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LOW GRAVITY FLUID-THERMAL EXPERIMENTS

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W. J. Krotiuk
J. M. Cuta

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Pacific Northwest Laboratory
Richland, Washington 99352

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INTRODUCTION

Pacific Northwest Laboratory (PNL) is the lead laboratory for the thermal-hydraulic research in the U. S. Department of Energy Multimegawatt Space Nuclear Power Program. PNL must provide the tools necessary to analyze proposed space reactor concepts, which include single- and two-phase alkali metal and gas-cooled designs. PNL has divided its activities for this task into three basic areas: computer code development, thermal-hydraulic modeling, and experimentation. Activities in these areas are discussed in detail elsewhere (see References 1 and 2). The subject of this paper is the low-gravity experimental program currently underway at PNL in support of the MMW Program.

LOW-GRAVITY EXPERIMENTAL DATA

Existing computer codes and correlations for calculation of two-phase flow in normal gravity were found unacceptable for low-gravity conditions (see Reference 1). Two-phase flow is dramatically affected by the absence of gravity, and two-phase flow computer codes must be modified significantly for reduced-gravity applications. No verified reduced-gravity two-phase correlations for pressure drop, heat transfer coefficient, critical heat flux, or flow regime determination currently exist. These correlations are necessary to predict pressure, temperature, and flow distributions in a two-phase reactor core or plenum. The experimental data base needed to develop and verify low-gravity two-phase computer codes does not currently exist. A reduced-gravity experimental program is needed to obtain data with which to build constitutive models and computer codes.

An intensive review of the literature on low-gravity experimental fluid-thermal data was conducted as part of the MMW Reactor Thermal Hydraulic activities. (A summary of this effort is contained in Reference 2.) The results of this review vividly illustrate the current lack of a reduced-gravity fluid-thermal data base. The experiments surveyed were all qualitative in nature, not quantitative. The most that could be obtained from existing data were ideas about trends in behavior, and even these are in some cases open to contradictory interpretation. For example, the data show that two-phase pressure drop is probably higher at reduced gravity, and heat transfer coefficient and critical heat flux may be lower than for normal gravity conditions. The two-phase flow regime map is different, with transition lines significantly shifted, but the map is by no means complete in reduced gravity. This data does not offer enough information for constitutive model development, and an extensive low-gravity experimental program was determined to be necessary.

A limited amount of reduced-gravity experimentation is currently being supported by NASA, but only a few experiments are concerned specifically with fluid-thermal problems. Dr. A. E. Dukler, at the University of Houston, is responsible for flow regime-pressure drop delineation in reduced gravity and for determining burnout heat fluxes. Dr. H. Merte, at the University of Michigan, is primarily responsible for examining pool boiling from flat surfaces and interfacial evaporation/condensation rates. Dr. F. Best, at Texas A&M University, has recently conducted reduced-gravity flow condensation experiments.

Other reduced-gravity experiments currently being conducted address fluid motion in tanks or diffusion flame behavior. Although these tank and flame studies will provide needed data for specific problems, the information obtained will not be readily usable in designing fluid-thermal management space systems. The recent Sundstrand KC-135 experiments, which examined a proposed Rotary Fluid Management Device, are designed primarily to confirm equipment operation, and do not study phenomena. The results obtained by the three university investigators may be the only data applicable to general low-gravity fluid-thermal system design.

REDUCED-GRAVITY EXPERIMENTAL PLAN

The experimental plan outlined in References 1 and 2 was intended to supply the data needed to design fluid-thermal equipment such as nuclear reactors to operate in low gravity. This plan proposes both benign fluid (e.g., water or Freon) and alkali metal experiments. Much information and experience could be obtained by performing low-gravity experiments with benign fluids before the more difficult two-phase alkali metal experiments would be attempted. A study was also initiated to determine the feasibility of simulating low gravity in alkali metal flow by counteracting gravity with a magnetic field. This study (Reference 1), performed by Princeton University's Plasma Physics Laboratory, resulted in a conceptual design and identified experimental problems. Further work is required to determine the ultimate feasibility of this approach.

The available methods of conducting reduced-gravity experiments are drop towers, aircraft parabolic flights, sounding rockets, and shuttle experiments. Limitations exist in the use of all these facilities. The low-gravity interval obtainable in a drop tower is of short duration (2-5 seconds). Aircraft flying parabolic trajectories obtain longer intervals (up to 25 seconds), but the g-levels are not very low or stable. Experience using sounding rockets is limited, and the costs are prohibitive. The shuttle will not be available in the near future and is very expensive. Therefore, emphasis was placed on experiments in drop towers and parabolic aircraft flights. Only experiments with benign fluids are being investigated currently.

