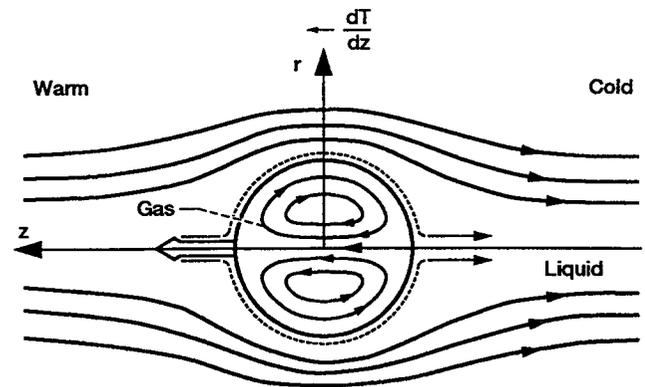


Figure 31.—Marangoni convection around bubble.

the bubbles or droplets would be very small and the gradients very large. In such a case, small bubbles with short transit times would make data gathering more difficult. In microgravity, larger bubbles can be realized while remaining in a capillary-dominant environment. Thus, larger Marangoni- and Reynolds-numbers experiments can be conducted in a microgravity environment and their data used to test the theories of the aforementioned references. Possible refinement of these analyses could result.

**Experiment description.**—In the basic experiment a simple bubble or droplet of known size will be introduced into a liquid with an established temperature gradient. The bubble will be injected into a predetermined position within the fluid chamber, and the subsequent motion will be studied. The primary objectives will be to measure the velocity and temperature fields external to the bubble or droplet and to measure bubble or droplet size, shape, and velocity. The region of influence around the translating bubble is expected to be of the order of five radii or less. Various bubble sizes, temperature gradients, and fluid pairs will be studied. Temperature gradients, and bubble diameters should be chosen so that for some of the cases, nonspherical bubbles are realized. Identifying independent parameters, ranges, and the types of fluids to be used will be discussed later.

There are several capabilities that the FP/DF should or could have to maximize the scientific return. Among them, fluid changeout of the apparatus should be relatively easy. Whether this will be done by physically replacing the test chamber or by using a fluid fill-and-drain system remains to be seen. Another feature that the apparatus could have is the ability to inject bubbles or droplets at varying distances from the walls, orthogonal to the temperature-controlled plates. This would allow the study of wall effects on the bubble motion. Multiple simultaneous injections of bubble or droplets could also be a capability of this apparatus, thereby permitting study of bubble coalescence or interactions. These latter two capabilities (near-wall injection and simultaneous injections) are seen as future capabilities, not part of the initial design.

TABLE III.—PROPERTIES OF TEST FLUIDS

(a) External fluid properties

Fluid	Dynamic viscosity, $\mu$ , g/cm-sec	Density, $\rho$ , g/cm <sup>3</sup>	Thermal diffusivity, cm <sup>2</sup> /sec	Prandtl number, $Pr$
Silicone oil	0.045	0.91	$8.24 \times 10^{-4}$	60.0
Methanol	.0055	.79	$10.03 \times 10^{-4}$	6.9

(b) Interfacial fluid properties

Fluid combination	Surface tension $\sigma$ , dyne/cm	Surface tension gradient, $\sigma_T$ , dyne/cm-°C
Silicone oil with air	19.7	-0.07
Silicone oil with methanol	To be determined	To be determined
Methanol with air	22.6	-.09

**Science requirements.**—This section presents the detailed preliminary science requirements for the Immersed Bubble/Droplet Dynamics and Interactions Experiment. In various subsections fluids, fluid handling, chamber dimensions, data, and optical requirements will be discussed. The final section will cover the gravitational requirements.

**Test fluids and their properties:** Three fluid combinations are contemplated for this experiment; two of these use silicone oil as an exterior fluid into which either liquid droplets or gas bubbles are injected. The injected gas is to be air (or possibly nitrogen), and the liquid droplets are to be methanol. The third fluid combination is to be methanol into which air bubbles are injected. Both test liquids are to be supplied as nondegassed fluids. If degassed fluids were used, the rate at which air would be absorbed into the liquids would be unacceptable. Pressures will be approximately atmospheric and fluid temperatures will range between - 25 and 75 °C. Relevant fluid properties, which have been evaluated at 25 °C, are given in table III.

**Fluid transfer and handling:** Each experiment will have a vessel that is filled with the appropriate liquid and subjected to a certain temperature gradient. It is important that initially the container be completely filled with liquid, with no liquid-vapor interface. Once enough time has elapsed for steady-state thermal gradients to be established and any residual fluid motion to have subsided, a bubble or droplet will be injected into the bulk fluid and the subsequent motion studied. It is important that the bubble be precisely positioned and released so that the bulk fluid motion is minimized. For the bubble sizes and chamber heights to be discussed herein, a bubble-release position of 1 cm above the surface of the cold plate should be adequate.

Once the bubble or droplet has reached the hot-plate surface, the local temperature field will no longer be linear, and there may be residual bulk fluid motion induced by thermocapillary forces. For the smaller bubble sizes, we believe that multiple runs could be made without having to manage the accumulated bubbles or droplets. A criterion has

been established that requires the bubbles or droplets to somehow be removed before other runs can be made, if the total bubble area exceeds 0.1 percent of the hot-plate surface area. This removal could occur in one of three ways: the test chamber could be drained and subsequently refilled; the bubbles could be removed, perhaps by a suction device; or the chamber could be changed out. With any of these three scenarios, further consideration may also have to be given to cleaning the test cell and injector. These cleaning procedures would be done between fluid changeouts and between seeded-and unseeded-fluid runs.

**Test chamber description:** The test chamber (fig. 32) has a 10- by 10-cm cross section and can be 4, 7, or 10 cm high. Bubbles/droplets up to 2 mm in diameter will be tested in the 4-cm chamber, 3- and 5-mm bubbles in the 7-cm chamber, and 7.5- and 10-mm bubbles in the 10-cm chamber. To facilitate data gathering, the chamber sidewalls will be clear. The material chosen for sidewall construction should have a low thermal conductivity to minimize sidewall heat loss and any subsequent effect on the uniformity of the longitudinal temperature gradient. Another option would be to have a double wall with a vacuum to minimize lateral heat loss. With regard to the hot and cold ends of the chamber, their inner surfaces must be isothermal to a tolerance of  $\pm 0.1$  °C.

**Thermal requirements:** As mentioned previously, it is most important that in this experiment the temperature gradient be uniform. There are two reasons for this: (1) to minimize as much as possible lateral temperature variation in a given z-plane; and (2) to be able to determine when steady-state thermal gradients have been reached. This temperature gradient can be addressed by transient, one-dimensional heat-transfer calculations. These transient times are a function of cell height, fluid properties (thermal diffusivity), and to some extent, the boundary and initial conditions. These transient times have an impact on the operation of the experiment.

Another parameter that could affect the achievability of uniform temperature gradients is the presence of residual

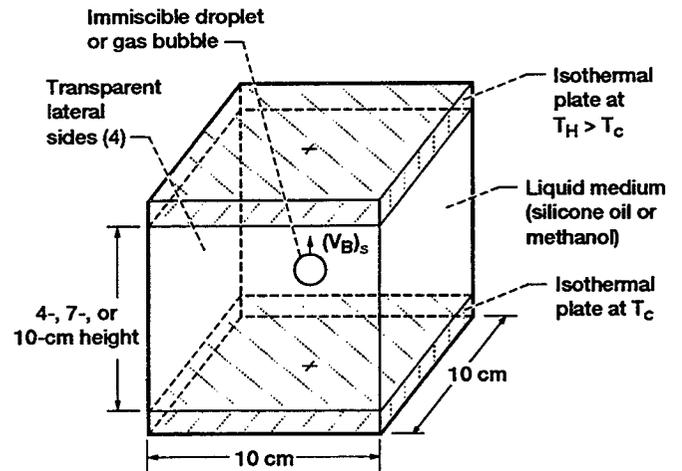


Figure 32.—Fluids experiment test chamber.

fluid motions. Such motions could be a result of either natural convection due to a low gravity (but not zero) environment, and/or bulk fluid motion caused by thermocapillary motion of bubbles trapped under the hot plate. The effect of convection due to low gravity could be negated by ensuring that the resultant gravity vector is oriented perpendicular to and in the direction of the cold plate. Thus, some vector orientation capability is desired. The motion caused by bubbles trapped under the hot plate could be addressed by requiring that the sum of cross-sectional areas of accumulated bubbles or droplets be less than some fraction of the hot-plate area. A bubble area limited to 0.1 percent of the hot-plate area was suggested.

*Data requirements:* Both temperature and velocity data will be needed.

*Temperature.* Two types of temperature information are required: (1) fluid temperature as a function of distance from the cold plate; and (2) the local temperature field around the bubble/droplet. The first type of data would verify the uniformity of the temperature gradient and could be acquired by a removable temperature rake. The appropriate region of interest for the second type of data is within 5 radii of the bubble center. Possible techniques for acquiring such data include schlieren, interferometry, and IR imaging.

*Velocity.* There are two kinds of velocity data that are of interest here. The gross bubble or droplet velocities are of primary interest. These velocities will be compared to those of available analyses. Maximum bubble velocities expected for the proposed test matrix are about 5 cm/sec for silicone oil and 50 cm/sec for methanol. These velocities will have an impact on the frame rates used by the filming devices. The other velocity data to be acquired are local velocity-field information within 5 radii of the bubble or droplet center. To acquire such data, particle seeding and laser-light-sheet techniques will have to be employed; most fluid runs will be made with seeded fluids. Although the relevant fluid properties are not expected to be affected, nine runs will be made with unseeded fluids so that comparisons can be made. Steps should also be taken in the operation of the experiment to ensure uniform particle distribution prior to each run. In order to obtain the necessary resolution with the sheeting method, a suggestion was made that the laser sheet be no more than 10 percent of the relevant bubble diameter. If 100  $\mu\text{m}$  is a baseline laser-sheet thickness, this criterion implies that only bubble diameters equal to or larger than 1 mm will be sheeted. As with the local-temperature data, local-velocity data will be used to fine-tune the appropriate analytical models.

*Optical requirements:* Recall that the maximum test chamber dimensions are 10 by 10 by 10 cm. Two opposite sides of the chamber will be the heat-transfer surfaces; the others will be used to visualize the flows. Particle seeding and laser-sheet techniques will probably be used to obtain the flow-field velocity information for steady-state bubble motion. This will require realignment of the laser-light sheet

or the use of a back-lighting system and an additional camera. Schlieren techniques will probably be used to generate temperature-field data. However, both temperature and velocity fields must be measured from the same planar view (from a single light sheet with a 100- $\mu\text{m}$  thickness). That means frame rates of 500 ft/sec are required for both cameras. In addition, we should have the capability of tracking the bubble's motion in the initial moments after release, which will account for any perturbations such as those caused by the injector. Bubble motion should be orthogonal to heater surfaces once steady-state motion has been achieved. A proposed arrangement, discussed earlier, clearly requires that the lateral surfaces be transparent. If orthogonal sides are flat, the chamber images will not have to be optically corrected.

*Gravitational requirements:* The intent of this effort is to conduct on-orbit experiments so that thermocapillary forces dominate gravitational forces. Several aspects of the steady-state gravity requirement will be discussed: buoyancy parallel to the temperature gradient, buoyancy perpendicular to the temperature gradient, and thermal convection. We would like the bubble's motion due to buoyancy to be small when compared to its motion due to thermocapillary forces. Assuming that the resultant g-vector is oriented toward the cold plate (for worse case comparison), we can estimate the bubble's terminal velocity from buoyancy as

$$(V_B)_g = [1/(3\nu_f)] R^2 g$$

where  $R$  is the bubble radius and  $\nu_f$  is the kinematic viscosity of the fluid. This expression also has used the following bubble-drag relationship:  $F_D = 4\pi R\mu(V_B)_g$ . Likewise, an expression for terminal bubble velocity can be written for thermocapillary effects. From Balasubramaniam (ref. 2), thermocapillary terminal velocity of the bubble is

$$(V_B)_\sigma = (0.235)(-d\sigma/dT)(dT/dz)(R/\mu)$$

where  $d\sigma/dT$  is the change in surface tension with temperature,  $dT/dz$  is the imposed temperature gradient, and  $\mu$  is the dynamic viscosity of the fluid. By imposing a criterion that  $[(V_B)_g]/[(V_B)_\sigma]$  be less than some fraction  $E$ , a gravity-level criterion can be generated. If  $E = 0.05$ , the following calculation can be made. Assume a silicone oil-air bubble combination with the following properties:

$$\nu_f = 0.05 \text{ cm}^2/\text{sec}$$

$$(-d\sigma/dT) = 0.07 \text{ g/sec}^2\text{-}^\circ\text{C}$$

$$P_f = 0.91 \text{ g/cm}^3$$

$$2R = 0.5 \text{ cm}$$

$$(dT/dz) = 5 \text{ }^\circ\text{C/cm}$$

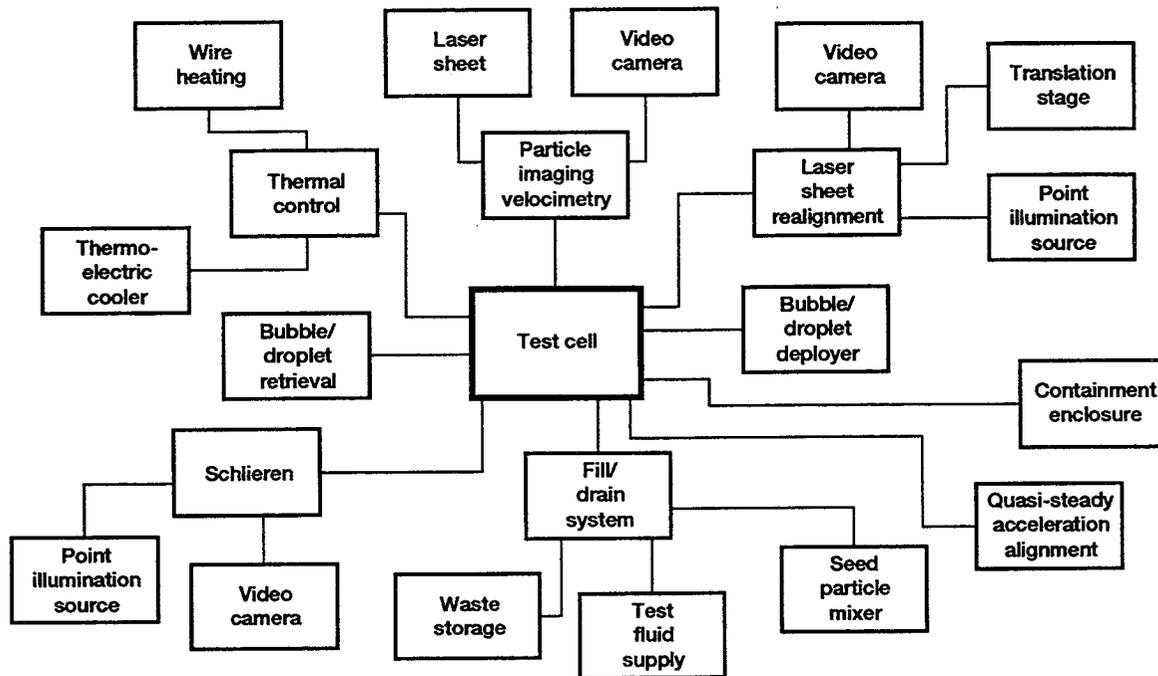


Figure 33.—Functional diagram of experiment.

By rearranging, we can show that

$$g \leq 5.53 \cdot 10^{-5} g_0 \text{ (where } g_0 = 980 \text{ cm/sec}^2\text{)}$$

The  $E = 0.05$  criterion is one that should be met for the range of bubble sizes and temperature gradients to be chosen.

Lateral accelerations can be minimized if the resultant  $g$ -vector is oriented and maintained in the direction perpendicular to (and pointing toward) the cold plate. It is, therefore, important to measure accelerations in the vicinity of the test cell. There are two definite advantages in being able to orient the  $g$ -vector in this way: lateral bubble velocities can be minimized (near zero), and the bulk fluid will be thermally stable (i.e., no convective motion would be induced). A lack of convective motion is desirable so that the uniform temperature gradients set up in the bulk fluid will not be disturbed.

**Test matrix and operational considerations.**—A variety of fluid combinations, bubble or droplet sizes, and temperature gradients will be studied. Bubble or droplet sizes will range from 0.1 to 10 mm in diam and temperature gradients will range from 1 to 25 °C/cm. Tests will be conducted on bubbles or droplets of the following diameters: 0.1, 0.2, 0.5, 1.0, 1.5, 2.0, 3.0, 5.0, 7.5, and 10 mm. Precise control of the injected bubble or droplet's size is less important than the accurate measurement of the resultant bubble or droplet's size during a test. For the silicone oil-air combination, the aforementioned ranges result in maximum Reynolds and Marangoni numbers of 200 and 12 000 respectively. These are much higher values than those that can be obtained

experimentally with one-g tests. A more complete test matrix discussion, presented elsewhere, assumes a 90-day time period for the completion of a full series of test runs.

The only operational consideration to be discussed here is test chamber heat-up time. The time typically required to establish a uniform temperature gradient for this experiment is of the order of hours. This length of time has a large impact on operations, so an accurate estimate of thermal heat-up times would be useful. The transient times required are functions of fluid properties, of initial or boundary conditions, and strongly, of chamber height. In fact, it is this strong sensitivity to height and the desire to minimize heat-up time, that has driven the variable chamber-height design. The relevant equation, whose detailed derivation will not be given here (it can be verified by solutions given in Carslaw and Jaeger (ref. 3)) is

$$t = (H^2/\alpha)(-1/4\pi^2) \ln \{(\theta\pi)/[4(1-B_2)]\}$$

where  $H$  is the chamber height (cm);  $\theta$  is the convergence criterion (e.g., 1 percent);  $\alpha$  is the thermal diffusivity (cm<sup>2</sup>/sec);  $\pi = 3.14159$ ; and  $B_2 = (T_H^o - T_c^o)/(T_H - T_c)$ ; where  $(T_H^o - T_c^o)$  is the difference between the initial temperatures of the hot and cold walls and  $(T_H - T_c)$  is the difference between their final temperatures.

Chamber heat-up times are approximately the same, whether one is going from an isothermal state or from one thermal gradient to another. The following results are given for two cases: (1) heat up from an isothermal condition to a 1 °C/cm gradient and (2) heat up from a gradient of

TABLE IV.—CHAMBER HEAT-UP TIMES

Chamber height, cm	Steady state heat-up time, hr			
	Isothermal to 1 °C/cm		20 to 25 °C/cm	
	Silicone	Methanol	Silicone	Methanol
4	0.66	0.54	0.44	0.36
7	2.0	1.7	<sup>a</sup> 1.6	<sup>a</sup> 1.3
10	4.1	3.4	<sup>b</sup> 3.5	<sup>b</sup> 2.9

<sup>a</sup>At 10 to 15 °C/cm.

<sup>b</sup>At 5 to 10 °C/cm.

20 °C/cm to 25 °C/cm. Heat-up times for silicone oil and methanol are given for the experiment's three standard chamber heights in table IV.

### Experiment Conceptual Design

The conceptual design of the Immersed Bubble and Droplet Dynamics and Interactions Experiment has been divided into the following 10 subsystems:

- (1) Test cell
- (2) Thermal control
- (3) Fill and drain
- (4) Bubble or droplet deployer
- (5) Bubble or droplet retrieval
- (6) Schlieren (temperature field and bubble/droplet velocity)
- (7) Particle-imaging velocimetry
- (8) Laser sheet realignment

- (9) Quasi-steady acceleration alignment
- (10) Containment enclosure

These subsystems and functions are graphically shown in figure 33, and a general isometric drawing of the experiment layout is shown in figure 34. Although each of these subsystems will be described in more detail in the following paragraphs, the chief purpose of each is briefly described here. The test cell and the thermal-control system (fig. 35) are used to contain the silicone oil and alcohol host fluids and to establish required temperature gradients across the test-cell height. The fill-and-drain system will provide for on-orbit changeouts of the host fluids, and in conjunction with the variable test-cell height, will allow the test cell to be completely filled with host fluid. The bubble or droplet deployer releases multisized bubbles or droplets which can be removed by the bubble- or droplet-retrieval system when a specified percentage of the hot plate is covered by bubbles or droplets. The fill-and-drain system will be used as a backup to bubble retrieval, because complete bubble retrieval could be unachievable. The schlieren system will measure the internal and external temperature gradients around the bubble/droplet, and the bubble or droplet gross velocities. Particle-imaging velocimetry (PIV) is the technique that has been chosen to measure the internal and external thermocapillary flow fields around a bubble or droplet. Laser-sheet realignment is a development option; it may be required to ensure that the bubble/droplet will remain in the light sheet for the PIV. The quasi-steady acceleration alignment system will keep the quasi-steady acceleration vector pointed toward the cold

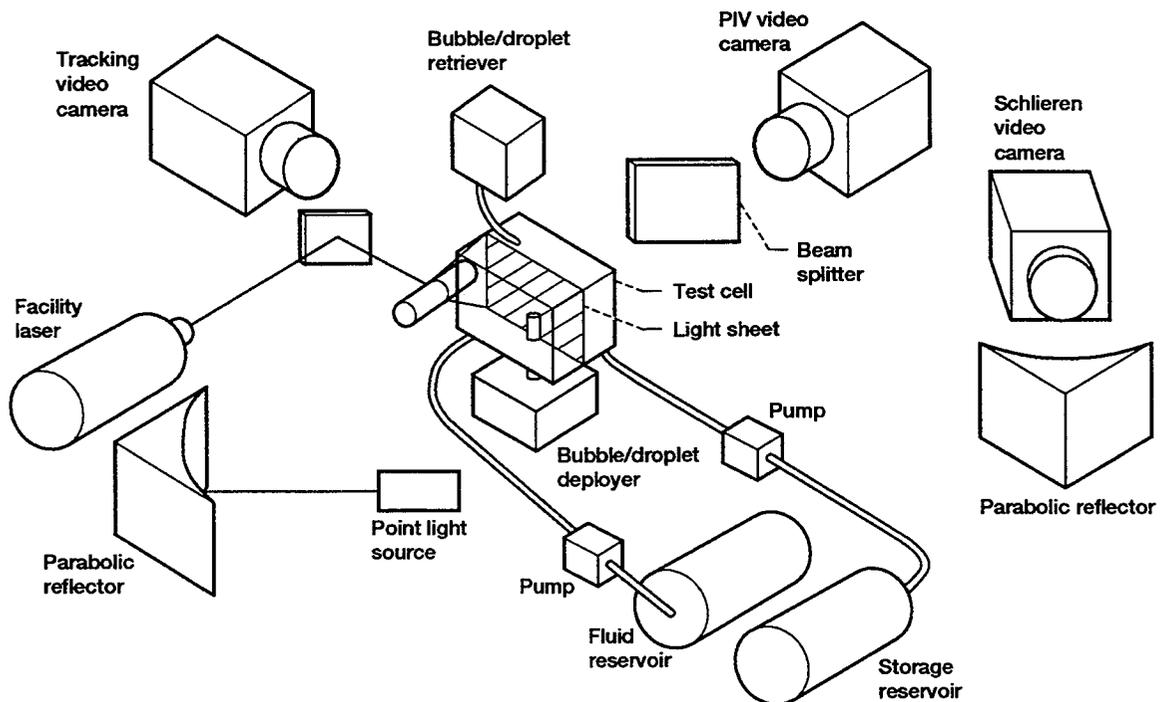


Figure 34.—Experiment layout diagram.

