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TWO-PHASE REDUCED GRAVITY EXPERIMENTS FOR A SPACE REACTOR DESIGN

Z. I. Antoniak

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Pacific Northwest Laboratory
Richland, Washington 99352

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TWO-PHASE REDUCED GRAVITY EXPERIMENTS FOR A SPACE REACTOR DESIGN

Zenen I. Antoniak

Pacific Northwest Laboratory

Richland, Washington

ABSTRACT

Future space missions envision the use of large nuclear reactors utilizing either a single or a two-phase alkali-metal working fluid. The design and analysis of such reactors require state-of-the-art computer codes that can properly treat alkali-metal flow and heat transfer in a reduced-gravity environment. New flow regime maps, models, and correlations are required if the codes are to be successfully applied to reduced-gravity flow and heat transfer. General plans are put forth for the reduced-gravity experiments which will have to be performed, at NASA facilities, with benign fluids. Data from the reduced-gravity experiments with innocuous fluids are to be combined with normal gravity data from two-phase alkali-metal experiments. Because these reduced-gravity experiments will be very basic, and will employ small test loops of simple geometry, a large measure of commonality exists between them and experiments planned by other organizations. It is recommended that a committee be formed, to coordinate all ongoing and planned reduced gravity flow experiments.

INTRODUCTION

The Pacific Northwest Laboratory (PNL) of the Department of Energy (DOE) has been assigned the role of modeling the thermal-hydraulics of advanced multimegawatt (MMW) nuclear reactors. Various reactor concepts are being proposed by other DOE National Laboratories, by industry, and by universities. This paper addresses the experimental requirements posed by one concept--where the reactor working fluid is a boiling alkali metal.

Future space missions envision the need for high power levels (up to hundreds of MWe), which are orders of magnitude greater than required by spacecraft launched previously. The concept that appears to have the best potential for supplying such power is a nuclear reactor-based one, with a heat engine and alternator providing the conversion of thermal to electrical power. Stringent weight, heat transfer, and compactness criteria lead to the use of an alkali metal heat transfer medium, with a boiling alkali metal (BAM) system offering significant advantages over a single-phase system with an intermediate heat exchanger. In any event, there is a crucial need for analytical tools that can simulate two-phase flows in a zero gravity (0-g) or variable gravity environment. Mature computer codes exist that consider single-phase liquid metal flow and two-phase steam-water flow, both in normal gravity. To be completely useful for the design and analysis of BAM reactors these codes will need to be modified to handle boiling alkali metals instead of water and to do it in variable gravity. Experimental 0-g two-phase flow data are needed to provide new models and correlations for flow regimes, drag, and heat transfer (see Table 1).

TABLE 1. Code Assessment and Changes Required for Modeling 0-g Convection

Code Limits No. Phases	Validity of "Uncorrected" Run at 0 g	Estimated Trend of "Uncorrected" Values of: Delta P	Estimated Trend of "Uncorrected" Values of: H	Modifications Required: Flow Regime	Modifications Required: Friction Factor Correlation	Modifications Required: Heat Transfer. Correlation	Modifications Required: Turbulence Intensity
1	Good[a]	Underpredicted	Overpredicted	No	Yes	Yes	Yes
2, Homogeneous	Good[b]	Underpredicted	Overpredicted	No	Yes	Yes	No
2, Multifield	Poor	Underpredicted	Overpredicted	Yes	Yes[c]	Yes[c]	Yes

(a) For single-phase flow.
(b) Where homogeneous representation is applicable.
(c) Magnitude of changes depends on effect of flow regime correlations.

Data on alkali metal two-phase forced convection in a normal gravity field are extremely limited; reduced-gravity data are practically nonexistent (only mercury condensation has been studied somewhat). However, reduced-gravity experiments with two-phase flow of more common fluids (e.g., water, air/water, halocarbons) have been more numerous. A comprehensive literature survey of these experiments has been completed. Results of this survey indicate that both the nature of boiling alkali metal and reduced-gravity experiments, and the acquired data, have been limited in various ways. Thus the utility of these past experimental efforts to the design and analysis of a space reactor is marginal, and new experiments will have to be performed.

FACILITIES AVAILABLE FOR REDUCED-GRAVITY EXPERIMENTS

Ideally, a manned, orbiting space station would be available with extensive laboratory facilities for reduced-gravity research. Also, launch costs, as well as the costs of developing space-qualified test hardware, would be reasonable in terms of the resulting data. Neither criterion is met currently. Small, low-power experiments can be performed on the shuttle albeit with nonhazardous fluids. The competition for the scheduled shuttle flights is keen, and tests must be planned years in advance of actual flight. Sometime in the 1990s a permanent manned orbiting laboratory may become available. At this time it is not clear if any alkali-metal experiments would be permitted there; hazardous materials are taboo on the shuttle. Regarding launch and test development costs, no appreciable cost reduction is foreseen in the near future.

