TWO-PHASE FLOW AND HEAT TRANSFER IN POROUS BEDS UNDER VARIABLE BODY FORCES

Final Report

Part VII

Project Director:

Harold R. Henry, Ph.D.
Professor of Engineering Mechanics
University of Alabama

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Submitted to

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

Contract No. NAS8-21143
University of Alabama No. 22-6560

May 1970
Bureau of Engineering Research
University of Alabama

Report No. 113-30
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PREFACE

This is Part VII of a seven part Final Report on work under contract No. NAS8-21143 between the George C. Marshall Space Flight Center and the University of Alabama. The purpose of this project has been to perform analytical studies and laboratory tests related to designing an Earth-orbital experiment to study two-phase flow and heat transfer in porous beds in a reduced gravity environment.

Part I explains the motivation for the project with reference to expected fundamental scientific achievements and a description of applications relating to space-flight and ground-b sed devices.

Part II is primarily an experimental study of the factors influencing two-phase flow. The results are obtained and expressed in such a manner that they allow extrapolation to reduced gravity situations. This provides a hypothesis for a description of the effect of reduced gravity. The primary purpose of the flight experiment will be to test this hypothesis

Part III is an anlytical and computer-based study conducted on an idealized model of two-phase flow in porous material. It clarifies the relations among pressure gradient, surface tension, inertia and gravity forces.

Part IV is a systems analysis of the transients occurring in an assumed model of the proposed flight experiment for boiling and vapor-bubble studies. The technique of digital simulation was employed in the analysis.

Part V is an account of the development of the experimental feasibility of a two-phase mass flow meter. After calibration the only measurements which are required to determine the mass flow of the liquid and gas separately are the pressure drop across each cartridge, the absolute pressure and the absolute temperature. This meter contains no moving parts and requires only a small pressure drop.

Part VI describes the development of the bread board including test models of two experimental flow channels with pumps, motors, instrumentation and peripheral equipment for power and data recording. Also included is an account of basic experiments on the vapor-bubble breadboard channel.

Part VII is an Experiment Implementation Plan. It details the selection of porous materials, liquids and gases. It also includes the parameters necessary for the design and development of a flight experimental system. It identifies, defines and establishes the general specifications for system elements requiring further development.

This Experiment Implementation Plan is as complete as it can be at the present stage of development of the project. There are some portions, particularly in Section I, the Experiment Summary, Section V, Experiment Development Approach, Section VI, Experiment Integration Approach, and Section VII, Experiment Programmatic Information which require inppt by NASA personnel. These sections lack the information which should be eventually supplied by NASA.

The format for the presentation of the Experiment Implementation Plan is that contained in NASA Form 1347 of December 1967.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

EXPERIMENT IMPLEMENTATION PLAN

FOR

MANNED SPACE FLIGHT EXPERIMENTS

TITLE Two-Phase Flow in Porous Beds

(Confine to total of 30 letters, numerals, spaces, punctuation marks, etc.)

EXPERIMENT NUMBER

May 1970

DATE

EXPERIMENT IMPLEMENTATION PLAN

FOR

TITLE Two-Phase Flow in Porous Beds Exp. No. ________

This Plan contains the following:

SECTION I	Experiment Summary (copy) (The original is forwarded by separate correspondence to Headquarters sponsoring office for signature and MSFEB submission)
SECTION II SECTION IV	Experiment descriptive information (Same as sections II through IV of the Experiment Proposal Form but updated to reflect current status)
SECTION V	Experiment Development Approach
SECTION VI	Experiment Integration Approach
SECTION VII	Experiment Programmatic Information

The information contained in this document was prepared and coordinated by the following organizations. The Principal Investigator participated in the preparation of Sections II thru VI of this document and these Sections are consistent with his experiment proposal.

________ SIGNATURE: ______________________
DATE Launch Operations Center (KSC/AA)

________ SIGNATURE: ______________________
DATE Mission Operations Office (MSC/KA)

________ SIGNATURE: ______________________
DATE Experiment Development Center

________ SIGNATURE: ______________________
DATE Experiment Integration Center

NASA FORM 1347 DEC 67

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

EXPERIMENT SUMMARY

MANNED SPACE FLIGHT

DATE PREPARED: May 1970

TO (Transmit Original Copy)

EXECUTIVE SECRETARY
MANNED SPACE FLIGHT EXPERIMENT BOARD

FROM (NASA or DOD Sponsoring Office)

SIGNATURE

PART I — ADMINISTRATIVE

1. TITLE (Confine to total combination of 30 spaces, punctuation marks, letters, numbers, etc.)	2. EXP. NO.
Two-Phase Flow in Porous Beds	

3. PRINCIPAL INVESTIGATOR

A. FULL NAME	B. INSTITUTION	C. PHONE
Harold R. Henry	University of Alabama	348-6550

4. OFFICE OR CENTER	5. CONTACT NAMES
SPONSORING PROGRAM OFFICE: Marshall Space Flight Center	
FLIGHT PROGRAM OFFICE	
DEVELOPMENT CENTER	
INTEGRATION CENTER	

6. MSF/MSFB ACTIONS
(To Be Completed by Executive Secretary, MSFEB, only.)

A. ACTIVITY OR RESULTS	B. DATES
COMPATIBILITY REVIEW AUTHORIZED	
COMPATIBILITY REVIEW BY	
MSFEB RECOMMENDATION	
FLIGHT PROGRAM ASSIGNMENT	
FLIGHT MISSION ASSIGNMENTS	

C. ADDITIONAL MSF/MSFEB COMMENTS

NASA FORM 1339 JAN 67 — REPLACES NASA FORM 1067, JUL 65, WHICH IS OBSOLETE — PAGE 1 OF 4 PAGES.

NASA FORM 1347 DEC 67

SECTION II - TECHNICAL INFORMATION

1. OBJECTIVES

The overall objective of this experiment is to determine the behavior of two-phase vapor-liquid and gas-liquid flow through porous beds, in low gravity environments. This specifically entails the testing of the hypothesis, already developed as a part of this study, for the description of the effects of reduced gravity upon two-phase flow in porous beds. It also includes the testing of the two-phase mass flow meter, the feasibility of which has been established as a part of this study, in low gravity environments. Further detailed objectives are listed below.

1. An important part of the experiment will be to obtain data useful in developing fundamental relations among capillary forces, viscous forces, pressure gradient forces, inertia forces, gravity forces, and heat transfer considerations. Varying the body force is necessary to obtain data for the complete range of parameters involved.

2. Since there are practical applications in space travel which concern two-phase phenomena in porous media, a major objective of this experiment is to accumulate specific data which will be useful in solving these problems. Examples of these are phase separation using capillary effects, vortex elimination, water purification schemes utilizing porous beds, packed bed nuclear reactors, heat pipes, and porous electrode fuel cells.

3. A very important objective is the obtaining of data which will be useful in non-space related applications. Examples are water purification schemes using porous beds, oil and natural gas flow through porous formations, disposal of contaminants in ground water formations, and flow through packed beds in chemical engineering processes.

2. SIGNIFICANCE

(a) Fundamental Aspect

When one considers ratios among the principal forces involved, namely capillary forces, viscous forces, pressure gradient forces, gravity forces and buoyancy forces, the following dimensionless parameters may be formed:

$$\frac{\text{Inertial Forces}}{\text{Viscous Forces}} = \text{Reynolds number}$$

$$\frac{\text{Gravity Forces}}{\text{Capillary Forces}} = \text{Bond number}$$

$$\frac{\text{Pressure Gradient Forces}}{\text{Viscous Forces}} = \text{Pressure coefficient or Darcy number}$$

$$\frac{\text{Inertia Forces}}{\text{Capillary Forces}} = \text{Weber number}$$

$$\frac{\text{Body Force and Inertial Effects}}{\text{Viscous Effects}} = \text{Grashof number}$$

Ground-based tests can be run in which each force except gravity can be varied from a very small value to a very large value by changing properties of the fluid or the porous medium or by changing the flow characteristics.

The fundamental reason for the flight experiment lies in the fact that there are certain combinations of parameter sizes which are virtually impossible to obtain on the ground.

Small Bond number, large Reynolds number, and small Pressure coefficient are impossible to obtain without reducing gravity. This is because in the normal gravity field, a small Bond number requires extremely small pores to give a high capillary force; these small pores also cause the viscous force to be large and thus Reynolds number is small unless the velocities are high; the pressure coefficient cannot be low unless the velocity and Reynolds number are low; thus this combination cannot be achieved on the ground.

Also low Bond numbers with the necessary small pores in ground-based experiments result in low Weber numbers. The combination of large Weber numbers and small Bond numbers can be obtained only by decreasing gravity.

One major significance of this experiment is that it will be used to test a hypothesis, developed in Part II of the Final Report of NASA contract NAS8-21143, concerning relationships which should exist in a gravitational field of any strength.

For ground-based tests, described in Part II, the most important dimensionless parameters were found to be as follows and were expressed in the following functional form for flow containing nitrogen bubbles in a Cargille liquid:

$$Da = f(S_g, Re_\ell, D/d, Gr) \tag{1}$$

where Da is the Darcy number, S_g is the volumetric gaseous quality, Re_ℓ is the liquid Reynolds number based on average velocity and bead diameter, D/d is bed to bead ratio, and Gr is the liquid Grashof number. An orderly correlation of families of curves for specific values of Gr and D/d were obtained when Da was plotted against Re_ℓ with S_g as curve parameter. Figure 1 presents the data for Gr = 202,000 and D/d = 8. It is noted that the single-phase liquid flow data define a curve which separates the two-phase flow data into two families of curves. Those for vertically upward flow fall below the single-phase curve and those for vertically downward flow fall above the single-phase curve. The parameter identifying a specific curve is S_g, the volumetric gaseous quality, and the larger the

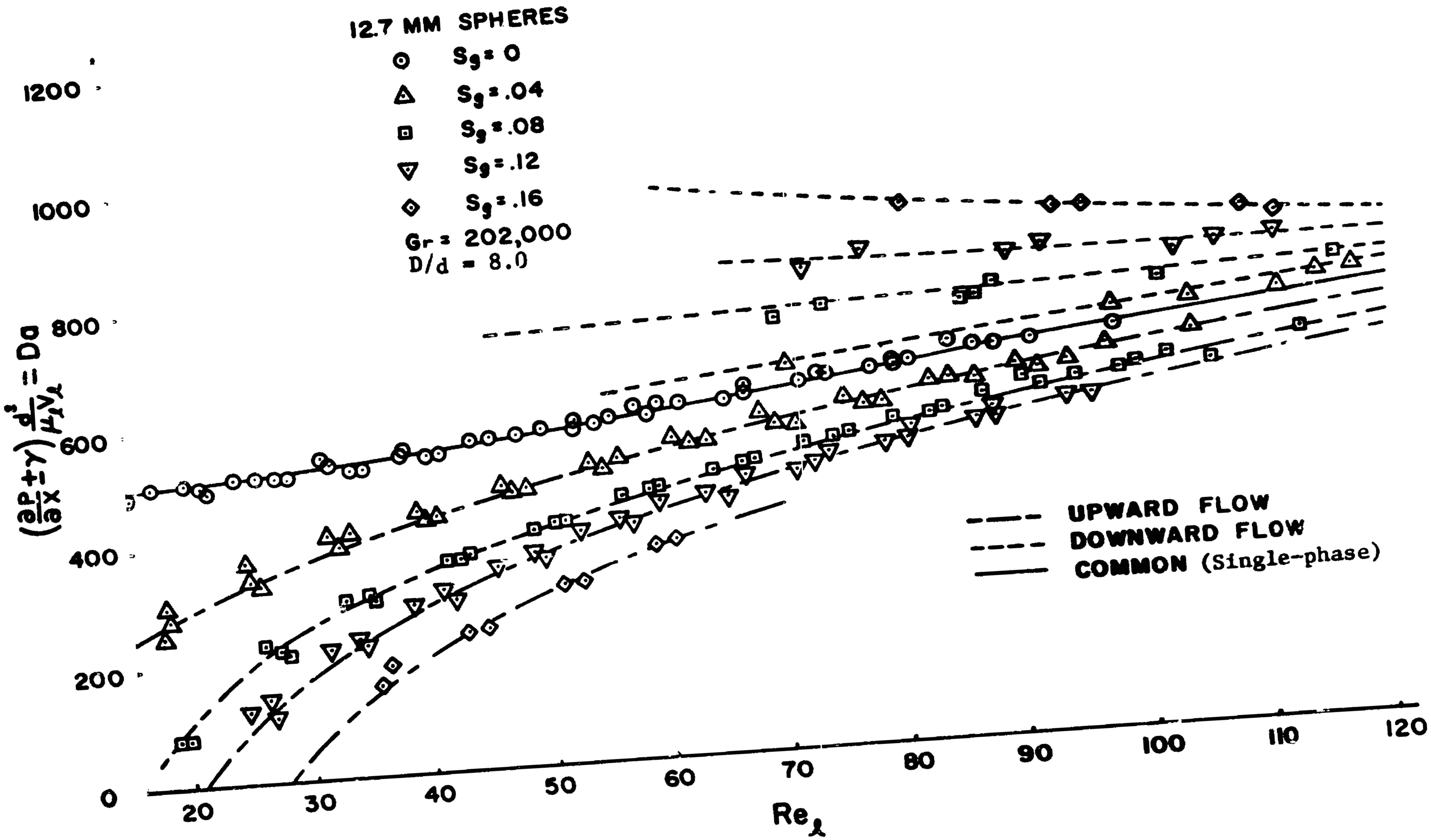


Figure 1. Darcy Number vs Liquid Reynolds Number.

quality, the further from the single-phase curve do the two-phase curves lie.