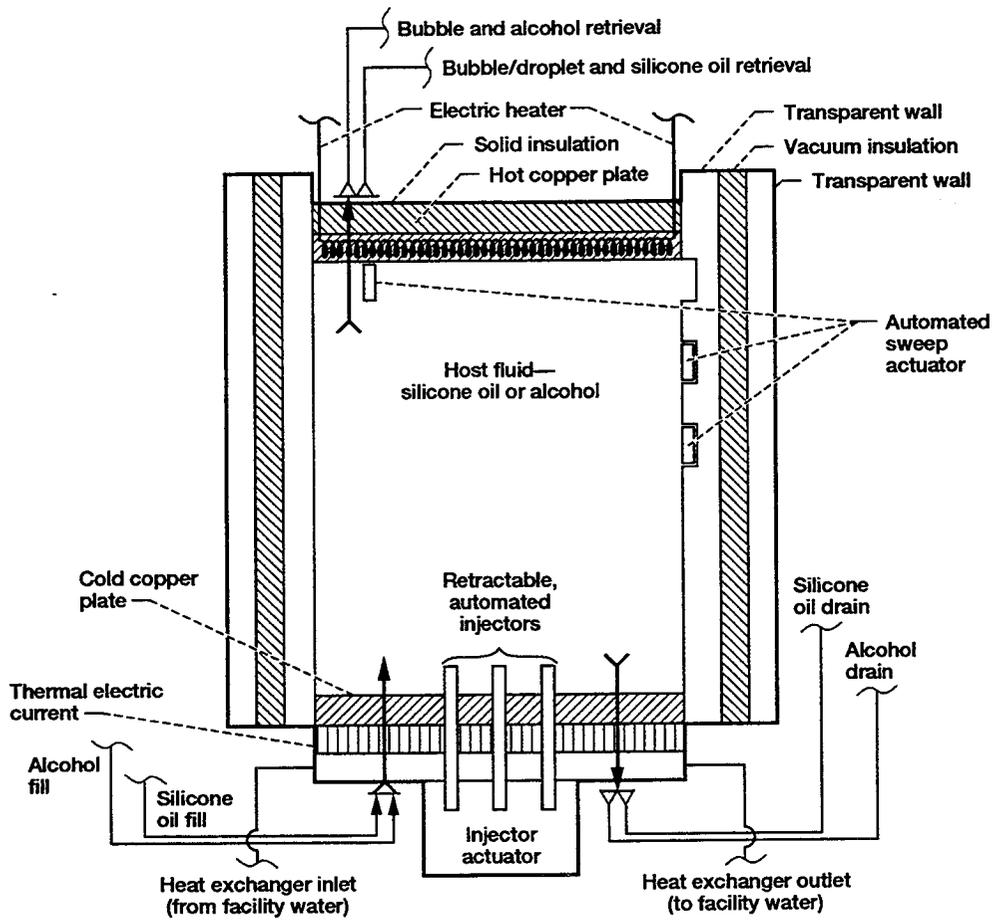
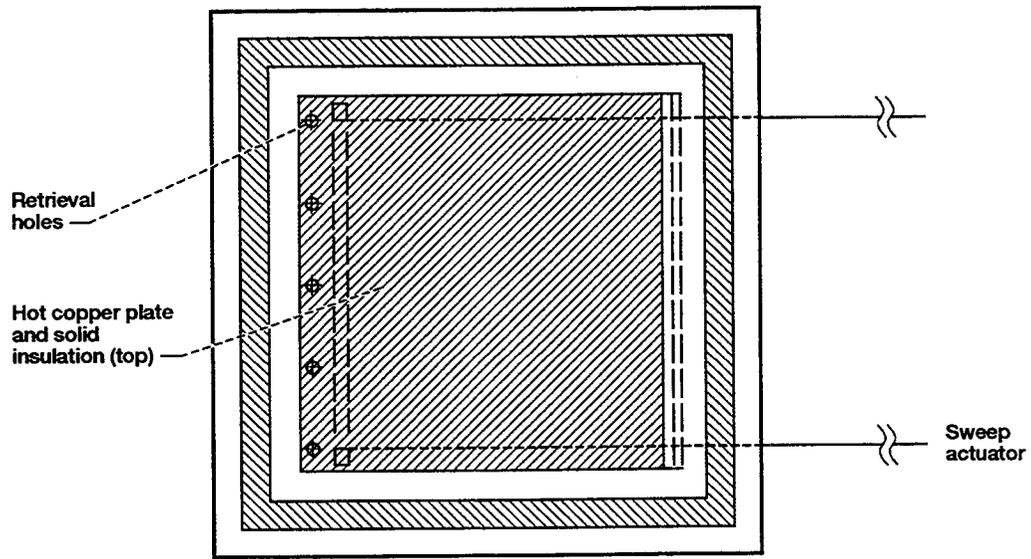


Figure 35.—Variable-height chamber arrangement.

plate. Finally, the containment enclosure will ensure safe operation of the experiment.

**Test cell.**—The test-cell design for the experiment will provide several science-requirement capabilities, including containment of 2 different host fluids (silicone oil and alcohol); generation of 6 uniform temperature gradients with no lateral gradients; the deployment of 10 sizes of bubbles or droplets; and the optical observation and illumination of immersed bubbles or droplets through the 4 transparent sidewalls of a rectangular enclosure. In order to conduct a large test matrix, maximize hardware use, and minimize crew labor, the test-cell design (fig. 35) will incorporate several functional capabilities, including automatic bubble or droplet deployment, filling and draining of the test cell, and automatic bubble or droplet retrieval. In order to avoid contamination between the two host fluids, only one on-orbit test-cell changeout will be required. Other design concepts considered included 12 interchangeable, prefilled, fixed-height test cells with assumed complete bubble or droplet retrieval capability, and 120 prefilled test cells with no retrieval capability.

The common design for the silicone oil and alcohol test cells will include a variable-height, heated, rectangular copper plate with a vacuum-tight seal; a stationary, cooled, rectangular copper plate; four vacuum-insulated, transparent sidewalls; vacuum-tight cold-plate seals that can receive retractable bubble or droplet injector probes; and leak-tight sidewall seals that can receive retractable bubble or droplet retrieval sweepers or "plows". Additional test-cell design details follow.

The height of the 10- by 10-cm hot plate will vary between 0 and 10 cm. This flexibility will enable filling and draining of the test cell while minimizing trapped bubbles and will provide accumulator capability for the injection of multisized bubbles or droplets (0.1 to 10 mm diam) into the filled chamber. Seal design and manufacturability will require rounded corners between the movable hot plate and the four sidewall corners.

The movable, copper hot plate will be electric-resistance-heated, whereas the stationary cold plate will be cooled by a custom-designed thermoelectric cooler and facility-cooled heat exchanger. The cooler and heat exchanger will be installed between the injector probe actuator and the receiving cold plate, but will not interfere with retractable probe travel. The thermoelectric cooler and heat exchanger will be attached to each test cell and thus will be changed out with the silicone oil and methanol test cells.

The test-cell construction will provide undistorted viewing and illumination with flat, parallel, and transparent sidewalls made of appropriate material with an appropriate surface finish. Sidewall design will accommodate schlieren imaging for bubble or droplet local thermal fields and gross velocities, video observation of local flow fields, and orthogonal viewing for tracking bubble or droplet movements for light-sheet realignment, if required. Double walled, vacuum-isolated sidewalls will insulate the test-cell volume to prevent lateral

temperature gradients. Other space experiments that have investigated the use of vacuum-insulated walls have found the thermal design requirements cannot be met by this design. Analysis and testing will be necessary to ensure that the vacuum can provide the appropriate thermal constraints. An active sidewall-cooling technique might be required, but it could severely restrict viewing. The sidewalls must also be designed to resist scratches that could be caused by the seals on the movable plate that will be wiping clean the sidewalls during test-cell filling or draining.

**Thermal control.**—The Immersed Bubble or Droplet Dynamics and Interactions Experiment requires precise thermal control of one relatively hot and one relatively cold surface. The temperature ranges and accuracies required for these two surface are given in table V.

TABLE V.—SURFACE TEMPERATURE RANGES AND ACCURACIES

Surface	Temperature range, °C	Accuracy
Hot	30 to 75	±0.1
Cold	-25 to +26	±0.1

With these temperature ranges and test cell heights of 4, 7, and 10 cm, experimentally required absolute temperature differences from 4 to 100 °C, and associated thermal gradients from 1 to 25 °C/cm, are obtainable.

The hot surface temperature is maintained by an electrical resistance heater attached to the test cell's movable copper plate. This plate, with the resistance heater attached, will move to provide various test-cell heights. Solid thermal insulation will help ensure a uniformly hot surface temperature. The initial design of the thermal control system combined a thermoelectric heater with a heat exchanger instead of wire heating. This concept was dropped because it would have required moving the thermoelectric device along with the heat exchanger. The fluid connections on the heat exchanger would have made such motion difficult.

The cold-surface temperature is maintained by a thermoelectric cooler attached to the test cell's stationary copper plate. Heat from the cold surface will be removed by a liquid-cooled heat exchanger at the hot side of the thermoelectric device. Cooling water for the heat exchanger will be supplied by the Facility. Small holes through the heat exchanger and thermoelectric cooler will be necessary to accommodate the bubble/droplet deployers.

The thermoelectric heat-pumping capability is proportional to electric current input. A microprocessor-based feedback-control circuit will enable precise temperature control by controlling the electrical input. Thermocouples or thermistors in the test-cell sidewalls will verify steady state temperature conditions and will correlate the schlieren temperature meas-

urement system. Thermocouples or thermistors embedded in the hot and cold surfaces will verify uniformity of the surface temperature and will provide feedback to the temperature control circuit.

**Fill-and-drain system.**—A fill-and-drain system that completely fills the test cell with fluid and drains it on orbit is required. The Facility-supplied fill-and-drain system is specifically designed for experiments that require a liquid free surface (i.e., will have a gas-liquid interface). At this time we do not know whether the Facility will provide fill-and-drain capability for experiments that need complete test-cell filling. Therefore we have proposed an experiment-specific system that will fill and drain, on orbit, the test cells, the host fluid supply, and the waste storage for the used host fluid. When more details of the Facility-supplied system are available, a decision can be made about its usefulness to the experiment.

The initial concept proposed completely prefilling multiple test cells with the host fluid while the experiment was on the ground. After the test matrix was investigated, however, the large number of test cells required—approximately 120 if no bubble-retrieval mechanism were provided—made this option impractical. This concept would have required significant crew interaction to perform 120 test-cell changeouts. Another design option, in which 12 test cells were to be filled on the ground, relied completely on a bubble-retrieval method to remove all the bubbles from the test cell. This option would have required 120 bubble-retrieval cycles. Because of the concern that complete bubble retrieval would be difficult to achieve, this concept was dropped. The present concept has both a bubble-retrieval mechanism and a fill-and-drain system, which will help maximize the science return from the experiment.

The fill-and-drain system will serve multiple functions in this experiment. First, it will fill the test cells with alcohol or silicone-oil host fluids before beginning a multiple deployment test series. Prior to each test, it will replenish the host fluid in the test cell after a bubble/droplet retrieval cycle. Finally, after a host fluid and test-cell height run is completed, the fill-and-drain system will drain the used host fluid and replace it with fresh fluid. This changeout is a precautionary measure in case the bubble/droplet-retrieval method does not completely remove all the bubbles.

Completely filling a test cell on orbit will be very difficult, because entrapped air bubbles will be hard to avoid. One of the first concepts discussed involved pulling a vacuum on the test cell and then allowing the host fluid to enter the cell; such a design would work only for test fluids that had been degasified, however. To degasify a fluid, all the gas that is trapped in solution must be pulled out. Since the silicone oil and alcohol to be used for this experiment cannot be degasified, this method was disregarded.

In the present design concept (fig. 35), a movable hot plate acts like a piston in a cylinder, bottoming-out against the stationary cold plate at the beginning of a test-cell fill cycle. A vacuum will be pulled to ensure that no air is trapped in the

small gap between the hot and cold plates; then the vacuum line will be closed and the valve on the test fluid line will be opened. The test fluid will then be pumped into the cell, forcing the hot plate away from the cold plate. This process will continue until the correct test cell height (hot- to cold-plate separation) is reached. The success of this design will depend on the seal between the hot plate and the sides of the test cell. This seal must be vacuum tight, but still allow translation of the movable plate. Before the beginning of a deployment test sequence, any air bubbles introduced during filling will be removed by the bubble/droplet retrieval system. This will be accomplished by first establishing the appropriate temperature gradient that will drive the bubbles to the hot plate and then by employing the bubble retrieval system. The test cell could be drained by forcing the fluid out with an actuator attached to the movable plate or by pumping out the test fluid. One benefit of this design is that the movable hot plate can remain free during a test and serve as a fluid accumulator for the test fluid displaced when a bubble is injected.

Two other important components of the fill-and-drain system are host-fluid supply and waste storage. The fluid supply reservoirs will consist of a flexible bag inside a rigid container. The flexible bag will collapse when the fluid is pumped out, thus insuring that no vapor pockets will interfere with the pump. Four different host fluids are required to perform the experiment: seeded silicone oil, unseeded silicone oil, seeded methanol, and unseeded methanol. The seeded host fluids are fluids into which micron-size aluminum oxide particles have been mixed so that the fluids can be used for the PIV technique. Very likely, four 20.3-cm (8 in.) diameter by 33.1-cm (13 in.) long fluid reservoirs will be required, one for each of the four test fluids. In addition, two 25.4-cm (10 in.) diameter by 33.1-cm (13 in.) long storage reservoirs will be necessary, one for each host fluid. The number of reservoirs needed could be reduced by reusing the empty supply reservoirs for waste storage, but this could complicate the design since more hardware changeouts would be required. Because space is limited within the experiment rack, we anticipate installing only one fluid supply reservoir in the experiment rack at one time. The remaining reservoirs will be stored in the facility-supplied chemical storage area in the facility rack. If space permits, both waste storage reservoirs could reside in the experiment rack.

Before a test with a seeded host fluid is started, the aluminum oxide particles must, for science reasons, be uniformly distributed throughout the fluid. During launch, however, g-forces could cause the seed particles to aggregate on the bottom of the reservoir. The supply reservoirs for the seeded host fluids, therefore, will require an on-orbit mixing capability, possibly by using a mechanical, magnetic, or acoustical stirrer, or circulatory flow.

**Bubble or droplet deployer.**—Deployers will release air bubbles and methanol droplets into the silicone-oil host fluid, and air bubbles into the alcohol host fluid. For the silicone

oil, three deployers are required—one for air bubbles, one for seeded methanol, and one for unseeded methanol droplets. For the methanol host fluid, only an air-bubble deployer is needed. As figure 35 shows, the deployers will enter the test cell through the stationary cold plate. An alternate design would use only one deployer for all test cases; however, such a design would require both the outside and inside of the deployer to be cleaned; this could be very difficult, if not impossible, on orbit. One advantage of having dedicated deployers for a bubble-host fluid pair is that the deployers can be installed in the test cells on the ground, thereby making it easier to design the seals around the deployers. The three deployers in the silicone oil will deploy the bubble or droplets independently, but could be actuated as a unit. The three deployers must be located in one plane, owing to laser light-sheet requirements, but be separated so that a bubble injected by one deployer would not be disrupted by another deployer. Should such a disruption occur, the deployers will have to be retracted when not in use.

Designing the deployers will be very challenging. It is important to note that much information can be gained from the designs of deployers, which can be used in other space experiments scheduled to fly onboard the space shuttle. In the present test matrix, approximately 260 bubbles or droplets will be deployed. If a crew member had to be involved every time a bubble was deployed, only a small section of the test matrix could be performed within a 90-day increment, because the crew's time is limited. Therefore, in order to maximize the science return from the experiment, the deploying mechanism should be automated.

Other factors that need to be considered in designing the deployers are injection retraction, which will permit various cell heights to be obtained; precise control of the air or methanol released, so that bubbles or droplets meet the 0.1- to 10-mm diameter size requirement; a method to force the bubble or droplet off the deployer that will counteract the effects of surface tension; a technique to minimize the velocity imparted to bubbles or droplets by the deployer, so that the bubble or droplet velocity measured is reflective of its flow; and a method for accurate placement of a bubble or droplet, so that meaningful data about the thermocapillary flow around the bubble can be realized with the laser light-sheet technique. If placement dependability in bubble or droplet deployment were achieved, the laser-light-sheet realignment capability would no longer be required.

**Bubble or droplet retrieval.**—Automatic bubble or droplet retrieval, a fill-and-drain system, and variable-height test cells are functional capabilities that are necessary to complete the science-designated test matrix within the 90-day Freedom Station duty cycle. The bubble or droplet-retrieval system will help satisfy the requirement that no more than 0.1 percent ( $10 \text{ mm}^2$ ) of the heated copper plate surface area may be covered by bubbles or droplets. Retrieval will also reduce the experiment run time needed to establish desired temperature gradients by reusing most of the host fluid between retrieval

cycles. Automated retrieval will replace the time-consuming, manual hunt-and-find techniques using syringe needles, as is done in Earth-based laboratories.

Since the retrieval system is not expected to completely clean bubbles and droplets from the test fluid, the fill-and-drain system will provide backup cleanout of all remaining bubble/droplets at the end of each designated test-cell height and deployment sequence. Without bubble/droplet retrieval, the test matrix of 260 bubble/droplet deployments would require 120 test-cell changeouts, or 120 host-fluid fill-and-drain heat cycles. Both of these options would significantly increase experiment run times.

The bubble or droplet-retrieval system is expected to be one of the most difficult experiment systems to design. As previously mentioned, it is also one of the most critical systems in the design of the experiment. One possible retrieval technique would sweep or push accumulated bubbles and droplets across the heated copper plate for removal through suction holes in the hot plate, as shown in figure 35. Automatically driven wipers would be actuated and retracted through the test-cell sidewall at the three locations necessary to sweep the hot-plate at the 4-, 7-, and 10-cm cell heights. When not in use, the wipers would be flush to the sidewall in order to allow the hot plate to travel. The wipers would be designed so as not to disturb the side thermal-boundary conditions. Positioned near a sidewall, the hot-plate suction holes would not affect the uniform temperature across the top plate.

In another design concept many small retrieval holes would be distributed over the entire hot plate. However, there is concern that the temperature uniformity would be affected if this method were employed. In addition, seed particles could clog the holes.

During retrieval, bubbles, droplets, and test fluid will enter the fill-and-drain system for storage. Since some fluids will be removed with the bubbles/droplets, replacement fluid will be introduced through the fill-and-drain system, if necessary, to maintain a constant test-cell height.

**Imaging techniques.**—Schlieren and particle-imaging velocimetry will be used to obtain temperature and flow information.

**Schlieren:** Rainbow (color) schlieren will be used to acquire data about the gradient of the index of refraction from inside the test fluid volume. From these data, the temperature field around and inside the bubble or droplet can then be extracted. The gross velocity and size of the bubble or droplet can also be measured because of the well-defined interface between the bubble/droplet and the host fluid. Temperature and gross velocity data are acquired concurrently with one camera, preprocessed, and stored. Owing to bandwidth constraints, video data cannot use telemetric links in real time. A schematic of the diagnostic system is shown in figure 36.

The use of the schlieren assumes a symmetric temperature field about an axis that intersects the bubble/droplet and is normal to the hot and cold plates. This assumption is true of

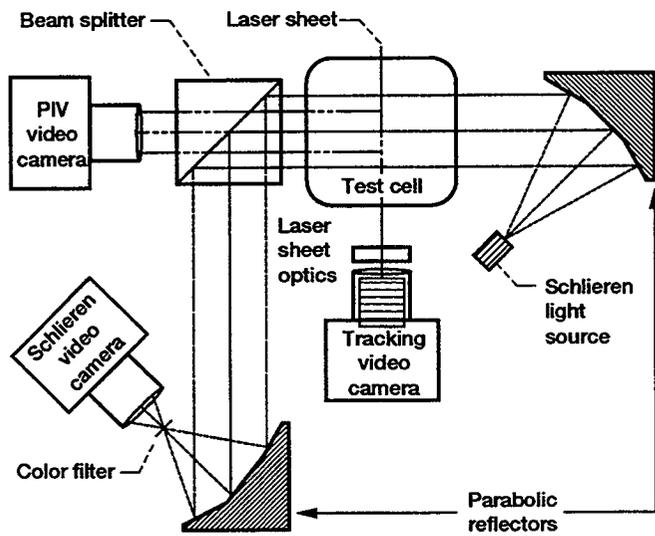


Figure 36.—Diagnostics concept.

any nontomographic technique, since a volume is being mapped into a two-dimensional imaging device.

