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THE SNAP II POWER CONVERSION SYSTEM
TOPICAL REPORT No. 13
ORBITAL FORCE FIELD BOILING AND CONDENSING EXPERIMENTS
(OFFFACE)

AEC RESEARCH AND DEVELOPMENT REPORT

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TAPCO a division of
Thompson Ramo Wooldridge Inc.
CLEVELAND, OHIO

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ABSTRACT

The Orbital Force Field Boiling and Condensing Experiments (OFFBACE Test Program) were conducted to investigate operation of a Mercury Rankine Turboelectric Power System similar to the SNAP I and SNAP II systems under zero gravity conditions. This work was done under Atomic Energy Commission contract for Atomics International. The report contains an analysis of the test data and, in addition, some advanced condenser design information based on these tests.

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1.0 SUMMARY

This report presents the results of a series of Orbital Force Field Boiling and Condensing Experiments, otherwise known as the OFFBACE Test Program. OFFBACE was undertaken to show the feasibility of operation of a mercury Rankine power system in a zero-gravity environment. A further purpose was to provide quantitative data concerning operation of the various components under zero-gravity conditions for future design consideration. Particular attention was paid to the condenser area since this component is very sensitive to gravity effects.

System gravity effects as observed in the OFFBACE test rig are discussed. The interaction of condenser, subcooler, pump, boiler, and nozzle due to gravity changes from 2.5 to 0 G's are evaluated. The net change in power plant performance in terms of power output is estimated.

The mechanics of condensing in gravity fields are developed from experiments conducted on mercury drops under both static and dynamic conditions. These observations are then compared with those obtained from the OFFBACE Mark II test apparatus both during ground testing and flight testing aboard the KC-135 aircraft. An attempt is made to establish the role played by gravity in the mechanics of two-phase flow. This gives the basis for analysis of operation of the SNAP II system in space by extrapolation of data obtained under gravitational influences.

Mercury-nitrogen two-phase flow data are presented for different flow rates and tube diameters. The influence of gravity on the flow was investigated by tilting the test section in both the upward and downward positions.

A method by which a lightweight mercury vapor manifold can be designed is presented. Test data from a manifold test rig is used to support and confirm the recommended design procedure.

The operational problems of multiple liquid interfaces in zero gravity are analyzed and the results related to the observations made in zero gravity with the OFFBACE apparatus.

This topical report summarizes the advancement of the state of the art in zero-gravity condenser design which has been accomplished through the effort expended during the 1959-1961 fiscal year.

2.0 INTRODUCTION

The series of experiments known as the OFFBACE Test Program has been accomplished by Thompson Ramo Wooldridge for Atomics International under AEC Contract At(11-1)-GEN-8. The purpose and scope are described by the full name of these tests, Orbital Force Field Boiling and Condensing Experiments, and can be further defined as an attempt to determine the effects of body forces upon the operation of a mercury Rankine power system similar in basic design to the SNAP I and SNAP II power systems.

The SNAP II auxiliary power unit for 3 kw of electrical output consists of a reactor heat source and a power conversion system. The power conversion system is a mercury Rankine engine consisting of a mercury boiler heated by a NaK heat transfer loop, an axial flow impulse turbine which extracts energy from the superheated mercury vapor, a condenser which returns the vapor to a liquid state, and a mercury pump which returns the condensate to the boiler. The turbine directly drives the alternator, the mercury pump, and a permanent magnet induction NaK pump which is designed to circulate the NaK between the mercury boiler and the reactor.

The OFFBACE system closely simulated the operation of the SNAP II system, with the exception that the turboelectric package was replaced by a nozzle, desuperheater, and electric motor-driven mercury pump. The nozzle was designed for choking under all operating conditions in order that the pressure downstream, the condenser inlet pressure, would be virtually independent of the upstream or boiler outlet pressure. This isolated these components from each other to aid investigation of the gravity effects on both of them. It also provided a convenient flow measurement.

A simulated zero-gravity environment was obtained by flying an Air Force KC-135 through a parabolic zero-gravity maneuver, known as a Keplerian trajectory (Figure 1), with the test package secured to the aircraft. With this equipment it was possible to examine the effect of a variable gravity field on the boiler, condenser, and pump characteristics. Evaluation of condenser performance was emphasized because this component is very sensitive to variations in body forces, and changes in condenser performance directly affect both turbine and pump performance.

This report contains a detailed analysis of the phenomena involved in condensing under variable gravity conditions. Much of this analysis has been based on results of investigations of the mechanics of two-phase flow and condenser-subcooler interface stability which have been previously substantiated in the SNAP I and SNAP II programs. The information given here represents the continued effort in condenser research and development which has emphasized OFFBACE flight testing. During the 1959-1960 fiscal year enough pressure drop data for mercury condensers was obtained so that an empirical correlation could be developed. Further interfacial stability tests were made, mercury drop size and entrainment velocities were measured, and zero-gravity flight data was obtained.

3.0 OFFBACE APPARATUS AND TESTING PROCEDURES

In contrast to the Mark I OFFBACE system which had been designed to furnish qualitative data on condensing phenomena in zero gravity (Reference 1), the Mark II OFFBACE system was designed to provide quantitative dynamic data on the performance of a realistically simulated mercury Rankine space power system in zero gravity. The Mark II OFFBACE system was the principal test apparatus developed and used in the OFFBACE program. Although designed principally to obtain boiling and condensing information, the apparatus included all key components of a Rankine system to enable study of component interaction as well as components themselves.

Mark II was designed specifically to operate in the zero-gravity environment provided by the Air Force KC-135 aircraft. To provide results directly applicable to the SNAP II program, system thermodynamic parameters were selected to duplicate those of SNAP II insofar as possible. Table I lists the key performance parameters of the Mark II OFFBACE system. A working fluid flow rate of 0.4 lbm/min was selected as the minimum flow rate for a lightweight portable system which would realistically simulate full-sized Rankine components. The flow rate governs the size of the components and the power supply required and therefore was as low as possible consistent with realistic simulation of components and instrumentation accuracy.

The zero-gravity environment was provided by flying a parabolic trajectory in the KC-135 aircraft as shown in Figure 1. The apparatus had to withstand the total environment provided by this vehicle - in particular the 2.5 G's acceleration experienced during entry and to a slightly lesser degree during recovery from the maneuver - and be compatible in electrical power requirements with the power supply system of the aircraft.

To permit maximum utilization of the KC-135, the OFFBACE apparatus was designed to be installed and removed quickly from the aircraft. While weight and volume occupied were considerations, the capabilities of the aircraft did not require that these be strictly minimized. As a safeguard against the biological hazards of mercury vapor as well as the corrosive characteristics of mercury in contact with aluminum, the entire Rankine loop was housed within a sealed enclosure. This required that a separate condenser air cooling loop be provided within the enclosure and an air-to-air heat exchanger be used to finally reject condenser heat to the air of the aircraft interior.

The primary components of the Mark II Rankine system are shown schematically in Figures 2a & 2b. The component arrangement is typical of Rankine space power system designs. A choked nozzle was used to simulate the turbine portions of the mercury space engine. The Mark II boiler tube consisted of three sections of tubing joined together to form a stepped tube 36.24 ft. long. A spiral wire turbulator was inserted in each tube. The tube was wound in the form of a coil 13.1 in. long and 3.5 in. diameter. Tube dimensions of the three sections were as follows:

inlet section:	3.3 ft long, 0.125 in. OD/0.085 in. ID, #25 GA wire at 0.34 in. pitch
----------------	--

TABLE I
KEY PERFORMANCE PARAMETERS OF MARK II OFFBASE SYSTEM

<u>Parameter</u>	<u>Design</u>	<u>Maximum</u>
Boiler inlet pressure	130 psia	230 psia
Boiler inlet temperature	100°F to T_{sat}	Saturation temperature
Boiler flow rate	0.4 lbm/min	0.6 lbm/min
Boiler outlet pressure	100 psia	150 psia
Boiler outlet temperature	1150°F	1300°F
Condenser inlet pressure	6 psia	10 psia
Condenser inlet temperature	600°F	700°F
Condenser flow rate	same as boiler	same as boiler
Pump inlet pressure	4 psia	2 psia minimum at low flows, no limit on max.
Pump discharge pressure	140	300
Pump flow rate	---	30 lbm/min with by-pass in operation

KC - 135 ZERO GRAVITY MANEUVER

FIGURE 1

OFFFACE MARK II MERCURY SCHEMATIC

FIGURE 2a

OFFFACE MARK II MERCURY BOILING, CONDENSING, PUMPING TEST RIG

- middle section: 4.4 ft long, 0.188 in. OD/0.132 in. ID, #21 GA wire at 0.53 in. pitch
- outlet section: 28.6 ft long, 0.250 in. OD/0.180 in. ID, # 19 GA wire at 0.72 in. pitch

The mercury was preheated, vaporized, and superheated in its passage through this tube. Control of the electrical heating permitted a wide range of boiler operating conditions. Figure 3 is a photograph of the boiler prior to assembly.

A choked nozzle and desuperheater were used to condition the mercury vapor prior to entrance into the condenser. This combination isolated the boiler from performance variations of the condenser, thus ensuring a constant mercury flow rate, and permitted varying the inlet conditions to the condenser.

The condenser for the Mark II system was designed for evaluation of a wide variety of condenser configurations. Multiple or single tube condensers could be installed in the baffle duct through which cooling air was forced. Varying the flow rate of the cooling air provided a wide range of condensing temperatures and heat fluxes. Continuous control of the condenser cooling rate was maintained using an electric motor driven blower controlled by a variable transformer. A second electric motor driven blower circulated air through the outside of an air-to-air heat exchanger to reject the condenser heat to ambient. The condenser tubes were made of steel and high-temperature glass. The glass permitted visual and photographic observation of condensing and vapor-liquid interface action. Figure 4 shows the condenser assembly and Figure 5A is a typical condenser tube design. Figure 5B defines the locations of the tabulated subscripted variables (Table IV and V) of the condenser.

A SNAP II mercury condensate pump driven by a high-speed electric motor was used to receive condensate and return it to the boiler. Pump speed and flow rate could be controlled independently to yield the operating range desired.

The mercury loop was sufficiently instrumented to yield quantitative dynamic data on each component as well as the overall system. Temperatures were measured with surface and immersed thermocouples; pressure with absolute strain gage transducers, flow rates with strain gage differential transducers measuring a pressure drop across a calibrated orifice. Accelerometers, also of the strain gage type, provided a method to determine the acceleration environment of the system. Instrumentation by component was arranged as follows:

- Boiler: Inlet and outlet pressure measurements, 25 temperature measurements, inlet flow rate measurements
- Condenser: Inlet and outlet pressure measurements, 20 temperature measurements
- Pump: Inlet and outlet pressure measurements, 7 temperature measurements, speed measurements, flow rate measurements

MARK II BOILER PRIOR TO ASSEMBLY

FIGURE 3

OFFFACE CONDENSER

FIGURE 5a

FIGURE 5b

The mercury loop in its sealed enclosure was connected electrically to an instrumentation and control console. This console consisted of instruments to record and read out the outputs of loop data pickups and to control the power supplied to the loop. All pressures, flow rates, accelerations, several key temperatures and pump speed were recorded on a 24-channel direct reading oscillograph. Two 20-point temperature loggers recorded the majority of temperatures. Transducer excitation was by solid state power supplies. Twelve channels of strain gage bridge balance units were provided.

Variable transformers were used to control the power supply to the electrical heaters of the mercury loop and also to provide speed control of the several electric motors of the loop. The power supply characteristics of the KC-135 aircraft made it necessary to design a rig to operate from both 400 and 60 cycle power. Approximately 2 kw of 400 cycle power and 4 kw of 60 cycle power, both at 115 volts, were utilized. Low weight was not a prime requirement for use of the Mark II system in the KC-135 aircraft. Therefore, commercial components and economical fabricating techniques were employed. Overall envelope dimension and weights of the two major units of the Mark II system are shown below:

	<u>Mercury Rankine Loop</u>	<u>Instrumentation and Control Console</u>
Length	4 feet	8 feet
Width	2.5 feet	1.5 feet
Height	3.5 feet	3.5 feet
Weight	285 pounds	780 pounds

In addition to the above two main pieces of OFFBACE Mark II equipment, two additional components were used: Motion picture cameras recorded condensing phenomena and a vacuum pump system permitted evacuation of noncondensables from the mercury loop during testing. Two motion picture cameras recorded the condensing phenomena. These cameras operated at film speeds of 16 to 64 frames per second and were used primarily to record the condenser interface location. The vacuum pump system was connected to the mercury loop with flexible plastic lines. The exhaust from the mercury pump was ducted overboard through a plastic line connected to ports in the KC-135 fuselage.