A phenomenological analysis for the total driving force and drag force on the liquid, presented in Part II of the final report, took into account the drag force of the moving gas bubbles on the liquid. As a result of this analysis equation (1) is modified as shown below:

$$Da(1+KS_g) \pm KS_gGv = f(S_g, Re_\ell, D/d, Gr) \qquad (2)$$

In equation (2) Gv is the ratio of liquid body forces to viscous forces and K is an empirical constant depending on the shape of the bubbles. The plus sign is used for upward flow and the minus sign for downward flow. When the left side of equation (2) is plotted against Re_ℓ the result for $Sg = 0.12$ is indicated in Figure 2 for three values of Gr and D/d.

The remarkable coalescence of the curves for upward and downward flow indicate that the difference in effects of positive and negative body forces have been taken into account by the form of the left side of equation (2).

After the application of a correction for the difference in D/d ratio to eliminate the discontinuities evidenced in Figure 2, the average curves for upward and downward flow are shown in Figure 3 for single-phase flow and four values of S_g. The discrepancies between the curves for upward flow and those for downward flow are within the limits of experimental error for the investigation.

Therefore, the hypothesis is presented that the relations indicated in Figure 3 will apply to two-phase flow in a gravitational field of any strength including a zero gravity environment. In order to test this hypothesis it is necessary that experiments be run in an environment yielding combinations of values of pertinent dimensionless parameters which, as

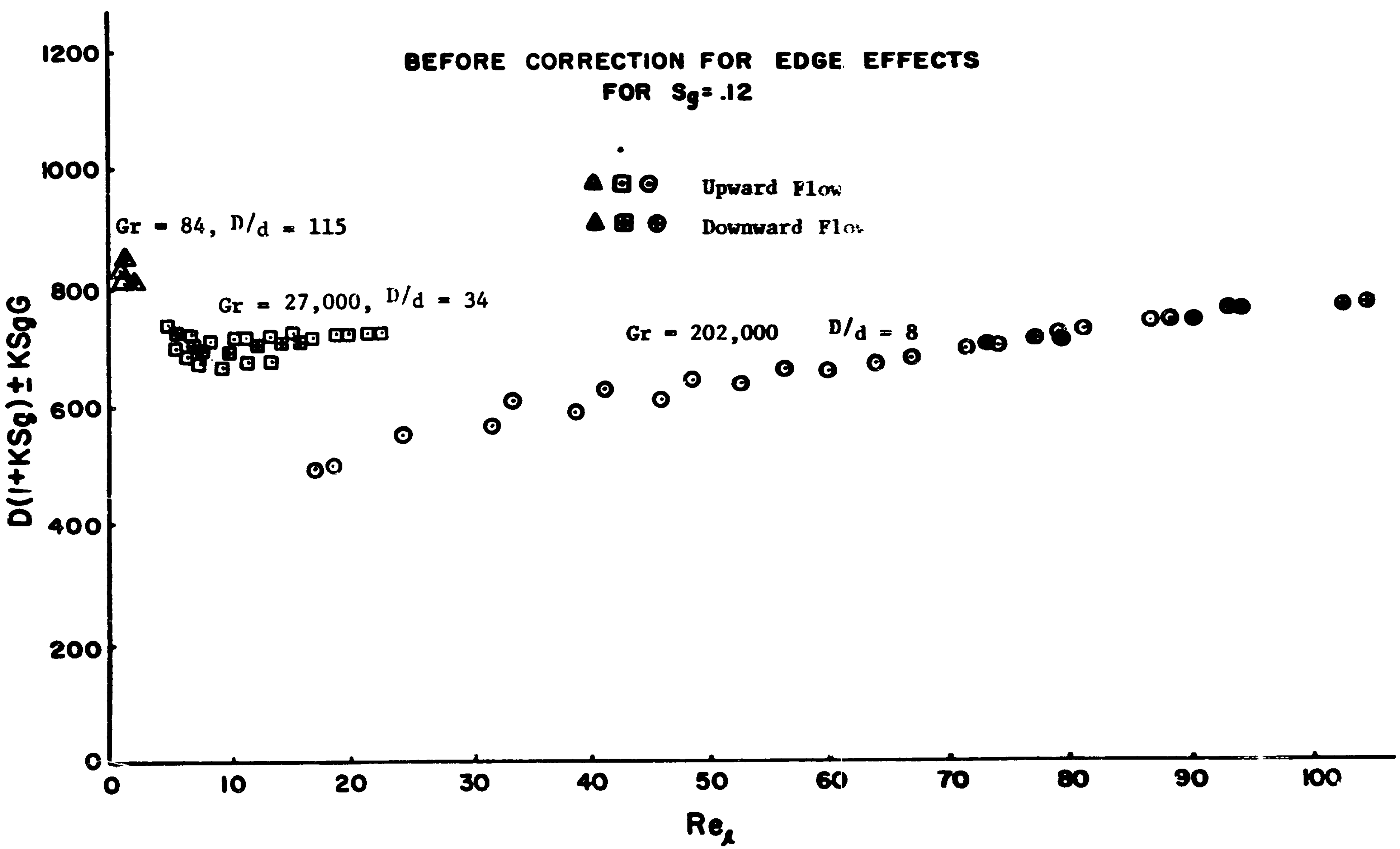


Figure 2. Darcy Number plus Relative Drag Correction vs Liquid Reynolds Number.

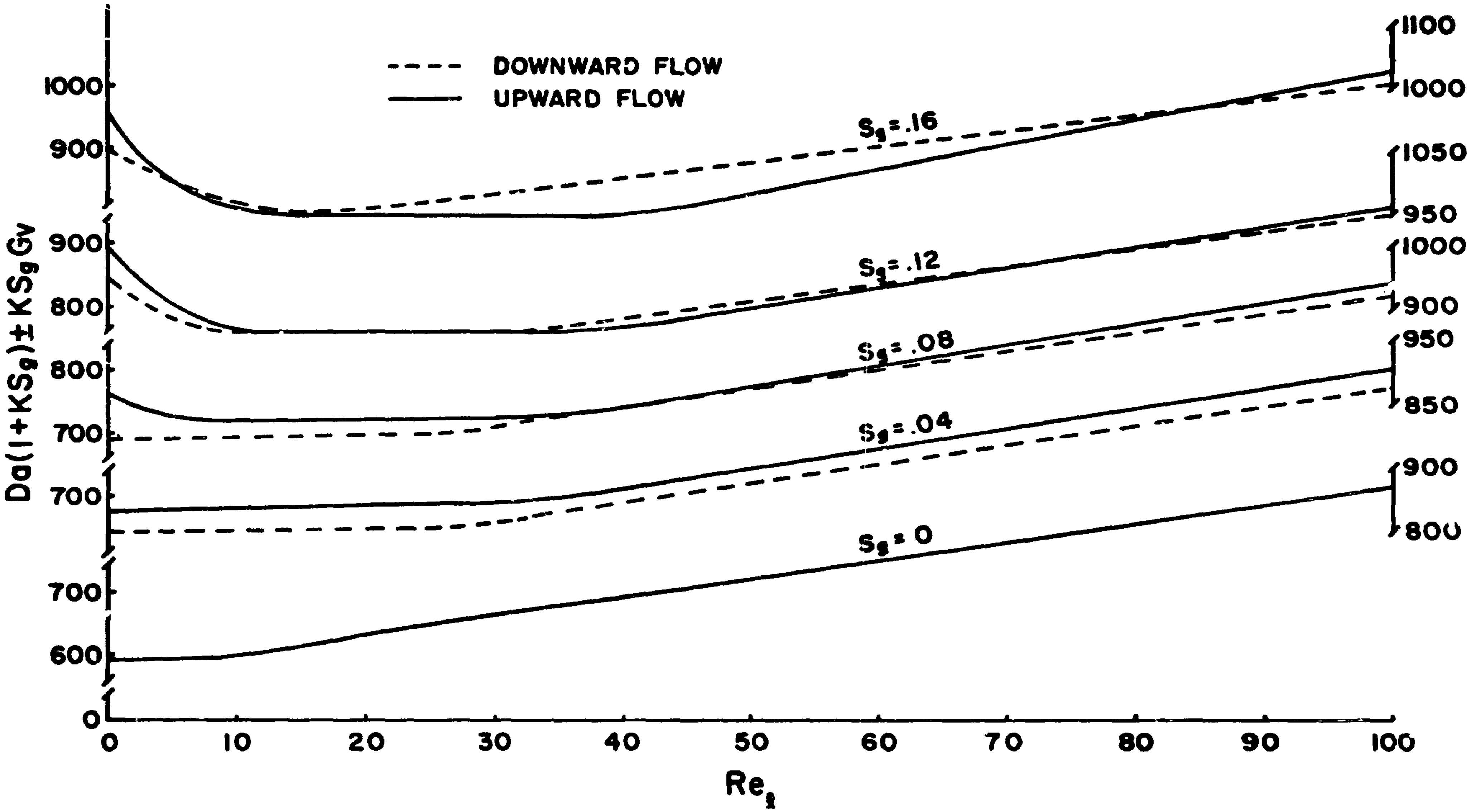


Figure 3: Average Curves. Darcy Number Plus Relative Drag Correction vs. Liquid Reynolds Number

discussed above, cannot be obtained on the ground.

A second major significance of this experiment is that it will be used to test the operation in various gravity environments of a two-phase mass flow meter developed under contract NAS8-21143 and described in Part V of the final report. Because of the difficulty in separating gases and liquids in the absence of gravity, the metering of two-phase flow is a problem associated with reduced gravity environments.

A porous material will exhibit a selective relative permeability to each of two fluid phases simultaneously flowing through it. In addition, when two-phase flow occurs through two porous cartridges, with greatly different pore sizes, placed near each other in a pipe, the characteristics of the flow through each will be extremely different with the proportion of the pressure drop caused by each phase differing markedly in the two cartridges.