The Facility utilizes a fiber-optic cable to supply the white-light source to the experiment for the schlieren optical system. The cable crosses the containment enclosure through quick disconnects. This light source is then conditioned to appear as a point source for the schlieren optics. All required optics between the light source and the video camera are specifically designed to optimize data quality and experiment volume. The volume required for schlieren optics is minimized by using mirrors in a folded design.

The Facility provides support for camera control, image acquisition, preprocessing, and storage. To limit mass, volume use, and heat dissipation, only the camera head is located within the experiment containment enclosure.

The color video camera for schlieren imaging requires a frame rate of 500 frames/sec and an imaging area of 450 by 425 pixels; the frame rate is determined by the bubble/droplet velocities expected to be encountered. The science requirements mandate that the video camera be able to resolve an image as small as 10 percent of the bubble/droplet diameter being viewed and be able to view the bubble/droplet as it travels a distance of at least 7.5 times its diameter. Because the bubble/droplet sizes vary between 0.1 and 10 mm, the resolution requirements are 0.01 to 1 mm. This requires that a variable field-of-view be provided. The field-of-view for the larger bubbles/droplets could be as large as 8 by 8 cm and still provide 0.165 mm of resolution. For the small bubbles, a 4- by 4-mm field-of-view would give the required resolution of 0.008 mm.

In order to achieve these fields-of-view, at least one lens change will be required. The lens change may, in turn, necessitate relocating the camera head to compensate for the different lengths of lenses. In addition, because of the change in cell heights and the reduction of the field-of-view for the small bubbles, the camera head will need a translation stage

to relocate the center of the field-of-view on the expected travel path of the bubble/droplets.

The color video camera must be flagged as a development issue. The required frame rates and resolution are in reach of current technology; however, the need has not been great enough for a manufacturer to offer such a camera. If obtaining a color video camera with these specifications becomes a problem, black-and-white or knife-edge schlieren techniques could be used.

Another option is to use a film camera instead of video. The advantage of film is that it gives increased resolution for a given field-of-view, and the resolution requirements might be possible with a fixed field-of-view. Some of the disadvantages of film are (1) greater light intensity is required; (2) telescience cannot be used for transmitting data to the ground, and (3) the changeout and storage of film would be necessary. But the major disadvantage of using film is its impact on volume and mass; the volume necessary for a film camera could be orders of magnitude above the volume required for video, and the mass of the film cartridges could severely affect the mass requirements for the experiment-specific hardware.

Other methods of measuring temperature fields were evaluated, but they were deemed less suited to this application. Interferometric methods require a higher degree of mechanical mounting stability and an additional laser source, and IR imaging is capable of making only surface temperature measurements, not those in the locality of the bubble/droplet.

*Particle-imaging velocimetry:* Particle-imaging velocimetry (PIV) is used to image internal and external thermocapillary flow fields. This technique, in which a laser light sheet illuminates a seeded fluid, makes visible only the particles in a thin plane intersecting the bubble or droplet. A computer then tracks these particles and maps the flow field velocities. The diagnostic concept is shown in figure 36, and the orientation of the laser mirror and lens is shown in figure 37.

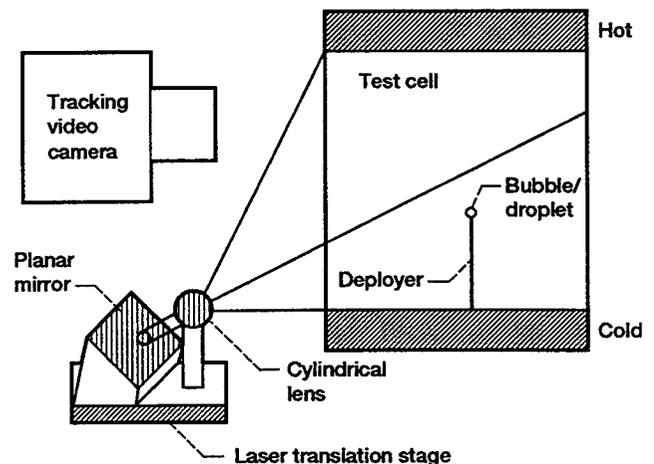


Figure 37.—Laser-sheet tracking.

Aligning the light sheet properly on the bubble or droplet, may present a problem in space. A tracking mechanism could be employed to ensure alignment during the initial bubble/droplet deployment period. The tracking mechanism used to ensure that seed particles stay in the illuminated plane could be disabled after the deployment transients have subsided. See the **Laser Light-Sheet Realignment** section, for further details of this potential system.

The Facility will supply a laser for the experiment via a fiber-optic-beam delivery technique. The fiber-optic cable crosses the containment enclosure through quick disconnects, thereby limiting power dissipation and mass within the experiment enclosure and using less experiment volume.

Light from the Facility laser is transformed into a 100- $\mu\text{m}$ -thick sheet by suitable optics. The plane of the light sheet slices through the test-cell fluid orthogonal to the viewing plane, bisecting the bubble or droplet (fig. 36). For internal flow visualization, a distinction must be made between bubbles and droplets. When droplets are in the host fluid, both the droplet and host fluid are seeded. This allows both internal and external flow patterns to be examined. For droplets less than 1 mm in diameter, the internal flow visualization requirement is omitted. When bubbles are used, only the host fluid is seeded; the internal flows are not examined.

The Facility supplies support for camera control, image acquisition, preprocessing, and storage. To limit mass, volume use, and heat dissipation, only the camera head is located within the experiment containment enclosure. The black and white video camera requires a frame rate of 500 frames/sec and an imaging area of 512 by 485 pixels. It is capable of producing 256 levels of grey, and because it is black and white, it provides slightly better resolution than does the color camera for the schlieren. The resolution requirements for the PIV technique are the same as previously discussed for the schlieren. A video camera with a remote head is still a development issue, but lower-frame-rate cameras with remote heads are available. Although a nonremote-head camera could be used, it would require more volume in the experiment rack.

**Laser light-sheet realignment.**—Of the three science parameters that are measured in this experiment—thermocapillary flow, temperature fields, and gross bubble/droplet velocity—it is the thermocapillary flow data that will be lost if the bubble/droplet motion is not linear. Unless the bubble/droplet remains within the laser light sheet, the surrounding seed particles will not be illuminated and the fluid flow will not be visible. If a uniform temperature gradient and accurate bubble/droplet deployment are achieved, the bubble will travel directly towards the hot plate. With appropriate insulation on the sidewalls, a high degree of temperature uniformity on the hot and cold plates, and strict control of the residual fluid motions, we assume that a uniform temperature gradient can be attained. However, there is concern that accurate bubble/droplet deployment might not be achievable.

If accurate deployment is not possible, the laser sheet could be positioned on the bubble or droplet after deployment. An automated realignment system would have to track the motion of the bubble or droplet and provide input to a laser sheet repositioner. Before thermocapillary flow data could be taken, the laser sheet would have to be locked into place, because the motion could cause a blurred image. Since this would add considerable complexity to the experiment design, it should be considered as a last resort solution to the potential problem.

One potential method of realigning the laser sheet is to use a video camera to locate the bubble/droplet and then use the video information to control a translation stage that repositions the light sheet. Some important features of such a design include a high response speed, alignment accuracy, and the ability to find the “center” of a nonspherical bubble/droplet.

**Quasi-steady acceleration alignment.**—The experiment will be mounted in the quasi-steady acceleration vector alignment system provided by the FP/DF. Although the desired orientation for the residual quasi-steady acceleration vector is normal to and pointing towards the cold plate, it will change by a maximum of  $26^\circ$  over an orbit. The science requires the magnitude of the quasi-steady acceleration to be below  $1.4 \times 10^{-6} g/g_0$ ; however, this level will not be available at all rack locations within the labs. The Facility will furnish two triaxial accelerometers mounted to the frame to provide six-degree-of-freedom acceleration information.

**Containment enclosure.**—The experiment will have to be placed in the facility-supplied containment enclosure because the alcohol could ignite and cause harm to the crew.

## Adiabatic Multiphase Flow Experiment

**Science background.**—Multiphase flow is defined here as the simultaneous flow of immiscible liquids or liquid and vapor (gas) mixtures in a conduit of some geometry. There are applications with heat transfer (flow boiling and condensation) and without heat transfer—for single, as well as multi-component flow. Examples of such adiabatic systems that are often studied are air-water and oil-water mixtures.

One of the basic questions in multiphase flow is how the two phases orient themselves with respect to the conduit walls and to each other. Depending on the experimental conditions, the nature of the flow can vary widely. Different gas-liquid flow regimes that exist for one-g flow are given in figure 38. Similar patterns exist for liquid-liquid systems, with the one exception being the occurrence of flow inversions, for both dispersed and continuous phases. For particular fluid pairs and conduit dimensions, these flow regimes can be delineated by the relative value of the flow of one phase to the flow of the second phase. In addition, various flow regimes owe their existence to the gravitational environment (e.g., stratified flow). In a microgravity environment, flow regimes have been identified as bubbly, slug, or annular.

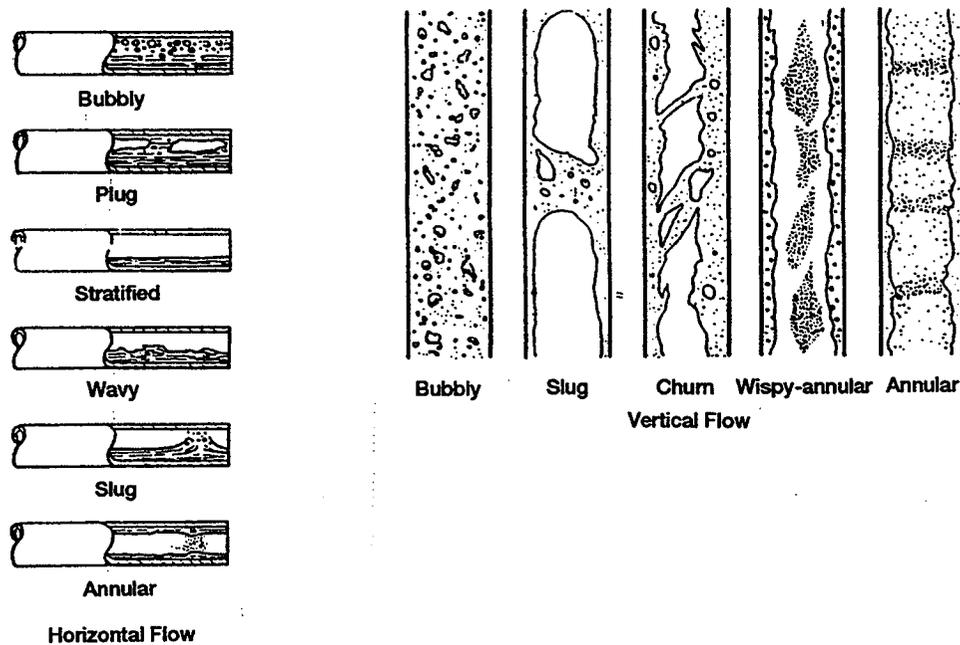


Figure 38. —Flow regimes for horizontal and vertical two-phase flow.

Being able to identify the appropriate flow regime is important because the flow regime is the basis for predicting a few of the parameters of interest (such as the heat transfer coefficient and the pressure gradient). The system variables determining flow regime include total mass flow, flow quality, tube diameter, fluid properties,  $g$ -level, and perhaps to some extent, pressure. Numerous attempts to predict flow regimes have been made in the past by using various combinations of the previously mentioned system parameters. An example of a one- $g$  flow map is given in figure 39. The key to producing such a map is being able to define the flow regime transition lines. Although flow transition boundaries are known to be a function of  $g$ -level, flow regimes (and their transition boundaries) are ultimately characterized by film thickness, slug geometry, and frequency; bubble or droplet size, velocity, and radial distribution; and the interfacial wave structure.

Low-gravity, multiphase flow experiments (which are difficult to simulate in one- $g$ ) allow the study of basic mechanisms outside the influence of body forces. Some useful testing can be (and has been) accomplished with low-gravity ground-based facilities such as drop towers and low-gravity aircraft. Even so, there are still reasons for doing on-orbit experiments in this field. Longer tube lengths and larger diameters can be accommodated without the constraints of a drop package; this allows study of the effects of a variety of diameters while entrance effects are further diminished with the larger length-to-diameter ( $L/D$ ) ratios.

Longer low-gravity test time is another obvious benefit of space-based facilities over ground-based facilities. For future multiphase experiments with heat transfer, even the longest ground-based low-gravity test time available ( $\sim 20$  sec) would not be sufficient to permit flow equilibration. Ground-based

testing is sufficient for many adiabatic applications, but not all; some exceptions are studies of low-frequency slug-type flow and studies of flow rates that rapidly change, thereby resulting in transitions from one flow regime to another. These two issues (low-frequency slug flow and flow rate step change) emphasize the need for on-orbit experiments. In addition, low-frequency slug flow is representative of flow in the area of the slug-annular transition line. And by studying the effects that rapid changes in the flow rates have on flow characteristics, a real concern in the design of multiphase flow systems for technological applications is addressed.

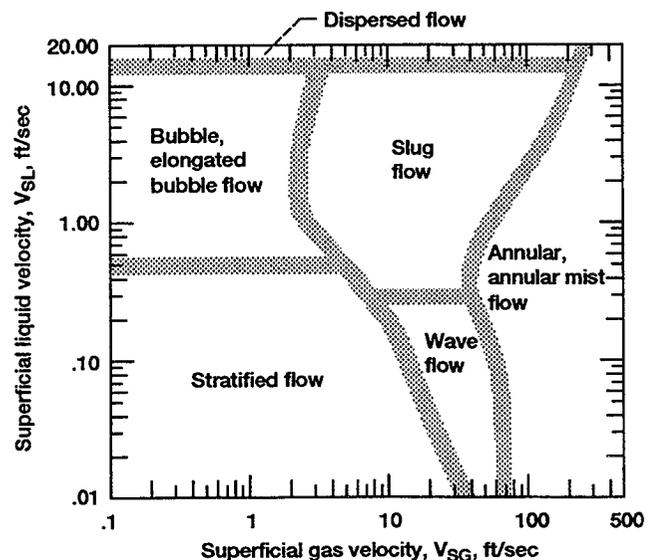


Figure 39.—Example of one- $g$  flow map for horizontal flow (ref. 4).

**Experiment description.**—This experiment will focus on adiabatic two-component, two-phase flow. It is seen as a first step in a larger program wherein single-component, two-phase flow with boiling and/or condensation would also be studied. The primary objectives of this experiment, however, are to study its flow characteristics and make the appropriate measurements under a variety of flow conditions; test pressures and temperatures will also be monitored. The emphasis will be on experiments requiring tests of 0.5 to 5.0 min duration.

The conceptual design for this experiment is described in detail later in this document, but briefly, the main components include the test section, phase separator, accumulator, mixer, and storage vessels. The phase separator is a key component since it allows real-time liquid recycling capability, thereby reducing storage requirements.

The phase streams will be routed and metered separately prior to entering a fluid mixer, whose output will be delivered to the test section. Superficial gas velocities will range from 1 to 25 m/sec and liquid velocities, from 0.1 to 1.0 m/sec. The slug to annular phase transition will be emphasized (discussed in detail later). The superficial velocity of the liquid in meters/second is defined as

$$j_f = Q_f/A$$

where  $Q_f$  is the volumetric flow rate ( $m^3/sec$ ) of liquid only, and  $A$  is the full cross-sectional area ( $m^2$ ) of the conduit. The superficial velocity  $j_g$  for the gas phase is similarly defined.

**Science requirements.**—The science background and a short description of the experiment have been given; now the detailed science requirements for the Adiabatic Multiphase Flow Experiment will be presented. Various subsections will be discussed, including fluids and fluid properties, fluid handling, test section description, thermal requirements, data and optical requirements, and finally, gravitational requirements.

**Properties of test fluids:** In addition to the baseline air-water combination, three other gas-liquid fluid combinations are being considered for this experiment; in these, either the surface tension or the liquid viscosity will be varied. The sur-

face tension could be varied by adding a surfactant to the water, and the viscosity, by creating a water-glycerin mixture. Other methods of varying surface tension, viscosity, and relative densities could also be employed. Some of the fluid properties that are relevant to describing the phenomena of interest are density, dynamic viscosity (for both phases), and interfacial surface tension. Test-section pressures will range between 1 and 3 atm and will be at ambient temperatures ( $\sim 25^\circ C$ ). There is some utility in being able to take advantage of the plumbed nitrogen ( $N_2$ ) gas source onboard Freedom Station. However, being able to test with both  $N_2$  and a higher density gas, like argon, will allow the study of the effect of gas density, shear, and droplet entrainment on annular flow. Table VI gives expected values of representative properties.

Similar experiments can be run with immiscible liquids such as water and silicone oils. Viscosity and surface tension variations, likewise, can be accommodated by changing the mixture ratio and amount of surfactant, respectively. Pressure and temperature ranges can be the same as for the gas-liquid case. Liquid-liquid systems, however, have significantly smaller density ratios, and thus their velocity gradients at the interface are also less.

**Fluid transfer and handling:** Fluid handling encompasses several tasks for this experiment: liquid fluid storage, fluid mixing, phase separation, and possibly, liquid-gas recycling. There are several possible methods for handling effluent: one is to dump effluents, another is to recycle either one or both phases. A related question is whether to recycle in real time or periodically between test runs. Although science requirements are not directly concerned with these issues, the flow rates and the number of test runs contemplated seem to indicate that recycling the liquid phase in real time is necessary. Whichever method is chosen, a constant flow rate, temperature, and pressure must be ensured at the inlet to the test section. This translates to constant conditions upstream of the mixing device. Furthermore, the liquid and gas streams should be of equal temperature ( $\pm 0.5^\circ C$ ) prior to entering the mixing device for these adiabatic tests.

Between fluid changeouts, it will be necessary to flush the system prior to filling the loop with new liquid, to ensure minimal contamination of the new fluid. This will be especially true following the water-glycerin and water-surfactant runs; two flushes with pure water, followed by two nitrogen-purge vents should be sufficient. A more complete picture of loop startup and shutdown is given later in this document.

**Test section description:** The main test section for this experiment is a straight conduit whose hydraulic diameter can range from 5 to 70 mm. Various types of cross-sectional geometries will be of interest, including circular, rectangular, annular, and packed-bed configurations. In addition to constant cross sections, gradually narrowing or expanding cross sections, as well as abrupt contractions and expansions, will be of interest. Rather than having to perform a test-section

TABLE VI.—PROPERTIES OF TEST FLUIDS—REFERENCE DATA FOR GAS-LIQUID TESTS

Fluid	Density, $g/cm^3$	Dynamic viscosity, cP	Interfacial surface tension, dyne/cm
Water	1.0	0.89	73.0
Glycerin	1.26	945	63.4
Water-glycerin mixture	1.12	5.04	69.9
Nitrogen gas	.0012	.017	-----

changeout in order to switch diameters or geometries, the design concept proposes running parallel lines so that flow could be routed to the appropriate conduit. Such a design feature would permit the study of parallel-flow instabilities, which is also of interest. If the larger diameter test sections are used, flow visualization will be easier and the influence of surface tension relative to inertial or gravitational forces will be reduced. One disadvantage of the larger diameters is the larger concomitant lengths, which are a problem from a design point-of-view. However, the longest possible straight-run test section is desirable so that entrance mixing effects can damp out by the time final data are taken. An L/D ratio of 100 is desirable, but may not be possible for larger diameters.

*Thermal requirements:* Both fluid streams will be near ambient temperature ( $\sim 25$  °C) and will enter the mixer at equal temperatures ( $\pm 0.5$  °C). It will also be necessary to ensure constant temperatures conditions to the mixer loop designed to recycle fluid.

*Data requirements:* The types of data required and the methods of acquiring them are as follows:

*Pressure.* The test section will be instrumented with absolute-pressure transducers that can measure pressures in the range of 1 to 3 atm, accurate to  $\pm 0.5$  percent. These pressures will be measured at the test-section inlet and at approximately 12 in. from the test-section outlet. Differential pressure transducers will also be on line to measure pressure differentials over the final 1 ft and final 3 ft prior to the outlet pressure transducer. We anticipate using pressure differential transducers with the following ranges: 0 to 0.05 psid; 0 to 0.5 psid; and 0 to 2.0 psid (all accurate to  $\pm 0.5$  percent full scale).

*Temperature.* Inlet and outlet test-section temperatures will be taken at approximately the same location as the absolute pressure measurements are to be taken (at the beginning of the test section and 12 in. from its end).

*Mass flow.* Mass-flow-rate measurements will be taken on each fluid stream leading into the mixer. Knowledge of these flow rates is necessary to correlate the relevant flow characteristics. The expected ranges of superficial velocity (a way of expressing mass flow) are 0.1 to 1.0 m/sec for the liquid streams, and 1 to 25 m/sec for the gas (for a 5.1-cm tube); an accuracy of 0.1 percent is required on these mass-flow-rate measurements.

*Void fraction.* Void fraction is similar to mass quality in that it measures a gas fraction. However void fraction is a measure of gas volume-to-total volume; it can be a function of position and can range from all liquid, void fraction = 0, to all gas, void fraction = 1. A relatively small mass quality ( $\sim 0.01$ ) gives a significant void fraction ( $\sim 0.5$ ). A conductance or capacitance probe may be used to measure void fraction.