Installation of the Mark II OFFBACE package into the KC-135 was similar to that indicated in Figure 6. All of the components were secured to the aircraft by cargo tie-down fixtures located on 20-inch centers on the aircraft floor. All electrical connections between the various modules and the aircraft itself were made with quick disconnect fittings. Installation time into the KC-135 aircraft was approximately four hours.

Preparations for testing required approximately two to three hours to perform necessary instrumentation balancing and calibrations and to permit the system to come to operating conditions. Prior to system warm-up the vacuum system reduced the pressure within the system to approximately 20 to 30 microns. At intervals during the warm-up period and after mercury flow had been established to the loop, the vacuum was reapplied to the system to draw off all noncondensables.

INSTALLATION OF MARK II OFFFACE PACKAGE INTO KC - 135 AIRCRAFT

● Used tie-down fittings

Alternate setup
Equipment moved aft 20 in.

A minimum distance of 30 in. is needed
between test package and instrumentation
console to allow test package operator
adequate room.

Maximum height of the instrumentation
console = 37 in.

Maximum height of test package = 40 in.

FIGURE 6

Consideration of noncondensables had been a factor in the design of the system. Thus, all welded or "O" ring connections were utilized wherever possible, in order to prevent air from leaking into the system. However, noncondensables were intermittently present in the system due to gases trapped in the mercury and the apparatus, and from air leaking into the lower pressure portions of the system. The point of removal of noncondensables was in the subcooler, where noncondensables tended to concentrate.

The operating characteristics of the KC-135 zero-gravity test vehicle and the thermal equilibrium characteristics of the OFFBACE system resulted in a flight test pattern that usually allowed approximately 12 zero-gravity trajectories per flight. This permitted attaining approximately six pairs of runs at identical conditions. The key system parameters that were varied to establish the different state points were the mercury flow which was varied from its design point of 0.4 lbm/min to a maximum of 0.6 lb/min and a minimum of 0.2 lb/min, and the heat rejection temperature of the condenser which was varied over a range that resulted in condenser pressure levels of from 2 to 10 psia. Sufficient time was allowed between trajectories to assure that the system had reached equilibrium operating conditions. The air cooling method of rejecting condenser heat proved to be very responsive to changes in blower speed and hence proved a rapid means for varying this parameter. The thermal inertia of the boiler portions of the system was the controlling factor in setting up new vapor flow rates.

The performance of the instrumentation and mercury loop proved to be very stable, requiring little attention of test personnel to maintain a test point. Since all data were recorded continuously and automatically, little manual taking of data was done and the little required was transcribed on a portable tape recorder. In view of the fast-moving events during flight, these characteristics of the system proved very valuable. The primary need for test personnel during flight, beyond changing controls to set up the test points, was to mark and identify the instrumentation recordings and to change film in the motion picture cameras.

4.0 CONDENSER RESEARCH

OFFBACE research was concentrated on the condenser-subcooler because the sensitivity of this component to body forces is a major consideration in designing mercury Rankine engines for space use. In the boiler where pressure level is high and high pressure drops can be tolerated, insertion of turbulators can make the hydrodynamic flow regime relatively insensitive to external body forces. The turbulators create centrifugal force fields many times larger than the expected body forces that act during zero-gravity operation. In addition, hydrostatic head variations in the preheat portion of the boiler are usually a fraction of a percent of the boiler pressure level and are therefore not crucial.

Satisfactory operation of the centrifugal pump depends on inlet conditions that are significantly affected by the acceleration environment. The net positive suction head required by the pump depends on a combination of hydrostatic head of the subcooler, condenser pressure, and the degree of subcooling of the liquid. Thus pump operation largely depends on condenser-subcooler conditions.

Because the bare condenser tube operates at low pressure levels and small pressure drops, variations in external body forces could cause flow regime perturbations with attendant large percentage variations in pressure level and pressure drop. In addition, low vapor velocities near the condenser-subcooler interface magnify the effects of imposed body forces in this region. When either a tapered or stepped condenser tube is used, a body force variation that causes a pressure drop change and consequently a change in subcooler length could result in relocation of the interface to a position where the tube diameter is greater than the critical value. If the variations in body force are periodic, the critical diameter could change as a result of amplitude and frequency of the disturbance.

Since the effect of external body forces on the condenser-subcooler is of prime importance, the major portion of the OFFBACE test analysis was directed toward this component. To design a condenser in which liquid and vapor flow concurrently through the tubes, detailed information is needed about pressure drop, flow regime stability, and the stability of the liquid-vapor interface.

When mercury condenses at 600°F, surface tension of the liquid is high and the volume ratio of vapor to liquid is large even though weight fractions of vapor to liquid are low. These factors produce a flow regime of liquid drops flowing with the vapor. To design a condenser with the maximum allowable pressure drop and thus minimum weight, pressure drop associated with the flow of such a mixture must be accurately determined.

The stability of the flow regime affects both the pressure drop and the operation of the condenser. A stable flow regime is one in which no appreciable changes occur as a result of a change in body forces over the range expected. If body forces cause a change in liquid inventory in the condenser, an equal change occurs in subcooler inventory. The con-

denser, and consequently the entire system, then operates off design. Variation in liquid inventory in the condenser also causes a change in pressure drop through the condenser.

Another important factor in condenser design is the stability of the liquid-vapor interface which separates the subcooler from the condenser. It can readily be visualized that if a conventional earth-bound condenser were turned upside down, the liquid in the "hot well" would be dumped into the vapor inlet line which would cause the condensate pump to fail. Similarly, a glass of water when inverted will spill its contents, although a sufficient barometric pressure is available to support a thirty-four foot water column. Instability and wave formation at the interface between liquid and gas are the major factors breaking the liquid phase into drops and ligaments during spilling.

When a liquid interface is placed in a zero-gravity environment, it may be subject to gravity disturbances - plus or minus with respect to the interface. These disturbances are similar to those experienced when inverting a container with a liquid interface. If the proper disturbing wavelength is imposed on the interface, an instability may cause the liquid to "spill." This must be avoided in a zero-gravity environment. A fixed column of liquid properly subcooled for the required net positive suction head is necessary for good performance of the power plant system.

The following sections describe in detail efforts and results in research devoted to problems of stability, flow regime, pressure drop, manifolding, and parallel tube operation. In addition, the development of a mathematical model for understanding mercury two-phase flow mechanics and a summary of the effect of gravity on the overall operation of a Rankine system are presented.

4.1 The Mechanics of Mercury Condensing in a Gravity-Flow Field

The mechanics of flow and heat transfer differ in laminar and turbulent flow, so the flow regime or flow pattern must be known before the Nusselt number or friction factor can be correlated. Defining the two-phase flow regime establishes the flow and heat transfer mechanisms and the resulting required correlation parameters. The physics of flow regimes is based on hydrodynamic stability,* a very difficult and complex engineering science. Experimentation is required, for very little progress can be made solely on an analytical basis.

A general classification of two-phase flow patterns is shown in Figure 7. In one extreme vapor bubbles are dispersed in a continuous phase of liquid and in the other extreme liquid droplets are dispersed in vapor. Further classification is possible if droplet size or bubble size is included as a variable. Between these two extremes exists a condition where both phases are continuous, e.g., a liquid film on the wall with a vapor core or a vapor film

* Also referred to as interfacial stability, that is, the stability of the interface between the flowing liquid and vapor phases.

TWO-PHASE FLOW REGIMES . . .

LIQUID - CONTINUOUS PHASE
VAPOR - DISPERSED PHASE

BOTH LIQUID AND
VAPOR PHASES ARE
CONTINUOUS WITH
SMOOTH INTERFACE

BOTH LIQUID AND
VAPOR PHASES ARE
CONTINUOUS WITH
WAVY INTERFACE

VAPOR - CONTINUOUS PHASE
LIQUID - CONTINUOUS AND
DISPERSED PHASE

LIQUID - DISPERSED PHASE
VAPOR - CONTINUOUS PHASE

FIGURE 7

on the wall with a liquid core. Further classification is possible if the form of the continuous interface (wavy, slug, smooth) is included.

The non-wetting property and high surface tension of pure liquid mercury are destabilizing factors for the liquid-vapor interface; as a result, films of pure liquid mercury are rare in a flowing system. Droplets dispersed in a vapor phase was the flow pattern observed in all two-phase flow tests made in transparent tubes using either liquid mercury in nitrogen gas or in mercury vapor. In postulating either a heat transfer model or a fluid dynamic model for analytic purposes, a flow pattern involving liquid drops is therefore assumed. In boiling a pattern of droplets sliding on a heated wall against which they are held by a swirl device is assumed (see Reference 3). In condensing, growing stationary surface drops are swept into the flowing vapor when they reach a certain critical size. The critical droplet size is determined by the vapor velocity (see Reference 1). Since gas velocity will vary axially in a condenser of constant tube diameter, droplets of different sizes result. Figure 8 illustrates the flow pattern encountered during condenser tests.

The two-phase static pressure drop for a differential element of a condenser with a flow pattern as depicted in Figure 8 can be obtained from the momentum equation as follows:

$$\begin{aligned}
 dp_{TP} \frac{\pi D^2}{4} = & \overbrace{N_v \frac{\pi D^2}{4} dL C_{d\delta} \frac{\pi \delta_c^2}{4} \rho_v \frac{u_r^2}{2g_s}}^{\text{1st Term}} + \overbrace{\tau_w \pi D dL}^{\text{2nd Term}} + \overbrace{N_s \pi D dL C_{d\delta} \frac{\pi \delta^2}{4} \rho_v \frac{u_v^2}{2g_s}}^{\text{3rd Term}} \\
 & \underbrace{- \pm n R_L \rho_f \frac{\pi D^2}{4} dL}_{\text{4th Term}} \pm \underbrace{d(\dot{m}_v u_v)}_{\text{5th Term}}
 \end{aligned}
 \tag{Equation 1}$$

In a flow of gas with entrained particles, it is useful to write the momentum equation of the gas while excluding the momentum of the droplets. Equation 1 is the momentum equation for the gas only.

The first term includes the effect of drag produced by drops in transit on the pressure drop. The drag represents a force exerted by the liquid phase on the gas.

The second term includes the effect of wall shear stress produced by the flowing vapor on the pressure drop.

The third term includes the effect of drag produced by stationary surface drops on the pressure drop.

The fourth term is the gravity effect in the axial direction on the liquid droplets in suspension.

The fifth term is the acceleration effect of the vapor phase.