As described in Part V, these facts were exploited in establishing the feasibility of making a two-phase mass flow meter from two porous cartridges. After calibration of the meter, the measurements necessary to determine the mass flow of each phase are pressure drop across each cartridge and absolute pressure and temperature downstream of the meter. It is assumed that properties of the gas and liquid are known. A calibration chart for an experimental meter is shown in Figure 4 where the pressure gradient H divided by the liquid viscosity μ across one porous cartridge is plotted against the same ratio for the other cartridge. Note that there are two families of curves crossing each other. The parameter specifying a particular curve in one family is the liquid flow rate q_L and in the other family is the gaseous flow rate q_g. In order to obtain the flow rates from a given set of pressure and temperature readings, one plots the point corre-

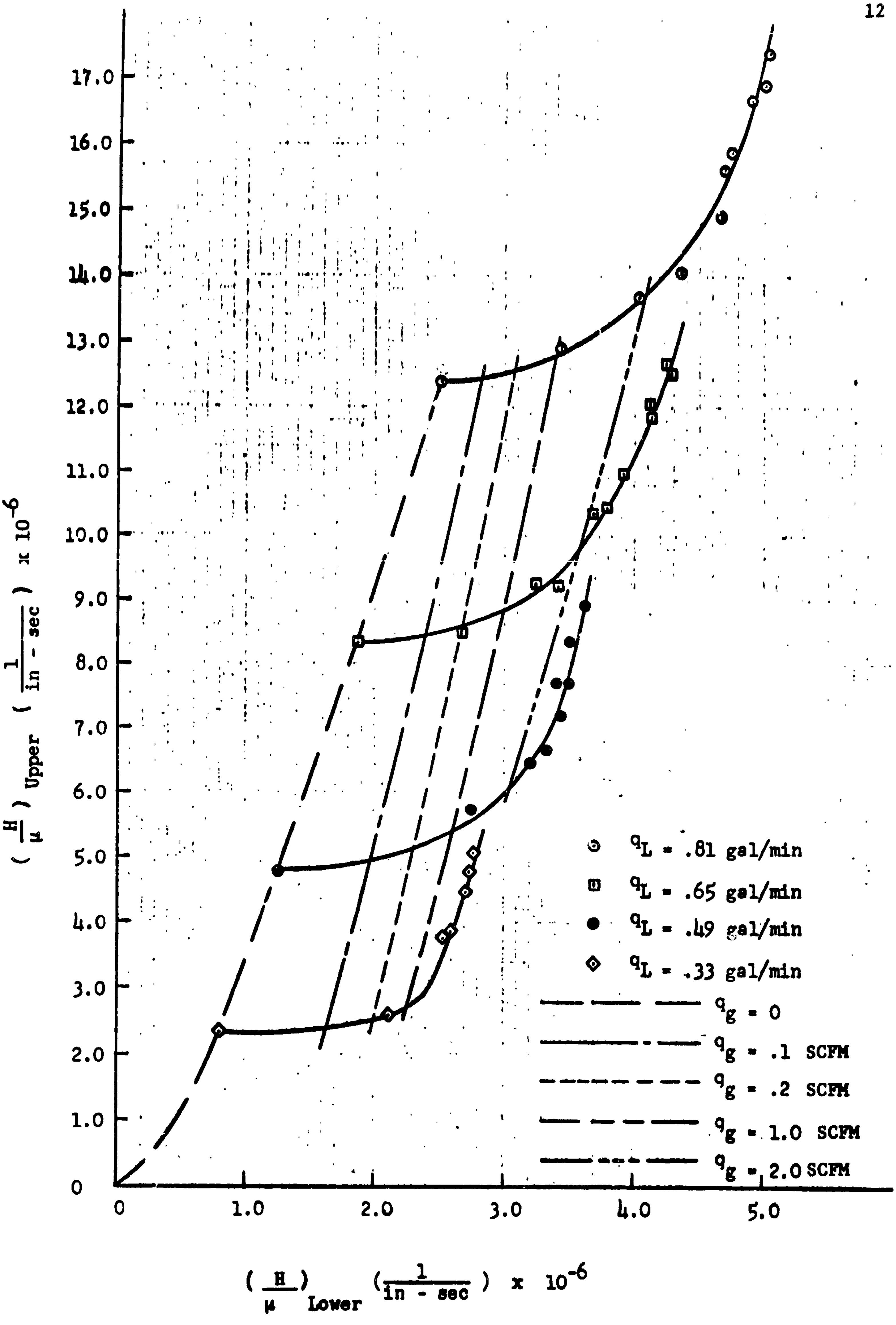


Figure 4. Calibration Chart for Experimental Meter.

sponding to the pressure drop across each channel and interpolates between curves for values of q_L and q_g. Rather simple corrections can be applied for variations in temperature and absolute pressure.

A given combination of cartridges constitutes a good meter for a specific range of liquid and gaseous flows. Outside this range the calibration curves for various flow rates coalesce so that they cannot be distinguished from each other.

The ground based tests were run with vertical flow both upward and downward with the best results for upward flow. It is hypothesized that the meter would function in the same manner in a zero gravity field as in the ground based tests. This experiment would provide the opportunity for testing this hypothesis.

Other possible space applications for data obtained from the experiment are as follows.

Phase Separation

When a porous material is submerged in a wetting fluid which contains bubbles of a non-wetting fluid, the pores will be occupied by the wetting fluid and non-wetting fluid will move into the material only when the driving pressure differential is greater than the capillary pressure difference. When a mixture consisting of liquid and gaseous phases is passed over a screen or thin porous bed, the wetting fluid will tend to move through the bed and the non-wetting fluid will not if the pressure differential is less than the capillary pressure difference.

Vortex Elimination

Porous baffles have been found effective in reducing vortexing tendencies and large eddies in the entrance to feed lines from propellant tanks. If there is vaporization, as will be the case with cryogenic liquids, vapor bubbles will tend to collect at the baffles and, because of capillary forces, will act as obstructions to the movement of liquid. Some studies have sought to predict analytically the effect of absence of gravity or zero Bond number for static conditions with extremely simple capillary geometry. However, these results cannot be extrapolated to the complex capillary geometry of porous flow straighteners under dynamic conditions in a low gravity environment.

Water Purification Schemes

Almost every scheme recommended for the reclamation of waste water in the closed environment of space travel involves flow through membranes and porous beds such as activated charcoal or catalyst beds for the removal of impurities. Usually, regardless of the principal method of removing wastes, a final filter is recommended.

In some cases it is difficult to maintain flow in the system without the ingesting of some gas into the liquid flow scheme. However, even if there is none of the gaseous phase present in the entrance to the treatment apparatus, the pressure drop required for flow through the porous beds may cause considerable dissolved gas to come out of solution. In some cases the permeability of the porous bed may be decreased by as much as 30% by the presence of as little as 10% gas by volume. Moreover, the purifying or exchange function of the porous bed is efficient only when there is a maximum liquid-solid area of contact. This is obviously reduced when vapor or gas bubbles are present.

Packed Bed Nuclear Reactors

The packed bed is of considerable interest as a nuclear reactor configuration for space applications. Nuclear fuel pellets are immersed in a flowing liquid which serves to transfer the heat generated to some sink for use and to simultaneously cool the bed to acceptable operating temperatures. For space applications considerable weight reduction in liquid required for a given heat transfer rate could be accomplished by allowing local boiling inside the reactor, thus using the heat of vaporization such as a heat pipe does. Since any stagnant vapor pocket would cause a disastrous reduction in local heat transfer rate, it is essential to understand the mechanics of vapor-liquid flow in packed beds in low gravity environments.

The Heat Pipe

The heat pipe is a simple inexpensive device that can transfer as much as 500 times as much heat per unit weight as a solid thermal conductor. The usual geometry consists of a straight, sealed tube containing a porous wick which extends the length of the tube and is saturated with a suitable liquid. The liquid is evaporated at the heat addition end and condensed at the heat sink end. Vapor bubbles form at the pipe wall in the heat addition area and must be subjected to a large enough pressure gradient to sweep them through the wick into the return vapor channel. For spacecraft applications, it is essential that the operational mechanics and thermo-dynamics of the heat pipe in a low gravity environment be completely understood.

The Fuel Cell

The hydrogen-oxygen cell consists of a porous anode bathed in hydrogen, a porous cathode bathed in oxygen and an electrolyte separating the anode and the cathode. Water is formed as a by-product in bath porous electrodes and must be flushed from the system to avoid liquid saturation. Cell power generation is directly proportional to the quantity of fuel utilized, and with an abundant supply of fuel, power generation is limited by the pore surface area in contact with fuel gases. Thus the maximum output is limited by the nature of the two-phase flow through the porous electrodes and the need for reliable flow prediction of both fuel components is evident.

3. DISCIPLINARY RELATIONSHIP

(a) Brief History of Related Work

Much fundamental work in the field of flow in porous media has been done by chemical engineers, geophysicists and petroleum engineers. A large body of literature containing fundamental studies of mass dispersion, including the effect of density gradients and two phase flow in porous media, has been directed toward applications to flow in water bearing aquifers (i.e., porous geological formations), to flow in oil bearing and gas bearing sands, and to flow through catalyst beds.

The principal investigator has provided direction for several theses which have been written recently in this and related areas (Lin, 1964; Adams, 1965; Miller, 1966; Toth, 1966; French, 1967; Evers, 1969; French, 1969; Piper, 1969; McDonald, 1970). He has also recently completed a research project consisting of an analytical and laboratory study of the effects of thermal and density gradients in saturated porous media (Henry, 1967).

One of the most significant results of this recently completed study is that the effective thermal diffusion coefficient in flow through porous media is shown to be an order of magnitude larger than the usual molecular diffusion coefficient. This is similar to results obtained by the principal investigator and others concerning mass diffusion in porous media. This large heat diffusion coefficient is of utmost importance in obtaining internal energy balances for the determination of whether or not the liquid will vaporize locally.

Because of its importance in many fields of engineering and especially in ground water technology, chemical engineering, and petroleum reservoir technology, the phenomenon of dispersion accompanying miscible displacement in saturated porous material has received much attention in recent years. As a natural consequence of the complexity of the subject, most investigations have been concerned with the case where the two fluids have similar mechanical and thermal properties. Such studies are exemplified by the following recent papers: (Adams, 1955; Banks and Ali, 1964; Bear, 1961; Gottschlich, 1963; Poreh, 1965; Schiedegger, 1958).

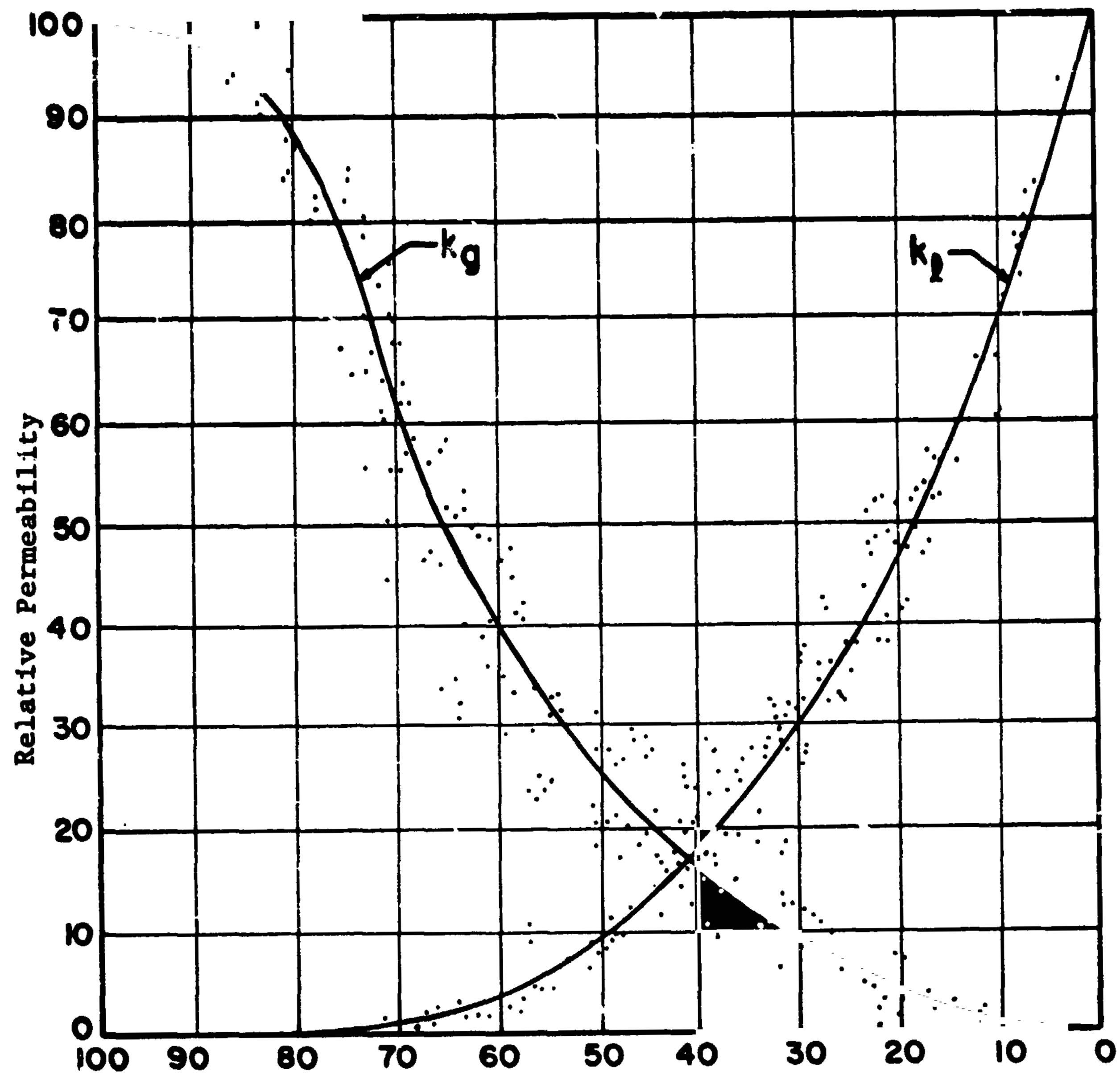
Recent studies have also been made on flow with density gradients, i.e., the mixing of two miscible fluids of different density. They fall into two categories; namely, those that assume a step change in density at a sharp interface and those that consider a zone of dispersion where the dispersion equation and the equation of motion are coupled because of the buoyancy change associated with the change in concentration of the solute. Representative recent papers which fall in the first category are: (De Josselin de Jong, 1960; DeWiest, 1961; Henry, 1959, 1962, 1964b; Lin, 1964). Some recent papers which treat the region of dispersion wherein there is a density gradient and associated buoyancy forces are: (Henry, 1961, 1964a).