*Film thickness.* There are various flow characteristics of interest here. In the case of the bubble/droplet flow, the size, velocity, and distribution of the bubble/droplets are

important. Where slug flow exists, vapor-bubble and liquid-slug shape and frequency are important. For annular and slug flow, film thickness and interfacial wave structure are relevant. Bubble sizes of 0.5 to 50.0 mm could be expected over a variety of flow rates and diameters. For slug flow conditions, the vapor-slug length exceeds its diameter and can be several meters long. These data should be characterized at several positions in the test section outlets and at positions in between. We anticipate that these measurements may be taken by instruments similar to those used for making void-fraction measurements.

*Fluid properties.* There are three fluid properties of interest with respect to this experiment: interfacial tension, viscosity, and density. For several reasons, these values should be measured periodically throughout the 90-day duration of the experiment. The main reason is to reduce the level of uncertainty in determining interfacial tension and viscosity. It is possible that correlations relating surfactant concentration to interfacial tension, and percent glycerol to viscosity could be constructed in one-g; however, such an approach would still require an on-orbit concentration measurement of some kind, thereby introducing a measurement error as well as correlation error. Thus, measuring the desired quantity directly would be best.

In measuring interfacial tension in one-g, gravity is key to being able to produce the desired quantity through some physical relationship. In order to be able to make this measurement on orbit, other methods must be devised.

*Optical requirements:* Simultaneous full-length test-section viewing will not be required. Either conventional tubing with viewing ports or full-length transparent tubing would be satisfactory. The two recommended port positions (or viewing positions) are immediately downstream of the mixing device and 12 in. from the end of the test section. Other viewing positions (ports) should be possible. Each viewing window should be 12 in. long, accommodate two orthogonal views, provide corrections for refraction, be backlit, and include a scale within the field-of-view (preferably in the same optical plane). The two cameras should be synchronized. Occasionally, there will be a need for strobe lights capable of freezing action at  $10^{-4}$  sec. Various frame rates in the range of 100 to 500 frames/sec should be available. Resolution of 2500 by 2500 pixels in one view and 2500 by 5000 pixels in the other is satisfactory. The visual data will enable the visualization of flow patterns, slug shape, slug frequency, and bubble distribution.

*Gravitational requirement:* Unlike most other fluid physics experiments, multiphase flow has no particular requirement that the g-vector be oriented in any particular fashion. The only requirement is that the acceleration be recorded in three directions orthogonal to the test section. Because of the possibility of vibrations resulting from severe slugging conditions, another set of accelerometers in the vicinity of, but isolated from, the experiment should be available to record Freedom Station background vibration levels. In multiphase

flow, three forces in relative competition help to determine the characteristics of the two-phase flow: inertia, gravity, and surface tension. Nondimensional parameters that express various ratios of these forces can be defined; the two most important are the Bond ( $Bo$ ) and the Weber ( $We$ ) numbers, expressed as

$$Bo = \text{gravity/surface tension} \\ = \rho g L^2 / \sigma$$

and

$$We = \text{inertia/surface tension} \\ = \rho V^2 L / \sigma$$

where

- $\rho$  liquid density, g/cm<sup>3</sup>
- $\sigma$  surface tension, dyn/cm
- $L$  reference length, cm (e.g., tube diameter)
- $V$  reference velocity, cm/sec
- $g$  local acceleration, cm/sec<sup>2</sup>

Three hydrodynamic regimes are defined on the basis of  $Bo$  and  $We$  values. If  $1 < Bo > We$ , a gravity-dominated regime is defined. If  $1 < We > Bo$ , an inertia-dominated regime is defined. And finally if both  $Bo < 1$  and  $We < 1$ , a capillary-dominated regime is defined. Gravity- and inertia-dominated regimes are easily generated with one-g apparatus; capillary-dominated regimes are not. Typically, such a regime implies scales of very small length (e.g., tube diameters of the order of 1 mm), or impractically high surface tensions (i.e., of the order of 100 dyn/cm). Low gravity makes feasible the exploration of the capillary-dominated regime; therefore, concentrating on low-gravity efforts in this regime makes sense. Consider the following example:

$$\sigma/\rho = 70 \text{ cm}^3/\text{sec}^2 \text{ (typical of air/water)} \\ L = 2.5 \text{ cm} \\ V = 2 \text{ cm/sec} \\ g = 0.9807 \text{ cm/sec}^2 \text{ (i.e., } 10^{-3} \text{ g)}$$

The resulting  $Bo$  and  $We$  numbers are 0.09 and 0.14, respectively. It is of scientific interest to consider not only cases wherein  $Bo$  and  $We$  are less than unity, but also cases wherein they are equal to and slightly greater than unity; studying these cases would help to characterize flow behavior in the transition zones.

**Proposed test matrix:** In the following detailed discussion of the conceptual design of the experiment, certain assumptions were made regarding the scope of the effort to be covered. This was done to have reference points from which to evolve a design and does not necessarily imply that a design cannot satisfy a broader test matrix. In summary, these assumptions were as follows:

- Test sections would have constant circular cross section
- Test section diameters would be 2.5 and 5.1 cm
- Gas-liquid two-phase flow would have fluid choices of water, water and glycerin, and water and surfactant; the gas choice would be nitrogen
- Steady-state and step-change runs would be made with one tube size for any given run
- Liquid-gas superficial velocity pairs would be chosen so as to better characterize the slug-annular flow transition boundary.

Concerning the last assumption, a proposed low-gravity flowmap (Dukler, ref. 4) was the basis on which superficial velocity pairs would be chosen. This flowmap and the proposed data points are given in figure 40. Steady state runs will be made at each of the three superficial liquid velocities (0.1, 0.25, and 0.6 m/sec) in conjunction with four, five, or seven superficial gas velocities, respectively. In addition, the figure indicates tests in which either the liquid or gas velocities will undergo a step change in value will be made; step changes will be in increasing and decreasing modes. The tests indicated in figure 40 (26 in all) will be repeated for a variety of fluid combinations, tube diameters (2.5 and 5.1 cm), and test-section pressures (ranging from 1 to 3 atm).

### Conceptual Design of Adiabatic Multiphase Flow Experiment

The main subsystems of the multiphase flow experiment have been identified as the test section, fluid management, thermal control, diagnostics, and environmental control systems. Figure 41 presents a block diagram of the various sub-

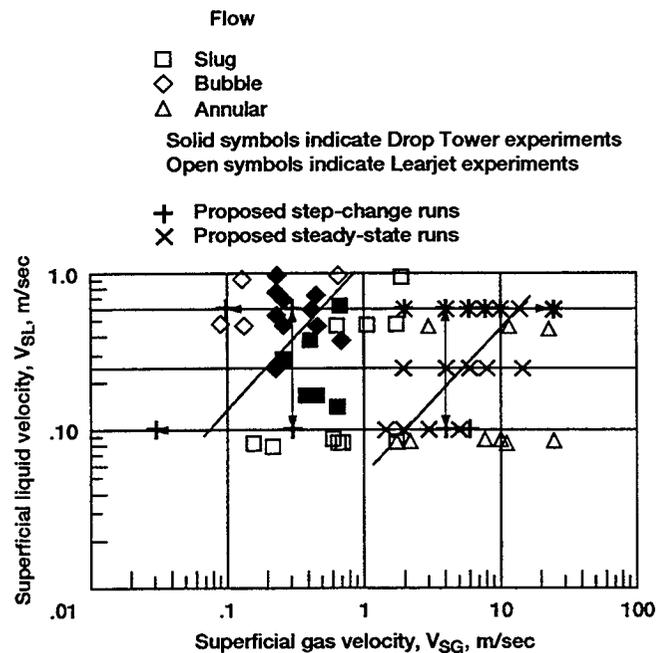


Figure 40.—Microgravity flow pattern map.

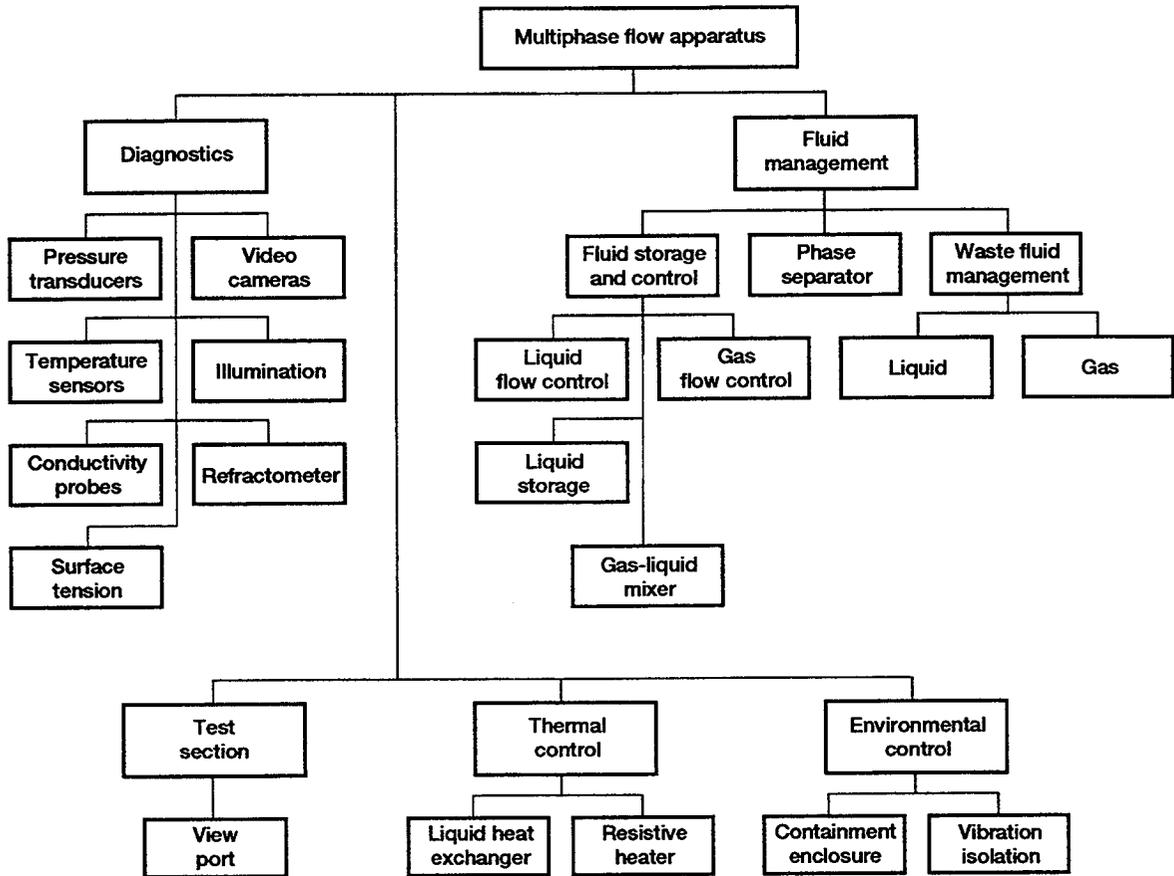


Figure 41.—Subsystems of experiment apparatus.

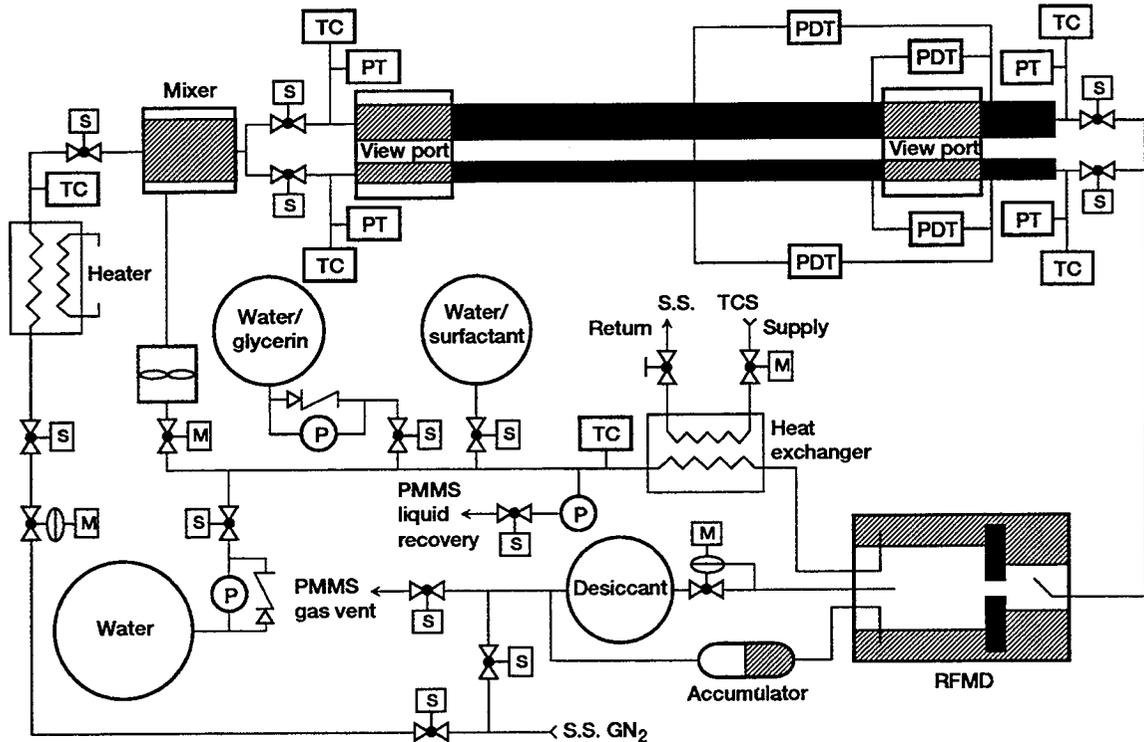


Figure 42.—Concept of Multiphase Flow experiment apparatus.

systems of the experiment apparatus. The experiment subsystems are described in detail in their respective sections.

Figure 42 is a conceptual drawing of the multiphase flow apparatus. This design has been limited to a subset of possible multiphase flow experiments, specifically, the case of adiabatic two-phase flow. Since the purpose of the design was to illustrate how this type of experiment could be accommodated in S.S. Freedom, the concepts presented may not represent the design that can best meet the science requirements. Future experiments will change the scope of the apparatus substantially; more elaborate heating and cooling devices and a variety of test-section geometries and section sizes are to be expected. An enlarged matrix of test gases and liquids will affect the design of the containment structure. Also, as our understanding of multiphase flow phenomena increases, so too, will the need for more elaborate diagnostics.

The constraint imposed by a 150-cm test section will have the greatest impact on the multiphase flow experiment. Because of the size of the experiment rack, only one rack can be transported into the USL module at a time. To solve the problems of integrating experiment hardware into multiple racks would exceed the level of effort required to conceptualize the experiment itself. Although we are not trivializing this constraint, it is left as a future exercise for a more detailed design.

**Test section.**—The design of the test section is of critical importance to the success of the multiphase flow experiment. Not only must the section provide containment capability for the flows circulating within it, but also, it must be designed so that perturbations are not introduced to the flow regime under observation. In addition, accommodations for diagnostic techniques, including visual observation ports, must be implemented.

As part of the flow loop, the test section is the first level of containment for the fluids used in the experiment. The initial test fluids (water, glycerin, surfactant, and gaseous nitrogen) could cause problems in the environment of space even though they are not considered hazardous materials. The test section must be designed to prevent leaks.

From an engineering viewpoint, stainless steel is the preferred material for test-section construction. The diagnostics, however, require optical-quality viewing ports, and thus, a multipiece test section is needed. The multipiece construction would also facilitate the installation of the test section into an experiment rack and enhance future in-orbit changeout capability. The entire test section could be constructed from a single piece of transparent material, but the difficulty in obtaining the required optical characteristics and ruggedness would outweigh any benefit.

A large test-section length-to-diameter ratio would allow the effects of inlet conditions to be damped-out well before the flow nears the outlet where data are being acquired. The

test section must be designed and constructed so as not to affect the experiment by introducing unwanted effects due to its multipiece construction.

Initially a cylindrical test section will be used for these adiabatic cases. To improve the test matrix, two test sections of different diameters will be provided. These sections will be mounted in parallel along the diagonal of the experiment rack, thereby giving the longest possible test-section length for the given rack dimensions. Inside diameters of 5 and 2.5 cm have been chosen for the sections, both of which will have a fixed length of 150 cm. Only one section at a time will participate in a test, although this is not a physical restriction. Valves will be located at both inlets and both outlets to enable automated selection of the test section.

The cylindrical test sections in the viewing port will be made of an optical-quality, transparent material. Four planar windows of the same material will form a box around the center sections. Fluid that matches the index of refraction of the windows and test sections will fill the space inside the box. Matching the index-of-refraction will reduce internal reflections and the edge effects from the curved test-section walls and, thus, improve the flow-imaging capability. Two viewports, one at the inlet and one centered at 30 cm from the outlet, will be required and will accommodate orthogonal viewing.

The test section will also allow access for pressure transducers, temperature sensors, and capacitive or conductivity probes. This instrumentation is necessary for complete diagnostic capability.

**Fluids management.**—The fluids management system for the multiphase flow experiment describes three major operational functions: phase separation, fluid storage and control, and waste fluid management.

**Phase separator:** Because of liquid delivery requirements and the storage volume needs, real-time recycling of the liquid phase is desirable. For real-time recycling to occur, active phase separation must be done. The phase separator and loop pump can be separate entities; however, we propose that these two functions be integrated into one unit. The rotary fluid-management device (RFMD) can provide pump capability for the flow loop as well as active phase separation through the use of centrifugal forces.

Several units of this type have been designed and built for the Freedom Station advanced development program. An RFMD was included both in the design of the Freedom two-phase thermal bus loop and in the design for one of the solar dynamic power options (organic Rankine cycle). These units operated with two-phase ammonia and toluene, respectively, as the working fluids. The RFMD performed five specific functions for these station systems:

- Active separation of fluid-phase
- Provision for pump flow capability
- Accommodation of changes in fluid inventory

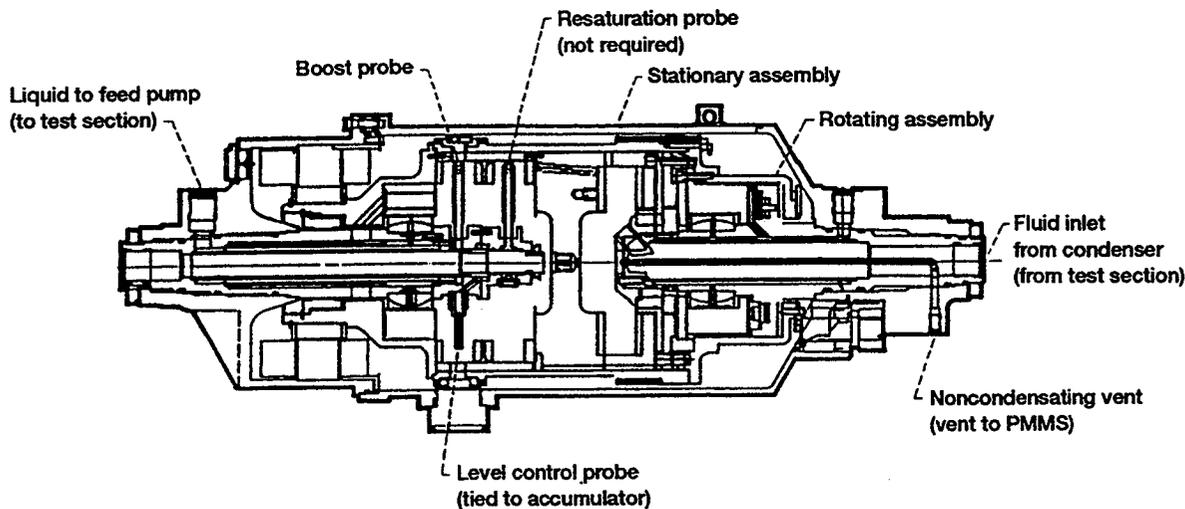


Figure 43. —Rotary fluid-management device (RFMD).

- Maintenance of saturated fluid state
- Venting of noncondensable gases

A drawing of the RFMD is shown in figure 43. The RFMD is an internally rotating vessel that induces liquid flow into the stationary pitot probes (boost probe); the outer housing does not spin. A static pressure probe (level control probe), tied to an accumulator in conjunction with a back-pressure regulator that is tied to the noncondensing vent, maintains a constant liquid level within the RFMD.

For reference purposes only, the basic data for the toluene-designed RFMD are as follows:

Mass, kg .....	36
Power, W .....	750
Length, cm .....	60
Diameter, cm .....	18
Nominal pump speed, rpm .....	3300
Fluid delivery, kg/hr .....	1000

In order to use this RFMD in the multiphase flow experiment, the design would have to be modified; however, the basic character of the device would remain intact. The greatest difference encountered would be the different operating fluids; this should present no major design problem (perhaps the aluminum surfaces that would be in direct contact with the water would have to be anodized). Another difference would be that a binary-fluid system would be in force, whereas in previous RFMD designs one-component, two-phase fluids were applicable; again, this should present no major problems. In fact, the design could be simplified since a saturation probe (whose sole function is to spray the vapor case with atomized liquid droplets, thereby saturating the vapor) would no longer be necessary. Previous designs delivered liquid at a maximum rate of about 6 gal/min; the modified design would have to deliver at a maximum flow rate of

20 gal/min. The increased flow rate is attainable by altering the pitot-probe pitch radius, the pitot-probe hole diameter, the speed (rpm), and the number of boost probes. Accommodating these higher flow rates should easily be within reach of the technology for this device.

There are two issues that need to be addressed with regard to the RFMD. In operating this device with the water-glycerin solution, separation of the glycerin from the water is not desired. The certainty that this will not occur in the RFMD, whose effective g-level is 200 g, must be assured, or else the delivery of a homogeneous solution to the test section would be more difficult. The second issue relates to how water vapor in the gas phase is handled in the RFMD. There should be no water vapor in the gas effluent from the device. It must be removed before venting to Freedom Station.