The droplets in suspensions are assumed to be at an average critical drop size of δ_c , and the wall surface drops at an average size, δ :

MERCURY CONDENSER FLOW PATTERN SHOWING: (1) DROP ON HEAT TRANSFER SURFACE GROWING DUE TO CONDENSATION, (2) DROPS IN TRANSIT FLOWING TOWARD SUBCOOLER INTERFACE, (3) DROPS OF DIFFERENT DIAMETERS DUE TO A VARIABLE AXIAL VAPOR VELOCITY, (4) MEAN DROP SELECTED FOR DYNAMIC ANALYSIS

FIGURE 8

Equation 1 may be reduced if the following substitutions are made:

$$dp_v = \frac{4\tau_w dL}{D} = f \frac{dL}{D} \rho_v \frac{u_v^2}{2g_s} \quad (a)$$

$$u_f = \epsilon u_v \quad (b)$$

$$u_r = u_v (1 - \epsilon) \quad (c)$$

$$R_L = N_v \frac{\pi \delta_c^3}{6} \quad (d)$$

$$\frac{\dot{m}_f}{\dot{m}_v} = \frac{1}{x} - 1 \quad (e)$$

Equation 2

$$\dot{m}_v = \frac{\pi D^2}{4} \rho_v u_v \quad (f)$$

$$\left(\frac{1}{x} - 1\right) = R_L \epsilon \rho_f / \rho_v \quad (g)$$

We then have,

$$dp_{TP} = \frac{R_L}{\pi \delta_c} 3 dL C_{d\delta} \frac{\pi \delta_c^2}{4} \rho_v \frac{u_v^2}{2g_s} (1 - \epsilon)^2 + \tau_w 4 \frac{dL}{D} + N_S \frac{dL}{D} C_{d\delta} \pi \delta_c^2 \rho_v \frac{u_v^2}{2g_s}$$

$$- - - \pm n \frac{R_L}{\pi \delta_c} 2 \rho_f DL \pm d\left(\frac{\rho_v u_v^2}{g_s}\right)$$

Dividing through by dp_v we have,

$$\frac{dp_{TP} \pm d(\rho_v u_v^2)}{dp_v} = \frac{3}{2} \frac{R_L}{\delta_c} C_{d\delta} \frac{D}{f} (1 - \epsilon)^2 + 1 +$$

$$- - - \frac{N_S}{f} C_{d\delta} \pi \delta_c^2 \pm \frac{n R_L \rho_f D}{f \rho_v \frac{u_v^2}{2g_s}}$$

Let

$$\frac{dp_{TP} \pm d\left(\frac{\rho_v u_v^2}{g_s}\right)}{dp_v} \equiv \Phi$$

Equation 3

therefore,

$$\Phi = \frac{3}{2} \frac{1}{\delta_c} \frac{\rho_v}{\rho_f} \frac{1}{\epsilon} \left(\frac{1}{x} - 1 \right) C_{d\delta} \frac{D}{f} (1 - \epsilon)^2 + 1 + \frac{N_S}{f} C_{d\delta} \pi \delta^2 \text{ ----}$$

$$\text{----} \pm \frac{n \left(\frac{1}{x} - 1 \right) D}{\epsilon f u_v^2 / 2g_s} \text{ ----}$$

Equation 4

Thus Φ represents the influence of liquid-phase friction and gravity on the frictional two-phase pressure drop. Note that the static pressure drop dp_{TP} corrected by the acceleration term (fifth) gives the frictional two-phase pressure drop including the gravity effect. Thus:

$$\Phi \equiv \frac{dp_{TP}(\text{friction})}{dp_v} \text{ ----}$$

Equation 5

The drag coefficient of the droplet, $C_{d\delta}$, can be evaluated if the droplet Reynolds number is known. The droplet Reynolds number $N_{R\delta}$ is:

$$N_{R\delta} = \frac{\rho_v u_v (1 - \epsilon) \delta_c}{\mu_v} \text{ ----}$$

Equation 6

Later the appropriate values for $C_{d\delta}$ will be selected knowing the range of $N_{R\delta}$. To make equation 4 applicable to design, the terms δ , δ_c , ϵ , and N_S must be evaluated. Note that $C_{d\delta}$ is a function of $N_{R\delta}$ and therefore $C_{d\delta}$ also depends on the terms ϵ , and δ_c . The subsequent analysis will contain the necessary physics for the evaluation of these terms (ϵ , δ_c , δ , N_S). Some of these terms may be sensitive to body forces. Therefore, the result of this analysis should give a means of estimating $\Delta \Phi$ due to changes in gravity.

4.1.1 Determination of Drop Size, δ , in a Gravity-Flow Field

Since estimates of mercury droplet sizes are of importance if gravity effects in mercury condensers are to be computed, experiments were conducted to measure the critical conditions at which the mercury drops will be induced to move toward the subcooler-condenser interface. Mercury drops grow on the heat transfer surface by condensation until they are large enough to be entrained into the flowing vapor by action of gravity and drag forces. The size to which the droplet will grow at incipient entrainment is denoted as δ_c . Critical drop size measurements were made in glass tubes with flowing nitrogen gas and on inclined plates in which only gravity effects play a role. These experiments will be described subsequently.

Figure 9 shows a droplet resting on a surface under the influence of gravity and drag forces. The retarding force which prevents movement is attributed to surface tension. It is surmised that the only property of a real fluid (Newtonian fluid) which can support stress without a rate of deformation is the surface tension. Without surface tension the action of any stress (drag or gravity) will immediately produce movement or flow.

The following is an equation for the force balance just at the condition of incipient movement; the momentum term is zero (see Figure 9):

$$\frac{\pi \delta_c^2}{4} C_{d\delta} \frac{\rho_v u_v^2}{2g_s} \pm n \sin \theta \rho_f \frac{\pi \delta_c^3}{6} = \pi \delta_c \sigma E_\sigma \quad \text{Equation 7}$$

where E_σ is a constant to be evaluated by experiment. E_σ is of the order of one and takes into account the effect of drop deformation, contact angle, and condition of surface on the magnitude of the retarding surface tension force. E_σ will be less than one since $\pi \delta_c \sigma$ represents an upper limit. The actual perimeter of contact will be less than $\pi \delta_c$ and the σ will be reduced by the cosine of the mean contact angle during deformation. The coefficient of drag for drops $C_{d\delta}$ is, of course, dependent on the deformation. Figures 10 and 11 from Ref. 4 and 5 respectively show drag coefficients for solid spheres, drops, and freely rising vapor bubbles. The values of the drag coefficients for the deformable bodies (bubbles and drops) are greater than for solid spheres and are near one. Therefore, for simplicity assume $C_{d\delta}$ equal to one and let E_σ accommodate the deformation effect. Equation 7 becomes:

$$\frac{\pi \delta_c^2}{4} \frac{\rho_v u_v^2}{2g_s} \pm n \sin \theta \rho_f \frac{\pi \delta_c^3}{6} = \pi \delta_c \sigma E_\sigma$$

$$\frac{\rho_v u_v^2}{2g_s} \pm n \sin \theta \rho_f \frac{2}{3} \delta_c = \frac{4 \sigma}{\delta_c} E_\sigma \quad \text{Equation 8}$$

Since the value E_σ is evaluated by test and its magnitude depends on the degree of deformation the drop can accommodate before it breaks loose from the surface, it is of importance to examine the shape of drops under the influence of forces. Figure 12 shows the shape of mercury drops of various sizes under the influence of gravity normal to the surface. These lines are the theoretical curves as computed by Bashforth and Adams (Reference 6). Figure 13 shows several mercury drops formed by condensation on a vertical surface sketched from a photograph in Reference 7. Note the greater deformity of the larger drops due to gravity. Figure 14 shows a falling water droplet in various stages of deformation and disintegration. Drag and gravity both act in this case. Figure 15 shows the action of the various interfacial tensions of a mercury drop and the equilibrium equation for computing the contact angle. Included in Figure 15 are measured values for interfacial tensions and contact angles for mercury.

DROP RESTING ON SURFACE UNDER THE INFLUENCE OF DRAG,
BODY FORCES AND INTERFACIAL TENSION

FIGURE 9

DRAG COEFFICIENTS FOR SPHERES, DISKS AND DROPS (REFERENCE 4)

FIGURE 10

DRAG COEFFICIENT VS. REYNOLDS NUMBER FOR STEAM BUBBLES RISING IN WATER AT ITS NORMAL SATURATION TEMPERATURE (REFERENCE 5)

FIGURE 11

SHAPE OF MERCURY DROP DUE TO GRAVITY AND CAPILLARITY
AS MEASURED AND COMPUTED IN REFERENCE 6

FIGURE 12

MERCURY DROPLETS ON CARBON STEEL
AS SKETCHED FROM PHOTOGRAPH (REFERENCE 7)

FIGURE 13

BREAKUP OF LARGE RAINDROPS

FIGURE 14

INTERFACIAL TENSIONS OF A MERCURY DROP (REFERENCE 9 AND 10)

Mercury

$\sigma_{fv} = 475$ dynes/cm @ melting point temperature coefficient
new entry of surface tension = -0.17 dynes/cm. C

$\sigma_{sf} = 22$ dynes/cm

σ_{sv} same order of magnitude as σ_{sf} , however,
 σ_{sf} is consistently lower by 10 to 30 percent.

$\beta = 139^\circ$ glass - mercury

$\beta = 41^\circ$ glass - water - mercury

FIGURE 15

Table II presents drop size measurements made in horizontal glass tubes of various diameters. These results were also reported in Reference 1. The dependence of tube diameter on critical drop size appears to be a Reynolds number effect. Rouse (Ref. 11) states that the ratio of the thickness of the laminar sublayer to the size of solid particles submerged in river beds is an important parameter in determining conditions of incipient particle transportation. Thus a plot of δ_c/D versus the gas Reynolds number was made in Reference 1 as a means of correlation since the ratio of the laminar sublayer thickness to the tube diameter is a function of the gas Reynolds number. According to Equation 8 the required correlating parameters should also contain inertia, gravity, and surface tension; thus the general function should be:

$$\delta_c/D = f(N_R, N_W, N_F) \quad \text{Equation 9}$$

where

N_R is the Reynolds number (inertia-viscosity)

N_W is the Weber number (inertia-surface tension)

N_F is the Froude number (inertia-gravity)

δ_c/D is geometric parameter

In Table II are the results of tests made on the critical conditions required for the incipient movement or entrainment of mercury drops due to both gravity and drag. In the flow tests a mercury drop was placed in a long glass tube. This drop was observed and its size measured by means of a microscope with calibrated cross-hairs. The nitrogen flow rate at the first instant of drop movement was recorded as the critical flow rate. In the plate test the angle of inclination was recorded when the drop appeared to move downward. The combined effect of gravity and drag or drop entrainment was observed by inclining the glass tube while nitrogen gas was flowing. Figures 16, 17, and 18 show the correlated results from Table II. The correlation parameters are those obtained from Equation 8. For horizontal tubes Equation 8 becomes

$$\left(\frac{\rho_v u_v^2 \delta_c}{\sigma 2g_s} \right) = 4 E_\sigma \quad \text{Equation 10}$$

Thus, the left term becomes the Weber number. The Weber number depends on the constant E_σ which is determined by the effect of drop distortion on the surface tension force.

For the inclined plate Equation 8 becomes:

$$n \sin \theta \rho_f \frac{2}{3} \frac{\delta^2}{\sigma} = 4 E_\sigma \quad \text{Equation 11}$$