Much of the investigational work on two-phase flow of immiscible fluids in porous media may be divided into three categories. The first category treats a "mixture" of the two fluids in which small bubbles of one phase exist uniformly embedded in the second phase and flow of both occurs simultaneously. This is the type of flow that has received principal consideration under contract NAS8-21143 at the University of Alabama. This type of flow is discussed in each of the seven parts of the Final Report which forms the basis for the preparation of this Experiment Implementation Plan.

In flow with low Reynolds numbers the concept of relative permeability becomes important (Wyckoff and Botset, 1936). It has been shown experimentally that as the saturation of the porous material by the second phase increases from zero, the permeability of the material to the first fluid decreases sharply. This is shown qualitatively in Figure 5. This phenomenon is important in water purification schemes where the pressure drop in the system allows air or other gases to come out of solution in small bubbles upstream of or within porous beds.

An example of investigations of flow through catalyst beds is the work by Weekman and Myers (1965) in which they observed that the presence of a gas phase greatly increases the effective thermal conductivity over that for single-phase liquid flow. They noted that there is a lack of information pertaining to heat transfer in packed beds with gas-liquid flow.

The second category is the displacement of one phase by a second phase. This type of flow has been a subject of much interest to the pertoleum reservoir engineers. Illustrative of investigations with this application are those by Hassler, et al. (1936) and Leverett (1939). Collins (1961) and Blackwell (1959) discuss this type of flow and point out that there is a critical velocity below which the line between the



Fraction of pores filled by gas

Figure 5. Relative Permeability vs. Saturation (Quality)
(After Wyckoff and Botset, 1933)

advancing fluid and receding fluid is very uniform. For velocities greater than the critical value, extreme viscous fingering may occur. This is illustrated in Figure 6.

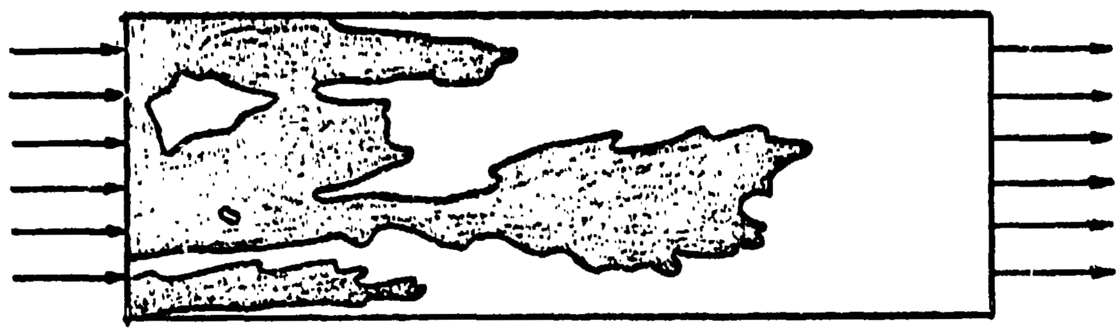


Figure 6. Formation of Viscous Fingers. (After Blackwell, 1959)

The third category treats the movement of large individual bubble formations through the porous materials. Østergaard (1965) studied experimentally the dynamics of a gas bubble as it moved upward through a porous bed fluidized by a liquid. Goring and Katz (1962) studied bubble rise in a packed bed saturated with liquids for the primary purpose of determining drag coefficients for the bubbles.

(b) State of Present Development in Field

The above discussion and the referenced publications describe the state of the present development in the field. There has been much work done on the flow of homogeneous fluids in porous media and relatively little work on two-phase flow. There is a lack of information pertaining to two-phase heat transfer and pressure drop in packed beds.

It appears that there has been no work on twc-phase flow in porous media under reduced or increased gravity conditions. This conclusicn is based upon a thorough literature search, information received from the Science Information exchange and information received from colleagues who are working in related fields.

REFERENCES

Adams, John, 1965, Dispersion in Anisotropic Porous Media, Ph.D. Dissertation, Michigan State University.

Banks, R. B., and Ali, Ibqal, 1964, "Dispersion and Absorption in Porous Media Flow," ASCE Journal of the Hydraulics Division, v. 90, no. HY 5, p. 13-31.

Bear, Jacob, 1961, "On the Tensor Form of Dispersion in Porous Media," Journal of Geophysical Research, v. 66, no. 4, p. 1185-1197.

Blackwell, R. J., Rayne, J. R., Terry, W. M., 1959, "Factors Influencing the Efficiency of Miscible Displacement," Transactions American Institute of Mining Engineers, vol. 216, no. 1.

Collins, E. C., 1961, Flow of Fluids through Porous Materials, McGraw Hill, New York

De Josselin de Jong, G., 1960, "Singularity Distribution for the Analysis of Multiple Flow through Porous Media," Journal of Geophysical Research, v. 65, no. 9, 3739-3758.

DeWiest, Roger J. M., 1961, "Free Surface Flow in a Homogeneous Medium," ASCE Journal of the Hydraulics Division, v. 87, no. Hy 4, p. 181-220.

Evers, James Leonard, 1969, An Investigation of Two-Phase Flow Through Porous Media, Ph.D. Dissertation, University of Alabama, 125 p.

French, J. V., 1967, An Investigation of Metering Two-Phase Flow Using Porous Cartridges, M.S. Thesis, University of Alabama, 70 p.

French, James V., 1969, Viscous Flow with Gas Bubbles in a Wavy Wall Tube, Ph.D. Dissertation, University of Alabama, 119 p.

Gottschlich, Chad F., 1963, "Axial Dispersion in a Packed Bed," American Institute of Chemical Engineers Journal, v. 9, no. 1, p. 88-92.

Gorring, R. L. and Katz, D. L., 1962, "Bubble Rise in a Packed Bed Saturated with Liquids," American Institute of Chemical Engineers Journal, v. 8, no. 1, p. 123-126.

Hassler, Gerald L., Rice, R. R., and Leeman, E. H., 1936, "Investigation on the Recovery of Oil from Sandstone by Gas Drive," Trans. Am. Inst. Mining Engrs., v. 118, p. 116.

Henry, Harold R., 1959, "Salt Intrusion into Fresh-water Aquifers," Journal of Geophysical Research, v. 64, no. 11, p. 1911-1920.

Henry, Harold R., 1961, "Salt Intrusion into Coastal Aquifers," International Association for Scientific Hydrology Publication, no. 52, p. 478-487.

Henry, Harold R., 1962, "Transitory Movements of the Salt-water Front in an Extensive Artesian Aquifer," U.S. Geological Survey Professional Paper 450-B, p. 34-35.

Henry, Harold R., 1964a, "Interfaces between Salt Water and Fresh Water in Coastal Aquifers," U.S. Geological Survey Water Supply Paper 1613-C, p. 35-70.

Henry, Harold R., 1964b, "Effects of Dispersion on Salt Enroachment in Coastal Aquifers," U.S. Geological Survey Water Supply Paper 1613-C, p. 70-82.

Henry, H. R., 1967, The Effects of Temperature and Density Gradients upon the Movement of Contaminants in Saturated Aquifers, Paper presented at Assembly of International Union of Geodesy and Geophysics, Berne, Switzerland, Sept.

Leverett, M. C., 1939, "Flow of Oil-water through Unconsolidated Sands," Trans. AIME, v. 132, p. 149.

Lin, Kuang-ming, 1964, Transient Two-phase Flow Through Porous Media, Ph.D. Dissertation, Michigan State University, 85 p.

McDonald, John R., 1970, An Experimental Study of Boiling Flow through Porous Beds, Ph.D. Dissertation, University of Alabama, 106 p.

Miller, David E., An Experimental Study of the Effects of Temperature and Density Gradients on Flow in Porous Material, M. S. Thesis, University of Alabama, 1966.

Østergaard, K., 1965, "On Bed Porosity in Gas-Liquid Fluidization," Chemical Engineering Science, v. 20, no. 3, p. 165-167.

Piper, Admiral S., 1969, The Analysis and Digital Simulation of a Fluid System Containing a Porous Bed in Which Boiling Occurs, M.S. Thesis, University of Alabama, 114 p.

Poreh, Michael, 1965, "The Dispersivity Tensor in Isotropic and Axisymmetric Mediums," Journal of Geophysical Research, v. 70, no. 16, p. 3909-3913.

Scheidegger, A. E., 1958, "The Random Walk Model with Autocorrelation of Flow through Porous Media," Canadian Journal of Physics, v. 36.

Toth, Richard, Maximum Column of Liquid Supported by Surface Tension Forces Between Parallel Elliptical Rods, M.S. Thesis, University of Alabama, 1966.

Weekman, V. W. and Myers, John E., 1965, "Heat Transfer Characteristics of Concurrent Gas-Liquid Flow in Packed Beds," American Institute of Chemical Engineers Jorunal, v. 11, no. 1, p. 13-17.

Wyckoff, R. D. and Botset, H. G., 1936, "The Flow of Gas-Liquid Mixtures through Unconsolidated Sands," Physics, v. 7, p. 325-345.

4. EXPERIMENT APPROACH

(a) Experiment Concept

The main idea in this experiment is to test hypotheses that have been developed by using analyses and ground-based experiments. The two principal hypotheses are described in Part II and Part V of the Final Report for contract NAS8-21143 and are summarized as follows:

(1) By a phenomenological analysis of all drag forces and driving forces on the bubbles, a method for plotting experimental data is suggested that yields identical curves for upward and downward flows, i.e., for positive and negative values of body force. It is hypothesized that the relationships indicated by these curves (shown in Figure 3) will apply to two-phase flow in a gravitational field of any strength.

(2) A two-phase mass flow meter has been developed from ground-based laboratory tests (the calibration chart for an experimental meter is shown in Figure 4) using two porous cartridges in sequence. It is hypothesized that the meter would function in the same manner in a zero gravity environment as in the ground based tests.

The testing of these hypotheses will be done by causing two-phase flow to occur through two porous beds in a low gravity environment while carefully measuring certain mechanical and thermodynamical variables so that interrelationships among the variables can be determined. Use of two beds, in addition to allowing two pore sizes, will also make possible the testing of the meter hypothesis with the one setup. Photographs taken through the transparent walls of the channels containing the porous beds will also yield important data and be used in interpreting other data.

The porous beds will be located in sequence in a self contained fluid circuit. Some tests will be conducted using liquid vapor as the gaseous phase and some using a foreign gas.

The range of parameters will be controlled in order (1) to obtain a wide range of values of the dimensionless groups which cannot be obtained on the ground and (2) to obtain a few conditions that can be essentially duplicated on the ground so that ground-based control data can be used to determine the integrity of the flight data.

In a previous section it is pointed out that certain ranges of dimensionless parameters can not be obtained in ground-based experiments. These very ranges can be expected in space applications. Only in a reduced gravity environment can (1) combinations of small Bond numbers and large Weber numbers, or (2) small Bond numbers, large Reynolds numbers and small Darcy numbers be obtained

Many important cases of flow in porous media occur with very low velocities. Thus, in a bed 15 inches long, which is anticipated for this experiment, several minutes in a reduced gravity environment could be required for the completion of an experiment. This is considerably longer than can be obtained by any method other than an Earth-orbital flight.

Incomplete data could be obtained from a drop tower or airplane flight experiment. However, bubble formation and removal (which are the phenomena of interest) would not be stabilized within the time available using either of these methods. The bubble configurations which may be obtained at zero gravity are unknown ar the present. However, the ground-based tests which have already been run indicate that even when the liquid flow rate is relatively large, the formation of bubble flow patterns may take several minutes to become stabilized. This indiates a long time requirement inconsistent with anything but an Earth-orbital flight.