Given the situation described, at best only a few shuttle experiments will be performed within the time frame allotted for two-phase reduced-gravity experiments. For the majority of the experiments, earth-based facilities such as drop towers and aircraft will have to be employed. These present various limitations--the chief ones being the duration and steadiness of the reduced-gravity environment. Another set of constraints is imposed by scheduling and cost restrictions. The latter provide a strong incentive for cooperation among organizations involved in reduced-gravity experiments.

PROPOSED TWO-PHASE REDUCED-GRAVITY EXPERIMENTS

The twin issues posed by experimental facility limitations and the difficulties inherent in working with alkali metals must be squarely faced by any realistic test program. Thus, the only viable approach is to perform, to the maximum possible extent, experiments with innocuous fluids such as air, water, and Freon in place of the alkali metals. Only if the desired data were to be seriously flawed by replacement fluids will alkali metals themselves become the working fluids. At this time the feeling is that perhaps alkali metals might be acceptable for use in drop towers and the KC-135 aircraft, but would present an unacceptable hazard in any other reduced-gravity test facilities.

The objective of the first experiment conceived here is a narrow one: to obtain data on two-phase flow regimes and pressure drop. This can be met through the use of an air-water mixture in a suitably instrumented test section. It is planned to perform most of the tests in the NASA/Lewis Research Center (LeRC) 5.2s drop tube, which is evacuated to 10^{-2} Torr prior to a test. However, because a large number of tests is foreseen, the small 2.2s drop tower may have to be used in conjunction with the large drop tube. This tower is open to the atmosphere, and even when a drag shield is employed, the attainable g-level is approximately 10^{-3}, versus $<10^{-5}$ for the tube. The high g-level, plus the short duration of freefall, may limit the utility of the 2.2s facility.

The experiment will consist of a series of tests, done at various mass flow rates and qualities. A preliminary test matrix is given in Table 2 and ought to accomplish a full mapping of zero-g adiabatic phenomena. It is anticipated that useful correlations of several important parameters will result; Table 3 lists those of interest. Data for the correlations will be provided by instruments and cine/video film records. The measurements will consist of pressures, mass flow rates, velocities, and void fractions; flow regimes will be obtained from the films (see Figure 1).

TABLE 2. Test Matrix

Mass Velocity	Quality (-) (~Void Fraction)						
$kg\ s^{-1}\ m^{-2}$	0.002 (~0.10)	0.01 (0.65)	0.02 (0.75)	0.05 (0.83)	0.1 (0.9)	0.2 (0.92)	0.5 (0.97)
10	x	x	x	x	x	x	x
20	x	x	x	x	x	x	x
50	x	x	x	x	x	x	x
100	x	x	x	x	x	x	x
150	x	x	x	x	x	x	x
200	x	x	x	x	x	x	x
300	x	x	x	x	x	x	x
400	x	x	x	x	x	x	
600	x	x	x	x	x	x	
1000	x	x	x	x	x		

Σ = 66 data points

TABLE 3. Desired Correlations

Parameter	Function
ΔP	G, X, flow regime, Fr
Φ	ΔP_{liquid}, Re, G, α
α	Fr, flow regime, X
Flow regime	G, X, Fr, α
K_I	G, α, flow regime, Fr

Nomenclature

G = mass velocity, kg/s m^2

X = quality, $\dot{m}_{vapor}/\dot{m}_{total}$ (-)

Φ = two-phase pressure loss multiplier (-)

α = void fraction (local volume fraction), V_v/V_{total} (-)

Fr = Froude number, v^2/Dg (-)

Re = Reynolds number, vD/ν (-)

K_I = interfacial friction coefficients(-)

The intent here is initially to map the flow fields against various parameters. Thus the quality and/or void fraction data will be graphed versus the total mass velocity, and versus ΔP. The flow regimes associated with these parameters will be superimposed on the plots. Flow pattern maps will also be plotted. These maps will be compared, at 1-g and zero-g conditions. Trends ought to be evident, suggestive of which existing pressure drop correlation might be modified or corrected to extend its applicability to low-gravity situations. In the simplest case of homogeneous flow, a correlation might be of the form

$$-\left(\frac{dp}{dz}\right)_{2\text{-phase}} = -\left(\frac{dp}{dz}\right)_{1\text{-phase}} \Phi^2 \quad (G, X, P, \text{etc.})$$

where Φ^2 is known as the two-phase frictional multiplier.