TABLE II
MERCURY DROP SIZE MEASUREMENTS

Gas Flow - Mercury Drops - Horizontal Tubes									
Tube Inside Diam., In.	Drop Diam., in.	Gas Velocity, ft/sec.	Gas Density lb/ft ³	Reynolds Number (Tube)	Drop Diam. Tube Diam.	Weber Number (Drop)	Froude Number (Drop)	4E _g	Gravity Number (Drop)
0.395	0.012	61.0	.08	11,900	0.0304	0.143	16.9	0	
	0.005	88.5	.08	17,200	0.0127	0.126	85.8		
	0.010	63.0	.08	12,200	0.0254	0.127	21.6		
	0.0085	63.0	.08	12,200	0.0215	0.108	25.4		
	0.017	40.0	.08	7,760	0.0431	0.087	5.15		
	0.040	36.0	.08	7,000	0.101	0.166	1.77		
	0.023	43.0	.08	8,350	0.0584	0.136	4.39		
	0.0082	65.0	.08	12,600	0.0208	0.111	28.1		
	0.005	99.0	.08	19,200	0.0127	0.157	107.0		
Gas Flow - Mercury Drops - 31° Upward									
0.171	0.050	75.5	.075	6,720	.292	0.856	5.82	0.709	0.147
	0.035	52.0	.074	4,550	.205	0.281	3.95	0.209	0.072
	0.040	58.4	.0745	5,160	.234	0.406	4.34	0.312	0.0938
	0.035	53.2	.0725	4,550	.205	0.289	4.00	0.217	0.0721
	0.040	58.8	.0725	5,050	.234	0.402	4.25	0.308	0.0938
	0.040	68.8	.0725	5,900	.234	0.550	5.85	0.456	0.0938
	0.0097	179.0	.081	17,200	.056	1.01	182.0	1.004	0.00552
	0.0091	262.0	.095	29,300	.053	2.38	486.0	2.375	0.00486
	0.0078	193.0	.0825	18,800	.045	0.962	268.0	0.958	0.00358
	0.040	75.0	.073	6,480	.234	0.657	6.95	0.563	0.0938
	0.025	112.0	.075	10,000	.146	0.944	25.8	0.907	0.0366
	0.015	144.0	.078	13,300	.088	0.973	73.5	0.960	0.0132
	0.012	162.0	.080	15,400	.070	1.01	119.0	1.002	0.00844
Gas Flow - Mercury Drops - 12.5° Downward									
0.171	0.100	42.8	.0725	3,670	.585	0.534	0.91	0.780	0.246
	0.035	97.5	.0745	8,600	.205	0.992	13.8	1.022	0.0302
	0.0145	115.0	.0755	10,300	.085	0.58	46.8	0.585	0.0052
	0.0135	123.0	.0765	11,200	.079	0.629	58.5	0.634	0.00448
	0.0043	160.0	.079	15,100	.025	0.348	320.0	0.349	0.000456
	0.0250	88.5	.074	7,750	.146	0.582	15.8	0.597	0.0154
	0.0141	114.0	.075	10,100	.082	0.551	47.2	0.556	0.0049
	0.0061	151.0	.079	14,100	.035	0.441	201.0	0.442	0.000916
	0.0045	232.0	.089	24,500	.026	0.865	724.0	0.866	0.0005
	0.035	77.4	.074	6,760	.205	0.621	8.60	0.651	0.0303
	0.025	110.0	.075	9,760	.146	0.906	24.7	0.921	0.0154
	0.020	116.0	.075	10,300	.117	0.810	34.4	0.82	0.00984

TABLE 11 (Continued)

Mercury Drops on Inclined Plate							
Sin θ	Drop Diam. in.		Gravity Number				
0.0182	0.312	Glass Plate	0.202				
0.0296	0.250		0.211				
0.0410	0.1875		0.165				
0.0684	0.156		0.190				
0.0956	0.125		0.170				
0.150	0.099		0.168				
0.264	0.0786		0.186				
Remarks:							
On ground glass surface drops required less angle to move.							
Greasy surface caused drops to "stick"; greater angle required to move.							
Gas Flow - Mercury Drops - Horizontal Tubes							
Tube Inside Diam. in.	Drop Diam. in.	Gas Velocity ft/sec.	Gas Density lb/ft ³	Reynolds Number (Tube)	Drop Diam. Tube Diam.	Weber Number (Drop)	Froude Number (Drop)
0.171	0.075	57.5	.0755	5,150	.438	0.75	2.28
	0.085	57.5	.0755	5,150	.496	0.85	2.0
	0.040	82.1	.0775	7,550	.234	0.815	8.4
	0.0091	127.0	.087	13,100	.0532	0.513	105.0
	0.0064	137.0	.088	14,300	.0374	0.425	177.0
	0.070	71.0	.0765	6,370	.409	1.08	3.76
	0.0175	98.4	.080	9,360	.102	0.543	30.3
	0.0220	80.6	.077	7,380	.129	0.441	15.5
	0.0196	85.6	.078	7,940	.115	0.448	20.0
	0.0227	112.0	.082	10,900	.133	0.937	30.7
	0.0080	144.0	.0915	15,700	.0467	0.606	162.0
	0.030	72.5	.077	6,640	.175	0.486	9.23
	0.016	117.0	.084	11,700	.0935	0.736	49.1
	0.008	143.0	.092	15,670	.0467	0.604	161.0
	0.025	65.2	.0795	6,160	.146	0.339	9.25
	0.0191	93.7	.077	8,580	.112	0.518	24.2
	0.006	212.0	.047	24,450	.035	1.05	495.0
0.233	0.030	55.7	.0745	6,720	.129	0.282	5.26
	0.0122	93.0	.079	11,870	.0524	0.337	38.2
	0.0113	118.0	.083	15,800	.0485	0.53	70.1
	0.0076	115.0	.082	15,200	.0326	0.332	97.0
	0.0076	127.0	.0845	17,320	.0326	0.421	123.0
	0.0850	40.7	.074	4,860	.364	0.422	0.985
	0.0180	82.5	.0775	10,320	.0771	0.384	20.0
	0.0058	75.0	.0765	9,260	.0249	0.101	50.6
	0.0058	81.0	.077	10,090	.0249	0.119	59.6
	0.0108	80.2	.077	9,960	.0463	0.217	31.3
	0.0068	71.5	.076	8,780	.0292	0.107	39.0
	0.0070	85.0	.077	10,570	.030	0.157	54.3
	0.0022	93.8	.090	13,620	.00944	0.07	246.0

$$\text{Gravity Number} = n \sin \theta \rho_f \frac{2}{3} \frac{\delta_c^2}{\sigma}$$

$$\text{Weber Number} = \rho_v u_v^2 \delta_c / 2g_s \sigma$$

$$\text{Reynolds Number} = D u_v \rho_v / \mu_v$$

$$\text{Froude Number} = \frac{3}{2} \frac{\rho_v u_v^2}{\delta_c \rho_f n g_s}$$

ANGLE OF INCLINATION REQUIRED OF A PLATE TO CAUSE MOVEMENT OF A MERCURY DROP

FIGURE 16

GAS FLOW RATE REQUIRED TO CAUSE MOVEMENT OF A MERCURY DROP IN HORIZONTAL GLASS TUBES EXPRESSED IN TERMS OF A WEBER NUMBER

FIGURE 17

GAS FLOW RATE REQUIRED TO CAUSE MOVEMENT OF A MERCURY DROP IN INCLINED GLASS TUBES

FIGURE 18

For this case the left term is a nameless group representing the ratio of gravity to surface tension. This group could be called the Mansfield number since a drop on a vertical plate has the suggested form (see Figure 9).

When results are obtained from flow test in inclined tubes, both terms in Equation 8 are required for correlation. Figure 17 correlates the results for horizontal tubes. Note that the ordinate values represent four times the factor E_{σ} . The value of E_{σ} varies with δ_c/D since the curvature of the tube in relationship to the curvature of the drop affects the surface tension force and thus the value of E_{σ} . As the drop size becomes small the tube surface approaches that of a flat plate, and thus E_{σ} approaches a constant value as $\delta_c \ll D$.

The value for E_{σ} for the inclined plate is indicated in Figure 16. This value should compare with the E_{σ} obtained from the flow test results (Figure 17) for the condition of δ_c/D approaching zero. As can be seen, the agreement is good. Figure 18 shows the correlation for the inclined tubes and the values for E_{σ} are indicated.

A theoretical approach for determination of E_{σ} is available, if the analytical procedures of Bashforth and Adams (Ref. 6) are applied. They computed the entire shape of a mercury drop in a gravity field normal to the surface upon which the drop rested (see Figure 12). The combined effect of surface tension and gravity established the surface film curvature and thus the value of the contact angle and the contact (solid-liquid interface) surface area. This could be done in a gravity field of different orientation or for a given distribution of surface forces (pressure and shear). Figure 19 shows the hydrodynamic pressure distribution on a rigid sphere. This distribution of force can be used to calculate the deformation of a fluid drop. Reiteration would be required since the distorted drop would have an altered distribution of surface forces. The combined effect of surface shear and pressure forces is incorporated into the measured coefficient of drag (see Figures 10 and 11). When once the drop shape has been analytically established, E_{σ} can be determined by a line integral around the contact perimeter as shown in Figure 9 as follows:

$$E_{\sigma} = \frac{1}{\pi \delta_c} \int_0^S \sin \beta dS \quad \text{Equation 12}$$

when S is the perimeter length. The mathematical procedures appear difficult and the experimental techniques appear more fruitful.

Equation 8 together with the experimental values for E_{σ} can now be used to determine the value for δ_c in a combined gravity-flow field. The determined value for δ_c can be inserted into Equation 4 as one of the required quantities for computing gravity effects ($\Delta \Phi$) in condensers.

PRESSURE DISTRIBUTION AROUND A SPHERE AS MEASURED
BY FLACHSBART IN AIR (REFERENCE 12)

FIGURE 19

4.1.2 Determination of Condensing Surface Drop Population

The surface droplet population per unit area, N_S , is related to the condensation heat transfer coefficient h_c by the following equation:

$$h_c A (\Delta T) = N_S \frac{\pi \delta^2}{4} h_\delta A (\Delta T) \quad \text{Equation 13}$$

$$h_c = N_S \frac{\pi \delta^2}{4} h_\delta$$

Since the droplets are in contact with the wall, the drop heat transfer coefficient can be evaluated from the drop Nusselt number (see Ref. 3) Nu_δ where:

$$Nu_\delta = \frac{h_\delta \delta}{K_f} \quad \text{Equation 14}$$

Combining we have,

$$h_c = N_S \frac{\pi}{4} \delta Nu_\delta K_f \quad \text{Equation 15}$$

For a drop in contact with a metal having about the same conductivity as the liquid mercury, Nu_δ is 1 (see Ref. 3). Stainless steel and mercury have roughly the same thermal conductivity. At any instant there are droplets of all sizes on the heat transfer surface. Each drop grows due to condensation until it is sufficiently large to be entrained by the flowing gas. The size is denoted by δ_c . The δ in Equation 10 should be replaced by the average drop size as computed from the droplet Nusselt number as follows:

$$\text{Since } h_\delta = 2 h_{vf} \frac{\rho_f}{\Delta T} \frac{d\delta}{d\theta'} \quad (\text{Eq. 28 Ref. 3})$$

and

$$\frac{Nu_\delta K_f \Delta T}{2 h_{vf} \rho_f} d\theta' = \delta d\delta$$

Integrating,

$$\frac{Nu_\delta K_f \Delta T \theta'}{2 h_{vf} \rho_f} = \frac{\delta^2}{2} \quad \text{Equation 16}$$

The mean drop diameter for the growth period of θ'_c is,

$$\bar{\delta} = \int_0^{\theta'_c} \frac{\delta d\theta'}{\theta'_c} \quad \text{Equation 17}$$

Substituting Equation 16 into 17 we have,

$$\bar{\delta} = \frac{\text{const.}}{\theta'_c} \int_0^{\theta'_c} \theta'^{1/2} d\theta'$$

$$\text{where constant} = \sqrt{\frac{Nu_{\delta} K_f \Delta T}{h_{vf} \rho_f}}$$

integrating

$$\bar{\delta} = \frac{\text{const.}}{\theta'_c} \frac{2\theta_c'^{3/2}}{3}$$

$$\text{also constant} = \frac{\delta_c}{\theta_c'^{1/2}}$$

and

$$\bar{\delta} = \frac{2}{3} \frac{\delta_c}{\theta_c'^{1/2}} \frac{\theta_c'^{3/2}}{\theta_c'} = \frac{2}{3} \delta_c$$

therefore Equation 15 becomes:

$$h_c = N_S \frac{\pi}{6} \delta_c Nu_{\delta} K_f \quad \text{Equation 18}$$

The surface drop population N_S can either be established by inserting an experimentally determined value for h_c or else by postulating a judicious spacing and then checking the calculated value of h_c with experiment. The latter will be done. It should be recalled that the value for δ_c is computed by Equation 8 for a given gravity-flow field.