(b) Methods and Procedures for Carrying out the Experiment

The fluid circuit will consist of the two porous beds, pump, pressure regulators, accumulator and necessary piping. The first test channel will be 15 inches long with a two inch square test section and will be filled with glass beads approximately 3 mm in diameter. The second channel will be 6 inches long with a two inch square cross section and will be filled with glass beads approximately 0 80 mm in diameter. Liquid and gas flow meters will be located upstream of the first test channel.

In one series of tests metered nitrogen will be introduced into the metered liquid between the liquid flow meter and the first test channel. Data taken in the test channels will be wall pressures, volumetric quality (or gas saturation of pores) and photographs.

In the other series of tests the second phase will be vapor produced by boiling by use of an immersion heater within the first channel. Data taken will be the same as those in the first series with the addition of centerline and wall temperatures and power input to the heater.

The experiment will be designed so that it can be initiated by closing a switch and stopped by opening a switch. Various pre-determined test conditions will be obtained by the astronaut setting the liquid flow valve and the gas flow valve (or the heater power control) to predetermined positions. The data recording or transmission will be initiated when the experiment has reached a steady state or a predetermined transient state.

The value of the spacecraft acceleration or the apparent level of gravity can be any arbitrary value. However, it must be precisely measured and recorded. Tests at two gravity levels are required and it would be desirable to have tests at more than two g levels. If testing of this experiment can be accomplished during periods when the spacecraft is accelerated for other purposes, it will not be necessary to require pre-determined g levels. If this is not the case, testing will be performed during levels of 10^{-3} and 10^{-6} g's specifically produced for this experiment.

(c) Measurements to be Made and Range of Numerical Values

The measurements to be made in order to accomplish the objectives of the experiment within the procedures described above are listed below.

Measurement	Number of Transducers	Range/Accuracy	Frequency Response
Pressure drop in beds	5	0 - 20 ± .10 psid	100 cps
Pressure N_2 Storage	1	0 - 500 ± 10 psia	2 cps
Pressure N_2 reg. outlet	1	0 - 50 ± .50 psia	2 cps
Liquid flow rate	1	0 - 5 ± .025 gal/min	20 cps
Gas flow rate	1	0 - 5 ± .025 scfm	20 cps
Film cameras	1	8 - 1000 frames/sec	
Temperature	5	420 - 920 ± 1°R	2 cps
Voltage to pump motor	1	0 - 28 ± .1 V	20 cps
Power to heater	1	0 - 200 ± 1 W	20 cps
Volumetric quality	3	0 - 20 ± 1%	20 cps
Linear accelerations	Sufficient to determine magnitude and direction (±2%)		
Angular accelerations	Sufficient to determine magnitude and axis (±2%)		

(d) Method for Analysis and Interpretation of Data

The experimental data will be used to compute the values of the appropriate dimensionless groups derived from dimensional analysis and the differential equations. The empirical functional relationship existing among these dimensionless parameters will be determined by plotting. Insofar as is possible, the data will be fitted into the framework provided by the combination of the analytical treatment and experimental correlation of ground-based data obtained during work on contract NAS8-21143. The data will be interpreted in terms of the hypotheses described in an earlier section. If the hypotheses are confirmed, this will be considered adequate interpretation of the data. If discrepancies arise between the flight data and the hypotheses. explanations and interpretations will be sought by resorting to the basic equations of motion, continuity, and energy for each phase, together with the interface conditions and to the phenomenological type of interpretation described in Part II of the Final Report of NAS8-21143.

The film data will be correlated with the simultaneous pressure and temperature data so that the effect of the geometrical form and movement of the bubbles may be evaluated and used in constructing the mathematical model for analysis.

(e) Prime Obstacles or Uncertainties

The successful performance of this experiment will require the following:

(1) High quality measuring systems which will perform within the range and accuracies specified.

(2) Competent observers who are able to make decisions regarding modifications of procedure when necessary.

(3) An experimental set-up which will allow any of a set of alternative procedures to be followed according to the particular outcome of a previously unpredictable result.

One problem which must be considered in the design and successful operation of the experiment is the problem of separating and venting the nitrogen from the recirculating system during the foreign-gas series of tests. Phase separaters must be designed into the system. There is some question about obtaining a phase separator which will be effective to the degree necessary for these experiments. However, proper venting of the gas from the accumulator should take care of this problem.

Considerable film will be used in this experiment and film retrieval and storage may be a problem. Also th design of the experiment so that the liquid used has no opportunity to leak or be discharges into the vehicle or into space is a consideration which must be accomplished.

A flow instability is exhibited in some ground-based experiments as large slugs of gas and liquid alternate in passing through the pipes or test channel. In such a case, the astronaut is needed to monitor the experiment and adjust flow rates and pressures so that the integrity of the experiment may be maintained.

After assuming that the above problems are overcome, measurements of pressures, temperatures, vapor/gas quality, flow rates, and accelerations; the obtaining of good photographs of bubble travel; and the ability to control flow rates of gas and liquid will determine the success of the experiment. The requirements for these measurements are all within the present state-of-the-art and present no specific difficulties.

The obtaining of a meaningful photographic record will require channels with transparent walls and will be facilitated by forming the porous material from glass beads which have an index of refraction near that of the liquid used. Thus when the porous material is filled with the liquid, it will be translucent and the presence of bubbles can be more easily detected visually.

(f) <u>The significance of the Astronaut in Performing the Experiment</u>

The presence of astronauts to change parameters for different test conditions will mean that testing can be performed for a meaningful range of parameters with much less hardware, weight, and power than would otherwise be necessary. This is especially true if the experiment is located so the astronaut has physical access to it.

In a zero gravity environment unstable flow conditions may be exhibited in certain parametric ranges which cannot be previously predicted. As mentioned above, an instability associated with gravitational force is exhibited in some ground-based experiments as large slugs of gas and liquid alternate in passing through the pipe or test channel. In such a case of instability, the astronaut is needed to monitor the experiment, adjust flow rates and pressures so that the integrity of the experiment may be maintained.

A very important portion of the flight data will be photographic records of bubble movement. A large quantity of film will be required It is planned that the astronaut change film as required and that the film be stored on board and returned with the astronaut.

As part of the experiment development plan, alternative operational schemes will be devised for use in case some minor failure would otherwise cause a loss of the experiment. The astronaut is needed to carry out the alternative scheme in the event it is required.

The astronaut will not be required continuously over long periods of time. The experiments may be run intermittently with each time interval for a run equal to or less than five minutes.

A tentative experimental procedure will be as follows after a particular linear acceleration has been obtained. The astronaut activity may be reduced by building in an automatic program of operation.

Event	Astronaut Activity
Initiation of experiment	Close switch.
Occurrence of desired liquid flow	Adjust the liquid valve to yield predetermined flow rate.
Occurrence of desired gas flow	Adjust the gas valve to yield predetermined gas flow rate.
or	or
Heating initiated	Set heating power at predetermined level.
*Evaluation of experiment operation	Observe flow through each porous bed and system pressure valve on an indicating gage.
Obtain data	Start data acquisition system. Check and verify operation of system.
Obtain photographic record	Set camera at predetermined speed. Start and Stop camera.
End of run	Stop data acquisition system.
Stop gas flow	Close gas valves.
Reduce pressure on system	Depressurize system by opening vent on accumulator.
Stop liquid flow or begin next run by starting new liquid flow rates	Adjust each liquid valve to yield predetermined flow rate.

*A built in redundancy or alternative scheme is needed here in case a minor failure is observed.

5. BASELINE OR CONTROL DATA

(a) Support Studies

Several support studies and concurrent investigations that are necessary to augment the flight investigations are as follows.

(1) Further development of a Two-Phase Mass Flow Meter

Because of the difficulty in separating gases and liquids in low gravity environments, the desirability of metering two phases is encountered in space flights. Experiments have already been run, as part of this project, which demonstrate the feasibility of using two porous cartridges as the primary elements in a two-phase mass flow meter. Two experimental models have been calibrated. The range of error needs to be reduced and the range of applicable flow rates needs to be increased. The equipment also needs to be refined in further support studies and laboratory tests. The efficacy of this method should also be compared with that of other methods of metering two-phase flow.

(2) Development of a Phase Separator

After the mixture of two phases is forced through the porous bed, the phases must be separated to prepare for another experimental run. This requires the incorporation of phase separators in the experimental hardware. The development of a suitable phase separator must proceed as a support study prior to fabrication of the experiment. Preliminary investigation indicates that advantage can be taken of the capillary action of a screen or a porous material to serve as a phase separator. Further quantitative investigation of this should be undertaken in the support study.

(3) Design Concepts for Flight Hardware

Further ground-based laboratory tests on equipment and apparatus similar to that which will be flown are necessary to determine the exact design of the flight equipment and also necessary to insure the correct interpretation of the flight data. Studies have already been conducted as part of this project on the pilot experimental set-up and on the bread-board hardware. The results have led to a considerable reduction in weight and power required when the recommendations in this Experiment Implementation plan are compared with those in the Experiment Proposal submitted in the Fall of 1967.

(4) Fundamental Experimental Studies

As has been stated in a previous section, ground-based tests have been used to establish hypotheses which will be tested in the flight experiment. These tests were run with the orientation of the test-channel flow either vertically up or vertically down. For a more complete range of orientations, further tests should be run with the channel at various inclined orientations. Also numerical values of $Da\ (1+KS_g) \pm KS_gGv$ (the composite parameter used as the ordinate for data correlation in Figure 3) which are expected in the flight experiment should be utilized in ground-based experiments.

As a matter of necessity in calibrating and testing the equipment, many tests will be run with parameter values which cannot be duplicated in the flight tests. This will provide useful data which will complement the flight data to present a more complete investigation of the two-phase flow problem.

(5) Analytical and Computer Studies of System Transients

Part IV of the Final Report for NAS8-21143 is a report on the beginning of a systems analysis of the transients which would occur in an assumed model of the flight experiment under specified initial conditions. The technique of digital simulation was used to solve the set of system equations. Much more analytical and computer work needs to be conducted on analysis of possible transients for two principal reasons. First, conditions leading to imminent catastrophic failure conditions of the experiment may be predicted by the analysis so that procedures can be worked out to save the experiment if such conditions actually occur. Second, some of the most interesting and troublesome phenomena in two-phase flow involve transients (such as flashing). In order to make the flight experiment more complete, some of these conditions should be studies by computer simulation as well as by ground-based experiments and then planned for the flight experiment.

SECTION III - ENGINEERING INFORMATION

1. EQUIPMENT DESCRIPTION

(a) Narrative Description of Experiment Hardware

The experiment hardware will consist of a self-contained fluid circuit with two test channels, pump, motor, and the necessary equipment for instrumentation (including lighting and cameras) environmental protection, mechanical support, and a controlled supply of liquid,gas, and heat to the channel. A block diagram of the hardware is shown in Figure 7. Each channel will be 2 inches square in cross section. The upstream channel will be 15 inches long and will be packed with glass beads approximately 3 mm in diameter. The downstream channel will be 6 inches long and will be packed with glass beads approximately 0.8 mm in diameter. The walls of each channel will have transparent windows to allow photographs to be taken of the bubble flow pattern.

The channels and fluid circuit will be constructed and instrumented so that one series of tests will be conducted using the liquid vapor as the gaseous phase and another series of tests using nitrogen as the gaseous phase. The liquid for both series will be water. The instrumentation will be such that the temperature, pressure, and quality data taken in both test series will be sufficient to allow the evaluation of the operation of the mass flow meter formed by the two channels in sequence.