NASA KC-135 REDUCED-GRAVITY EXPERIMENTS

In the summer of 1986, PNL had the opportunity to cooperate on a joint low-gravity experiment with Dr. F. Best of Texas A&M University. Dr. Best was funded by NASA to design condensation experiments to be run in the NASA KC-135 aircraft. The object of the experiment was to study reduced-gravity condensation at space station design conditions using water as the working fluid. Battelle supplied an instrumented boiler for the experiment. The boiler consisted of an 8-mm ID quartz tube wrapped in a helix of nichrome wire. The pitch of the helix resulted in a gap of about 1/4 inch between wires, a spacing sufficient to permit flow visualization. The boiler was enclosed in a 15-mm diameter pyrex tube to guard against inadvertent contact with the hot wires. The condenser consisted of a clear pyrex tube enclosed in a pyrex cooling jacket. Measurements of pressure, temperature, heater power, flowrate, accelerometer readings, and gamma densitometer measurements were recorded. A schematic of the test assembly is shown in Figure 2. Experiment conditions are indicated in Table 1.

The experiment package was first flown in November 1986. A description of the test package and proposed test matrix is contained in Reference 3. The experiment was fastened to the floor of the aircraft for some of these tests, but the majority were free floated by NASA personnel during the reduced-gravity portion of a parabolic manuever. The free-float procedure afforded a better low-gravity condition, since it eliminates extraneous accelerations imparted by the aircraft.

The experiment was modified before the April 1987 flight to increase flows and heat fluxes and to improve instrumentation. The changes in the experiment condition are indicated on Table 1. Adiabatic nitrogen-water two-phase flow visualization tests were also performed during the April 1987 flights. Due to instrumentation and space limitations, only bolted-down experiments were permitted in these flights. The test data obtained from the KC-135 flights are currently being interpreted and studied. Until these efforts are completed, only qualitative observations can be made.

REDUCED-GRAVITY EXPERIMENTAL DESCRIPTION - APRIL 1987

The test matrix for the April flights consisted of 15 boiling/condensing tests--12 unique points, plus 3 repeat points--to be run on the first day in the KC-135, and 10 nitrogen/water adiabatic tests to be run on the second day. The planned conditions for these tests are listed in Tables 2 and 3. The boiling/condensing test points were at flow rates that would be expected to produce either stratified or slug-stratified flow in 1-g. The adiabatic tests were for the most part at low flow rates, where the 1-g flow regime would be slug, stratified-slug, or bubbly flow.

The adiabatic tests were included in the full test matrix in order to obtain reliable two-phase data at the lower flow rates. During the November 1986 tests, experience with the test section in boiling with very low flow rates had shown that the flow was very unstable, probably due to transition effects during a parabolic maneuver. The process of void formation in the boiler caused the flow to chug erratically, and even reverse direction periodically. This tended to obscure and overwhelm the hydrodynamic behavior of the two-phase flow, making it difficult to interpret the significance of the data obtained at low flow rates.

The test procedure followed on the KC-135 was to set up conditions for a given test point in level flight, then take data while executing three zero-g parabolas in succession. This permitted three zero-g periods of approximately 20 seconds for each test point, separated by a 1-minute-long period of acceleration at 1.7 to 1.9 g's. The acceleration period ensured that the flow would be fully stratified before each transition to zero-g.

For every test point, the flow became annular immediately on entering zero-g. Since data was taken continuously throughout the sequence, it is possible to see the effect of the flow regime transition.

In addition to the instrument readings taken by the data acquisition system during the tests, recordings were made of the boiler and condenser flows using NASA high-speed cameras and a high-speed video imaging system. The NASA cameras operated at 2700 frames per second, and provided approximately 4 seconds of real-time recording. The high-speed video system (provided on a demonstration basis by Eastman Kodak's Spin Physics Division) was operated at effectively 1000 frames per second, but was capable of recording up to 30 seconds of real time. The high-speed video was downloaded immediately after each flight onto standard half-inch video tape. This immediate availability, plus the relatively long interval the video system could record, more than made up for the lower quality of the video image as compared to the high-speed camera.