Assume that the minimum drop spacing (maximum value for N_S) on a surface is determined by the critical drop size δ_c (also the maximum size). Figure 20 shows this spacing with drops in different stages of growth. Any closer spacing would result in agglomeration and interference during growth. No appreciable amounts of agglomeration were observed during condenser tests in downward and in zero-gravity condensing; thus this appears to be

MERCURY DROPS IN VARIOUS STAGES OF GROWTH AT
 AN ASSUMED SPACING OF ONE DROP PER δ_c^2

FIGURE 20

a reasonable assumption. Therefore,

$$N_S = \frac{1}{\delta_c^2} \quad \text{Equation 19}$$

Equation 18 now becomes,

$$h_c = \frac{\pi}{6} \frac{1}{\delta_c} Nu_\delta K_f \quad \text{Equation 20}$$

This assumption can now be checked by dropwise condensation heat transfer coefficient data for mercury on vertical surfaces (see Figure 21). Applying Equation 8:

$u_v = 0$, $\sin \theta = 1$, $n = 1$, E_σ from plate tests (see Figure 16) is 0.0464 and the computed drop size δ_c , is 0.0402 inch; therefore, by Equation 20:

$$h_c = \frac{\pi}{6} \frac{12}{0.0402} \times 1 \times 8 = 1250 \text{ Btu/hr. ft}^2\text{°F}$$

where $Nu_\delta = 1$ $K_f = 8 \text{ Btu/hr-ft-°F}$

Since the measured h_c from Figure 21 are of the same order but generally greater than 1250, it can be concluded that the drop population N_S is somewhat greater than was postulated in Figure 20. The indicated close proximity of surface drops makes the application of a drop drag coefficient, $C_{d\delta}$, in the third term of Equation 4, questionable. It appears more plausible to apply the data of Nikuradse for artificially roughened pipes using sand particles bonded to the surface. Reference 13 thoroughly covers the subject of surface roughness. The roughness as constructed by Nikuradse was characterized by a single parameter, namely, the relative roughness (ratio of tube radius to sand grain size). Schlurhtiny introduced an additional parameter, namely, the roughness density (ratio of projected area of all roughness elements on the plane normal to the flow direction to the total area). Schlichting found that for small roughness densities the drag coefficient of the individual roughness elements could be applied. As the roughness density is increased, the flow resistance (tube friction factor) at first increases as is expected; but as the packing is made closer, the individual roughness elements become less effective and the flow resistance decreases. Schlichting found that for spherical roughness elements, the maximum resistance occurs at a roughness density of 0.4 (40 percent of surface is covered with spheres). The average roughness density for the spacing assumed in Figure 20 is,

$$\text{Mean roughness density} = \frac{\frac{\pi}{4} \left(\frac{2}{3} \delta_c\right)^2}{\delta_c^2} = \frac{\pi}{9} = 0.349$$

where $\bar{\delta} = 2/3 \delta_c$

EXPERIMENTAL MERCURY CONDENSING HEAT TRANSFER COEFFICIENT,
DROPPWISE CONDENSATION (REFERENCE 7)

FIGURE 21

Reference 13 contains data obtained from flow tests made on spheres having a roughness density equal to 0.349. In order for this data to be applicable, an equivalent sand roughness factor must be used so that the flow resistance or friction factor can be computed from the correlation of Nikuradse (see Figure 22)* which can be found in any standard text on fluid mechanics. This "equivalent sand roughness" factor is defined as the ratio of an equivalent sand grain size to the sphere diameter for producing the same flow resistance. Thus, the relative sand roughness is introduced into Nikuradse's correlation for computing the wall friction factor. From Reference 13, for a roughness density of 0.349 using spheres, the equivalent sand roughness factor is given as:

$$\frac{\delta_{\text{(sand)}}}{\delta_{\text{(sphere)}}} = \frac{1.56 \text{ cm}}{0.41 \text{ cm}} = 3.8$$

For mercury drops condensing the mean drop size is,

$$\bar{\delta} = 2/3 \delta_c,$$

$$\text{thus } \delta_{\text{(sand)}} = 3.8 \cdot 2/3 \delta_c = 2.54 \delta_c$$

and the equivalent sand roughness factor becomes

$$\frac{r_o}{\delta_{\text{(sand)}}} = \frac{r_o}{2.54 \delta_c} = 0.394 r_o / \delta_c = 0.197 \frac{D}{\delta_c} \quad \text{Equation 21}$$

As previously pointed out the measured condensing heat transfer coefficient, h_c , indicates drop populations N_g greater than $1/\delta_c^2$. Reference 13 shows that $\delta_{\text{(sand)}}$ approaches $\delta_{\text{(sphere)}}$ for the closest sphere spacing tested. Therefore, pending further test data, it is recommended that the factor $\delta_{\text{(sand)}}/\delta_{\text{(sphere)}}$ be taken as one.

Therefore,

$$r_o / \delta_{\text{(sand)}} = 3/4 D / \delta_c \quad \text{Equation 22}$$

where r_o is the pipe radius. Thus, the combined friction factor of mercury drop adhering to the heat transfer surface and the smooth surface between the drops can be taken into account by a friction factor from Nikuradse's correlation which we will denote as f_g . Figures 22 and 23 can be used to obtain this friction factor. As can be seen, f_g depends on the critical drop size δ_c (obtained from Equation 8) and the gas Reynolds number. The second and third term in Equation 4 can now be modified if we apply the droplet friction factor, f_g , thus:

* Reference 13, p. 141, Fig. 84.

FRICITION FACTOR FOR SMOOTH AND SAND ROUGHENED
PIPES AFTER NIKURADSE. THE DROPLET FRICTION FACTOR
FOR CONDENSING MERCURY HAS BEEN INCLUDED
(REFERENCE 12, FIGURE 84)

FIGURE 22

DROP FRICTION FACTOR VERSUS DROPLET SIZE. CURVE CONSTRUCTED
USING THE "FULL ROUGHNESS" DATA OF FIGURE 22

FIGURE 23

$$dp_{\delta}(\text{wall drops}) = \tau_w \frac{4 dL}{D} + N_s \frac{dL}{D} C_{d\delta} \pi \delta^2 \frac{\rho_v u_v^2}{2g}$$

and

$$dp_{\delta} = f_{\delta} \frac{dL}{D} \rho_v \frac{u_v^2}{2g_s} \quad \text{Equation 23}$$

thus Equation 4 can now be presented as:

$$\Phi = \frac{3}{2} \frac{1}{\delta_c} \frac{\rho_v}{\rho_f} \frac{1}{\epsilon} \left(\frac{1}{x} - 1 \right) C_{d\delta} \frac{D}{f} (1 - \epsilon)^2 + \frac{f_{\delta}}{f} \pm \frac{n \left(\frac{1}{x} - 1 \right) D}{\epsilon f u_v^2 / 2g_s} \quad \text{Equation 24}$$

where f_{δ} depends on D/δ_c and the gas Reynolds number. Note that according to Figure 22, as the grain size of the sand or the size of the mercury spheres approaches zero, f_{δ} approaches f and the factor f_{δ}/f becomes one. The drop friction factor is sensitive to gravity due to its connection with Equation 8 by way of the critical drop diameter.

4.1.3 Determination of the Slip Ratio

Both the liquid holdup term, R_L , and the slip ratio, ϵ , apply to the droplets in transit from the heating surface to the subcooler interface. The mean velocity attained by these moving drops must be computed from dynamic considerations. Since drops of all sizes are entrained due to the variable vapor velocity field encountered in constant diameter condensers, drops of different diameters and velocity are intermingled downstream from the condenser inlet. To apply a dynamic analysis to such a system would be prohibitive; however, a simplified approach can be devised if one postulates a mean drop history based on a single drop. The slip ratio computed for this drop will be assumed as the mean slip for the condenser. Figure 8 shows such a drop. Note that the drop originates at the mid-point of the condenser length. The local velocity causing entrainment is symbolized by u_e . Applying the momentum equation:

$$F = \frac{\pi \delta_c^3}{6} \frac{\rho_f}{g_s} \frac{d(u_v \epsilon)}{dt} \quad \text{Equation 25}$$

since

$$dt = dL / u_v \epsilon$$

and

$$F = C_{d\delta} \frac{\pi \delta_c^2}{4} \frac{\rho_v u_v^2}{2g_s} \pm \frac{\pi \delta_c^3}{6} \rho_f \frac{g}{g_s}$$

and

$$u_r = u_v - u_f = u_v (1 - \epsilon), \quad n = g/g_s$$

combining,

$$C_d \delta_c \frac{\pi \delta_c^2}{4} \rho_v \frac{u_v^2 (1 - \epsilon)^2}{2g_s} \pm \frac{\pi \delta_c^3}{6} \rho_f n = \frac{\pi \delta_c^3}{6} \frac{\rho_f}{g_s} u_v \epsilon \frac{d(u_v \epsilon)}{dL}$$

$$\frac{C_d \delta_c}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} u_v^2 (1 - \epsilon)^2 \pm n g_s = u_v \epsilon \frac{d(u_v \epsilon)}{dL}$$

$$\frac{C_d \delta_c}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} u_v^2 (1 - \epsilon)^2 \pm n g_s = u_v^2 \epsilon \frac{d\epsilon}{dL} + u_v \epsilon^2 \frac{du_v}{dL}$$

$$\left[\frac{C_d \delta_c}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{n g_s}{\epsilon^2 u_v^2} \right] dL = \frac{d\epsilon}{\epsilon} + \frac{du_v}{u_v}$$

Simplifying the mathematics by using average values for the variables, ϵ , u_v , and L and substituting finite differences for the differentials we have,

$$\left[\frac{C_d \delta_c}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{n g_s}{(\epsilon u_v)^2} \right] \Delta L = \frac{\Delta \epsilon}{\epsilon} + \frac{\Delta u_v}{u_v} \quad \text{Equation 26}$$

δ_c in Equation 26 is determined by Equation 8; thus δ_c is a function of n and u_v . The $\sin \theta$ can be introduced into Equation 26 as a multiplying factor for n thus accounting for tilt angles for condenser tubes during ground tests. The term ΔL represents the mean free path of the entrained mercury droplet. It is the average trajectory length between the two points at which the slip ratios, ϵ , are zero. The holdup, R_L , data in Reference 1 (Figure 9) affords a means of estimating the trajectory distance, ΔL . An analysis of this data indicated that ΔL equals the tube length when mercury is atomized at the entrance of the tube (test section) into flowing nitrogen gas.* The liquid hold-up measured by means of quick acting entrance and exit valves determines the slip ratio ϵ . Thus:

$$\Delta L = \frac{L}{2}$$

when L equals the total condenser length.

u_v in Equation 26 represents the average vapor velocity over the trajectory path. For a tube of constant diameter in which quality varies linearly along the tube axis we have:

* This will subsequently be substantiated by means of Figures 25 and 26.

$$u_v = u_e/2 \quad \text{and} \quad u_e = u_o/2$$

When: u_o is the condenser inlet velocity

or u_e is the critical entrainment velocity.

$$u_v = u_o/4 \quad (\text{diameter constant})$$

and

$$\Delta u_v = u_e - 0$$

$$\Delta u_v = u_o/2$$

For a tapered tube giving a constant vapor velocity:

$$u_v = u_o \quad \text{and} \quad \Delta u_v = 0$$

The effect of the axial vapor velocity gradient due to tube cross-section on the slip ratio is shown in Figure 24. As shown in Figure 24, it may be possible for droplets to have slip ratios in excess of unity during part of their trajectory for the constant diameter tubes. When the slip is greater than one, droplets do work on the gas which contributes a pressure recovery effect. Since the slip ratio is very near unity during this condition, and the droplet Froude number is small, drops become very sensitive to body forces. A constant diameter condenser tube may therefore have lower two-phase pressure drops but greater flow regime sensitivity to body forces than an equivalent tapered tube.