These requirements will make it necessary for a gas injector and an immersion heater to be located in the upstream end of the first channel. The nitrogen input line will lead to the gas injector and the water will flow through holes made specifically for that purpose. A sketch of the injector is shown in Figure 8. The gas will flow out of the short hypodermic tubes. The glass beads will be packed to the surface of the injector such that the gas injection tubes will extend into

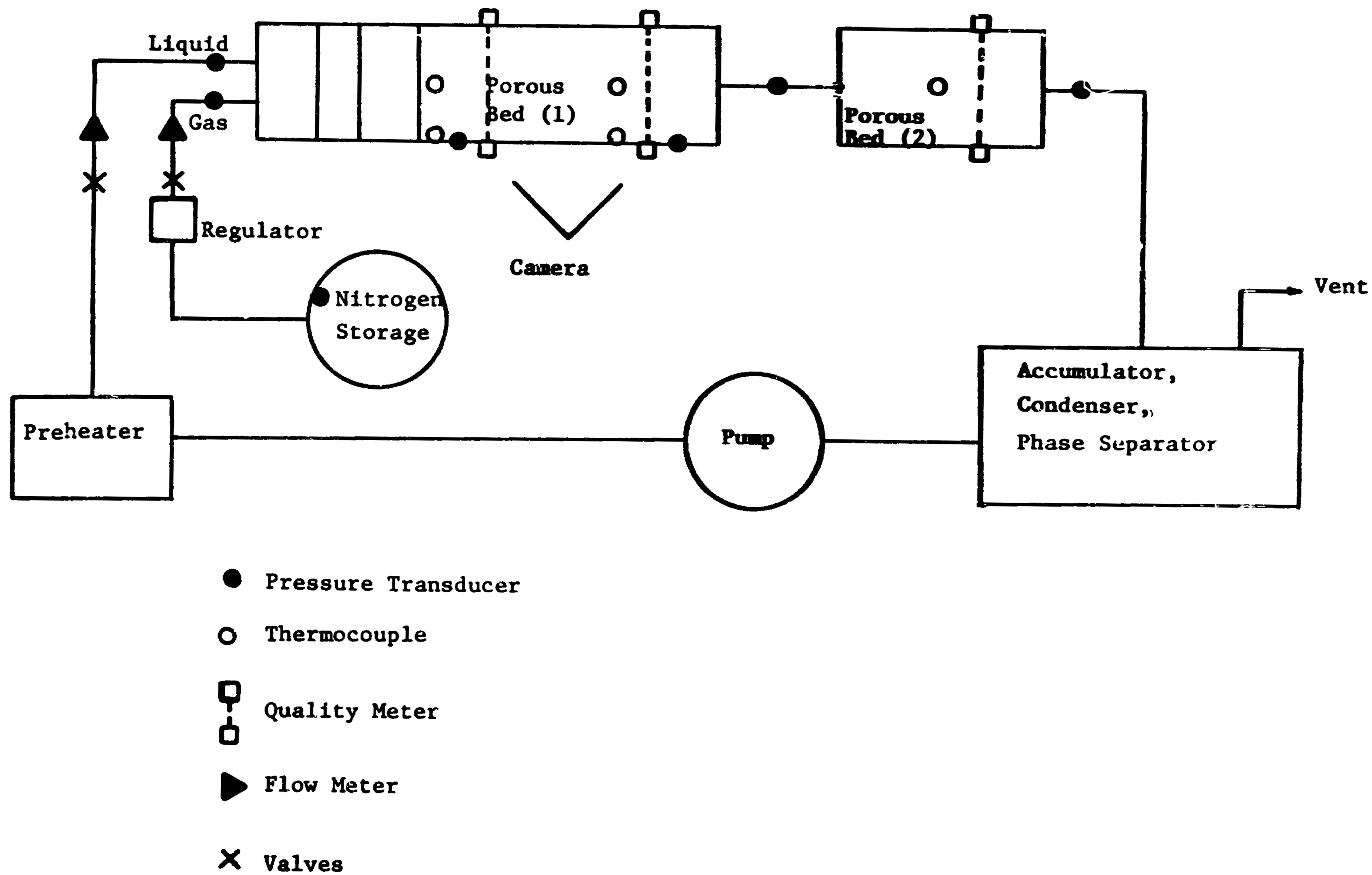


Figure 7. Block Diagram of Experiment Hardware

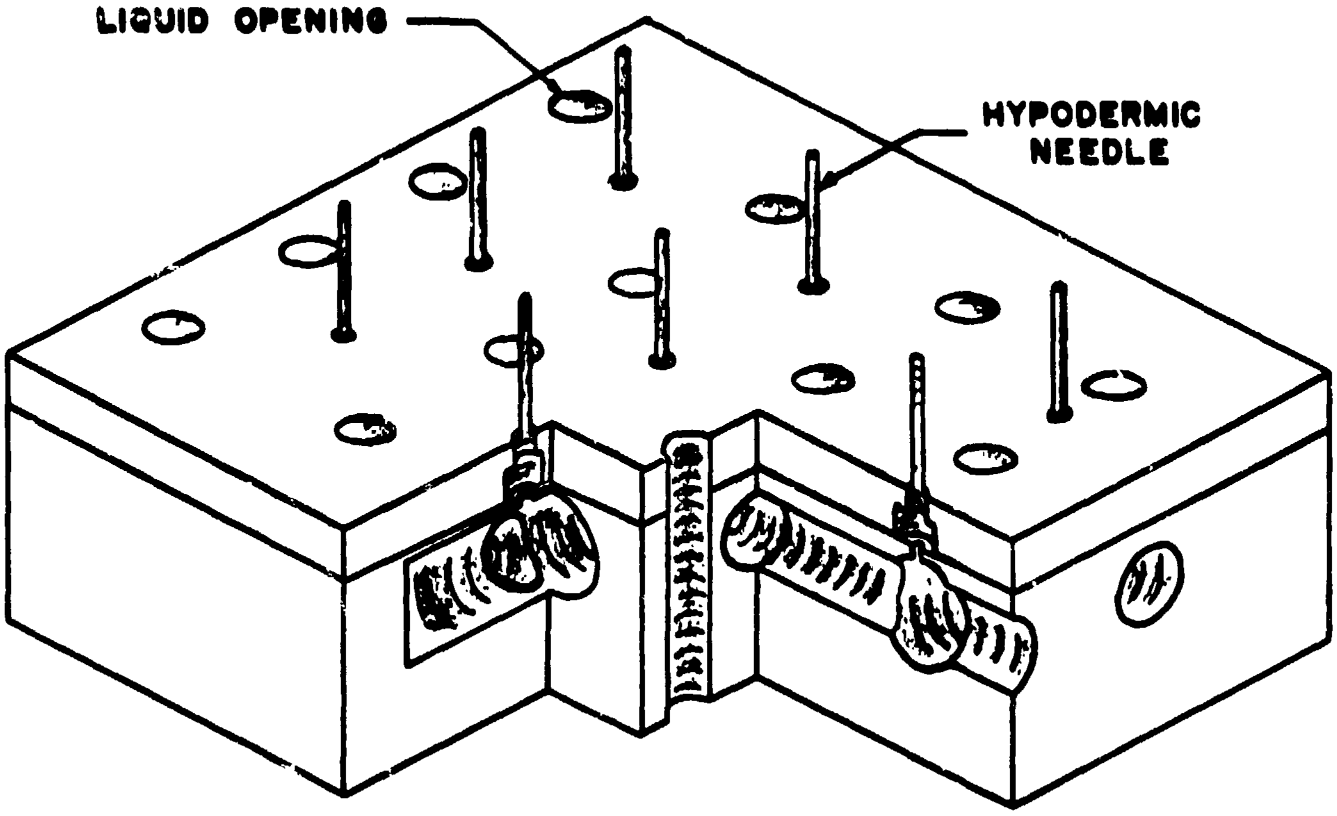


Figure 8. NITROGEN INJECTOR

the porous bed. The immersion heater (shown in Figure 9) will be placed in the porous bed immediately downstream of the gas injector. The electrical connections will pass through one wall of the channel. The struts and bars in heater hardware will be the same diameter as the glass beads. When the heater is being used the gas injector will not be used and vice-versa.

Individual control valves and flowmeters for liquid and gas will be located immediately upstream of the channels. The nitrogen will flow from a high pressure storage tank and will pass through a pressure regulator into the valve and meter.

Five pressure transducers will be necessary to determine pressures in and across the test channels. Five thermocouples and three quality meters will be required as indicated on the block diagram.

An accumulator tank which will also serve as a condenser and a phase separator will be located between the second test channel and the pump. A preheater, for the purpose of raising the water temperature almost to boiling, will be located between the pump and the first channel.

(b) <u>Required Equipment</u>

The required equipment for this project is as follows:

(1) Pilot model for preliminary studies.

(2) Breadboard model consisting of two experimental flow channels with required pump, motor, instrumentation, and peripheral equipment for power and data recording.

(3) Approximate mockup to use in developing exact dimensions.

(4) Exact mockup developed during detailed design.

(5) Prototype assembly which will be an exact duplicate of flight hardware for the purpose of qualification and testing.

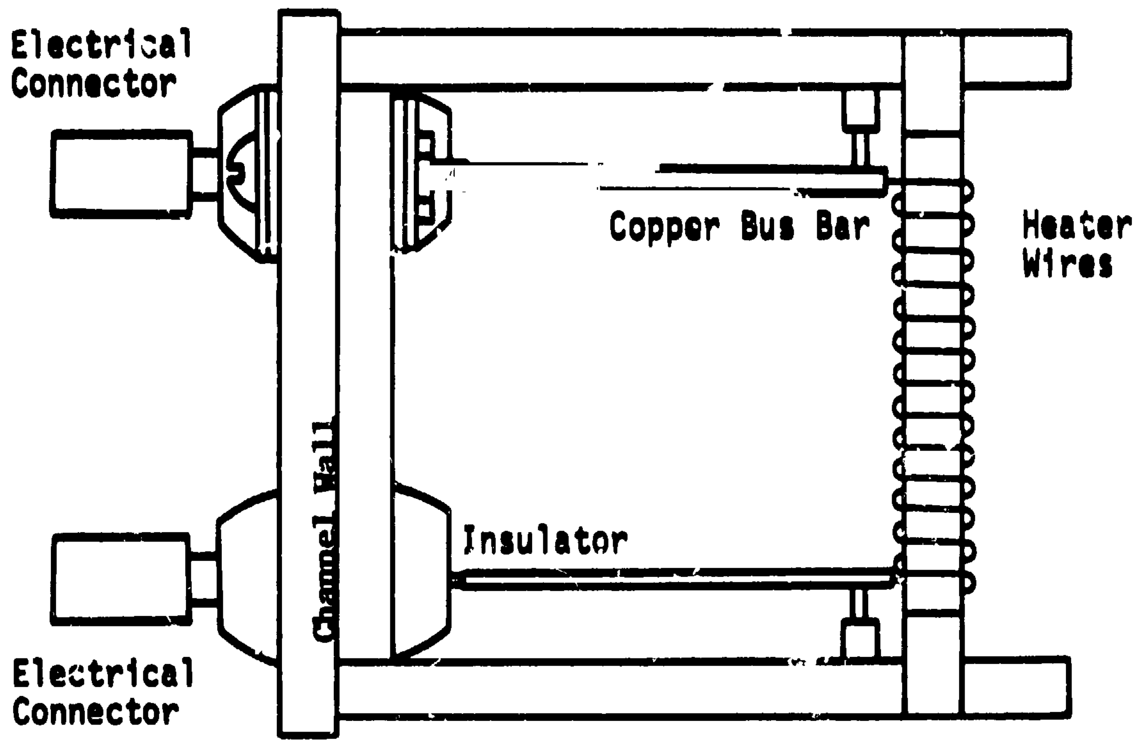


Figure 9. Immersion Heater

(6) Flight hardware as described in sections below entitled "Envelope" and "Weight and Size".

(7) A spare should be provided for every item of flight hardware.

(8) Ground support equipment will be necessary for the prelaunch checkout of equipment. This will include power supply and the necessary equipment to check the output of transducers, gas supplies, liquid supplies, data recording system, a test bench and working space suitable for use in making the checkout measurements.

(c) State of Equipment Definition

The equipment is in the conceptual stage of development. Siginificant testing of a pilot model for fundamental studies and of breadboard models has already been accomplished at the University of Alabama. Reports of this are included in earlier parts the Final Report for NAS8-21143. However, as discussed in Section II-5 herein, a much more efficient design and operation of the flight experiment can be planned if further definition of the equipment is obtained by means of groundbased testing especially since there has been considerable change in the proposed experiment hardware since the preparation of the Experiment Proposal.

2. ENVELOPE

The flight equipment is planned to fit within a space approximately 33" x 20" x 20". A sketch of the envelope is shown in Figure 10.