On the first day of testing, 8 of the boiling/condensing test points were obtained in the course of 24 parabolic zero-g maneuvers. High-speed video images were recorded for 7 of the tests, and high-speed NASA films were taken on 5 of them. In going to the very high power required for the last points in the boiling/condensing matrix, however, the boiler failed. Attempts to fix the problem, during which 4 more parabolas were executed, were unsuccessful, and testing was terminated for that day.

On the second day of testing, all ten of the adiabatic points in the test matrix were obtained in the course of 30 parabolic maneuvers. High-speed video images were obtained for 7 of the tests, and high-speed NASA film was shot on 6 of them.

The following narrative describes the boiler fluid behavior as seen on the video tape for Test 7 from Table 2. Recording started at the beginning of the zero-g interval, and the image initially shows almost stagnant flow. Boiling on the tube inner surface is clearly evident; bubble formation is quite vigorous, and appears to be occurring in an annular film on the wall. At about 2 seconds elapsed time there is evidence of a high-speed burst of vapor shooting down the center of the tube, probably as a result of boiling upstream. The high speed of the vapor flow is clearly evident in the unstable annular film, from which drops are being stripped off and entrained by the vapor. This goes on until approximately 5 seconds elapsed time, then the film thins out, has fewer waves on the surface, and may even dry out partially. Then a surge of annular flow appears, and the surface is clearly wet. The annular film has a ripply, wavy appearance, but there is no visible bubble formation in the liquid. In a few more seconds, the film thins once more, and may have again dried out at about 7-8 seconds elapsed time. Then the film returns, again with a ripply, wavy surface, and by 8-9 seconds there is evidence of bubble formation in the annular film. This behavior alternates with surges of annular flow with a very wavy surface, and significant entrainment.

The flow patterns exhibited in the boiler for this test are typical of the behavior seen in the other tests that were recorded. The apparent unsteadiness of the flow, with the alternating of thin films and very wavy unstable-looking films is particularly interesting. The behavior might be due in part to disturbances caused by void formation as the fluid boils. However, this cannot be the sole explanation, for the same pattern was observed on some of the adiabatic tests. This leads one to suspect that there may be a flow transition point that was bracketed by some of the test conditions. Possibly the flow source was not steady enough in the reduced-gravity conditions. The "surges" that show up on the video will be checked against the accelerometer measurements for the aircraft, to see if there is any correlation that can explain the behavior.

The following narrative describes the flow conditions of test point 2 of the adiabatic portion of the test matrix (see Table 3). Video images were recorded in level flight for these test conditions, for approximately 11 seconds of real time; then the video recorder was turned off, and not re-activated until the zero-g interval.

The recording begins with well-defined slug flow at normal gravity, with stratification clearly evident in the smaller bubbles and at the ends of the long channel-filling gas slugs. The interface is asymmetric with a long "foot" of fluid on the bottom. The image recorded at low gravity is at the same conditions as the stratified slug flow seen in normal gravity, but now the smaller bubbles are centered in the flow, with fluid on the wall, forming what may be termed a bubble-annular flow. Instabilities exist in the interface, particularly for the small bubbles. They may be at least partially due to extraneous accelerations, but it seems too regular and continuous to be due solely to what must be a random unsteady influence. It has been suggested that it is due to the bubbles trying to coalesce, and there is some of that occurring at various times, but it is not clear if that is a cause or an effect.

The film and video records clearly show that two-phase flow behavior in low gravity is quite different from what one sees in normal gravity. This data is still being reduced, and continuing analysis should yield a clearer understanding of what is going on in the flow field under low-gravity conditions. Some of these tests are being simulated with the COBRA/TRAC and ATHENA computer codes. This comparison of predicted flow behavior with the data will help determine the extent of modifications needed to the models and the constitutive relations in these codes for application to zero-gravity analyses. It will also indicate where additional experimental and analytical work is needed to correctly predict the hydrodynamic and thermodynamic behavior of fluid in zero gravity.

FUTURE LOW-GRAVITY EXPERIMENTS

A series of KC-135 flight experiments are required to obtain sufficient data to form the basis for the development of theories and constitutive models describing reduced-gravity fluid behavior. The open-loop water experiments performed in November 1986 and April 1987 are the start of this experiment series. The completed KC-135 experiments were primarily concerned with obtaining data to increase understanding of the low-gravity boiling and condensing process. Additional efforts are required to further quantify knowledge of two-phase phenomena. The next logical step is to construct a new experimental package based on the experience and knowledge obtained from the earlier KC-135 flights. A conceptual design of this new experiment package is shown on Figure 3. Significant differences between the old and new equipment are:

1. The new equipment is a Freon closed loop system with a water-cooled condenser.
2. A transparent resistance-heated gold film will be used in the boiler. The use of a fully instrumented gold film will permit the determination of boiler surface temperature by voltage measurement.