From a study of Figure 24, it is clear that the constant diameter tube has a greater slip ratio than the tapered tube at all points along the trajectory. Although the incremental slip increases, $\Delta \epsilon$, are larger in the early portions of the constant tube trajectory they become practically zero when ϵ exceeds unity. Thus, it is reasonable to assume that for the average values

$$\frac{\Delta \epsilon}{\epsilon} \text{ constant diameter} < \frac{\Delta \epsilon}{\epsilon} \text{ tapered}$$

The following approximations are therefore made.

$$\begin{aligned} \frac{\Delta \epsilon}{\epsilon} \text{ constant diameter} &\cong 0 \\ \frac{\Delta \epsilon}{\epsilon} \text{ tapered} &\cong 2 \end{aligned}$$

Equation 27

VARIATION OF LIQUID VELOCITY AND SLIP RATIO WITH TUBE LENGTH FOR MEAN DROP SELECTED FOR DYNAMIC ANALYSIS FOR TAPERED AND CONSTANT DIAMETER TUBES

FIGURE 24

Therefore, Equation 26 becomes:

$$\frac{C_{d\delta}}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{16 \sin \theta n g_s}{\epsilon^2 u_o^2} = \frac{4}{L} \quad \text{----- Equation 28 (D = constant)}$$

and

$$\frac{C_{d\delta}}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{\sin \theta n g_s}{\epsilon^2 u_o^2} = \frac{4}{L} \quad \text{----- Equation 29 (u_v = constant)}$$

Equations 28 and 29 allow one to compute the slip ratio, ϵ , in a gravity-flow field. The drop size is computed from Equation 8. The mechanics by which the drop coefficient of drag $C_{d\delta}$ is determined is in itself a profound treatise. Reference 4 states that, in general:

$$C_{d\delta} = f (NR_\delta, N\sigma_\delta, N_{wt\delta}, NA_\delta, \rho_v/\rho_f, \mu_v/\mu_f) \quad \text{Equation 30}$$

where

$$NR_\delta \quad - \text{Reynolds Number, } \frac{\rho_v u_v \delta}{\mu_v}$$

$$N\sigma_\delta \quad - \text{surface tension group, } \frac{g_s \sigma \delta \rho_v}{\mu_v^2}$$

$$N_{wt\delta} \quad - \text{gravity group } \delta \left[\frac{4}{3} \frac{g \rho_v (\rho_f - \rho_v)}{\mu_v^2} \right]^{1/3}$$

$$NA_\delta \quad - \text{acceleration group } \frac{\delta}{(\epsilon u_v)^2} \frac{d(\epsilon u_v)}{dt}$$

The complexity indicated by Equation 30 is attributed mainly to the undefined shape of the drop. The geometry is usually assumed as spherical and the groups $N\sigma_\delta$, $N_{wt\delta}$, and NA_δ adjust this assumption to the actual facts. As a general rule acceleration drag exists and is taken into account by NA_δ . For mercury drops the effect of acceleration on the drag coefficient is estimated to be small (based on Figure 3 of Reference 4). The distortion of the drop is the average shape about which the drop oscillates. These oscillations are started by the elongations caused during drop breakup. These oscillations also affect the coefficient of drag. Figure 10 shows a correlation from which the drag coefficient for liquid droplets can be estimated. The effect of distortion is taken into account by the group, $N\sigma_\delta$.

The validity of Equations 28 and 29 was tested by means of the mercury-nitrogen test apparatus to substantiate the assumed dynamics and trajectory of mercury drops, thus allowing one to apply Equations 28 and 29 to mercury condensers in a gravity-flow field with confidence. Mercury was introduced into the inlet of a glass tube by means of an atomizing nozzle. The slip ratio in Equations 28 and 29 was determined by measuring the liquid hold-up fraction by means of quick-acting valves on both ends of the four foot test section (see Reference 1). The relationship between the slip ratio, ϵ , and the hold-up liquid fraction, R_L is given by Equation 2g. The subsequent analysis shows the methods by which Equations 28 and 29 were tested.

Slip Ratio, ϵ , as Measured in Nitrogen-Mercury Test Rig

Since Equation 8 cannot be utilized for computing drop sizes from spray nozzles as is the case for the nitrogen-mercury test rig, a different means must be applied. At high relative velocities the effect of distortion may become so pronounced that large drops or filaments of liquid will break up. The speed of the liquid issuing from the atomizing nozzle usually ensures the secondary atomization of large drops that are initially formed. It is usually assumed that viscous drag is small, and that deformation is the result of interplay between surface tension which maintains the spherical shape and the dynamic vapor pressure ($\rho_v u_v^2 / 2g_s$) which is the deforming agent. The ratio of these quantities is called the Weber number and its value must be determined experimentally. Values ranging from eight to numbers near one are typical values as measured by experimenters. The criterion for drop stability is $N_W \leq 1$ according to Reference 14; therefore, a Weber number of one will be selected for estimating mercury drop sizes.

The mercury-nitrogen test data (Reference 1) encompasses a gas velocity range of 145 to 40 ft/sec. Since the tests were made in horizontal tube, $\sin \theta = 0$ in Equations 28 and 29. Thus we have for computing the slip ratio:

$$\frac{C_d g}{g_c} = \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 = \frac{4}{L} \quad \text{Equation 31}$$

Table III shows the computed results. The liquid hold-up ratio, R_L , can be computed from the slip ratio in Table III by Equation 2g. The results are plotted in Figure 25 as two curves compared with test data for measured liquid hold-up values. The agreement between the plotted curves based on Equation 31 and the test data is good.

Since Equation 31 gives the slip ratio, and a Weber number of one determines the drop size, Equation 24 can be used to compute Φ values for the mercury-nitrogen test section for the two extremes in gas velocity (145 to 40 ft/sec). The computed values should check the measured values. The subsequent analysis shows the methods by which Equation 24 is substantiated.

TABLE III

COMPUTED SLIP RATIOS FOR MERCURY - NITROGEN FLOW TEST

	Gas Velocity = 145 ft/sec Reynolds No. = 51,800	Gas Velocity = 40 ft/sec Reynolds No. = 7750
Drop Size, ft $N_w = 1$	1.24×10^{-3}	1.63×10^{-2}
Drop Reynolds Number	1160	4210
Surface Tension Group	6.72×10^5	8.85×10^6
Drop Coefficient of Drag, Figure 10	0.6	0.45
Slip Ratio ϵ by Equation 31	0.16	0.0438
$N_w = \frac{\rho_v u_v^2 \delta c}{2 g_s \sigma}$ $N_{R_\delta} = \frac{\delta c \rho_v u_v (1 - \epsilon)}{\mu_v}$ $N_{\sigma_\delta} = \frac{g_s \sigma \rho_v \delta c}{\mu_v^2}$ $\mu_v = \frac{L}{D} = \frac{4 \text{ ft}}{0.394 \text{ in.}}$ $\mu_v = 1.24 \times 10^{-5} \text{ lb/ft-sec. (nitrogen)}$ <p> $\sigma = 0.0324 \text{ lb/ft}$ $\rho_v = 0.08 \text{ lb/ft}^3$ $\rho_f = 800 \text{ lb/ft}^3$ assume $\epsilon \ll 1$ </p>		

EQUATION 31 COMPARED WITH HOLD-UP DATA OBTAINED FROM THE MERCURY-NITROGEN TEST RIG IN WHICH LIQUID MERCURY WAS INJECTED INTO FLOW GAS BY A NOZZLE. QUICK ACTING VALVES AT ENTRANCE AND EXIT OF TEST SECTION WERE USED TO ENTRAP THE FLOWING LIQUID.

FIGURE 25

Φ Values from Mercury-Nitrogen Test Rig Compared with Equation 24

Since no mercury droplets are generated on the glass surface by condensation, f_g/f in Equation 24 equals one. The gravity term can also be eliminated since the test section is horizontal; therefore, Equation 24 becomes:

$$\Phi = \frac{3}{2} \frac{1}{\delta_c} \frac{\rho_v}{\rho_f} \frac{1}{\epsilon} \left(\frac{1}{x} - 1 \right) C_{d\delta} \frac{D}{f} (1 - \epsilon)^2 + 1 \quad \text{Equation 32}$$

Combining Equation 32 and 31 and eliminating $(1 - \epsilon)^2$, we have:

$$\Phi = 8 \left(\frac{1}{x} - 1 \right) \frac{D}{L} \frac{\epsilon}{f} + 1 \quad \text{Equation 33}$$

for turbulent flow in smooth tubes $f = \frac{0.316}{Re_v^{1/4}}$,

$$\text{therefore, } \Phi = \frac{8}{0.316} Re_v^{1/4} \left(\frac{1}{x} - 1 \right) \frac{D}{L} \epsilon + 1 \quad \text{Equation 34}$$

Substituting the values in Table III into Equation 34, we have the two curves in Figure 26. The two curves represent the extremes in the gas velocities encountered during test. The agreement between test data and curves is reasonable.

4.2 Zero-Gravity Tests

A condenser tested in a gravity environment will not give true zero-gravity data no matter what tube orientation is used. In horizontal tubes gravity is still a factor in drop entrainment although its direction is normal to the flow direction. In addition, the pattern of the flowing droplets is affected by gravity. At high gas velocities the gravity effects can be minimized since the droplet Froude number becomes large.*

One of the purposes of the OFFBACE test is to obtain valid zero-gravity data for condensers. In this section the basic equations which have been developed from ground test experiments will be compared with zero gravity condenser data. The following analysis indicates the pertinent steps required to modify Equation 8 for correlation purposes:

$$\frac{\rho_v u_v^2}{2g_s} \pm n \sin \theta \rho_f \frac{2}{3} \delta_c = 4 \frac{\sigma}{\delta_c} E_\sigma$$

Constructing dimensionless groups,

$$\frac{1}{8} \frac{\rho_f}{\rho_v} \left(\frac{D u_v \rho_v}{\mu_v} \right)^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) \frac{\delta_c}{D} \pm n \sin \theta \frac{1}{6} \frac{\rho_f D^2}{\sigma} \left(\frac{\delta_c}{D} \right)^2 = E_\sigma \quad \text{Equation 35}$$

* Reference 1, page 28.

EQUATION 34 COMPARED WITH TEST DATA OBTAINED
FROM THE MERCURY-NITROGEN TEST RIG

FIGURE 26

For condensers in which the flow velocity may be a variable (constant diameter tubes) the average Reynolds number should be used, that is:

$$Re_o/2 = Re_v(\text{average})$$

therefore,

$$\frac{1}{32} \rho_f / \rho_v Re_o^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) \frac{\delta_c}{D} \pm n \sin \theta \frac{1}{6} \frac{\rho_f D^2}{\sigma} \left(\frac{\delta_c}{D} \right)^2 = E_\sigma \quad \text{Equation 36}$$

Equation 36 applies to condensers with tubes of constant diameter.

Equations 28 and 29 (for determining slip ratio ϵ) become:

$$\frac{C_{d\delta}}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{16 \sin \theta n g_s}{\epsilon^2 u_o^2} = \frac{4}{L} \quad \text{Equation 37} \\ (D = \text{constant})$$

$$\frac{C_{d\delta}}{\delta_c} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{\sin \theta n g_s}{\epsilon^2 u_o^2} = \frac{4}{L} \quad \text{Equation 38} \\ (u_v = \text{constant})$$

Constructing dimensionless groups,

$$\frac{D}{\delta_c} C_{d\delta} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{16 \sin \theta n}{\epsilon^2 Re_o^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right) = 4 \frac{D}{L} \quad \text{Equation 39}$$

and For $D = \text{constant}$

$$\frac{D}{\delta_c} C_{d\delta} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2 \pm \frac{\sin \theta n}{\epsilon^2 Re_o^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right) = 4 \frac{D}{L} \quad \text{Equation 40}$$

For $u_v = \text{constant}$

Since we are concerned at the moment with tubes of constant diameter, combine Equation 39 with 36, eliminating D/δ_c ; therefore:

$$\frac{\frac{3}{128} \text{Re}_o^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) C_{d\delta} \left(\frac{1}{\epsilon} - 1 \right)^2}{4 \frac{D}{L} \pm \frac{16 \sin \theta n}{\epsilon^2 \text{Re}_o^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right)} \pm \frac{n \sin \theta \left(\frac{\rho_f D^2}{\sigma} \right) \left[\frac{C_{d\delta} \frac{3}{4} \frac{\rho_v}{\rho_f} \left(\frac{1}{\epsilon} - 1 \right)^2}{4 \frac{D}{L} \pm \frac{16 \sin \theta n}{\epsilon^2 \text{Re}_o^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right)} \right]^2}{2}$$

= E_σ for $D = \text{constant}$.

Equation 41

Equation 41 allows computation of the slip ratio, ϵ , in a gravity-flow field for condensers of constant diameter.