*Fluids storage and control:* The operating capabilities described here include storage of three test liquid mixtures, flow control of the test liquids and of one gas ( $\text{GN}_2$ ), and two-phase mixing of a liquid mixture and gas. The capability to store gas is not required.

*Liquid storage.* Storage is provided for three liquid mixtures that will be used in the two-phase flow testing apparatus and for two of those liquid mixtures that will be retrieved subsequent to testing. Liquid storage capacities are water, 6 gal; water containing 50 wt % glycerin, 3 gal; and water containing 5 wt % surfactant, 3 gal. The minimum combined rack volume needed to store these three mixtures is approximately 1.7 ft<sup>3</sup>, which is 4 percent of the 42.2 ft<sup>3</sup> of the 80-in. U.S. Standard Equipment Rack or 4.4 percent of the 38.5 ft<sup>3</sup> of the 74.5-in. U.S.–International Payload Rack.

The three liquid mixtures will be stored in flexible metal bellows, or bag liners, inside rigid external tank walls. In order to minimize ullage problems, these storage volumes will have sufficient expansion capability to receive and evacuate full liquid-mixture loads. This containment flexibil-

ity will be accommodated and/or controlled by external gas pressure.

The mixtures will be prepared in one-g (on the ground) to attain component ratio accuracy and will use sterile water and sterilized supply tanks to eliminate microbial growth during long-term ground storage. The ground-supplied sterile water used in this experiment will be distilled. Freedom Station ultrapure water was considered, but it was found to be unsuitable because of the leaching hazard of the deionized water.

During the on-orbit fill-and-drain procedure, the water, water-glycerin, and water-surfactant storage tanks will deliver their liquid mixtures to an evacuated experiment test apparatus. After their respective test sequences, only the water and the water-glycerin tanks will retrieve their liquid mixtures—the water because it is to be used in later rinse cycles and the glycerin mixture because it is too highly concentrated to be accepted by the waste system. After the water-surfactant test sequence, which is to be performed last, the mixture will be drained directly to the ultrapure (reclaimable) water system.

There is no gas-storage provision in this experiment concept. The required quantity and flow rate of GN<sub>2</sub> will be directly supplied by the space station Process Fluids Distribution System, and it will be collected by the waste fluid (gas) management system. In the 90-day test interval, it is estimated that the experiments will consume as much as 1000 lb of GN<sub>2</sub>.

*Liquid- and gas-flow control.* The three test-fluid flow-control sequences that comprise this two-phase flow experiment will occur in the following order:

- (1) water and GN<sub>2</sub>
- (2) water-glycerin mixture and GN<sub>2</sub>
- (3) water-surfactant mixture and GN<sub>2</sub>

Since a relatively small quantity of surfactant will substantially reduce surface tension and thus could impact ensuing experiments, this mixture will be tested last to avoid problems arising from surfactant residue in the control loop.

The following is a general description of the liquid- and gas-flow control capability that is applicable for each of these sequences. As shown in the concept drawing (fig. 42), liquid flow will enter the gas-liquid mixer upstream of the test section. It then passes through the test section, a phase separator (the RFMD), and a heat exchanger before recirculating into the mixer. Freedom Station-provided dry GN<sub>2</sub> will simultaneously enter upstream of the gas-liquid mixer and pass through the test section, the RFMD, and then a desiccant, before delivery to the Freedom Station waste fluid management system, with no recirculation.

During the test sequence, an FP/DF computer will monitor liquid and gas temperature, pressure, and flow rate at points shown in the concept drawing. Using this information, the computer will then adjust pump power (RFMD) and flow valves in order to obtain target test-matrix conditions.

Upstream of the phase separator (RFMD), liquid flow will be driven by the RFMD's integral pumping capacity, which

will provide liquid superficial velocities from 0.1 to 0.6 m/sec in the test section. Test-matrix liquid-flow points will then be paired with various gas-flows (having superficial velocities from 1.5 to 25 m/sec). The combined flows will pass through the adiabatic test section to the RFMD.

Centrifugal phase separation in the RFMD is fundamental to establishing and maintaining various test-matrix flow parameters in the test section; refer to the section on phase separation for details on this operation. Downstream of the RFMD, the phase-separated liquid will be cooled by a heat exchanger; then the liquid mixture will be returned to the liquid-gas mixer in a continuous liquid-cycle sequence for a test duration of up to 5 min.

Unlike the procedure in the liquid-flow sequence, dry GN<sub>2</sub> gas injected into the apparatus test section will be provided by the Freedom Station and not from experiment-provided storage or recycling. Although this gas will not be recirculated, it will be dehumidified before being vented to the waste PMMS of Freedom.

*Gas-liquid mixer.* The purpose of the gas-liquid mixer is to deliver to the test section entrance the two-phase flow, while not forcing the phases into a particular flow configuration. Since the test sections are short (limited in length by the experiment-rack dimensions), the two-phase flow could not fully develop from an initial flow configuration that is greatly different from that which develops near the end of the section. The proposed mixer must deliver to a test rig a wide range of gas- and liquid-flow configurations. The design shown in figure 44 has been tested previously in low-gravity experiments.

As designed, the gas-liquid mixer injects liquid jets into annular gas flow through distributor holes in the inner cylindrical wall separating the gas and liquid flows. At high liquid flow rates, the liquid penetrates the gas flow to the opposite wall, flooding the inner tube. The resulting flow can be described as gas dispersed in liquid (e.g., slug or bubble flow). For relatively slow liquid flow, the liquid regime is along the wall, and the gas flow is in the core (i.e., annular flow).

Liquid jet flow in the mixer will be strongly influenced by liquid viscosity. Since the glycerin-water test fluid will have a viscosity up to an order of magnitude larger than the water alone, the aqueous glycerin-gas mixer may have to be sized differently from the water-gas mixer. For the complete test sequence, several mixer sizes may have to be provided, along with a means of interchanging them.

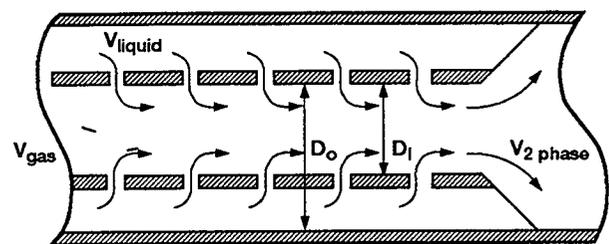


Figure 44.—Gas-liquid mixer.

*Waste-fluid management:* The waste-fluid management system provides the capability to reuse and/or dispose of fluids used in the multiphase flow experiment.

*Waste-liquid management.* On completion of the test sequence with water and GN<sub>2</sub>, the single-phase water is to be returned to the 6-gal storage tank. This will be done by using the RFMD pump, a tank-dedicated return-flow pump, and a controlled volume inside the storage reservoir. The storage-reservoir volume is controlled by adjusting the pressure between the rigid reservoir walls and the flexible bellows. The 6 gal of available water will be used later for rinsing the flow loop after the water-glycerin test sequence.

After the water-glycerin and GN<sub>2</sub> test sequence, the separated water-glycerin liquid will also be returned to its supply tank, in the manner previously described. There, it will be held for downloading on the space shuttle because the heavy glycerin content (>5 wt %) precludes water reclamation by Freedom Station. The 6 gal of storage-tank water will be used for two rinse cycles of the test apparatus. After each rinse cycle, the rinse-water and glycerin-residue (≤ 5 wt % glycerin) mixture will be pumped to the Freedom ultrapure water reclamation system.

A flow-loop drain sequence, which will be necessary for changing the liquid mixtures under test, promises to be a complex procedure in microgravity. Initially, the RFMD with its pumping capability will direct the liquid to the Freedom water reclamation system. However, at some point, using the RFMD will become physically impossible, and a separate pump must then be used to drain the flow loop. A more detailed analysis of this procedure and its feasibility in microgravity needs to be undertaken.

After the two rinse cycles following the completion of the water-surfactant and GN<sub>2</sub> test sequence, the separated water-surfactant liquid (≤ 5 wt % surfactant) will be pumped to the Freedom ultrapure water reclamation system.

*Waste-gas management.* The gas effluent from the RFMD will not be recirculated in the experiment and must be disposed of outside of the experiment rack. The GN<sub>2</sub> effluent will be directed to the Freedom PMMS, which requires the gas to be free of contaminants and to be dried to a low-humidity level (to be determined).

The waste gas, once separated in the RFMD, will be at the temperature of the phase separator and may be saturated with water vapor. In addition, a small concentration of glycerin vapor (boiling point, 29 °C) from the aqueous glycerin runs will be present in the waste GN<sub>2</sub>; minute amounts of surfactant may also be present in gas effluents from experiments using surfactants to modify the gas-liquid surface tension. All of these contaminants are unacceptable to the Freedom vent system and, therefore, must be removed.

In the experiment-concept drawing (fig. 42), downstream of the RFMD there is a desiccant container in the waste-gas line. The undesired species are stripped from the GN<sub>2</sub> effluent when the gas flows through a bed of adsorbent pellets. An efficient desiccant for adsorbing polar molecules (such as

water and glycerin) is silica gel, which, while drying a humid gas at ambient saturation, can hold up to half again its weight in adsorbed water. Since the effluent gas will contain less than 2 wt % water vapor, large amounts of desiccant will not be required.

The design of the desiccant system requires that the GN<sub>2</sub> pressure-drop through the unit be small, but sufficient to move the gas through the pellet bed at the rate needed to keep the two-phase test flow at steady state. The pressure upstream of the desiccant unit must be maintained at a level such that the gas pressure in the gas-liquid mixer never exceeds the liquid pressure there.

*Thermal control.*—The thermal requirements for the adiabatic experiments specify that both gas and liquid streams enter the mixer within 0.5 °C of each other and at approximately ambient temperatures (i.e., 25 °C). Both streams will be thermally conditioned to achieve the required temperature level. Upstream of the mixer, the input gas will be heated and the liquid will be cooled.

Before being delivered to the experiment, GN<sub>2</sub> from Freedom Station will be throttled down to 80 psia by the FP/DF fluid supply system. This adiabatic throttling will drop the gas temperature as much as 60 °F (33 °C), if the storage bottle's pressure is 2000 psia and its temperature is ambient. The throttled gas must be heated to bring it to ambient temperature, so a compact electric heater will be placed around the gas tubing upstream of the mixer. Sensing of the gas temperature and facility control of the heater power will provide gas temperature regulation.

The RFMD and its motor are totally enclosed within the experimental-liquid loop. All mechanical power imparted to the liquid stream, and the thermal output due to motor inefficiency, will continuously add heat to the liquid during a test run. Although the amount of heat is not large, it must still be removed in order to maintain the ambient temperature required for these experiments. A counterflow liquid-liquid heat exchanger will provide the moderate thermal control needed for this application. The experiment-concept drawing (fig. 42) shows the liquid-liquid heat exchanger downstream of the RFMD. The coolant will be water from the Freedom thermal control system.

*Diagnostics.*—The multiphase-flow-experiment diagnostic system will acquire science data with a variety of classical and nonintrusive measurement techniques. These diagnostics will be fully supported by the FP/DF video, diagnostic illumination, and computer systems. The apparatus will accommodate the instrumentation necessary to acquire all data without crew intervention.

Temperature and pressure will be monitored throughout the experimental apparatus. Thermocouples and/or RTD's will measure temperature, and appropriate pressure transducers will measure absolute and differential pressures. The analog data will be digitized and the information processed by the FP/DF computer.

In accordance with the science requirements, a constant temperature must be maintained in the test section, although an absolute value is not specified as being critical. Temperature data will serve mainly as a parameter for the FP/DF thermal control system. Pressure information, on the other hand, is an important outcome of the test conditions and needs to be precisely determined in the test section. In addition, pressure information collected at other points in the flow loop will be used as a control parameter for establishing the test conditions.

The ratio of gas volume to total liquid volume, as the two phases flow through the test section, is known as the void fraction; this measurement is made by using conductivity or capacitance probes. In annular flow, the fluid travels only along the inside diameter of the test section, and the measurement becomes one of film thickness; this information is obtained as part of the science requirement. The acquisition of the data from the conductivity probes is a responsibility of the FP/DF computer and is handled in a manner similar to the acquisition of temperature and pressure data.

Determining the surface tension of the test fluid is a requirement that needs further development. Ground-based methods rely on gravity and are unsuited for space applications.

Optical diagnostics will be applied to determine the gas- and liquid-flow velocities, bubble sizes and distributions, and flow patterns in the test section. The technique to be used relies on two views that are radial to the test section and orthogonal to each other. The imaging will be provided by video cameras with an illumination source backlighting the test section.

Obtaining orthogonal images of two parallel test sections will require the use of two to three cameras, depending on the setup chosen. Using two cameras would require an automated mirror positioning arrangement; however, using three cameras may offer the advantage of simultaneously testing in

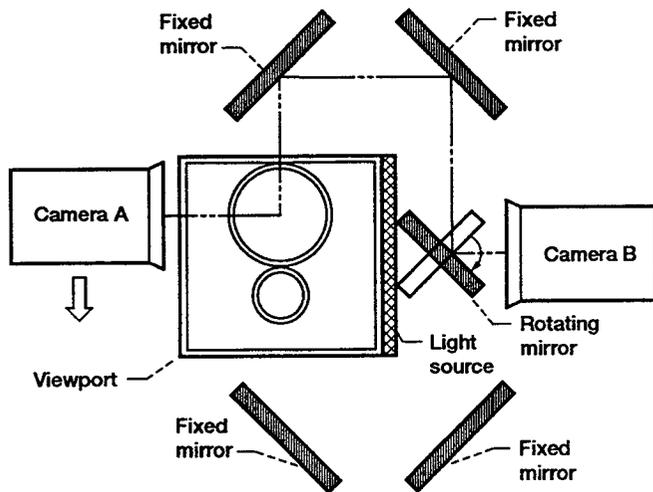


Figure 45.—Concept for multiphase-flow-experiment diagnostic system.

both test sections. Orthogonal images will be acquired at both viewports, which doubles the total number of imaging devices to four or six.

Figure 45 shows the concept for the multiphase-flow-experiment diagnostic system. In this two-camera configuration, camera (A) would image a plane axially bisecting both test sections. Provisions to reposition the camera directly above each section may be required. Using a system of mirrors, the second camera (B) would provide an orthogonal view of the one section under test. To view the adjacent test section, a mirror positioned directly in front of the camera (B) would rotate 90° to redirect its view to the other section. In a three-camera configuration the mirror system would be replaced with separate cameras providing the orthogonal views.

The field-of-view will be adjusted to image a 12.5-cm length of the test section. The resolution of a camera with 512 by 485 pixels at the stated field-of-view is 0.25 mm. As an alternate design, film cameras could be used to increase resolution. The problems of frequent film-magazine changeout, film storage, and bulky devices are the main disadvantages of using film cameras. These problems are substantial, considering frame rate, length of tests, and camera placement. Three minutes of 16 mm film at 500 frames/sec would consume 4724 ft of film (twelve 400-ft cartridges).

Black-and-white video cameras operating at frame rates of 500 frames/sec will provide the imaging capability. The fast frame rates are necessary to obtain information on the interaction of the phases as they flow through the viewport at the higher velocities. In the case of lower fluid velocities, a variable-frame-rate camera, operating between 100 and 500 frames/sec, could reduce redundant data. Alternately, the video processor could selectively reject frames. Since the length of the test section offers no flexibility in its location in the experiment rack, cameras with remote heads could be used to minimize any expected clearance problems. All cameras used in the experiment will interface to the Facility video system, which provides control and power.

A fiber-optic cable that penetrates the experiment containment enclosure will provide the backlighting to illuminate both viewports. The cable, which will have quick disconnects, will be supplied by the Facility.

A refractometer will measure the index of refraction of the test liquid, thereby obtaining the data to determine the liquid's properties. This instrument will be automated and will require optical access to a liquid line; a laser from the Facility will serve as the illumination source for the device. The refracted beam will be detected by experiment electronics that interface with the Facility computer. The measurement, which must be performed on a static fluid to minimize gradients in the index of refraction, will be done periodically during a 90-day experiment.

**Environmental control.**—The purpose of the environmental control system for the multiphase flow experiment is to maintain an atmosphere conducive to microgravity research.

This system is designed to maintain such an environment both inside and, more importantly, outside of the experiment rack.

**Containment enclosure.**—The multiphase flow experiment will require the use of a containment enclosure. Glycerin, the most hazardous substance to be used in the adiabatic tests, is a mild irritant and must not be allowed in the crew areas. Although in the event of a leak glycerin would not be life-threatening to the crew, the lack of an enclosure would mandate unscheduled maintenance. The first level of containment is the experiment apparatus. Ground testing will verify the ability of the apparatus to contain the fluids with an adequate margin of safety. In the event of a leak in the apparatus, a sealed enclosure would contain the experiment liquids and gas, which would be at ambient temperature and pressure. This enclosure could be the experiment rack, modified to be leak-proof, or a separate enclosure inside of the experiment rack. Detection of a leak would cause the experiment to shut down, after which it could be safely returned to Earth.

**Vibration isolation.**—A vibration isolation system is required for the multiphase flow experiment. The experiment itself is not particularly sensitive to vibration; rather, it is a source of vibration from which Freedom Station needs protection. The vibration isolation system will employ a variety of passive and active isolation techniques. Energy-absorbing mounting materials will be used throughout the apparatus as the primary (passive) method of vibration damping. However, an active method of control will be required for a major source of undesirable vibration, such as the startup of the rotating phase separator.

## Facility and Experiment Integration and Operation Scenarios

### Background

Operations and integration activities needed to support the microgravity fluids experiments planned for S.S. Freedom are described in this section. Each phase of facility-rack, experiment-rack, and experiment-specific equipment integration on the ground and on orbit are identified. Typical experiment integration will start at the Lewis Research Center Integration Center with rack-level testing to verify operational integrity. Final integration of the FP/DF will be achieved on orbit by the S.S. Freedom crew members. Some of the operations activities that have been identified are assembly, setup, run, recycle, de-integration, and stowage of experiments. Associated crew time required to perform these activities is also estimated.

### Assumptions and Constraints

Experiment-facility definition and development work, including experiment definition, hardware development, and certification, will have been done at the experiment developer's facility.

### Integration

**Integration phases.**—Two types of racks will be required to run a typical fluids experiment. These are the facility and experiment flight racks, which will be assembled and tested at the Integration Center. Personnel at the Lewis Integration Center will physically integrate experiment and facility hardware into flight racks and then conduct the necessary testing and verification activities. Next, the experiment modules will be integrated into the racks for further extensive testing. After flight certification, the facility and experiment flight racks will be shipped to Kennedy Space Center for integration into the space shuttle. On orbit, the facility and experiment flight racks will be moved to the S.S. Freedom USL module and integrated into the FP/DF. When required fluids tests have been completed, the experiment rack will be de-integrated from the FP/DF and returned to Earth for post-test analysis. The facility rack will remain in orbit and will be refitted as necessary to support multiple experiment racks.

**Integration Center.**—The primary functions to be performed at the Integration Center are (1) flight-rack staging and integration and (2) flight-rack testing and verification. The duties inherent in these functions are as follows:

- (1) Flight-rack staging and integration
  - Experiment hardware receiving, inspection, and functional testing
  - Racks and integration hardware receiving, inspection, and checkout
  - Form, fit, and function testing
  - Rack staging
  - Experiment hardware-to-rack interface tests
  - Integration of experiments into racks
  - Testing and verification of integrated experiments and racks
  - Stowage verification
  - Procedures verification
  - Verification of analytical integration predictions
  - Testing remote interfaces
- (2) Flight-rack testing and verification
  - Simulator testing of integrated racks-to-module interface
  - Preparation and shipment of training hardware to payload-integrated training facility
  - Preparation and shipment of integrated racks,

resupply, stowage items, and equipment hardware

—Verification of data packs

These activities are expected to begin approximately 2 years before launch and be completed 1 year before launch.

*Facility-rack integration:* The facility-rack integration process involves required assembly, checkout, and shipment of the FP/DF rack that will support the experiment racks on orbit. Space Station Freedom Program-furnished racks will be received at the Integration Center with the following standard options:

- Equipment attachment hardware
- Cable and wire assemblies
- Backplane tubing and ducting
- Drawer slides
- Cold plates
- Rack-release mechanisms
- Fire-suppression hardware
- DMS multiplexer/demultiplexer equipment

Following inspection and acceptance testing, the FP/DF systems and subsystems previously described will be integrated into the S.S. Freedom Program-furnished rack to form the facility rack.

After the components are installed in the facility rack, Integration Center personnel will perform hardware and software verification testing to ensure on-orbit facility-rack integrity. Facility rack-to-experiment rack and facility rack-to-DMS interfaces will be verified, along with exhaust and gas supply system pipe and ducting networks. Housekeeping interfaces (i.e., electrical, thermal, and mechanical) will also be verified.

Subsequent to Integration Center checkout and certification, the facility rack will be shipped to the Kennedy Space Center for space shuttle integration and preparation for launch. Facility-rack integration at Kennedy will consist of a two-step process. The first step is installation of the rack into the logistics module, which is a type of canister that will be used to simplify the transfer of payload items from the space shuttle to the S.S. Freedom. The second step in the process is logistics module-to-space shuttle integration, which includes any late access stowage support required and critical-hardware status monitoring.

On-orbit integration of the facility rack from the space shuttle to S.S. Freedom will consist of physically inspecting and transporting the rack from the logistics module to the USL module. After unpackaging the facility rack and visually inspecting it, crew members will begin the task of physically integrating the rack hardware with the associated S.S. Freedom mountings and interconnects. These interconnects, consisting of fluid and electrical connections to the module, will be made through flexible hoses and cables connected to the standoff S.S. Freedom interface plate. Rack cabinets will be secured within Freedom by means of pin-latching mecha-

nisms on the top and bottom of the rack. After the facility rack has been completely integrated into the USL module, crew members will complete a predefined rack powerup and self-testing calibration run.