3. WEIGHT AND SIZE

The estimated total weight of the complete experiment assembly is 200 pounds of hardware and 130 pounds of liquid and gas. The weights of the separarate items in the completed hardware are given in the following table. Reference should be made to Figure 10 to identify items on the geometrical sketch. The overall volume of the completed assembly will be 7.7 cubic feet. The

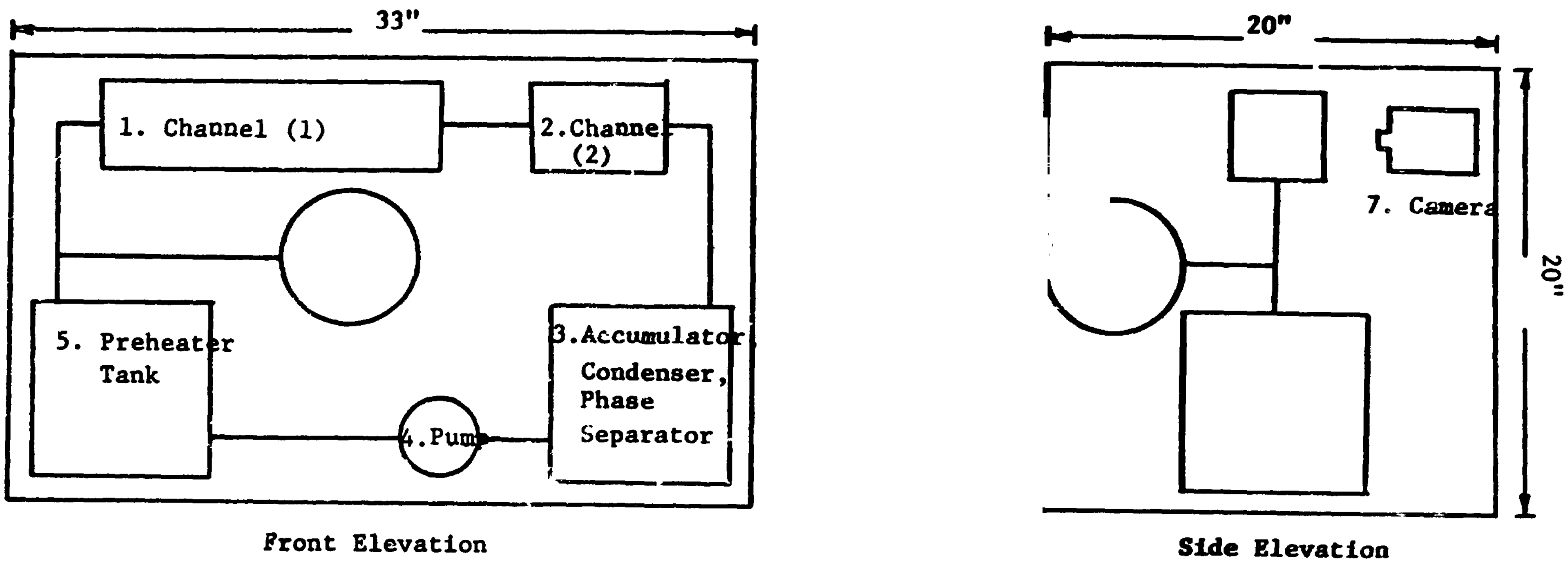


Figure 10. Envelope

volume, dimensions, and shape of items will be the same for stored and operation conditions. The film and data tape are the only items that need to be stored in the command module and recovered.

Item No.	Description	Weight, lbs.
1.	Channel (1)	25
2.	Channel (2)	10
3.	Accumulator, Condensor, Phase Separator	30
4.	Pump and Motor	25
5.	Pre-heater Tank	10
6.	Nitrogen Tank	25
7.	Camera	5
	Lighting	5
	Tubing, Fittings, Valves, Regulators	20
	Film and Data Tape	20
	Support Structure	25
	Total Weight Hardware	200 lbs.
	Liquid and Gas	130 lbs.
	Total Weight Hardware and Fluids	330 lbs.

4. POWER REQUIREMENTS

Certain items listed in Item 3 above require power to operate. These items with the estimated power required are listed below. The items not listed below do not require power.

Item Description	Standby	Power in Watts Average	Maximum
Pump Motor	-	30	60
Camera	5	5	5
Lighting	50	50	50
Heaters	100	50	100
Preheater	100	50	100
Instrumentation	15	15	15
Total Power Required	330	200	330

5. SPACECRAFT INTERFACE REQUIREMENTS

(a) Required or Desired Location

This experiment can be located anywhere inside or outside the spacecraft. The design of the supporting structure can be performed for either location. An environmental protective jacket will be required if the experiment is located outside the spacecraft.

(b) Mounting Requirements

Three hard points on the vehicle will be needed to mount the supporting structure.

(c) Subsystem Support Requirements

Maximum electrical power as estimated in a preceding section will be 330 watts. A total energy expenditure of 2 Kwh will be required for a total of 10 hours of tests. No special guidance is needed. No communication requirements are anticipated if the data is stored on film and tape. Data recording system will require 19 channels. Accelerations of 10^{-3} or 10^{-5} g will be required during the tests.

(d) Mechanical Linkage or Control Requirements

No special mechanical linkage or control requirements will be needed.

6. ENVIRONMENT CONSTRAINTS

(a) Environment Extremes

The experiment is to be inside the spacecraft or surrounded by a protective environmental jacket which will be principally a thermal insulator. The thermal tolerances listed below, which are required inside the protective jacket, apply to the entire experiment assembly.

Constraint	Tolerance Limits
Thermal	
Stored	420 - 920 °R
Operational	440 - 480 °R
Atmospheric Pressure	No Restrictions
Relative Humidity	No Restrictions
Air Movement Rate	No Restrictions
Contaminants	No Restrictions
Acceleration (Storage)	No Restrictions
Acceleration (Operation)	10^{-3} and 10^{-5} g's
Vibration (Storage)	To be determined
Vibration (Operation)	To be determined
Noise	No Restrictions
Light Tolerance	No Restrictions
Radiation Tolerance	No Restrictions (Except as it might affect film. Possible tolerances for film containers will be investigated).

(b) Interference and Contamination Caused by Experiment

It is expected that this experiment will not cause any interference with other equipment.

7. DATA MEASUREMENTS REQUIREMENTS

The following tables contain a preliminary list of the measurements which will be required with some of their characteristics.

In addition to the measurements listed in the tables, photographic records from two film cameras will be required. The operational speeds of the cameras will be in the range from 8 to 1000 frames per second. Television cameras may be used but at present they are not planned as an essential part of the experiment.

Measurements of accelerations are not shown in the table. However, the magnitude of linear and angular accelerations should be determined within 0.5% and their directions within one degree of angle.

Time lapse must be measured and the experiment measurements must be correlated in time with the measurements of spacecraft acceleration.

Each test (corresponding to a specific combination of parameters) will take five minutes. There will be 12 groups of 10 tests, i.e., one group for each combination of gaseous phase (N_2 or water vapor), channel flow orientation ("up", "down", or "horizontal"), and value of gravity (10^{-5} g or 10^{-3} g).

Parameter to be Measured		Pressure at and Near Test Channels	Nitrogen Pressure
Expected Values of Parameter	Units	psi	psi
	Average	10	30 in Flow Tube 200 in Tank
	Range	0-20	0-40 in Flow Tube 0-500 in Tank
Measurement Characteristics	**How Often (e.g. Times per Day)**	**12 tests per hour for 10 hours.**	
	Duration of Each (Avg.)	5 min	5 min
	Total Number in Mission	120	120
Output Signal of Instrument	Type	Analog	Analog
	Frequency Range, CPS	0-100	0-2
	Amplitude Range (e.g. 0-5 Volts)	0-28V	0-28V
	Instrument Resolution (% Total Scale)	0.5%	1%
Read-Out Requirements	No. of Channels	5	2
	Sampling Rate (Times per Sec.)	1	1
	Recorder Needed	yes	yes

Parameter to be Measured		Temperature	Volumetric Quality
Expected Values of Parameter	Units	°R	percent
	Average	460	20
	Range	440-480	0-40
Measurement Characteristics	How Often (e.g. times per day)	12 tests per hour for 10 hrs.	
	Duration of Each (Avg.)	5 min	5 min
	Total Number in Mission	120	120
Output Signal of Instrument	Type	Analog	Analog
	Frequency Range, CPS	0-2	0-20
	Amplitude Range (e.g. 0-5 Volts)	0-28V	0-28V
	Instrument Resolution (%Total Scale)	0.5%	0.5%
Read-out Requirements	No. of Channels	5	3
	Sampling Rate (Times per Sec.)	1	1
	Recorder Needed	yes	yes

Parameter to be Measured		Liquid Flow Rate	Gas Flow Rate
Expected Values of Parameter	Units	GPM	SCFM
	Average	1.0	1.0
	Range	0-5.0	0-5.0
Measurement Characteristics	How Often (e.g. Times per Day)	12 tests per hour for 10 hours	
	Duration of Each (Avg.)	5 min	5 min
	Total Number in Mission	120	120
Output Signal of Instrument	Type	Analog	Analog
	Frequency Range, CPS	0-20	0-20
	Amplitude Range (E.G. 0-5 Volts)	0-28V	0-28V
	Instrument Resolution (% Total Scale)	0.5%	0.5%
Read-out Requirements	No. of Channels	1	1
	Sampling Rate (Times per Sec.)	1	1
	Recorder Needed	yes	yes

Parameter to be Measured		Motor Voltage	Channel Heater Power
Expected Values of Parameter	Units	Volts	Watts
	Average	20	50
	Range	0-28	0-100
Measurement Characteristics	How Often (e.g. Times per Day)	12 tests per hour for 10 hrs.	
	Duration of Each (Avg.)	5 min	5 min
	Total Number in Mission	120	120
Output Signal of Instrument	Type	Analog	Analog
	Frequency Range, CPS	0-20	0-20
	Amplitude Range (e.g. 0-5 Volts)	0-28V	0-28V
	Instrument Resolution (% Total Scale)	1%	1%
Read-out Requirements	No. of Channels	1	1
	Sampling Rate (Times per Sec.)	1	1
	Recorder needed	yes	yes

SECTION IV - OPERATIONAL REQUIREMENTS

1. SPACECRAFT ORIENTATION REQUIREMENTS

(a) Describe Maneuvers

The maneuvers required are those necessary to maintain 10^{-3} g level for 5 hours and 10^{-5} g level for 5 hours. These may be in intervals as small as 5 minutes each.

(b) Type of Orbit

Any type of orbit will be adequate.

(c) Orbit Parameters

There are no particular requirements regarding orbit parameters.

(d) Lighting Constraints

Necessary lighting will be built into this experiment therefore there are no external lighting constraints.

(e) Time of Month, Day, Phase of Moon, etc.

No particular requirements.

(f) Number of Measurements Required

Approximately 120 tests will be run.

(g) Time Per Measurement

The time each run will average about 5 minutes.

(h) Orbital Location During Measurements

There are no particular requirements regarding orbital location during measurements.

(i) Spacecraft Pointing Accuracy: Pitch, Roll, Yaw.

No particular requirements on pitch, yaw and roll orientation.

(j) Allowable Spacecraft Rate: Pitch, Roll, Yaw.

This experiment will require that the total accelerations caused by pitch, roll and yaw be kept to less than one percent of 10^{-5} g. Assuming a rotation radius of 8 feet, this will allow 8 revolutions per day.

2. ASTRONAUT TRAINING

A preflight training program lasting about 8 hours should be sufficient for the astronauts and will include the following:

(a) Instruction on the purpose, objective and background of the experiment.

(b) Explanation of the physical principles involved and why the desired measurements are important.

(c) Operation of a prototype of the experiment by the astronauts so that they will be familiar with every aspect of the operation and objectives.

No training program will be necessary for the ground and installation crews.

3. ASTRONAUT PARTICIPATION PLAN

The following is a list of tasks which will be repeated for each test. Each of the tasks can be performed by one man. All of these activities will be performed in flight with no particular requirements regarding orbital position. The average time for a run will be about 5 minutes. The tasks occur primarily at the beginning and end of the run. The activity during the run is "evaluation of experiment operation". Approximately 120 runs of this type are planned.

Event	Astronaut Activity
Initiation of experiment	Close Switch.
Occurrence of desired liquid flow.	Adjust the liquid valve to yield pre-determined flow rate.

Event (cont.)	Astronaut Activity (cont.)
Occurence of desired gas flow	Adjust the gas valve to yield predetermined flow rate.
or	or
Heating initiated	Set heating power at predetermined level.
Evaluation of experiment operation	Observe flow and system pressure level.
Obtain data	Start data acquisition system. Check and verify operation of system.
Obtain photographic record	Set camera at predetermined speed, start and stop camera.
End of run	Stop data acquisition system.
Stop gas flow or stop heating	Close gas valve or turn off heater.
Reduce pressure on system	Depressurize system by opening vent on accumulator.
Stop liquid flow or begin next run	Adjust liquid valve to yield predetermined flow rate.

4. PRE-LAUNCH SUPPORT

(a) Preliminary Shipping and Handling Procedures

The experiment will be shipped to KSC from MSFC where some qualification tests will have been previously run. The details of shipping and handling procedure will be worked out.