Equation 24 (for computing Φ):

$$\Phi = \frac{3}{2} \frac{D}{\delta_c} \frac{\rho_v}{\rho_f} \left(\frac{1}{x} - 1 \right) \frac{C_{d\delta}}{f} \frac{(1-\epsilon)^2}{\epsilon} + \frac{f_\delta}{f} \pm \frac{n \left(\frac{1}{x} - 1 \right) D}{\epsilon f u_{v2}/2g_s} \quad \text{Equation 42}$$

Constructing dimensionless groups and including the $\sin \theta$ as a coefficient for n :

$$\Phi = \frac{3}{2} \frac{D}{\delta_c} \frac{\rho_v}{\rho_f} \left(\frac{1}{x} - 1 \right) \frac{C_{d\delta}}{f} \frac{(1-\epsilon)^2}{\epsilon} + \frac{f_\delta}{f} \pm \frac{2n \sin \theta \left(\frac{1}{x} - 1 \right)}{\epsilon f \text{Re}_v^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right)$$

Equation 43

For condensers in which the flow velocity is a variable (constant diameter tubes) use,

$$\text{Re}_o/2 = \text{Re}_v$$

and $\bar{x} = \frac{1}{2}$

also eliminating the term D/δ_c from Equation 43 by substituting Equation 39:

$$\Phi = \frac{2}{f} \epsilon \left[\frac{4D}{L} \pm \frac{16n \sin \theta}{\epsilon^2 \text{Re}_o^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right) \right] + \frac{f_\delta}{f} \pm \frac{8n \sin \theta}{\epsilon f \text{Re}_o^2} \left(\frac{g_s D^3 \rho_v^2}{\mu_v^2} \right)$$

Equation 44

Equation 44 can be used to compute Φ for a gravity-flow field (diameter constant) if the value for the slip ratio ϵ as computed from Equation 41 is substituted. Since f_δ is a function of δ_c/D and Re_v , Equation 36 can be utilized for computing f_δ (also see Figure 23).

For the case of zero gravity, Equations 41 and 44 can be greatly simplified. For $n = 0$, the following expressions are obtained:

Equation 41 becomes:

$$\frac{3}{128} \text{Re}_o^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) \frac{C_{d\delta}}{E_\sigma} \left(\frac{1}{\epsilon} - 1 \right)^2 = \frac{4D}{L} \quad \text{Equation 45}$$

Equation 44 becomes:

$$\Phi = \frac{2}{f} \epsilon \frac{4D}{L} + f_\delta / f \quad \text{Equation 46}$$

Equation 45 and 46 can be combined eliminating the slip ratio ϵ . The mathematics can be simplified somewhat by using the approximate expression:

$$\left(\frac{1}{\epsilon} - 1 \right)^2 = \frac{0.279}{\epsilon^{2.5}} \quad \text{Equation 47}$$

(See Figure 27 for the source of Equation 47). Equation 47 becomes,

$$\epsilon = \frac{(0.279)^{0.4}}{\left[\left(\frac{1}{\epsilon} - 1 \right)^2 \right]^{0.4}} \quad \text{Equation 48}$$

Substituting Equation 45 into Equation 48 we have:

$$\epsilon = \left[\frac{3}{128} \text{Re}_o^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) \frac{C_{d\delta}}{E_\sigma} \frac{1}{4} \frac{L}{D} \right]^{0.4} 0.279^{0.4} \quad \text{Equation 49}$$

Substituting Equation 49 into 46, we have:

$$\Phi = \frac{2}{f} 0.279^{0.4} \left[\frac{3}{128} \text{Re}_o^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) \frac{C_{d\delta}}{E_\sigma} \frac{1}{4} \frac{L}{D} \right]^{0.4} \frac{4D}{L} + \frac{f_\delta}{f}$$

and

$$\Phi = \frac{0.608}{f} \text{Re}_o^{0.8} \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right)^{0.4} \left(\frac{C_{d\delta}}{E_\sigma} \right)^{0.4} \left(\frac{D}{L} \right)^{0.6} + \frac{f_\delta}{f} \quad \text{Equation 50}$$

APPROXIMATION USED FOR COMBINING EQUATIONS 45 AND 46
(SEE EQUATION 48)

FIGURE 27

If we approximate the curve in Figure 23 by a straight line we have:

$$f_{\delta} = \frac{0.14}{(D/\delta_c)^{0.307}} \quad \text{Equation 51}$$

and Equation 51 substituted in Equation 36 results in:

$$\frac{1}{32} \rho_f / \rho_v \text{Re}_o^2 \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right) \left(\frac{f_{\delta}}{0.14} \right)^{3.25} \pm \frac{n \sin \theta}{6} \frac{\rho_f D^2}{\sigma} \left(\frac{f_{\delta}}{0.14} \right)^{6.5} = E_{\sigma} \quad \text{Equation 52}$$

which is an equation for computing a drop friction factor in a gravity-flow field if the Reynolds numbers are sufficiently large for the pipe walls to become fully "rough." For zero gravity Equation 52 becomes:

$$f_{\delta} = \frac{0.406}{\text{Re}_o^{0.614}} \left(E_{\sigma} \frac{\rho_v}{\rho_f} \frac{g_s \rho_f D \sigma}{\mu_v^2} \right)^{0.307} \quad \text{Equation 53}$$

Also using a "gas only" friction factor of:

$$f = \frac{0.316}{(\text{Re}_o/2)^{0.25}} \quad \text{Equation 54}$$

Substituting Equation 54 and 53 into Equation 50 we have:

$$\Phi = 1.62 \text{Re}_o^{1.05} \left(\frac{\mu_v^2}{g_s \rho_f D \sigma} \right)^{0.4} \left(\frac{C_{d\delta}}{E_{\sigma}} \right)^{0.4} \left(\frac{D}{L} \right)^{0.6} + \frac{1.08}{\text{Re}_o^{0.364}} \left(E_{\sigma} \frac{\rho_v}{\rho_f} \frac{g_s \rho_f D \sigma}{\mu_v^2} \right)^{0.307} \quad \text{Equation 55}$$

Certain limitations are associated with Equation 55. They are:

1. f_{δ}/f can never be less than one; therefore, the second term of Equation 55 can never be less than one.
2. The flow must be turbulent enough to produce full roughness on the tube walls.
3. Equation 55 applies only to zero-gravity conditions.

In order to compare Equation 55 with OFFBACE zero-gravity results, the following quantities can be substituted:

$$\mu_v = 0.367 \times 10^{-4} \text{ lb/ft-sec. (Hg vapor at 600°F)}$$

$$\rho_f = 800 \text{ lb/ft}^3$$

$$L = 1.67 \text{ ft}$$

$$D = 0.136 \text{ in.}$$

$$\sigma = 0.0324 \text{ lb/ft}$$

$$\frac{D \rho_f \sigma g_s}{\mu_v^2} = 7 \times 10^9$$

$$C_{d\delta} = 0.7 \text{ estimated from Figure 10 (See Appendix I for calculations)}$$

$$E_\sigma = 0.0464 \text{ from inclined plate experiment. See Figure 16.}$$

Equation 55 with the given values becomes:

$$\Phi = 2.75 \times 10^{-5} \text{ Re}_o^{1.05} + \frac{57.6}{\text{Re}_o^{0.364} v_v^{0.307}} \quad \text{Equation 56}$$

Equation 56 is plotted in Figure 28 and compared with the zero-gravity results obtained from Table IV. Since Φ cannot be less than one in zero gravity, the tabulated data (Table IV) indicating Φ less than one has been considered incorrect. A spread in data is to be expected and can be attributed to: (1) instrument error, (2) small pressure drops, and (3) unknown physics not taken into account by the mathematical analysis. Pressures were measured simultaneously during ground calibration by both manometer and transducer, and it was noted that a 0.1 psi error is possible. Thus, an error of 0.2 psi in the pressure drop is obtained, since:

$$\Phi = \frac{\Delta p + M}{\Delta p_v} \quad \text{Equation 57}$$

TABLE IV
CONDENSER FLIGHT TEST DATA

OFFBACE SERIES II FLIGHT TEST - FLIGHT "A" - (11-22-60)

Raw Data Primary Reductions

		Visicorder Deflections							Temperatures				Pressures				Flow					Accelerations								
		Channels																												
G	Loop	2	3	4	5	7	9	12	A-20	58	A-19	53	B-5	59	A-12	30	P ₃	P ₄	P ₅	P ₇	T ₃₀	$\sqrt{T_{30}}$	Nozzle .16 P ₇ $\sqrt{T_{30}}$	Trans. Flow lb/min	Quality	m _o lb/min	Fore & Aft	Vert. 0-1G	Vert. 0-5G	
		Loop Flow inches	P ₃ inches	P ₄ inches	P ₅ inches	P ₇ inches	Fore & Aft inches	Vert. 0-5G inches	T ₃ °F		T ₄ °F		T ₅ °F		T ₃₀ °F		psia	psia	psia	psia	°R									
1.16	1	1.73	4.04	4.44	5.70	1.74	.10	.16	160		165		80		1115		11.53	11.37	14.47	87	1575	39.7	.350	.318	100%	.334	.02	-	1.16	
2.55		1.92	4.34	4.70	-	1.78	.60	1.55	160		165		80		1115		12.27	12.11	-	88.5	1575	39.7	.357	.335		.346	.12	-	2.55	
0		1.80	4.09	4.60	5.10	1.70	-.11	-.98	160		165		80		1115		11.65	11.88	12.66	85	1575	39.7	.343	.325		.334	-.02	0	0	
1.06	2	1.92	3.44	3.98	4.46	1.74	-.10	.06	160		170		80		1120		10.03	10.39	11.27	87	1580	39.75	.350	.335		.343	-.02	-	1.06	
2.49		1.98	3.65	4.20	-	1.79	.15	1.49	160		170		80		1120		10.55	10.92	-	89	1580	39.75	.358	.342		.350	.03	-	2.49	
0		1.82	3.40	3.95	3.62	1.74	-.10	-.96	160		170		80		1120		9.90	10.30	9.17	87	1580	39.75	.350	.327		.339	-.02	0	0	
1.00	3	1.76	2.48	2.96	3.80	1.73	0	0	160		170		75		1125		7.60	7.87	9.60	86.5	1585	39.8	.348	.320		.334	0	-	1.00	
2.49		1.92	2.70	3.24	5.66	1.78	.35	1.44	160		170		75		1125		8.16	8.56	14.25	88.5	1585	39.8	.356	.335		.346	.07	-	2.44	
0		1.73	2.40	2.96	2.64	1.72	-.07	-.96	160		170		75		1125		7.40	7.87	6.75	86	1585	39.8	.346	.317		.332	.01	0	0	
1.05	4	1.82	2.39	2.90	3.72	1.74	-.10	.05	160		168		70		1120		7.40	7.71	9.40	87	1580	39.75	.350	.327		.339	-.02	-	1.05	
2.53		2.00	2.62	3.18	5.52	1.80	.50	1.53	160		168		70		1120		7.93	8.41	13.88	90	1580	39.75	.362	.343	.353	.10	-	2.53		
0		1.79	2.51	3.01	2.72	1.76	-.10	-.96	160		168		70		1120		7.68	8.00	6.90	88	1580	39.75	.354	.325	.340	-.02	0	0		
1.00	5	2.00	.82	1.26	1.86	1.79	0	0	150		160		70		1115		3.26	3.58	4.77	89	1575	39.7	.358	.343	.351	0	-	1.00		
2.58		2.14	.96	1.32	3.60	1.83	.35	1.58	150		160		70		1115		3.62	3.71	9.10	91.5	1575	39.7	.368	.356	.362	.07	-	2.58		
0		1.88	.78	1.28	.80	1.76	-.10	-.95	150		160		70		1115		3.13	3.65	2.17	88	1575	39.7	.354	.333	.344	-.02	0	0		
1.10	6	1.96	.84	1.26	1.91	1.78	-.10	.10	145		155		70		1110		3.20	3.56	4.90	88.5	1570	39.6	.358	.340	.349	-.02	-	1.10		
2.60		2.22	1.00	1.40	3.53	1.83	.30	1.60	145		155		70		1110		3.60	3.91	8.93	91.5	1570	39.6	.370	.364	.367	.06	-	2.60		
0		1.85	.85	1.34	.82	1.76	-.05	-.96	145		155		70		1110		3.22	3.76	2.16	88	1570	39.6	.356	.329	.343	-.10	0	0		
1.10	7	.50	2.78	3.10	3.98	1.15	0	.10	150		145		70		1090		8.17	8.07	10.04	57	1550	39.3	.232	.190	.211	0	-	1.10		
2.45		.48	2.70	3.12	-	1.12	.15	1.45	150		145		70		1090		7.98	8.08	-	56	1550	39.3	.228	.185	.207	.03	-	2.45		
0		.47	2.65	3.02	2.75	1.11	-.07	-.96	150		145		70		1090		7.83	7.84	7.00	56.5	1550	39.3	.230	.185	.208	.01	0	0		
1.00	8	.52	.41	.84	1.52	1.08	-.05	0	140		140		70		1080		2.05	2.40	3.91	54	1540	39.2	.220	.195	.208	-.01	-	1.00		
2.42		.50	.51	.92	3.10	1.10	.30	1.42	140		140		70		1080		2.30	2.62	7.85	55	1540	39.2	.224	.190	.207	.06	-	2.42		
0		.44	.39	.82	.42	1.06	-.10	-.96	140		140		70		1080		2.00	2.36	1.16	53	1540	39.2	.216	.175	.197	-.02	0	0		
1.05	9	3.78	3.21	3.66	4.38	2.50	-.05	.05	150		150		70		1060		9.25	9.42	11.04	125	1520	39.0	.513	.486	.500	-.01	-	1.05		
2.35		4.00	3.40	3.92	5.88	2.55	.45	1.35	150		150		70		1060		9.71	10.05	14.78	127	1520	39.0	.521	.500	.511	.09	-	2.35		
0		4.00	3.27	3.76	3.30	2.50	-.10	-.95	150		150		70		1060		9.37	9.68	8.85	125	1520	39.0	.513	.500	.507	-.02	0	0		
1.50	10	-	1.57	2.05	3.07	2.48	-.10	.50	145		150		80		1058		5.01	5.45	7.79	123	1518	39.0	.505	-	.505	-.02	-	1.50		
2.51		-	1.71	2.22	4.25	2.50	.33	1.51	145		150		80		1058		5.40	5.85	10.75	125	1518	39.0	.513	-	.513	.07	-	2.51		
0		-	1.58	2.08	1.46	2.44	-.06	-.95	145		150		80		1058		5.05	5.52	3.80	121.5	1518	39.0	.498	-	.498	-.01	0	0		