This will permit the calculation of surface heat transfer coefficient and critical heat flux.

3. The positive displacement pump used in the previous experiments will be replaced with a fluid metering gear pump which would be less affected by acceleration.
4. All data measurements will be recorded on a IBM/PC with a hard disk at a faster sampling rate than previously used.

Since many proposed space reactors will be launched cold, the cooling fluid, especially alkali metals, will be initially frozen. This condition presents problems regarding thaw out in microgravity. A preliminary small thaw experiment is being built by Oregon State University to be flown with the larger PNL experiment on a future KC-135 flight. Safety concerns preclude the use of an alkali metal for an initial experiment, and this test uses water ice. The proposed experiment design is shown in Figure 4. The experiment is designed to visually examine the solid ice to liquid water phase change in reduced gravity. Figure 5 shows the details of the ice thaw tube assembly. The assembly is being designed for easy removal and installation to permit its replacement before each parabolic maneuver. Initial tests have already been successfully performed using this equipment in normal gravity.

The Freon closed loop and the freeze-melt experiment on the KC-135 will be flown in the later part of 1987. Because of the limited number of test points that can be obtained in any one flight, it is anticipated that further flights will be required using the closed loop experiment during 1988. The additional tests are necessary to cover the full range of conditions, verify earlier data, address additional concerns identified in the first tests, and possibly run the experiment using a different working fluid. Ultimately, the data should be verified in shuttle experiments. This is necessary to identify the extent of disturbances that the aircraft parabolic trajectory has introduced into the test data and the limitations of the short zero-g interval, particularly the concerns regarding the time needed approach to steady-state conditions during a parabola. A space-based experiment represents the only place that low-flow, thermal-fluid reduced-gravity tests would be performed because the time duration needed to reach steady-state exceeds the duration of the low-gravity conditions during an aircraft parabola. It is only after the completion of this entire test series could confidence be placed in the fluid-thermal relations developed for low-gravity applications.

Additionally, in order to supply the alkali metal relations needed for low-gravity component design, an alkali-metal experimental program should be started. This program would supply missing thermophysical properties, and conduct normal gravity loop experiments to better understand the behavior of alkali metals in the operating ranges proposed for space applications. Reduced-gravity alkali metal experiments should also be performed to develop appropriate low-gravity alkali metal constitutive models.

CONCLUSIONS

The completed KC-135 boiling-condensing experiments show that significant differences exist between normal and low-gravity fluid-thermal behavior. The predominance of the annular flow regime for low-gravity two-phase flow has been demonstrated. The data obtained from the completed experiments is currently being reduced and studied. Quantitative conclusions will be published in the near future.

Additional low-gravity fluid-thermal experiments are needed to develop and verify reduced-gravity constitutive models for design of space-based nuclear reactors and other space-based thermal components. These experiments should initially be performed using earth-based low-gravity facilities such as the NASA KC-135 aircraft. Ultimately this data and resultant models must be verified in shuttle experiments. The shuttle experiments are also necessary to study low-flow conditions which cannot be addressed on earth because of the short reduced-gravity duration in earth-based facilities.

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REFERENCES

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TABLE 1. Low-gravity Boiling/Condensing Experiment

Experiment Date	11/86	4/87
Operating Fluid	Water	Water
Experiment Type	Open loop	Open loop
Maximum Flowrate	0.1 l/min (33 kg/m^2-s)	1 l/min (330 kg/m^2-s)
Boiler Size	8 mm ID	8 mm ID
Boiler Active Length	0.86 m	0.86 m
Maximum Boiler Heating	3 kW	5 kW
Condenser Size	6 mm ID	8 mm ID
Condenser Active Length	0.9 m	0.9 m

TABLE 2. Planned Test Matrix for Boiling/Condensing Two-Phase Flow in Microgravity

Test No.	Flow Rate (l/min)	Boiler Power (Watts)	Exit Quality	Homogeneous Void Fraction
1	0.91	3583	0.01	0.65
2	0.91	3934	0.02	0.75
3	0.91	4987	0.05	0.83
4	0.30	1194	0.01	0.65
5	0.30	2247	0.10	0.90
6	0.45	3371	0.10	0.90
7	0.45	2494	0.05	0.83
8	0.45	1792	0.01	0.65
9	0.45	5127	0.20	0.92
10	1.20	4544	0.005	0.10
11	1.20	4778	0.01	0.65
12	1.20	5246	0.02	0.75
13	0.30	1194	0.01	0.65
14	0.45	5127	0.20	0.92
15	1.20	4544	0.005	0.10