ADIABATIC AIR-H_2O ΔP AND FLOW REGIME EXPERIMENT

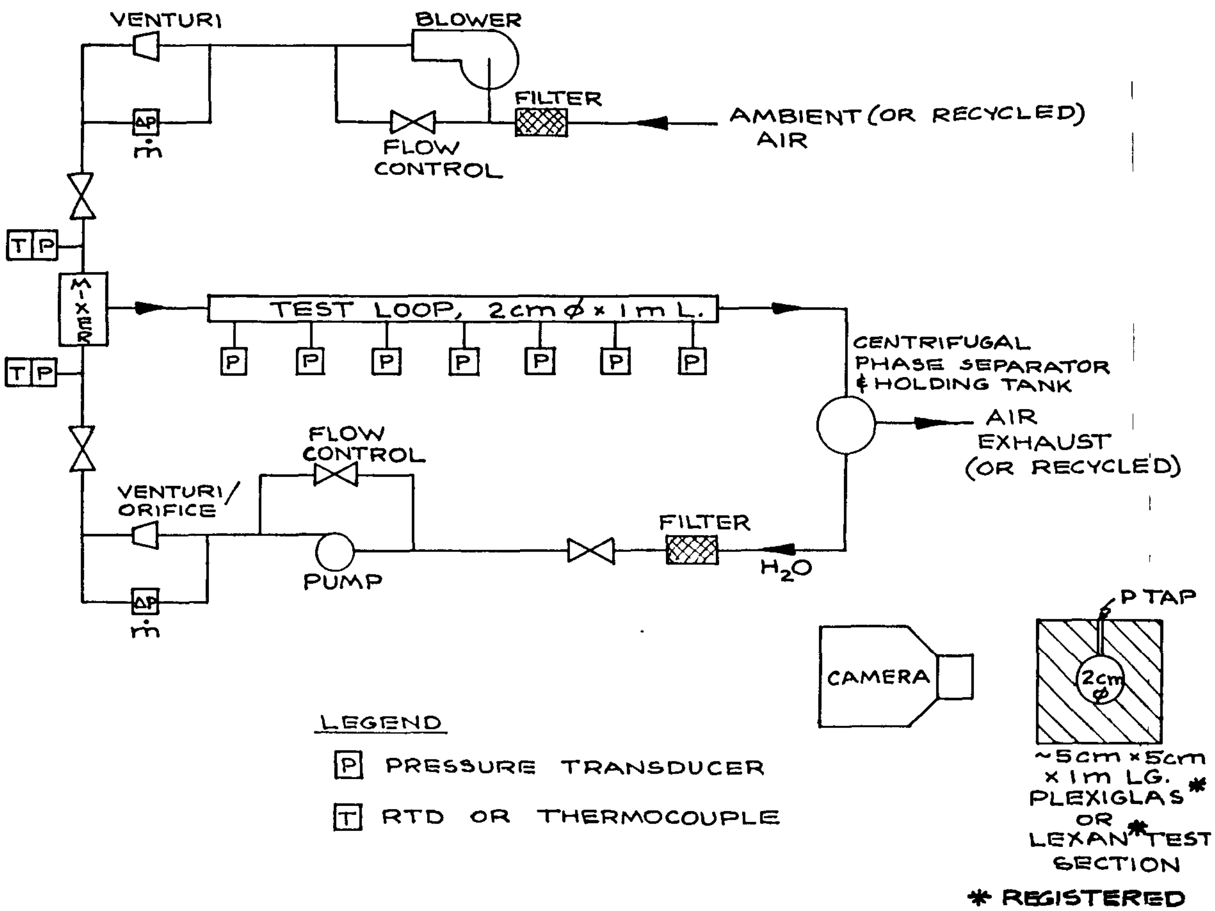

FIGURE 1.

For advanced two-fluid two-phase flow models, the improved flow regime characterization along with pressure drops and (if possible) void measurements will help to develop improved models for interfacial drag. The nature of this adiabatic experiment, as well as of similar experiments exploring heat transfer and critical heat flux, is a fundamental study of heat transfer and fluid flow phenomena. While these experiments have a definite goal, the data resulting from them ought to have broad applicability.

In fact, commonality with another experimenter has already been determined. A condensation experiment currently being performed on the KC-135 aircraft at

Johnson Space Center (JSC) incorporates a boiler supplied by PNL. This boiler is instrumented to permit measurement of flow and heat transfer within it. This results in a net gain to both participants. Texas A&M University obtains the condensation data it seeks, while PNL simultaneously obtains some of the boiling data that it requires. The willingness of Texas A&M University to share its experiment with PNL has allowed us to acquire data well in advance of what the original plan stipulated (see Figure 2).