(b) Preliminary Installation and Checkout Procedures

A considerable amount of testing will need to be done to check out the equipment. This will take several days at KSC.

(c) Facilities

During the checkout time office space for one man and about 150 square feet of laboratory space will be required.

(d) Test Equipment

The test equipment required will be a laboratory bench and power supply and the necessary equipment to test the output of each of the transducers and cameras which will be used to obtain data.

(e) Services

The services required will be:

(1) Power supply identical to that on spacecraft.

(2) Nitrogen supply.

(3) Air and water supply.

5. FLIGHT OPERATIONAL REQUIREMENTS

There is a possibility that because of thermal requirements while operating, this experiment may have to be placed in a specific position with respect to the sun while a run is being made. Communications between crew and ground will be required for reorientation of experiment in case of minor failures.

6. RECOVERY REQUIREMENTS

The only items to be recovered will be the data tape and the film. It is estimated that the total weight will be 20 pounds, and that it can be placed in a container 12" x 8" x 8". No special equipment is needed on recovery ships. The recovered film and reduced data should be sent to the principal investigator at the University of Alabama.

7. DATA SUPPORT REQUIREMENTS

The pre-flight control and support data will be gathered in the engineering laboratories at the University of Alabama in Tuscaloosa, Alabama.

SECTION V - EXPERIMENT DEVELOPMENT APPROACH

(This section will require additional investigation and some input by NASA personnel).

This section should provide the guidelines and ground rules to be followed in preparing the reliability, qualification and test specifications to be followed during the development of the experiment hardware. Existing NASA directives, policies, and procedures, with any special instructions, shall be followed where applicable.

In formulating these guidelines, the reliability, qualification and test program should be consistent with the magnitude and complexity of the experiment and with the importance of the experiment to the primary mission objective. All experiment equipment, systems and subsystems must be designed, constructed and tested to standards adequate to prevent compromise of crew safety or vehicle performance and to ensure a high probability of successfully accomplishing the experiment in space. Close coordination is essential between the Payload Integration Center and the Experiment Development Center in preparing these guidelines to ensure that the requirements of the experiment, as well as the flight program, are adequately satisfied.

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1. RELIABILITY PROGRAM

   Identify the principal elements of the reliability program for the experiment.

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2. APPLICABLE PUBLICATIONS

   Cite the applicable R&QA Publications which will be followed.

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3. QUALIFICATION PROGRAM

   Specifically identify the qualification guidelines by which the experiment will be developed.

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4. TEST PLANS

   Provide specific test plans for the development, acceptance and qualification of the experiment equipment.

---

5. DOCUMENTATION

   Identify the documentation that will be required to validate the R&QA program.

SECTION VI - INTEGRATION APPROACH

(This section will require additional investigation and some input by NASA personnel).

This section must present the plan for meeting the requirements of the preceding Sections II, III, and IV. Sufficient detail is necessary to define the complete integration requirements and to assess the experiment/spacecraft compatibility. The information shall include, but not necessarily be limited to, data pertinent to the following areas:

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1. EXPERIMENT LOCATION

   Selection of the experiment locations for storage and operation during the various phases of the mission, such as launch, orbit, and reentry, shall be described.

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2. INSTALLATION AND STRUCTURAL MODIFICATIONS

   Identify the spacecraft modifications, including structural, plumbing and wiring, necessary to accommodate the experiment.

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3. SPACECRAFT SUBSYSTEMS

   Determine the modifications needed to supply the experiment with the storage and operational requirements, such as power, environmental control, data measurement and recording or transmission facilities. Provisions for spacecraft guidance and navigational requirements shall also be included.

---

4. EXPERIMENT OPERATION

   Describe the provisions for operating the experiment, such as control panels, displays, linkages for experiment control, etc.

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5. EXPERIMENT CONSTRAINTS

   Describe the means for accommodating the experiment constraints required by . Section III.

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6. PRE AND POST LAUNCH SUPPORT

   Discuss the provisions for providing pre- and post-launch items, such as facilities, test equipment, services, etc.

SECTION VI - INTEGRATION APPROACH (Cont'd)

7. ASTRONAUT TRAINING EQUIPMENT

Describe the plan for providing identified astronaut training equipment, such as simulations, training units, and special equipment.

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8. SPECIAL SERVICES

This part should describe the provisions for communication network support, recovery requirements, special data handling, etc.

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9. ASTRONAUT PERFORMANCE

Assess the astronaut capability to perform the experiment.

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10. REAL TIME FLIGHT OPERATIONAL SUPPORT

Describe the plan for providing the real operational support required by the experiment including the following areas:

a. Telemetry data.

b. Command data uplink.

c. Voice data, both to the crew and ground controllers.

d. Any other special requirements identified to conduct the experiment.

SECTION VII - PROGRAMMATIC INFORMATION

(This section will require additional investigation and some input by NASA personnel).

1. MANAGEMENT ARRANGEMENTS

This section should designate the elements at the Payload Integration Center (PIC) and the Experiment Development Center (EDC) responsible for the development and implementation of the experiment. Further, it should identify the relationship between the PIC, EDC, the principal investigator and all other organizations including contractors involved in implementation of the experiment. A diagram detailing this management structure should be included. Specific areas to be covered include:

a. Assignment of experiment management responsibility in terms of its systems, subsystems and flight objectives.

b. A description of the management organization for the experiment. Clearly indicate the individuals to be assigned responsibility for management, and identify their lines of authority and responsibility and any specific authority limitations.

c. A description of the responsibilities and relationships to NASA of any external organizations involved in the experiment.

d. A description of any permanent advisory bodies, such as standing committees and evaluation groups.

e. An assessment of possible international requirements of the experiment or opportunities for international cooperation, stating whether or not existing overseas facilities are likely to be used or additional facilities needed. Describe support of any kind by foreign organizations or governments which will be advantageous.

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2. MANAGEMENT REPORTING

Provide a description of the procedures to be used in reporting status of the experiment implementation. Identify the principal reports to be prepared and describe their nature, frequency and distribution. Include reports used at the installation level to manage program effort between all Centers and organizations including contractors.

SECTION VII - PROGRAMMATIC INFORMATION (Cont'd)

3. PROCUREMENT ARRANGEMENT

This section will summarize necessary procurement plan arrangements and procurement activity as follows:

a. List each planned contract or subcontract effort for each phase of the experiment.

EXPERIMENT PHASE	AGENCY PERFORMING WORK	TYPE	CENTER MONITORS & TECHNICAL ADMN.

b. List the planned schedule for each procurement activity.

EXPERIMENT PHASE	WORK STATEMENT COMPLETE	RFP RELEASE	AWARD CONTRACT	SUBCONTRACT REVIEW COMPLETE

c. Provide the following information relative to experiment hardware contract activity.

(1) Role of the Principal Investigator (PI) as prime contractor or technical consultant.
(2) Capability of the PI's institution to manage the work involved.
(3) Willingness of the PI to entertain competitive procurement in his hardware development efforts.
(4) Provisions for providing requirements of hardware commonality between previously qualified flight hardware and that which is now proposed.
(5) Provisions for providing the interface requirements of the proposed experiment hardware and other experiments contained in the common payload package (if applicable).

The experiment can be designed and built in a period of two years.

SECTION VII PROGRAMMATIC INFORMATION (Cont'd)

4. SCHEDULE AND RESOURCE REQUIREMENTS -- DEVELOPMENT SCHEDULE

Major Milestones	PLANNED DEVELOPMENT SCHEDULE											
SPACECRAFT MODULE SUMMARY	FY ______				FY ______				FY ______			
	QUARTERS				QUARTERS				QUARTERS			
	1	2	3	4	1	2	3	4	1	2	3	4
Experiment Approval (MSFEB)												
CCA Issued												
PI Contract Let												
Hardware Contract Let												
Integration Specification Issued												
ICD Complete												
DEP Complete												
Mockup Delivered												
Prototype Delivered												
Crew Training Unit Delivered												
Quality Testing Completed												
Flight Units Fabrication & Delivery												
Acceptance Test Complete												
Ground Support Equipment Delivered												
Installation & Checkout												
Shipped to Launch Site												
Flight Analysis Complete												
Final Report												

5. FUNDING REQUIREMENTS

Provide the funding requirements of the experiment by quarter as indicated on the following page (Quarterly Funding Requirements). The total funds necessary for completion of the experiment will be estimated, both for in-house and contract effort. The funding should be broken into the areas indicated on the sheet and should identify the source of funding for each area. The amount of detail and the selection of elements of work breakdown and cost categories to be used will depend upon the complexity and particular nature of the experiment; however, the general objectives of the fund estimate presentation should be to facilitate validation of the completeness and reasonableness of the fund estimate, as well as to provide a historical point of departure for meaningful revision of fund estimates as experiment assumptions and/or pricing factors change.

The experiment can be designed and built during a period of two years for an estimated cost of $200,000.

During this period of time further fundamental and supporting studies should be conducted at the University of Alabama. A brief description of these studies is indicated in Section II-5. Funding for these supporting studies should be $60,000 per year for two years.

SECTION VII - PROGRAMMATIC INFORMATION (Cont'd)
Quarterly Funding Requirements (Dollars in Thousands)

ITEMS	FUNDING SOURCE	FY ____				FY ____				FY ____				FY ____				TOTALS
		QUARTERS				QUARTERS				QUARTERS				QUARTERS				
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
DESIGN																		
Exp. Hardware																		
Training Equip.																		
Checkout Equip.																		
SUPPORT EQUIPMENT																		
Mock-up																		
Engineering Test units																		
Fabrication																		
Assembly																		
Test																		
Prototype																		
Fabrication																		
Assembly																		
Test																		
Training Units																		
Fabrication																		
Assembly																		
Test																		
Checkout Equipment																		
Fabrication																		
Assembly																		
Test																		
FLIGHT EQUIPMENT																		
Flight Unit																		
Fabrication																		
Assembly																		
Testing																		

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SECTION VII PROGRAMMATIC INFORMATION (Cont'd)

Quarterly Funding Requirements (Dollars in Thousands) (Cont'd)

ITEMS	FUNDING SOURCE	FY ______				FY ______				FY ______				FY ______				TOTALS
		QUARTERS				QUARTERS				QUARTERS				QUARTERS				
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
Spares																		
Fabrication																		
Assembly																		
Testing																		
SUPPORT STUDIES																		
SUPPORT FACILITIES AND SERVICES																		
TRAVEL																		
VEHICLE INTEGRATION																		
Vehicle Modif																		
Installation																		
Checkout																		
DOCUMENTATION																		
Major Documentation																		
Def. Exp. Plan																		
Rel. Predictions																		
Qual. Test Rept.																		
Failure Analysis																		
etc.																		
Periodic Reports																		
Briefings & Reviews																		

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SECTION VII PROGRAMMATIC INFORMATION (Cont'd)
Quarterly Funding Requirements (Dollars in Thousands) (Cont'd)

ITEMS	FUNDING SOURCE	FY ____				FY ____				FY ____				FY ____				TOTALS
		QUARTERS				QUARTERS				QUARTERS				QUARTERS				
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
PUBLICATION Data Reduction Analysis Reporting																		
YEARLY TOTALS																		
GRAND TOTAL																		

6. MANPOWER

a. In-house manpower estimates are to be shown for each center and/or installation, and categorized insofar as possible by systems and subsystems, and by fiscal year for the life of the experiment. The experiment totals should be resummarized to reflect for each system (and by fiscal year) the manpower effort required within each center and/or installation in its conduct of:

(1) Research and development, and

(2) Experiment and system management, including contractor monitoring.

b. The contract manpower estimates are to be shown in a similar manner to the in-house estimates.

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7. FACILITIES

All major facilities and lab equipment (including those of contractors and other Government agencies) essential to the experiment in terms of its systems and subsystems, are to be indicated, distinguished insofar as possible between those already in existence and those that will be developed in order to execute the experiment. The outline of existing facilities should indicate their scheduled availability. The outline of new facilities should indicate the lead time involved and the planned schedule for construction, modification, and/or acquisition of the facilities.

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8. EXPERIMENT RESULTS

a. Specify the channels and facilities to be used for retrieving raw data, processing them into usable records, and transmitting them to the experimenter and other appropriate users.

b. List the technical reports required for

(1) "Quick Look" records

(2) Data reports

(3) Preliminary analysis

(4) Technical notes/memoranda (NASA and contractor)

SECTION VII - PROGRAMMATIC INFORMATION (Cont'd)

c. Indicate the planned schedule for release of the above technical information to

(1) Headquarters sponsoring program offices

(2) The news media

(3) The scientific and technical community