TABLE 3. Planned Test Matrix for Adiabatic Nitrogen/Water Two-Phase Flow in Microgravity

Test No.	Water Flow (l/min)	Nitrogen Flow (l/min)
1	0.15	0.905
2	0.75	0.905
3	0.15	3.016
4	0.75	3.016
5	0.15	3.400
6	0.03	0.905
7	0.03	3.016
8	0.03	3.400
9	0.75	6.075
10	0.30	3.016

KC-135 Aircraft Trajectory

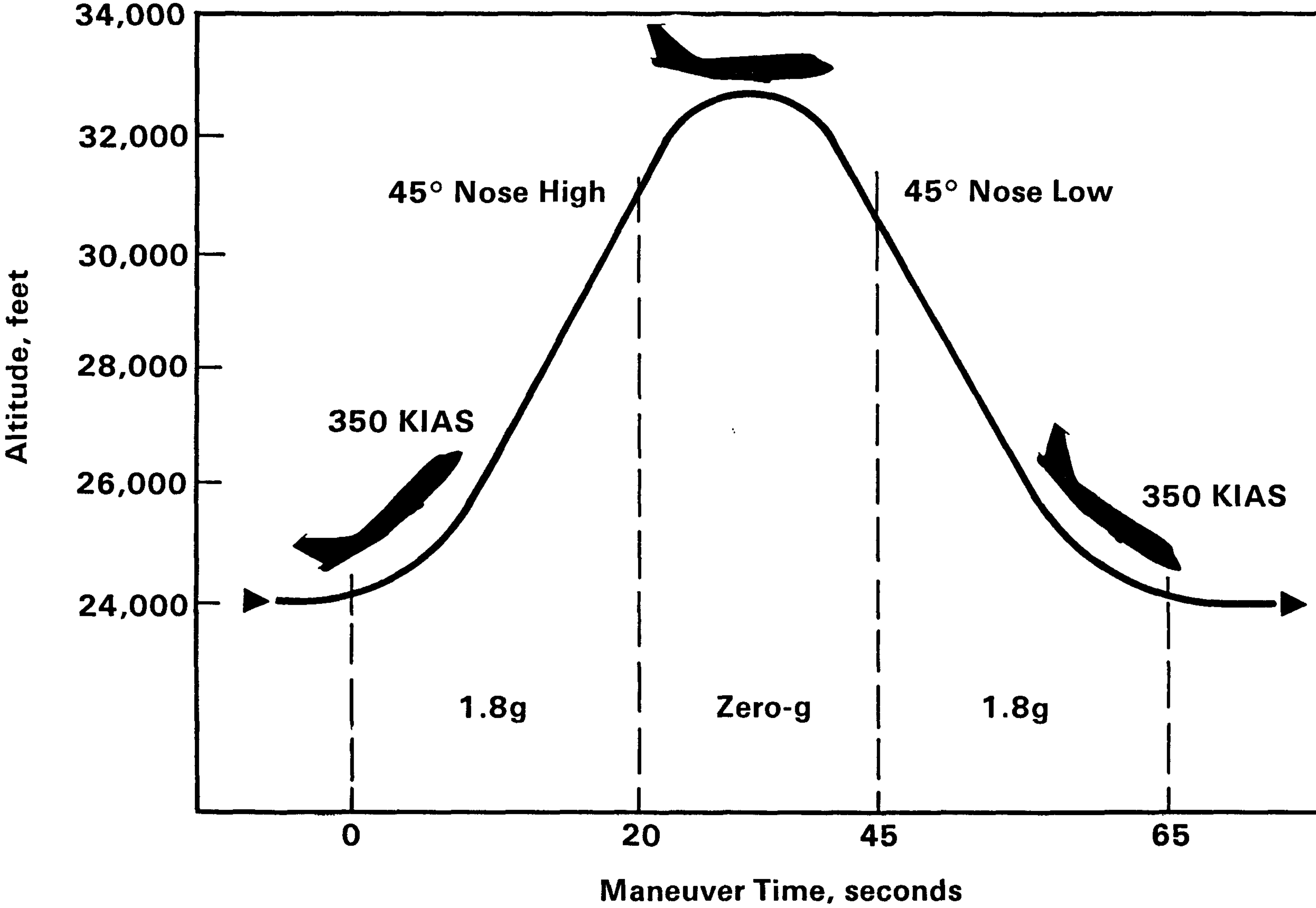


Figure 1.