CONCLUSIONS AND RECOMMENDATIONS

The MMW thermal-hydraulic reduced-gravity two-phase experiments, as described herein, will initially seek very basic information. These experiments will employ ordinary fluids and small test loops with simple geometries. The data obtained with these loops ought therefore to be of interest to other organizations and programs. Which suggests that benefits would accrue to all participants in reduced-gravity research if experiments were coordinated. Currently, there exists no means for doing so.

We highly recommend that a coordinating committee be formed, under LeRC's aegis. This committee would ensure sharing of information, tests, and data among all reduced-gravity researchers. We at PNL would like to participate in, and work with, such a committee.

TWO-PHASE REDUCED-GRAVITY EXPERIMENTAL TASK FLOW

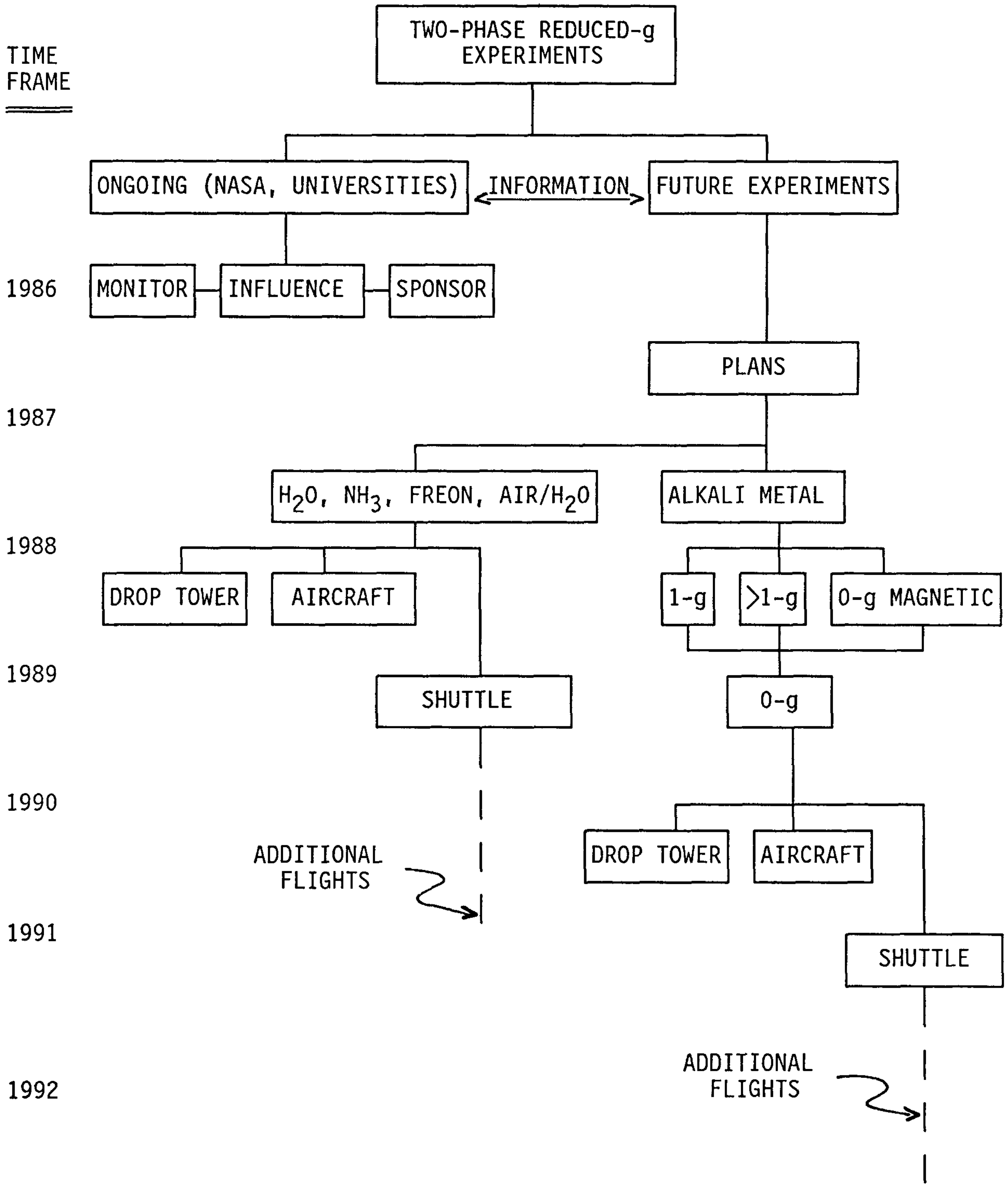

FIGURE 2.