*Experiment-rack integration:* The experiment-rack integration process is similar to the process described for the facility rack. Components associated with the experiment rack will be installed on a mission- or experiment-unique basis. The Integration Center personnel will process multiple experiment racks over the expected life of the FP/DF project. The experiment rack can be modified to support new experiments in two ways: changeout of the experiment-specific hardware from the experiment rack and changeout of the entire experiment rack. Integration Center activities for the experiment rack begin with the S.S. Freedom Program-furnished racks with standard options, as described earlier.

The types of components that will be integrated into the experiment racks differ. The experiment-specific components may include, but are not limited to, the following:

- Accelerometer
- Cameras (35-mm film, 16-mm film, and video)
- Cup fuel holder
- Droplet release mechanism
- Flowmeters
- Gas bubbles
- Heaters
- Holographic equipment
- Lasers
- Lights
- Probes
- Radiometer
- Robot arm
- Signal conditioners
- Specialized test chambers
- Transducers
- Video recorder

Any vibration-isolation equipment and/or methods necessary to conform to experiment-unique restrictions will be incorporated. Any experiment-unique interconnections will be made. Verification testing will be performed to ensure the experiment-rack flight unit functions properly. This integrated test of the facility-rack verification unit and the experiment-rack flight unit will demonstrate the compatibility between hardware and software elements, thus ensuring on-orbit operational integrity.

After Integration Center checkout and certification, the experiment rack will be shipped to Kennedy Space Center, where it will be installed in the logistics module that will fly on the space shuttle. Once on orbit, the experiment rack will be moved from the space shuttle to S.S. Freedom's USL module. The experiment rack and the facility rack will be interconnected through the between-rack interface plate. Any experiment-unique connections or additions to the experiment rack will be made at this time. After the experiment rack has been completely physically integrated into the Freedom Station USL module, crew members will complete a predefined FP/DF powerup and self-testing calibration run.

As required, the experiment rack will be de-integrated from the Freedom Station in preparation for the installation of

another experiment rack. This process will involve disconnecting, securing, packaging, and stowing the rack in preparation for the logistics module return flight. When back on Earth, the experiment rack will be shipped to the Integration Center for post-test analysis, sample removal, and refurbishment for future missions.

## Operations

Operations for the FP/DF include pre-mission planning of the on-orbit experiments, crew and ground-personnel training, and on-orbit operations. These activities will be supported concurrently at the User Operations Center (UOC) at Lewis.

**User Operations Center.**—The UOC is a NASA Lewis facility that will provide support to the fluids experimenters using the FP/DF on Freedom Station. Operations to be performed at the UOC include, but are not limited to, the following:

- Mission planning and replanning
- Training of ground personnel
- Providing procedures for experiment-specific crew training and real-time operations
- Supporting integrated tests and simulations
- Monitoring data flow, processing user-specific data, and managing data distribution
- Providing ground video interface
- Troubleshooting of user-provided equipment
- Providing uplink services, including real-time video uplink capability, camera control, voice system interfaces, and command generation and issue
- Providing short-term scientific data storage
- Recalling from long-term data storage
- Providing short-term storage and real-time recall for users

**Planning.**—Planning operations for the FP/DF fall into two categories—increment planning and execution planning. An increment is defined as the period between space shuttle visits to S.S. Freedom. The increment, nominally 90 days in length, will be the basic unit for coordinating the development, shipment, and on-orbit installation of racks with respect to the space shuttle manifest. Increment planning will establish which experiment will be run during the increment. Execution planning will detail the steps required to perform each experiment run. Support equipment requirements, consumables, and the associated specimens for each experiment will be determined, and a complete list developed. The following functions will be performed during an increment:

- (1) Weekly planning
  - Generate short-term plan
  - Update payload operating sequences
  - Update payload procedures
  - Update software data tables

- (2) Data management
  - Schedule and coordinate data networks
  - Coordinate onboard data systems operations
  - Distribute data
  - Archive and store data
- (3) Operations control and support
  - Execute the short-term plan
  - Execute payload procedures and sequences
  - Manage payload and intersystems
  - Command FP/DF operations
  - Coordinate crew communications
  - Monitor payload and systems interface
  - Assess, coordinate, approve, and implement plan deviations

**Training.**—There are two types of training: increment-dependent and increment-independent. Increment-dependent training will include familiarizing the crew with the setup and checkout of the experiment-specific equipment in the experiment rack. Experiments runs will be simulated to ensure crew efficiency in specimen changeout, equipment reconfiguration, and interactions between the USL module and ground-control centers. Increment-independent training will include familiarizing the crew with the setup and checkout of the facility rack, support equipment, glovebox, and any other nonexperiment-specific equipment associated with the facilities module. Crew facility-rack calibrations and data transfer exercises among the Freedom Station, the Integration Center, and the UOC will be simulated. Both types of exercise will use simulated data and video flows to train the principal investigator (PI), the facility systems engineers, and the facility operations engineers. These training exercises will ensure the compatibility of operating the Facility, running an experiment, transferring science data to the Earth, and allowing PI interaction with the operation.

**On-orbit operations.**—The operation of the Facility will be experiment-dependent. Several factors need to be considered in defining a given operation. These include crew time, experiment class (exploratory or matrix test), on-orbit characterization of samples, telescience capability (PI interaction), and automation. The crew will operate the Facility primarily through the S.S. Freedom ECWS, which is a centralized workstation in the USL module that will be used to initiate and monitor the experiment operation. The Freedom DMS will handle all of the data storage and data downlink for the Facility.

Typical Facility operations will entail setting up the rack and interconnecting the experiment and facility racks. Hookups between these racks and the Freedom Station power, computer, gas, cooling and thermal, venting, and hazard and fire detection systems will be made as described in the discussion of the particular system in this section. During the setup and interconnection of the racks, ground personnel will be available to assist crew members as needed. The following list shows the required Facility operations and the estimated crew time for their performance:

- Initial visual inspection of racks upon receipt (1/2 hr)
- Material handling (1 to 2 hr)
- Facility rack installation (1/2 hr)
- Experiment rack installation (1/2 hr)
- Interconnections of racks (3 hr, maximum)
- Interconnections of racks and Freedom Station (3 hr)
- Rack software loading and checkout (1 to 2 hr)
- Rack checkout and calibration (2 hr for both)
- Rack-to-ground interface testing (1 to 2 hr)
- Experiment setup (1 to 3 hr)
- Experiment run (5 min to 7 1/2 hr)
- Experiment reconfigure (5 min to 3 hr)
- End experiment, secure and/or safe rack, power down (1/2 hr)
- Cleanup (15 min to 2 hr)
- Experiment rack and module de-integration (1 to 2 hr)

For example, operations could proceed as follows. The payload scientist installs and tests the hardware and software associated with the experiment; next, the scientist loads a sample and does any manual setup required. The experiment is then ready to run. Startup is initiated and experiment process parameters are adjusted either through a command issued by the payload scientist at the ECWS or by a ground operator at the UOC. After the experiment has been run, the payload scientist shuts down the experiment and does such post-test activities as retrieving samples or storing hazardous materials. The PI evaluates the data and takes whatever actions might be necessary before the next test run.

## Facility Development Plan

### Planning Assumptions and Approach

The plan for the development of the FP/DF is based on some basic assumptions about how the project will be managed, who will develop the FP/DF and when it will be flown, what S.S. Freedom Program- and Code EN-provided facilities will be available, and where those facilities will be located.

For this plan the following assumptions have been made: NASA Lewis will manage the project and will also develop the FP/DF; the FP/DF will be launched and transported to Freedom Station via the space shuttle around the turn of the century, and it will be made operational shortly thereafter; the S.S. Freedom Program will provide a set of USL module emulators, flight racks, and other miscellaneous equipment to accommodate integration of the FP/DF into Freedom Station; and most importantly, there are a sufficient number of fluid science experiments to justify the FP/DF and the FP/DF can accommodate them.

To define the development plan, an FP/DF development scenario that identifies the activities of the project has been prepared, based on typical NASA project milestones and current assumptions.

### Facility Development Scenario

This plan addresses the development of the FP/DF from conceptual design through operations of flight hardware. In this scenario the FP/DF development (fig. 46) has four

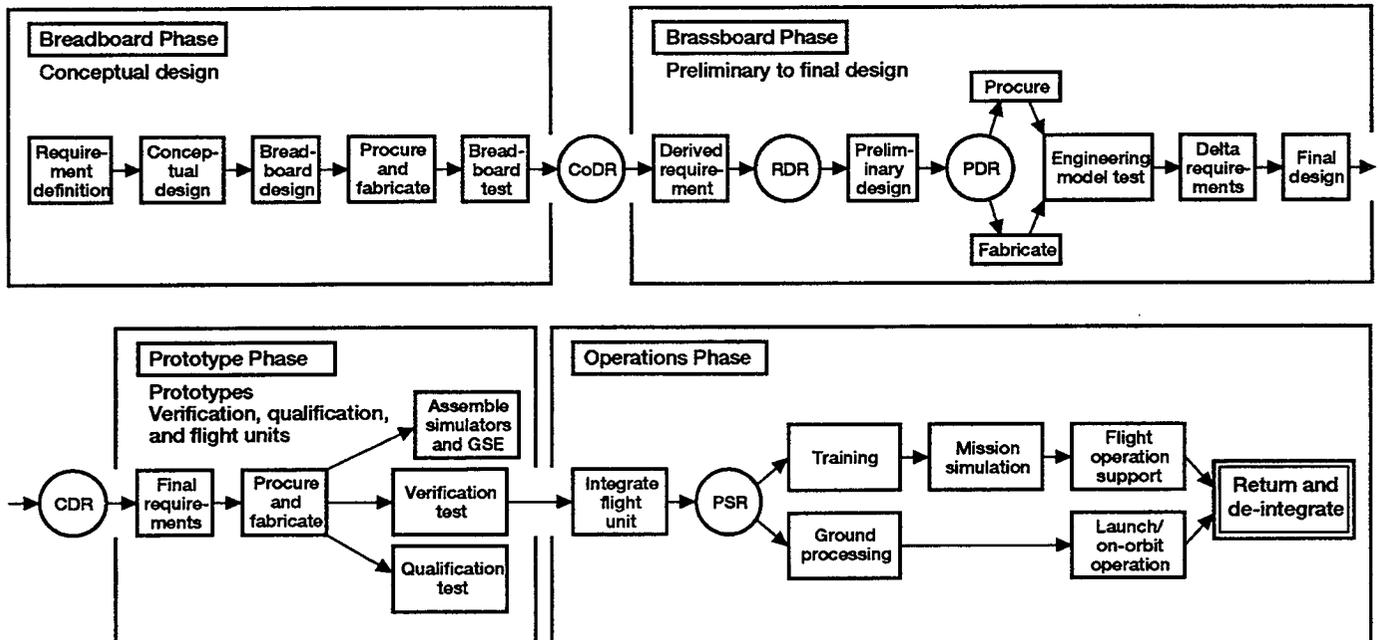


Figure 46.—Facility development scenario.

phases: (1) the breadboard phase, (2) the brassboard (engineering model) phase, (3) the prototype phase, and (4) the operations phase.

Each of these phases and the nature and purpose of the hardware developed during these phases are described in the following sections. The end products of the development are (1) FP/DF and experiment modules, (2) verification units, (3) ground-support equipment (GSE), (4) advanced technology enhancements (ATE), and (5) experiment-specific hardware.

**Breadboard phase.**—On the assumption that a decision to pursue a flight development project has been made and that ground-based research and testing have demonstrated that a space experiment is justified, this phase addresses the earliest part of flight-experiment development. The main objectives of this phase are to develop a conceptual design of a flight experiment and to validate the concepts by fabricating and testing engineering breadboard versions before committing to full-scale development. Breadboards are typically made up of a mix of commercial-grade, readily available components and specially fabricated hardware. The breadboard phase starts with requirements definition and concludes with the conceptual design review.

**Sequence of activities:** The general sequence of breadboard-phase activities is as follows:

(1) *Requirements definition.* The preliminary science requirements, the safety requirements for S.S. Freedom, the reliability requirements of the experiment apparatus, and the interface requirements, including mission-specific requirements, are determined.

(2) *Conceptual design.* Design concepts to meet the science and safety as well as the engineering objectives of the project are developed and evaluated. Early structural, thermodynamic, thermal, and electrical analyses are performed to determine the functional envelope of the designs and to determine if the design concepts can be accommodated within the S.S. Freedom physical and operational constraints.

(3) *Breadboard design.* Breadboards of systems and subsystems are designed to provide development test-bed designs for validation of the design concepts and analyses. The breadboard design is also used to verify system compatibility and to gain insight into system performance characteristics.

(4) *Procurement and fabrication.* The breadboards are fabricated and assembled to the specifications of the breadboard design, and necessary components are procured.

(5) *Breadboard test.* The breadboards are tested as individual subsystems but may also be integrated with other subsystems and emulators of USL module utilities.

(6) *Conceptual design review (CoDR).* This is the first major design review. The design concept, with supporting analyses and test data, is reviewed to ensure that the original science requirements of the project are being met and that the project can meet its mission schedule and achieve its mission objectives.

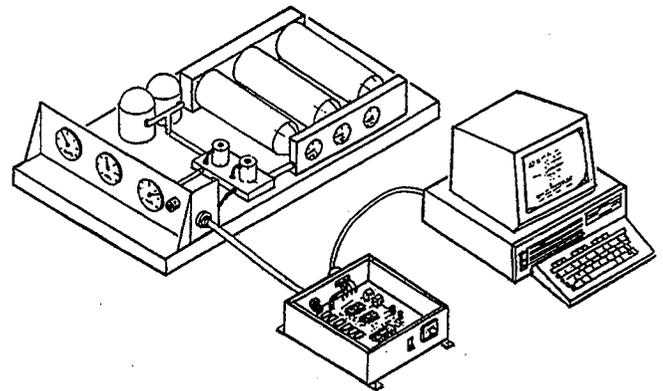


Figure 47. —Engineering breadboards.

**Development hardware:** Engineering breadboards serve as models for evaluating design concepts. They may be a combination of both off-the-shelf and custom-built hardware, and often they are only temporary setups that may be discarded once their purpose has been served (fig. 47). Initially, breadboards permit experiment designers to explore different concepts and design approaches. They provide flexibility and accessibility, which minimizes the time and cost of evaluating alternative concepts, and they also provide insight into the concept characteristics and operational behavior, which may otherwise be overlooked in a strictly analytical approach. Breadboard models of Facility and module subsystems will vary in levels of complexity, depending on the breadboard test objectives, technical risk of achieving design objectives, and the availability of equivalent off-the-shelf hardware. By testing models in such short-duration microgravity facilities as drop towers or aircraft (e.g., Learjet and the KC-135), breadboards will determine if design concepts with high technical risk, such as systems that operate only in microgravity, are feasible.

Subsystems are breadboard-modeled individually to validate subsystem design concepts; they can also interface with other subsystems to verify compatibility. Breadboards often have nonflight or development-only instrumentation and test points to aid in system characterization. Furthermore, they may be both manually and electronically controlled. Long after the FP/DF development is complete, breadboards can continue to provide service by supporting experiment-specific hardware development, ATE, and flight operations.

The following is a list of breadboard applications in the FP/DF development:

- Designing evaluation test bed for components and subsystems
- Characterizing components and systems
- Identifying failure modes
- Fault-tolerance testing and redundant system isolation
- Life-cycle testing of components
- Verifying compatibility between systems

—Verifying interfaces with USL module and experiment emulators

—Supporting the development of control algorithms

The FP/DF and experiment-module breadboards will continue supporting the development of hardware after the initial breadboard phase. They will be used in interface development between Facility and module subsystems and space experiments, breadboard-level development and evaluation of GSE, and breadboard-level development of ATE

Since full-scale development of the FP/DF and the support facilities will require emulation of USL module systems and their interfaces, the S.S. Freedom Program will create such emulators. However, in the early phases of Freedom Station development, they may not be available, so Lewis-built USL module emulator breadboards may be required to support development until the S.S. Freedom Program-supplied emulators are made available. The following USL module systems will be emulated: (1) power, (2) thermal control, (3) fluid management, (4) environmental control and life support, and (5) data management.

**Brassboard phase.**—In this phase the bulk of the project's engineering design is done, starting with the outcome of the CoDR and concluding with the critical design review (CDR). Both the preliminary and final designs are completed, the flight design is fixed, and all aspects of the design come under configuration control. Engineering models of subsystems are fabricated and then utilized in the development of the integrated FP/DF. As a final design is derived, the engineering models are also used to solve design problems not encountered in the previous design phases. Some of the subsystems are developed entirely by vendors; therefore, the design reviews of those subsystems must occur prior to the design milestones of the overall FP/DF.

**Sequence of activities:** The general sequence of brassboard-phase is as follows:

(1) **Derived requirements.** Requirements that are derived from the conceptual design, as well as safety, reliability, and carrier interface requirements, functional requirements, and software requirements that are defined and documented in the project plan, are determined. These derived requirements along with initial requirements are the basis of the preliminary and final design process.

(2) **Requirements definition review (RDR).** In the RDR all of the science and engineering requirements that have been derived from original science requirements are reviewed. The purpose of the RDR is to ensure that all requirements have been identified and are being properly addressed by the development plan.

(3) **Preliminary design.** Once the latest requirements have been established, the preliminary design of the FP/DF begins. With more definitive design goals, emphasis is on the design of an integrated system, which includes emulators of carrier interfaces and development support equipment.

(4) **Preliminary design review (PDR).** At this milestone the preliminary design, along with results from the supporting analyses, is reviewed prior to committing the design to hardware or major procurement.

(5) **Procurement and fabrication.** These two activities occur in concert. Some systems are fabricated in-house while others are procured from commercial sources or subsystem contractors. In many cases the procurement of the flight hardware, as well as the procurement of engineering models, occurs as part of the same effort. This is typical when hardware developed by a vendor requires a long development lead-time.

(6) **Engineering model (brassboard) tests.** Components, subsystems, and eventually, completely integrated engineering models of the experiment system are tested to verify that the design can meet the project design requirements and mission objectives. The need for design revisions will become evident as characteristics of the integrated system become known.

(7) **Final design.** The final design incorporates design and performance information gathered from engineering model testing; it represents the flight design. At this point, configuration control and safety, reliability, and quality assurance become more significant, and the fidelity of engineering models increases in importance as interfaces between systems and the carrier become fixed.

(8) **Critical design review (CDR).** This milestone marks the review of the final design; science requirements; test and analyses data; GSE and test plans; safety, integration, qualification, and verification plans; and flight operations plans. The detailed schedule of activity through flight is also reviewed.

**Development hardware:** The brassboard subsystems are a first attempt at a flight design; generally, engineering models are another step in the evolution of a flight design. Although the engineering models have greater fidelity than the forerunner breadboards, they generally consist of nonflight hardware (fig. 48).

The Facility and/or module subsystems are integrated and packaged into a unified system occupying the intended flight envelope. The primary function of the brassboard is to support FP/DF and experiment-module development, but it will also serve as a prototype for derivative models such as the simulation model, the GSE, and the validation units.

All FP/DF mechanical and electrical subsystems are integrated into an FP/DF double-rack envelope. Hardware is integrated and configured in a manner that supports software development. Interfaces with USL module emulators are supported, and thus, the FP/DF can be controlled through an emulated DMS workstation.

The engineering brassboards will support the integration of FP/DF and experiment-module systems by doing the following:

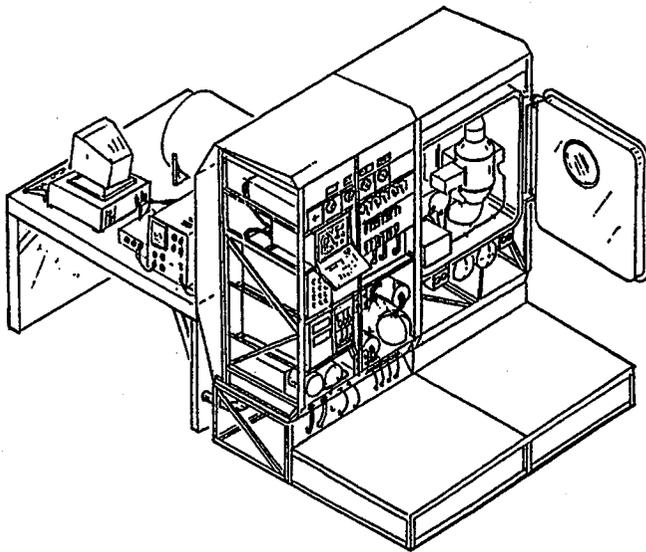


Figure 48. —Brassboard system.

(1) Verifying that the mechanical fluids systems, electronic control and data systems, and structural support mechanisms can physically fit in the FP/DF and experiment module envelopes.

(2) Verifying that operation of the packaged system meets design requirements in the following areas:

- DMS compatibility
- EMC
- Fluid system stability
- System reliability and safety
- Ergonomics
- Static and dynamic structural integrity
- Thermal stability
- Accessibility and maintainability

(3) Developing and testing software

(4) Characterizing the integrated system

(5) Verifying failure mode and effects analysis (FMEA) and failure tolerance and fail-safe operation

(6) Verifying module and Facility compatibility

The engineering models may continue to provide program support beyond the development phase by acting as troubleshooting tools to

- Simulate failures with closely controlled and heavily instrumented system models
- Isolate subsystems faults
- Isolate redundant or failure-tolerant subsystems and components
- Evaluate the system impacts of failed components

Brassboards will support the development of experiments and ATE by

- Verifying experiment and module interfaces
- Verifying that the packaged system operation conforms with Freedom Station payload design requirements

- Supporting development of experiment-specific software
- Characterizing the experiment or system enhancements
- Verifying FMEA

**Prototype phase.**—In this report the term “prototype” refers to hardware that represents the flight design, but it does not always refer to the specific flight hardware. In this phase, the emphasis is on fabrication and integration, as well as verification and qualification, of the flight design. Once the final flight design has been established by the CDR, any design changes will have major schedule and cost impacts on the project. This happens because multiple sets of prototype hardware are being fabricated, integrated, and tested in parallel. Therefore, configuration control is essential so that coordination and control of unavoidable changes is ensured.