Boiling/Condensing KC-135 Experiment

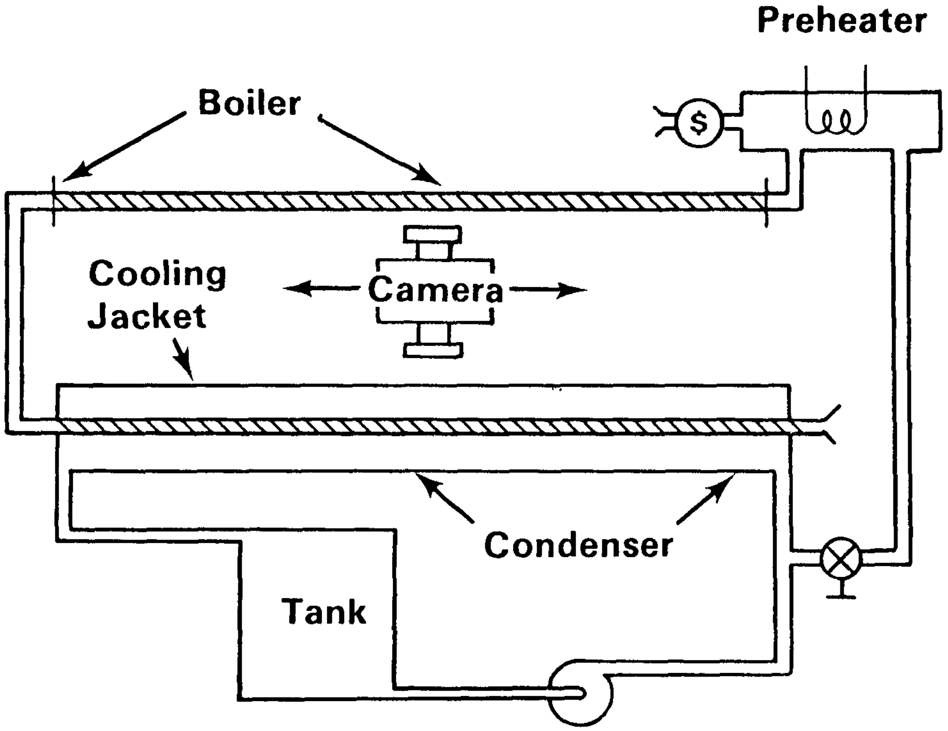
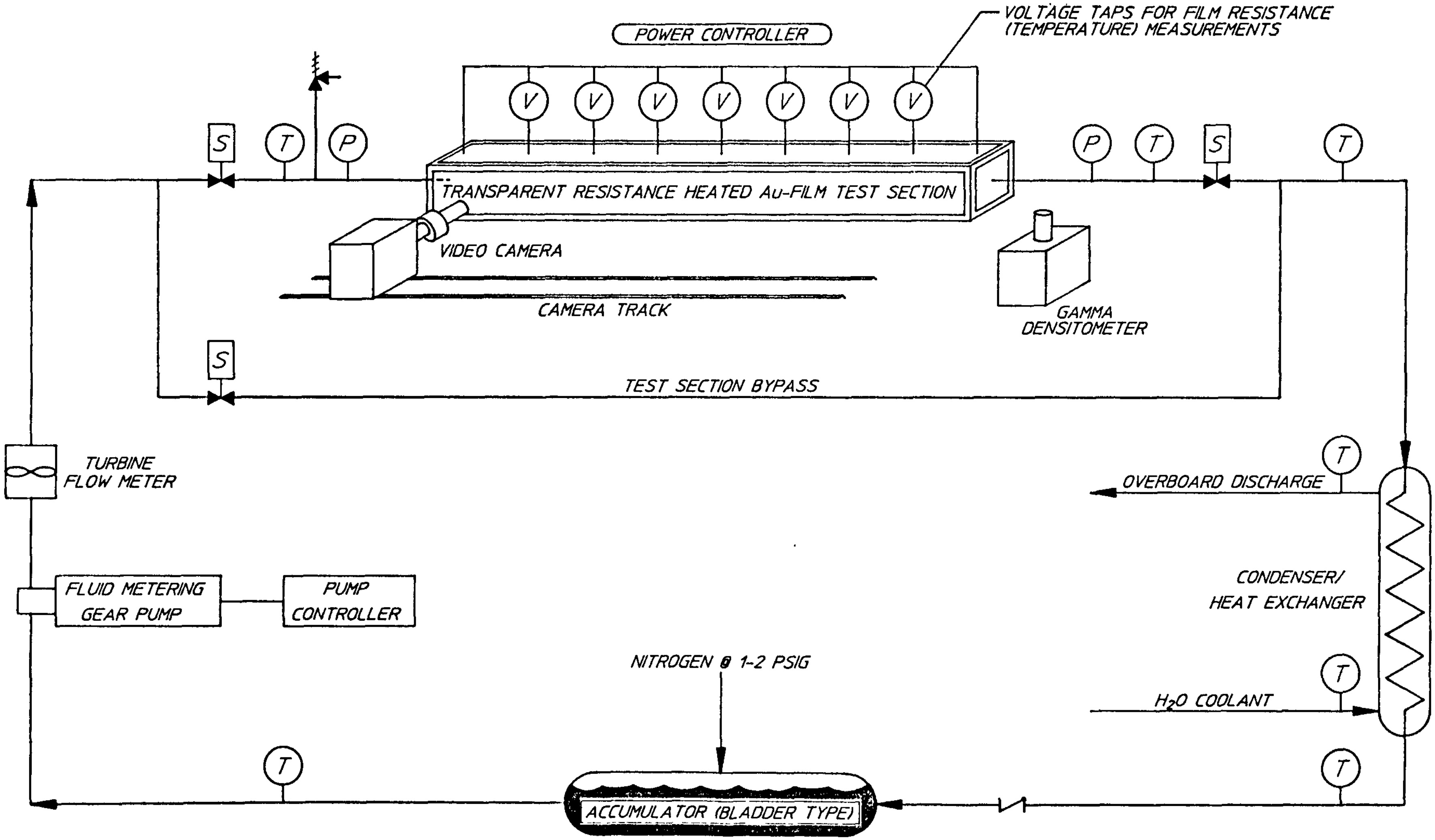


Figure 2.



FREON CLOSED LOOP KC-135 REDUCED GRAVITY EXPERIMENT

Figure 3.

Microgravity Thaw Experiment (MITEX)

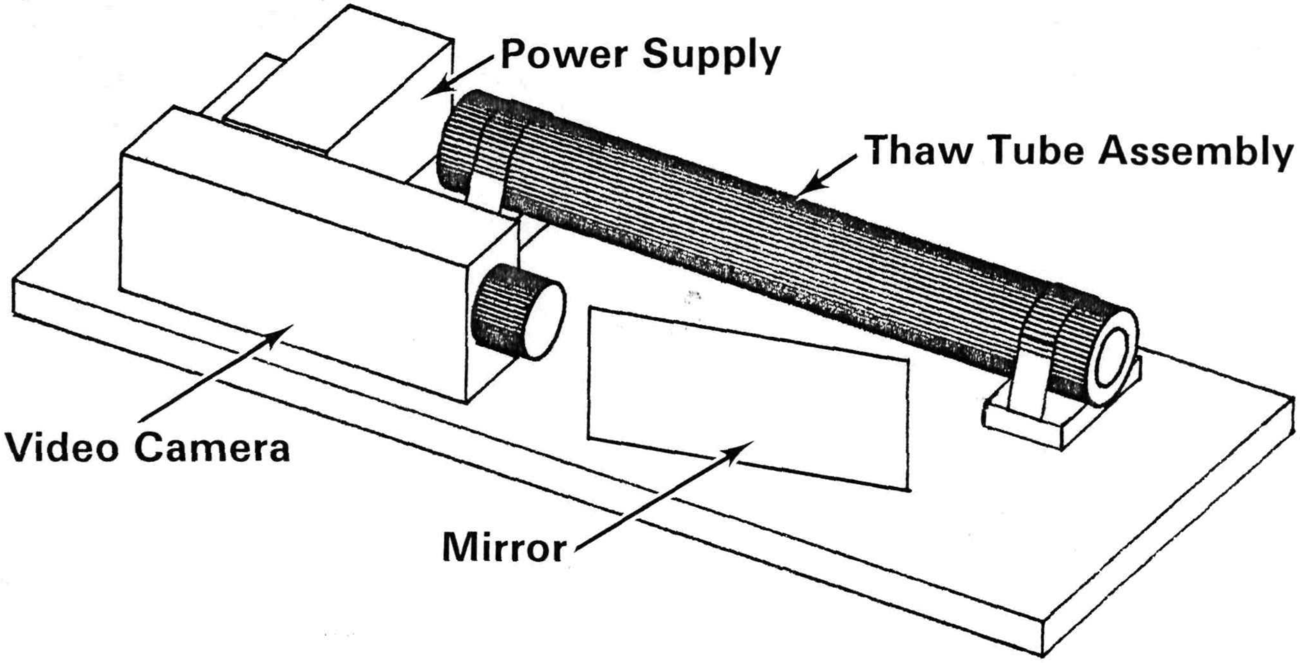