**Sequence of activities:** The prototype phase progresses as follows:

(1) *Procurement and fabrication.* For the most part, the procurement of prototype hardware should already have been done in the brassboard phase, leaving only hardware necessitated by contract changes or revisions of requirements to be procured at this point. Miscellaneous prototype hardware is fabricated in-house or is locally procured.

(2) *Verification, integration, and testing.* Each modular subsystem is tested and then integrated into the verification unit. The assembly or integrated verification unit is tested at the system level to verify requirements for operation, compatibility, safety, and science. This is the first opportunity to verify that the final flight design will meet subsystem- and system-level requirements. Failure to meet requirements will mandate corrective action that will affect the qualification unit and the flight unit.

(3) *Qualification.* Qualification refers to the testing and analysis which show that a design meets the requirements for flight-qualified hardware dictated by Freedom Station and space shuttle programs. The single most important set of requirements pertain to mission safety. Qualification is needed primarily at the subsystem level, but ultimately the entire system will be qualified. In this development scenario, system qualification occurs concurrently with verification testing, but the completion of qualification is planned to follow completion of verification, with enough of a time lag to accommodate a minor design change. With this approach the need to repeat an entire qualification test sequence is avoided.

(4) *Simulator and GSE fabrication.* After the design for the flight system is fixed, simulators are fabricated and assembled. These simulators will be provided to other NASA centers for use in training and mission simulation. The GSE is fabricated to verify flight hardware interfaces and will be used at the Integration Center as well as in the post-receiving inspection and prelaunch checkout at the launch site. Since the GSE hardware interacts directly with flight hardware, special attention to interface configuration is required.

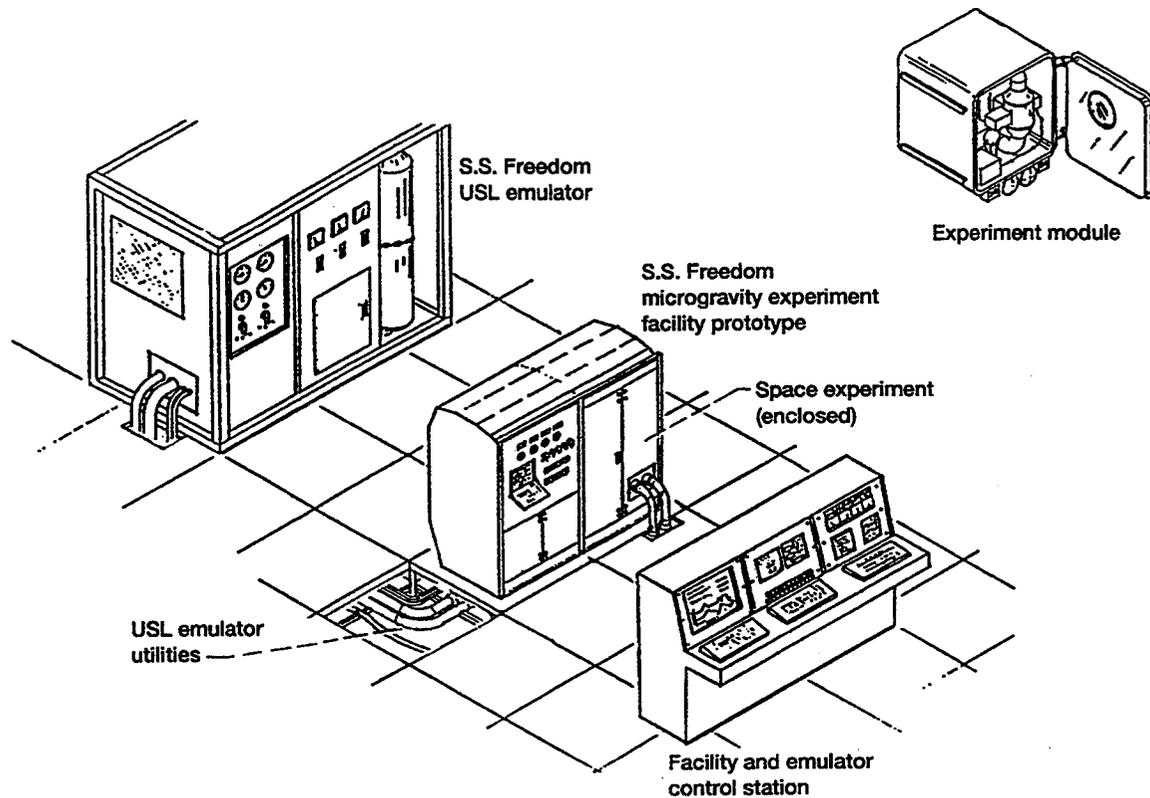


Figure 49.—Fluid Physics/Dynamics Facility verification unit.

*Prototype hardware:* Three basic prototypes will be built to represent the flight design: (1) the verification unit, (2) the qualification unit, and (3) the flight unit. Each of these will have its own special function in the program. The qualification and flight units will be built for both the FP/DF and the experiment module. However, only the FP/DF requires a verification unit, because once on orbit, the FP/DF is not available for integration and verification.

The first set of hardware representing the flight design will be the FP/DF verification unit (fig. 49); this will be used initially to verify the flight design requirements. Once that function has been served, the FP/DF verification unit then becomes a means to integrate and verify future experiment modules, experiments, and system upgrades while the flight unit is onboard Freedom Station. In addition, the FP/DF verification unit will support operations training and simulations by acting as a high-fidelity simulator. This verification unit will be identical to the flight hardware, but it will not necessarily be built from flight-grade components. Because the experiment modules will return to Earth periodically, a verification model of every experiment module will not be necessary.

The FP/DF verification unit will be maintained as a physical and functional identical twin of the flight unit and will be operated in a clean-room environment located at an integration laboratory. The verification unit will operate in conjunc-

tion with the integration GSE once the flight unit is operational on Freedom Station; it will be under configuration control wherein the configuration changes only when the flight unit changes. Since software installed in the verification unit will be identical to that of the flight unit, the verification unit can also be linked to the communications network and thus support telescience. The qualification units of each FP/DF subsystem will be identical to the actual flight units and will be fabricated from flight-grade hardware. The complete system will undergo a series of qualification tests to demonstrate the operational reliability of the FP/DF and experiment-module systems when subjected to the environmental extremes of the space shuttle and Freedom Station. Additional tests to verify that these systems meet the space shuttle and Freedom Station Program requirements will be performed. If a system fails a qualification test because of an inadequate design, the affected systems will have to be redesigned. Design changes, such as incorporation of technology enhancements, will compel a requalification of the design. Once qualified, provided that it has not been overstressed, the qualification unit hardware becomes the backup flight unit.

The FP/DF qualification unit will consist largely of flight-qualified hardware in the configuration of a flight unit. Special instrumentation, installed for qualification testing, will help determine whether qualification goals are met. The

qualification unit will verify that the Facility and module subsystems designs are capable of meeting the requirements defined by payload classification, program safety, compatibility, and reliability requirements. It may also support the flight qualification of technology enhancements and design changes.

Ultimately, the FP/DF flight unit is the end product of the development project; all other equipment supports the development or operation of this unit. Previous sections of this report have described the nature of the flight systems in detail. The actual flight hardware will be received at the Integration Center and integrated into S.S. Freedom Program-provided racks. Both the facility rack and the experiment racks with the fluid experiment modules will be integrated in the same manner. The facility rack should have to be integrated only once since it is expected to remain on Freedom Station for a 20-yr operational lifetime; however, many integrations of the experiment racks are likely since they can be used for multiple 90-day Freedom Station increments and because modules will be replaced periodically with new ones to perform new experiments.

**Operations phase.**—The operations phase includes all activities associated with experiment operations and integrations, not only those that occur at Lewis but also those that Lewis supports at other NASA centers. Such activities include flight hardware integration and verification, launch-site carrier integration and ground operations, flight operations, crew and support personnel training, and FP/DF experiment operations.

**Sequence of activities:** The operations phase proceeds as follows:

(1) **Flight systems integration.** Work begins when flight subsystems, sent by subsystem development contractors, are delivered to the rack-level integration laboratory to be integrated and tested as a unified package. Since the nonflight FP/DF verification unit has already verified the software and system design, flight units are tested to verify the quality of their material and workmanship. In addition to flight hardware, the GSE and training simulators are integrated and tested, both separately and in conjunction with the flight systems. Once all verification is complete, the hardware is prepared for shipment to the launch site.

(2) **Preshipment review.** The preshipment review (PSR) takes place when the program managers review the verification, qualification data, and all related integration documentation, and assesses the readiness of the flight systems for shipment to the launch site. This review is important because of the difficulty in correcting any problems once the flight unit has been shipped and is no longer controlled by the development center. Beyond this point, activities progress along two parallel paths. The flight hardware follows the integration path, in which the flight systems are tested and integrated into a logistics module and launched via the space shuttle to Freedom Station. The operations path addresses the utilization of the flight hardware.

(3) **Ground processing (integration).** The facility rack and any experiment racks are shipped from the Integration Center to the space station processing facility at Kennedy Space Center. Following initial receiving inspections, the flight hardware is thoroughly tested in off-line laboratories prior to on-line integration into the logistics module. Except for unusual circumstances, the off-line laboratory is the last station where changes can be made or system anomalies debugged.

(4) **On-orbit operations.** During launch and transport to Freedom Station, the FP/DF, being inactive, requires minimal attention. Onboard Freedom Station, the Facility is transported to the USL module and installed in a rack location. Freedom Station-provided utilities are connected, and the Facility is checked out for operation. Experiment-module hardware and experiment-specific hardware are installed, and the Facility is prepared for an experiment sequence. Telescience permits experiments to be performed with both flight-crew and ground-based investigators involved.

(5) **Return and postflight de-integration.** Eventually the experiments are completed. The experiment-specific hardware and, occasionally, experiment racks are removed from the USL module and returned to Earth. Here, equipment is de-integrated from the shuttle logistics carrier and returned to the Integration Center. The test specimens and related hardware are then removed from the experiment module and given to the PI for data and specimen analysis.

**Operations activities:** The following activities are also part of the operations phase.

(1) **Training.** Training prepares the flight crew (payload specialists), the science investigator (or PI), and the support personnel (systems engineers) to operate the FP/DF on Freedom Station. Individual scientists and engineers are trained to act as a team in operating the experiment. Special Facility and module training simulators will be available for this purpose at Lewis and at other centers such as Marshall Space Flight Center and Johnson Space Center.

(2) **Mission simulations.** Simulations act not only as a rehearsal for flight operations but also as systems verification tests. A number of mission simulations are conducted to verify the communications network between NASA centers and Freedom Station. These simulations test network effectiveness, establish command and communications protocols, and verify telescience capabilities.

(3) **Flight operations.** Once onboard Freedom Station, the FP/DF is integrated into the USL module, checked out, and made operational. These on-orbit duties are supported by a ground-based systems engineering team at the operations center. When the FP/DF is fully operational and ready to perform experiments, the payload scientist, in concert with the ground-based PI, initiates the experiment. The PI can observe data and interact with the experiment via telescience.

**Simulation module.**—The S.S. Freedom Program may require that users provide simulation modules. These prototype derivatives will possess the level of fidelity necessary to

provide effective payload specialists training in a Freedom Station operational environment at the Marshall Space Flight Center and Johnson Space Center. The user-provided modules must be operable with the USL module and experiment simulators and be compatible with telescience; they must also support operation simulations and help in the evaluation of the FP/DF's effectiveness in a simulated Freedom Station environment. The simulation modules can be used to

- Train payload specialists, technicians, and systems engineers
- Evaluate flight operations and experiment procedures
- Support joint intercenter simulations
- Aid in the development of telescience (remote interactive operation)

**Integration ground-support equipment.**—The integration GSE (fig. 50) will be used at the Integration Center and at the launch site. It will support Freedom Station integration and the preflight checkout of both the FP/DF and the experiment modules, as well as system troubleshooting. The integration GSE consists of three emulators: (1) A USL-module-utilities emulator, (2) an FP/DF emulator, and (3) an experiment-module emulator. Each emulator can be used separately for integration support and testing of its counterpart's flight hardware. The integration GSE has configuration-controlled system interfaces with high interface fidelity, and it is capable of interfacing with the actual flight hardware or its emulator. It is also capable of isolating and testing individual systems. Special test controls, instruments, and displays are included for supporting Facility and module or experiment checkouts. The following is a list of integration GSE applications:

- Provides emulation support of the Facility simulator model
- Evaluates Facility or experiment interfaces

- Evaluates flight readiness
- Provides preshipment checkouts
- Troubleshoots malfunctioning Facility and module subsystems
- Tests to verify corrective actions

### Future Space-Experiment Accommodation

The experiment module concept provides varying levels of accommodation for experimenters who have varying levels of resources for equipment and varying levels of sophistication in working with the space program.

**Classes of experiment accommodation.**—Three levels of accommodation are possible. They are classified on the basis of the equipment that the user supplies.

(1) *Experiment modules:* The user provides a complete self-contained experiment module. This approach is the most costly to the experimenter and requires considerable sophistication in experiment design and available resources. In addition the user bears much of the responsibility for safety and mission success. However, the approach does give the experimenter maximum flexibility and a greater assurance that the experimental hardware best achieves the intended scientific objectives.

(2) *Experiment-specific hardware:* In this case the microgravity program provides an experiment module with interface hardware, support subsystems, and experiment containment. The user provides experimental apparatus, experiment-specific software and instrumentation, and control algorithms. In this approach the cost of designing, developing, and qualifying systems with complex interface requirements is reduced by using program-developed or existing hardware. Responsibility for safety and fault tolerance shifts toward the program, but the flexibility to develop an apparatus specific to an experiment is preserved.

(3) *User-specific configuration:* The microgravity program provides the experiment module and experiment apparatus. The user provides the experiment information that affects the existing hardware configuration, such as experiment test parameters, new test specimens, and data format and acquisition rates. The cost to the user and the development time are minimized by the use of existing experimental apparatus and software. Safety and mission success are almost entirely the responsibility of the microgravity program. This option offers a minimum level of flexibility because it relies on already existing hardware. Program support may consist of providing the experiment developers with development kits and the use of Facility engineering models, prototypes, and verification equipment. Freedom Program-provided experiment-module interface kits would be available through the Mission Integration Office.

In an experiment module development scenario, the FP/DF brassboard (engineering model) is used for verification of module hardware and software (including electronic compat-

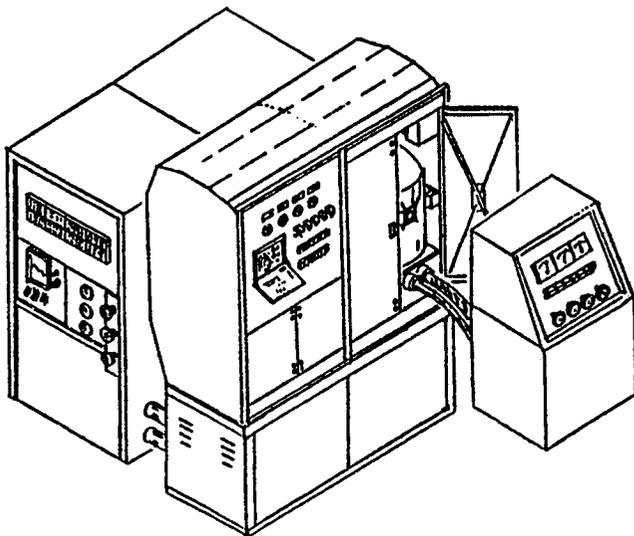


Figure 50.—Integration ground-support equipment.

ibility) and fluids system stability, as well as for software validation and such. Experiment simulators for training and evaluation are built or configured and installed in the FP/DF simulator. Experiment modules very likely require qualification testing to ensure that Freedom Station requirements for safety and reliability are met. The experiment module flight unit is interfaced with the FP/DF verification unit so that it may be certified as compatible with the actual flight FP/DF onboard Freedom Station.

In an experiment-specific hardware development scenario, all experiment-specific hardware undergoes development similar to the experiment modules, but because it is less complex, a less rigorous and time-consuming process is involved. Development testing of the hardware starts with the brassboard level and proceeds toward verification and qualification. Unlike the Facility and module development, the first set of hardware that satisfies the module verification and qualification requirements could become the flight unit, with no need for hardware duplication.

Experiments based on a user-specific configuration utilize an existing apparatus that is already flight qualified, so only configuration-dependent qualification needs to be addressed. In many cases the change in experiment configuration may be trivial, and essentially no development effort is required. If the experiment poses no safety issues or mission conflicts, a potential user gains an experiment opportunity by supplying the proper information to the Mission Integration Office.

**Experiment development support kits.**—To simplify the experimenter's development effort and assure interface compatibility with the FP/DF, a set of experimenter interface and development kits is being considered. They are as follows:

**Facility information kit:** This kit would provide information to assist the user in the conceptual design of an experiment. Such a kit would include (1) a Facility-user handbook with guidelines for FP/DF operations, (2) Facility capabilities documentation, (3) program information and contact points, and (4) Facility simulation model software. This kit would also provide information that would help in selecting the experiment accommodation option.

**Experiment module interface kit:** This kit would provide the experiment developer with both hardware and software for developing compatible experiment hardware prior to verification testing with the Facility engineering models and prototypes. Such kits would include (1) interface requirements data, (2) interface panels and connection hardware, and (3) Facility control and data acquisition simulation software.

**Experiment module qualification and flight kit:** To support the qualification and flight hardware phase, a set of flight-

qualified hardware would be available. Depending on the experiment hardware, this kit could include (1) a payload integration plan for space shuttle and Freedom Station, (2) an experiment containment enclosure (if required), (3) a qualification and integration plan, (4) a telepresence and flight operations handbook, and (5) a Mission Operations Center handbook.

In addition to these development kits, the experiment developer is encouraged to use the in-house FP/DF development models, prototypes, emulators, and simulators to assure that module and Facility compatibility is established early in the development and is maintained through flight. Furthermore, users are expected to participate in and support training exercises as required.

## Concluding Remarks

Fluids research is science that is well suited for the S.S. Freedom environment, and the Facility design that has been discussed herein should help to minimize the overall development costs for this type of research. The FP/DF can accommodate the wide range of experiments that are currently being proposed; however, it should also have the flexibility to accommodate experiments that have not yet been identified. The key to effective Facility usage will be well-designed experiments; those that are designed to be flexible and that consider sharing systems with other experiments will help to maximize the science return from the FP/DF. It is imperative that the science community, industry, and government continue to work together as Freedom Station and the FP/DF become realities.

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## Appendix A Definitions

ACB	automatic circuit breaker	IRU	isothermal reference unit
A/D	analog-to-digital	L/D	length-to-diameter
ATE	advanced technology enhancements	LED	light-emitting diode
AV	analog video	MCVC	miniature color video camera
CDR	critical design review	MDM	multiplexer-demultiplexer
Code EN	NASA Headquarters MSAD Program Office	MIPS	million instructions per second
CoDR	conceptual design review	NTSC	National Television Systems Committee (code)
CP	cold plate	PC	power converter
CPU	central processing unit	PDCU	power distribution and control unit
DMS	data management system	PDR	preliminary design review
DV	digital video	PI	principal investigator
ECLSS	environmental control and life support system	PIV	particle imaging velocimetry
ECWS	element control workstation	PMMS	process materials management system
EDP	embedded data processor	PSR	preshipment review
EMI/EMC	electromagnetic interference/compatibility	RAM	random access memory
EPDS	electric power distribution system(s)	RDR	requirements definition review
FDDI	fiber-distributed data interface (protocol)	RFMD	rotary fluid-management device
FMEA	failure mode and effects analysis	ROM	read only memory
FP/DF	Fluid Physics/Dynamics Facility	RTD	resistive temperature device
GC/MS	gas chromatograph/mass spectrometer	SAMS	Space Acceleration Measurement System
GN <sub>2</sub>	gaseous nitrogen	SDP	standard data processor
GSE	ground-support equipment	SSE	software support environment
IEEE	Institute of Electrical and Electronics Engineers	STDCE	Surface Tension Driven Convection Experiment
I/F	interface	TBD	to be determined
I/O	input/output (usually with reference to a computer)	TCS	thermal-control system
IR	infrared	UOC	User Operations Center
		USL	United States Laboratory (module)

## Appendix B

### Summary of Assumptions and Constraints

The Fluid Physics/Dynamics Facility (FP/DF) is being conceptually designed as a pressurized payload that will be located in the S.S. Freedom's USL module. This future integration of the Facility into the USL module and Freedom Station imposes certain constraints on current efforts to design the Facility. Some of these constraints are related to USL module and Freedom Program safety requirements; some, to the capabilities and requirements of the USL module; some, to Freedom Program operations and logistic requirements and capabilities; and some, to program funding and schedule.

In addition to conforming to the above constraints, the Lewis project team was required to make certain assumptions in the current Facility design effort. Most of these assumptions, given in the following paragraphs, had to be made at the time the program was in the early predesign phase, when information on USL-module systems or Freedom Program operations was not available.

#### General

1. Lewis is chartered to conceptually design a multiuser, modular, user-friendly, host Facility (FP/DF) that will accommodate experiment-specific hardware modules and will provide common support systems and interfaces with the USL module utilities and subsystems.

2. The Lewis FP/DF study team is conceptually designing an FP/DF host Facility only (i.e., supporting systems). It has defined the requirements of a selected list of candidate experiments to a point that is sufficient to assess their support-systems requirements, and has conceptually designed two fluids experiments, with the purpose of identifying possible problems with the Facility.

3. The USL module was assumed to be the baseline carrier. The team did not rule out the possibility of flying in an international module, and in a few cases considered the possible impact of doing so.

4. The FP/DF will not be manifested in the initial outfitting of the USL module; it will be sent to Freedom Station via a pressurized logistic module.