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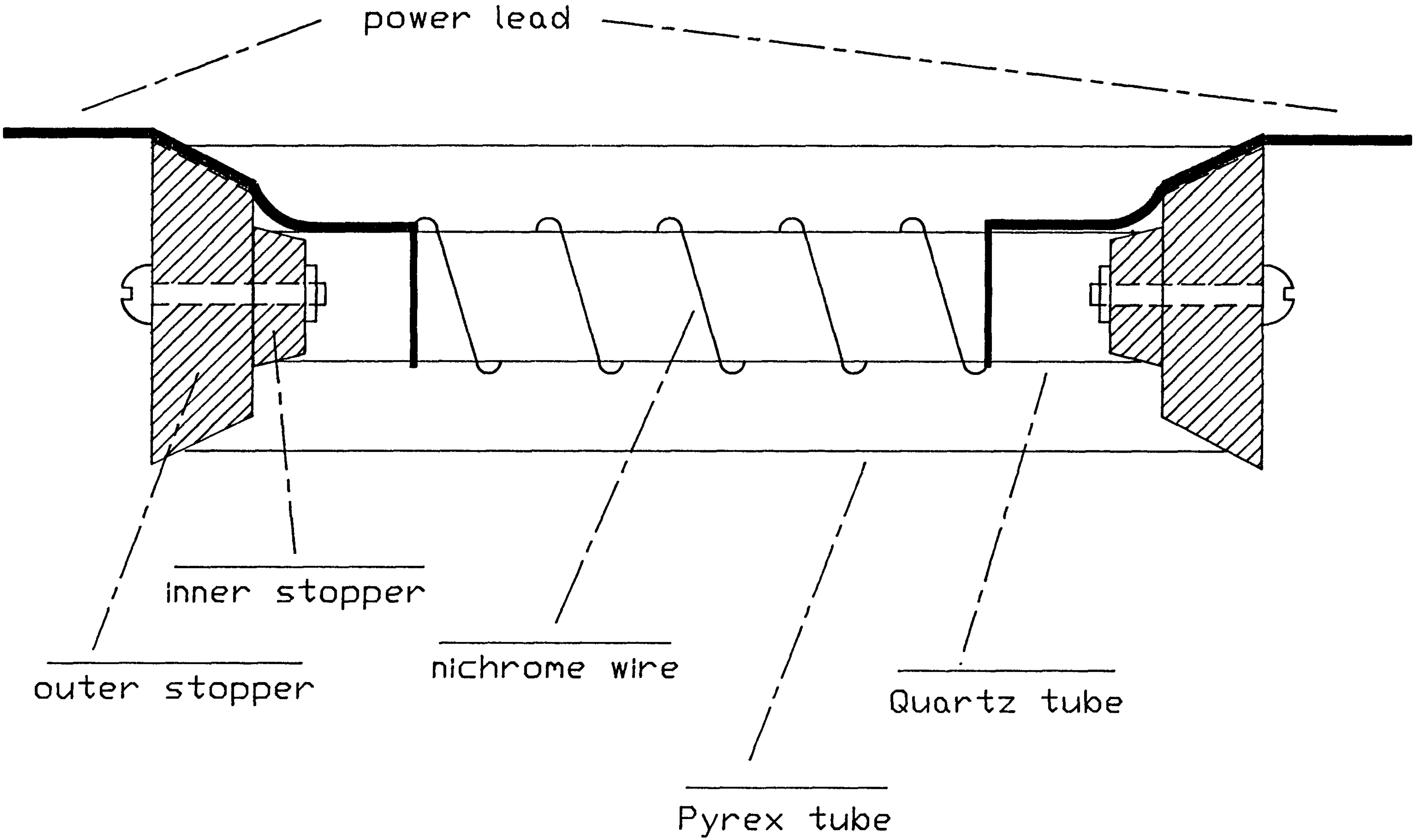
Figure 4.



MIcrogravity Thawing EXperiment

Figure 5