5. The FP/DF will remain onboard Freedom Station for an extended period of time. It will be designed for a 20-yr lifetime, and methods of incorporating advanced technology enhancements will be provided (i.e., via a modular design approach).

6. In defining the requirements of candidate users of this Facility, particularly in the area of consumables, a 90-day flight increment has been used. We have asked users, "If the Facility were available to you for a full 90-day period, how much of each consumable would you use?" This increment is

consistent with the Freedom Program reporting method, which is tied to the proposed 90-day cycle of shuttle visits to Freedom Station for logistic purposes.

#### Structures

1. The Facility will be housed in two standard Freedom Station racks.

2. The design of the FP/DF and the experiment module are constrained by the available working envelope of the Freedom Station rack enclosure and by the maximum allowable payload weight of 700 kg per rack. Payloads in excess of 700 kg can be incrementally incorporated into racks on orbit by means of additional payload deliveries.

3. Freedom racks may not be structurally modified. The FP/DF design must allow the racks to rotate about the lower front bottom edge to provide access to the back of the rack and to facilitate removal and installation.

4. The racks will have access panels on the sides of the racks for between-rack interfaces.

5. Two or more racks can be structurally tied together during experiment operation.

6. All of the changeable experiment hardware must be designed such that it can be removed and installed on orbit, without requiring removal of the primary rack structure.

7. The USL module hatch size allows the transfer of only one rack through it at a time. Therefore, each rack of the FP/DF must be designed to be transported to the station separately and then assembled in place on the USL module.

8. The Freedom Program will provide an interface panel at the bottom of each rack outside the user's envelope. Mechanical and electrical connectors on this panel will provide USL module fluids, thermal control, power, and data connections.

9. The FP/DF and the experiment modules must be designed to withstand the rigors of a shuttle launch.

10. All hardware incorporated in the design of the FP/DF or the experiment module, in particular pressure vessels, must be designed to withstand a scheduled decompression and recompression of the USL module without yielding, cracking, or suffering other damage.

11. The Freedom Program requires that structures be designed with an ultimate safety factor equal to or greater than 1.5. Pressure lines and fittings of less than 1.5 in. diameter must have an ultimate safety factor equal to or greater than 4.0.

12. The Freedom Program requires fracture analysis, stress corrosion analysis, and hazard analysis per specified documents.

13. An experiment containing a hazardous (toxic, flammable, etc.) test fluid must provide for three levels of containment for the fluid.

14. A containment enclosure that maintains a negative pressure relative to cabin pressure is assumed to provide two of three required safety containment levels.

15. The USL module crew members will be available to make interface connections between the racks.

### Fluids and Thermal Systems

1. Consumables to be provided by the USL module at the interface panel at the bottom of the rack are nitrogen and ultrapure water.

2. The Environmental Control and Life Support System (ECLSS) will supply cooling air to the Facility.

3. Fluids not furnished by the USL module (item 1) or by the ECLSS (item 2) must be furnished by the experimenter.

4. The Facility will provide storage of experiment-supplied consumables.

5. Dual shutoff valves are required to meet safety requirements for preventing possible leakage into the USL module.

6. Each component and subsystem of the Facility and experiment module will be required to be qualified for flight per Freedom Program requirements.

7. General purpose laboratory support equipment, supplied by the Freedom Program, will be available for use in setup and checkout of the Facility and experiment.

8. The Freedom Station thermal-control system will provide heat rejection of 30 kW (15 kW/rack) for the FP/DF.

9. Freedom Program-provided cold plates and heat exchangers will be designed and built by Marshall Space Flight Center (Work Package 1).

10. The vacuum vent system will be available for emergency venting of relief valves.

### Electric Power

1. The USL module will distribute 120 V dc electric power to the Facility at the rack interface panel.

2. The Facility will be required to minimize the voltage transients on startup and shutdown of equipment within the Facility; in other words, soft-starting of electrical equipment, such as large motors, will be required. Specific requirements are not known at this time.

3. The conversion of USL module-provided power to other voltages and frequencies will be accomplished by the Facility.

4. The Freedom Station power management system will tightly control the use of all electric power on the station. The power to the FP/DF will be available on a scheduled basis.

5. The power available to any rack in the USL module is dependent upon its location in the module. Rack locations will be rated at 3, 6, or 15 kW. The location of the FP/DF in

the USL module, and thus the power level available, has not been determined at this time.

### Computer System

1. There are three transmission paths that data may take. The local bus has a data rate of 1 Mb/sec. The payload network has a bandwidth of 100 Mb, and a throughput of 10 Mb/sec. The high-rate link will have a data rate of 300 Mb/sec.

2. The use of USL-module crew time, by either the Facility or experiment, must be kept to a minimum. Automation, instrumentation, and data processing will be used to compensate for the lack of available crew time. In addition, the Facility will be run, or controlled, from the Element Control Workstation (ECWS) or from the ground, thereby using the telepresence concept to the greatest extent possible; the ECWS is a centralized control center in the USL module.

3. The sharing of resources among all Freedom Station users will require strict scheduling of experiment run times. Resources include electric power, data transfer networks, fluid systems, and crew time.

4. The Freedom Program will provide computer hardware and software whenever practical. This includes networking hardware and software, processor boards, and some general-purpose I/O cards.

5. The Freedom Program will handle all data storage and data transmission for the Facility, with the possible exception of some video data.

### Diagnostic Systems

1. The optical components of an optical diagnostic system are experiment-specific, and thus would not be provided as part of the FP/DF. However, a laser and a white-light source will be provided as part of the Facility.

2. Imaging systems are somewhat experiment-specific, so a decision about whether video and film cameras and their optics can be provided as part of the Facility has not yet been made. However, the controls and electronics required to support film and video cameras, including storage and transmission capabilities, will be provided by the Facility.

### Controls

1. The FP/DF computer will be the primary controller; the software required for overall experiment control and to maintain safety will reside in the FP/DF computer.

2. All systems will be designed to be fail-safe. For example, if power is lost, all systems will be designed to go to a known safe condition.

3. At least two inhibits are required to activate or apply power to any device in the experiment system; three inhibits are required for hazardous devices such as lasers.

4. Multiple measurements will be provided for any parameter needed for safety monitoring.

### **Software**

1. The Facility software will be modular. It will be designed to allow the inclusion of experimenter-designed

software modules for control and data acquisition if the experimenters so wishes.

2. The Freedom Program has adopted Ada as the computer language to be used on Freedom. However, a non-Ada language may be used for some experiment software.

3. The software user interface will be menu-driven and user-friendly.

## Appendix C

### Operations Scenarios for Representative Experiments

This appendix includes overviews of the operations required to run the two representative FP/DF experiments discussed in this status report: the Immersed Bubble or Drop-

let Dynamics and Interactions Experiment and the Multiphase Flow Experiment. Operations flow diagrams for these two experiments are shown in figs. 51 and 52, respectively.

#### SPACE STATION FLUID PHYSICS/DYNAMICS FACILITY OPERATIONS SCENARIO FOR IMMERSED BUBBLE/DROPLET DYNAMICS AND INTERACTION MICROGRAVITY EXPERIMENT

Step	Description	Total time, min	Crew time	Methanol test run #1 comments
1.0	Setup			
1.1	Review experimental procedures	20	20	The crewmembers involved with running the experiment will review the procedure handbook.
1.2	Integrate cell	120	60	Cell integration will consist of the physical installation of the FO3 test cell into the experiment rack. The bubble insertion and retrieval mechanisms will be attached to the test cell along with connections between the cooling exchanger and the facility cooling loop. Connections will be made or checked to the instrumentation, video, thermal control and schlieren temperature measurement equipment in preparation for facility check out.
1.3	Check out and calibrate Facility	30	30	Facility check out will verify proper installation during the cell integration process.  Electrical connections will be checked for proper mating, and water cooling system lines will be leak checked.  The calibration of temperature sensors (schlieren system) and gross bubble velocity measurement systems will be performed.
1.4	Fill cell; turn on heater/cooling	120	30	The fill-and-drain system will be used to fill the test cell with methanol (unseeded) fluid. As the test cell fills, the fluid will push a piston setting the proper height of the test cell with respect to the bottom of the cell. The cell will be completely filled, thereby eliminating any ullage or bubbles. Heater and cooling plate turn-on will be initiated with the thermal control system. A warmup period of 1/2 to 4 hr will be required to create the proper temperature gradient.
2.0	Pretest	15	15	The telescience link with ground will be initialized, thereby ensuring that instrumentation data can be received and monitored by PI and ground operations personnel.
2.1	Initialize telescience link			
2.2	Test bubble mechanism	20	20	The bubble deployment and retrieval mechanisms will be tested by successfully deploying and retrieving two bubbles. Correct bubble size will be verified.
2.3	Turn on diagnostic equipment	10	10	The schlieren system and video system will be turned on at this time for support. Verification of video signal reception on the ground will be made.
3.0	Test			
3.1	Begin test; monitor video/temp	20	20	The test will begin with the automated deployment of three small bubbles. Video, schlieren, and temperature data will be monitored from the ground.
3.2	Vary temperature; deploy bubbles	180	10	The heater and cooling plate temperatures will be varied to increase the temperature gradient. A total of 27 small bubbles will be deployed during 6 gradient changes. Approximately 4 to 9 bubbles will be deployed per gradient change.
3.3	Recycle/retrieve/redeploy bubbles	1000	20	The test cell recycle process will involve the retrieval of bubbles, the re-establishment of a stable temperature gradient, and the re-deployment of new bubbles. A bubble retrieval will be performed before beginning the next deployment sequence. After the proper temperature gradient is reached, one large bubble will be deployed and observed. This process will deploy a total of four large bubbles in this test run. Because of the bubble size, each large bubble deployment requires a recycle.

Step	Description	Total time, min	Crew time	Methanol test run #1 comments
4.0 4.1	Post test Quick-look data analysis	45	15	<p>During post-test quick look data analysis, video data that were not sent to the ground in real-time will be sorted and analyzed before transmission.</p> <p>Images containing unique phenomena will be sent first to ensure PI viewing. Crewmembers will then sort through redundant images, sending only useful frames to the ground, thereby minimizing video telemetry bandwidth requirements from the space station. The diagnostic equipment will be turned off after analysis completion.</p>
4.2	Turn off heater/cooling	10	--	After PI approval of data received and science objectives being met, crewmembers will turn off the experiment cell heater and cooling plate system.
4.3	Drain cell	30	5	After the experiment cell has cooled down, the fill-and-drain system will be used to drain the methanol fluid for shutdown or for recycle into a new test run.
5.0 5.1	Shutdown Power down facility	5	5	The facility and experiment racks will be turned off, thereby removing all power from elements of the Facility. This will eliminate any electrical hazards to crewmembers during the cell de-integration process.
5.2	De-integrate chamber; clean up	60	60	The experiment cell will be removed from the experiment rack via the portable rack.
	Stow equipment	40	40	<p>After the cell is either cleaned or sealed in a safety container, it will be either reused (if feasible) or moved to the logistics module for return to Earth.</p> <p>Fluid waste used during the experiment will be moved to the logistics module for return to Earth. Tools and facility hardware will be stored in a locker within the Facility.</p> <p>Video systems will be tested and positioned, if required to verify their operation, by using the graphics processor and a quick look video monitor. The DMS will be run through a diagnostic program to ensure operation and system interfaces.</p>

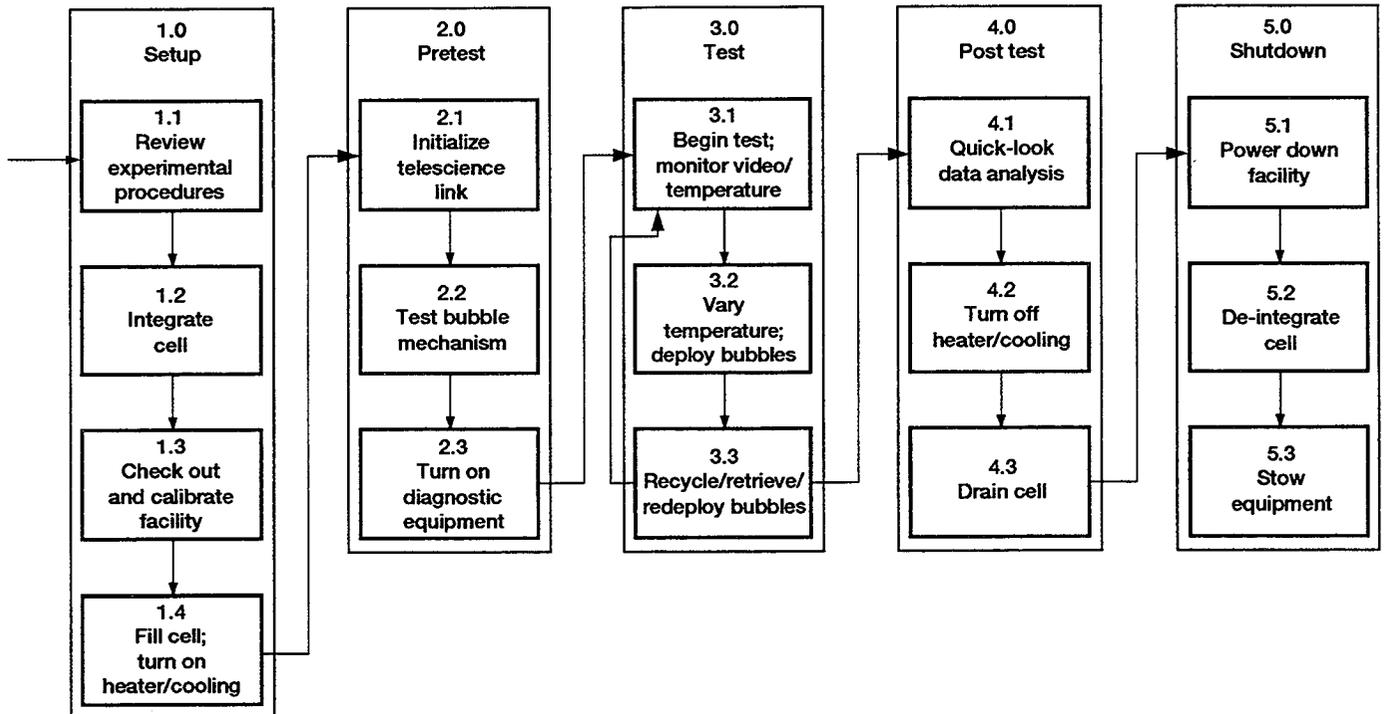


Figure 51.—Operations flow diagram for F03 Immersed Bubble/Droplet Dynamics and Interactions Experiment.

SPACE STATION FLUID PHYSICS/DYNAMICS FACILITY OPERATIONS SCENARIO FOR MULTIPHASE FLOW MICROGRAVITY EXPERIMENT

Step	Description	Total time, min	Crew time	Methanol test run #1 comments
1.0	Setup	20	20	The crewmembers involved with running the experiment will review the procedure handbook.
1.1	Review experimental procedures			
1.2	Check out and calibrate Facility	30	10	Facility check-out will verify proper flow loop water, air, waste, and electrical connections along with supply system lines being leak checked.  The calibration of pressure, temperature, and film thickness sensors will be performed.  The video system will be tested and positioned if required, thereby verifying its operation by using the graphics processor and a quick look video monitor. The DMS will be run through a diagnostic program to ensure proper operation and system interfaces.
1.3	Check out flow tube	5	5	Flow tube check out will consist of verifying the operational integrity of the flow loop.
2.0	Pretest			The teleseience link with ground will be initialized thereby ensuring that instrumentation data can be received and monitored by PI and ground operations personnel.
2.1	Initialize teleseience link	15	5	
2.2	Parameter loading	20	5	Each test run will conform to a 3 x 3 flow matrix selected by the PI along with a run duration. At this point the air/water flow setting matrix parameters will be loaded into the flow controller.
2.3	Turn on diagnostic equipment	10	2	The video system and backlighting system will be turned on at this time for test support. Veification of signal reception on the ground will be made.
3.0	Test			Test duration will last 60 to 300 seconds. Crewmember support may be required to provide visual analysis of experiment progression.
3.1	Begin test; monitor video/pressure	5	0	
3.2	Establish two-phase flow	<5	0	The automated startup of the experiment shall establish two phase flow. Air will be mixed into the water stream to establish a flow pattern.
3.3	Observe	<5	<5	Crewmembers and ground personnel will observe the phenomena. Wave structure and velocity images along with film thickness measurements will be analyzed.
3.4	Recycle; vary flow rate	100	<20	The test recycle process will complete a test and re-adust the air/water flow rates for the next test.  Each test will adhere to a flow matrix, which represents different liquid flow rates and tube diameter combinations. The test run will be completed when all of the matrix combinations have been met or if the PI decides to conclude the tests.
4.0	Post test			During post-test quick look data analysis, video data that was not sent to the ground in real-time will be sorted and analyzed before transmission.  Images containing unique phenomena results will be sent first to ensure PI viewing. Crewmembers will then sort through redundant images and send useful frames to the ground, minimizing video telemetry bandwidth requirements from the space station. The diagnostic equipment will be turned off after analysis completion.
4.1	Quick-look data analysis	45	15	
4.2	Purge flow loop	10	0	After PI approves data received and after science objectives are met, crewmembers will purge the flow loop of any air or water.
5.0	Shut down			The flow loop equipment will be cleaned.
5.1	Clean flow loop	20	0	
5.2	Power down Facility	5	5	The facility and experiment racks will be turned off, thereby removing all power from elements of the Facility. This will eliminate any electrical hazards to crewmembers during the stowage process.
5.3	Stow equipment	5	5	After cleanup the flow tube will remain in place to support the next test run. Tools and Facility hardware will be stored in a locker within the Facility.

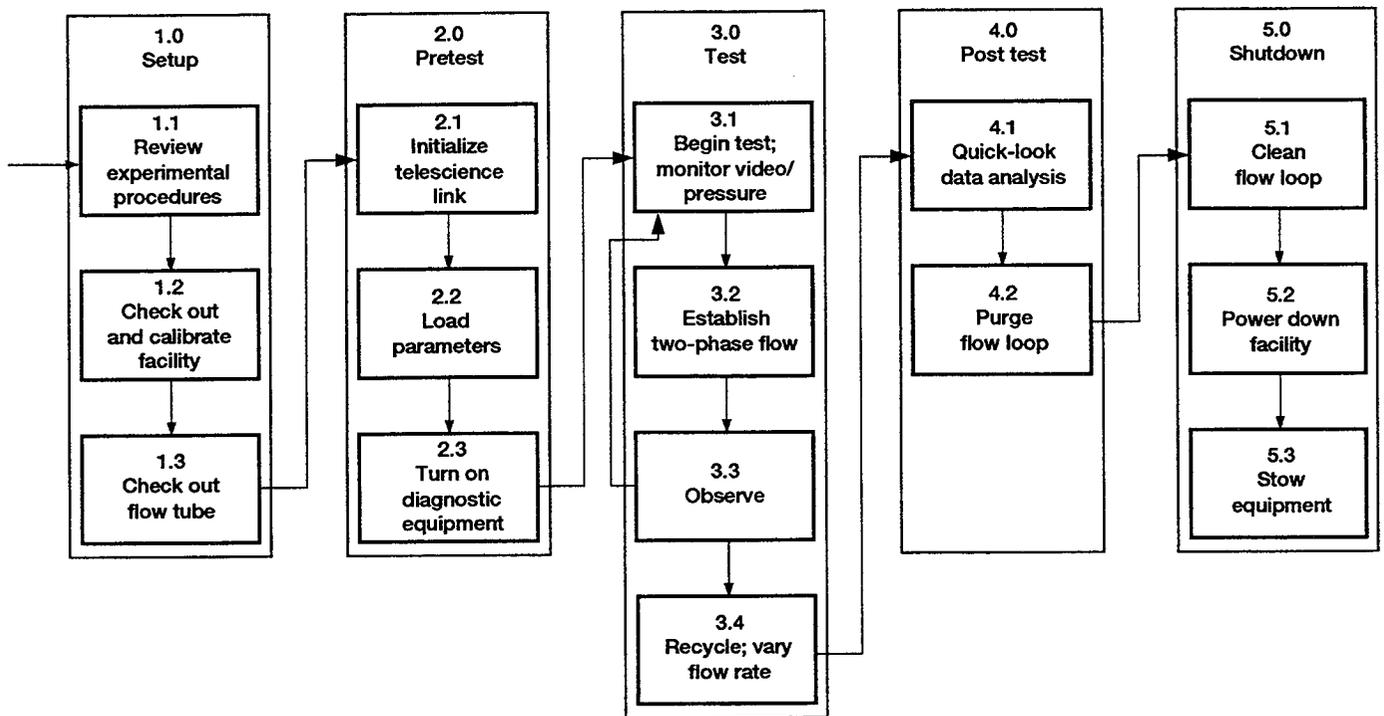


Figure 52.—Operations flow diagram for FO5 Multiphase Flow Experiment.

## Appendix D Contributors

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<b>13. ABSTRACT (Maximum 200 words)</b>  A study team at NASA's Lewis Research Center has been working on a definition study and conceptual design for a fluid physics and dynamics science facility that will be located in the Space Station Freedom's baseline U.S. Laboratory module. This modular, user-friendly facility, called the Fluid Physics/Dynamics Facility, will be available for use by industry, academic, and government research communities in the late 1990's. The Facility will support research experiments dealing with the study of fluid physics and dynamics phenomena. Because of the lack of gravity-induced convection, research into the mechanisms of fluids in the absence of gravity will help to provide a better understanding of the fundamentals of fluid processes. This document has been prepared as a final version of the handout for reviewers at the Fluid Physics/Dynamics Facility Assessment Workshop held at Lewis on January 24 and 25, 1990. It covers the background, current status, and future activities of the Lewis Project Study Team effort. It is a revised and updated version of a document entitled "Status Report on the Conceptual Design for the Space Station Fluid Physics/Dynamics Facility," dated January 1990.			
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