P₃ - P₇ - Subscripts indicate visicorder channels on which pressure was recorded.T₃ - T₇ - Temperatures were recorded at identical points as indicated by subscripts.T₃₀ - Temperature taken at nozzle inlet.

Four condenser tubes (3 glass: 0.137; 0.140; 0.135 in. I.D. - 1 stainless steel: 0.129 in. I.D.)

See Figure 5B for locations of subscripted variables.

TABLE IV (Continued)

OFFBACK SERIES II FLIGHT TEST - FLIGHT "A" - (11-22-60)

Intermediate Data Reduction

		Inlet Pressure Correction													Outlet Pressure Corrections										Δ P _{gf}			Δ P _{TP_f}		
G	Loop	P ₃ psia	v _{v3} ft ³ /lb	ṁ ₃ lb/min	ṁ _{A3} lb/min-in ²	$\frac{v_{v3} \dot{m}_{A3}^2}{2g}$ psi	P _o psia	v _{v0} ft ³ /lb	ṁ _{A3c} lb/min-in ²	$\frac{v_{v0} \dot{m}_{A3c}^2}{2g}$ psi	$\frac{v_{v0} \dot{m}_{A3c}^2}{2g P_o}$	$\frac{P_o}{P_{3c}}$	P _{3c} psia	v _{v3c} ft ³ /lb	P ₅ psia	Cond. Liq. Level inches	.491 gh psi	.736(1-g) psi	Liquid Head Corr. psi	P _{5C} psia	L _B inches	$\frac{P_{3c} + P_{5C}}{2}$ psia	$\bar{v}_v$ ft ³ /lb	Δ p _{gf} psi	P _{3c} - P _{5C} psi	M psi	Δ P _{TP_f} psi			
1.16 2.55 0	1	11.53 12.27 11.65	5.10 4.80 5.02	.084 .087 .084	5.83 6.04 5.83	.019 .019 .018	11.55 12.29 11.67	5.08 4.80 5.02	11.90 12.30 11.90	.078 .079 .077	.007 .006 .007	1.005 1.005 1.005	11.50 12.20 11.60	5.10 4.82 5.05	14.47 - 12.66	4.31 4.69 4.18	2.46 5.88 -	-.118 -1.141 .736	-2.58 -7.02 .736	11.89 - 13.40	18.69 18.31 15.32	11.70 - 12.50	5.03 - 4.71	.127 - .098	-.39 - -1.80	.156 .158 .155	- - -			
1.06 2.49 0	2	10.03 10.55 9.90	5.80 5.50 5.83	.086 .088 .085	5.97 6.11 5.90	.022 .022 .022	10.05 10.57 9.92	5.78 5.50 5.81	12.20 12.45 12.05	.093 .092 .091	.009 .009 .009	1.01 1.01 1.01	9.96 10.45 9.83	5.81 5.57 5.90	11.27 - 9.17	NR NR NR	- - -	.044 -1.098 .736	- - .736	- - 9.91	- - *18.5	- - 9.87	- - 5.85	- - .150	- - -.08	.187 .186 .185	- - .105			
1.00 2.49 0	3	7.60 8.16 7.40	7.45 7.00 7.65	.084 .087 .083	5.83 6.04 5.76	.027 .028 .027	7.63 8.19 7.43	7.43 6.98 7.63	11.90 12.30 11.75	.114 .114 .114	.015 .014 .015	1.01 1.01 1.01	7.55 8.11 7.35	7.50 7.02 7.72	9.60 14.25 6.75	4.56 4.69 1.00	2.24 5.74 -	- -1.060 .736	-2.24 -6.80 .736	7.36 7.45 7.49	18.44 18.31 18.50	7.46 7.78 7.42	7.61 7.32 7.62	.189 .193 .186	.19 .66 -.14	.230 .230 .230	.420 .890 .090			
1.05 2.53 0	4	7.40 7.93 7.68	7.65 7.17 7.40	.085 .088 .085	5.90 6.11 5.90	.029 .029 .028	7.43 7.96 7.71	7.63 7.17 7.38	12.05 12.45 12.05	.119 .120 .116	.016 .015 .015	1.01 1.01 1.01	7.35 7.88 7.64	7.72 7.22 7.42	9.40 13.88 6.90	4.06 4.19 .75	2.10 5.21 -	-.037 -1.127 .736	-2.14 -6.34 .736	7.26 7.54 7.64	18.94 18.81 18.75	7.31 7.71 7.64	7.78 7.38 7.41	.204 .205 .192	.09 .34 0	.242 .259 .233	.332 .599 .233			
1.00 2.58 0	5	3.26 3.62 3.13	16.25 14.70 16.80	.088 .091 .086	6.11 6.32 5.97	.066 .064 .065	3.33 3.69 3.20	15.80 14.50 16.50	12.45 12.90 12.20	.265 .261 .266	.080 .071 .083	1.10 1.085 1.105	3.03 3.40 2.90	17.30 15.60 18.00	4.77 9.10 2.17	4.06 4.25 .88	2.00 5.39 -	- -1.162 .736	-2.00 -6.55 .736	2.77 2.55 2.91	18.94 18.75 18.62	2.90 2.98 2.91	18.10 17.60 18.10	.506 .524 .479	.26 .85 -.01	.580 .560 .580	.840 1.410 .570			
1.10 2.60 0	6	3.20 3.60 3.22	16.50 14.80 16.40	.087 .092 .086	6.04 6.39 5.97	.065 .065 .063	3.27 3.67 3.29	16.20 14.50 16.10	12.30 13.05 12.20	.265 .267 259	.081 .073 .079	1.10 1.09 1.10	2.97 3.37 2.99	17.65 15.80 17.60	4.90 8.93 2.16	3.94 4.06 .75	2.13 5.19 -	-.073 -1.179 .736	-2.20 -6.37 .736	2.70 2.56 2.90	19.06 18.94 18.75	2.84 2.97 2.95	18.40 17.20 19.25	.506 .529 .460	.27 .81 .09	.577 .582 .566	.847 1.392 .656			
1.10 2.45 0	7	8.17 7.98 7.83	7.00 7.15 7.27	.053 .052 .052	3.68 3.61 3.61	.010 .010 .010	8.18 7.99 7.84	6.98 7.12 7.26	7.50 7.35 7.35	.042 .042 .042	.005 .005 .005	1.005 1.005 1.005	8.13 7.94 7.80	7.02 7.19 7.30	10.04 - 7.00	4.00 4.19 2.00	2.16 5.04 -	-.073 -1.068 .736	-2.23 -6.11 .736	7.81 - 7.74	19.00 18.81 17.50	7.97 - 7.77	7.15 - 7.32	.073 - .066	.32 - .06	.085 .084 .085	.405 - .145			
1.00 2.42 0	8	2.05 2.30 2.00	24.80 22.30 25.40	.052 .052 .049	3.61 3.61 3.40	.035 .031 .032	2.08 2.33 2.03	24.50 22.10 25.00	7.35 7.35 6.94	.143 .129 .130	.069 .055 .064	1.08 1.06 1.075	1.93 2.20 1.89	26.30 23.30 26.60	3.91 7.85 1.16	4.25 4.31 4.88	2.09 5.12 -	- -1.045 .736	-2.09 -6.17 .736	1.82 1.68 1.90	18.75 18.69 14.62	1.87 1.94 1.90	26.90 26.10 26.50	.260 .251 .178	.09 .52 -.01	.307 .272 .276	.397 .792 .266			
1.05 2.35 0	9	9.25 9.71 9.37	6.21 5.93 6.13	.125 .128 .127	8.69 8.90 8.83	.051 .050 .052	9.30 9.76 9.42	6.20 5.91 6.10	17.70 18.10 18.00	.210 .210 .214	.023 .022 .023	1.02 1.02 1.02	9.13 9.58 9.23	6.29 6.01 6.27	11.04 14.78 8.85	4.81 4.94 .75	2.48 5.70 -	-.037 -.994 .736	-2.52 -6.69 .736	8.52 8.09 9.59	18.19 18.06 18.75	8.83 8.84 9.41	6.50 6.50 6.11	.353 .366 .354	.61 1.49 -.36	.425 .425 .439	1.035 1.915 .079			
1.50 2.51 0	10	5.01 5.40 5.05	11.00 10.25 10.90	.126 .128 .125	8.75 8.90 8.69	.091 .088 .089	5.10 5.49 5.14	10.80 10.10 10.70	17.80 18.10 17.70	.370 .389 .362	.073 .071 .070	1.09 1.085 1.085	4.68 5.05 4.74	11.70 10.80 11.50	7.79 10.75 3.80	4.19 4.19 .88	3.08 5.16 -	-.368 -1.111 .736	-3.45 -6.27 .736	4.34 4.48 4.54	18.81 18.81 18.62	4.51 4.77 4.64	12.10 11.50 11.80	.689 .675 .657	.34 .57 .20	.800 .765 .780	1.140 1.335 .980			

P_{5C} - P_5 reading corrected

G = Mass Flow per Unit Area

*Estimated

TABLE IV (Continued)

OFFBACE SERIES II FLIGHT TEST - FLIGHT "A" - (11-22-60)

Plotted Data

G	Loop	T _{3c} °F	$\dot{m}_{3c}$ lb/min	μ_{3c} ($\times 10^6$) lb/ft-sec	Re _{3c}	1.25 $\left(\frac{\bar{v}_v}{10}\right)$	u _{3c} ft/sec	1.25 Re $\left(\frac{\bar{v}_v}{10}\right)$	Φ
1.16	1	650	.072	39.5	3410	.424	60.7	1440	-
2.55		-	.075	-	-	-	59.3	-	-
0		658	.072	40.0	3360	.390	60.0	1310	-
1.06	2	-	.074	-	-	-	71.0	-	-
2.49		-	.075	-	-	-	69.5	-	-
0		633	.073	38.5	3540	.512	71.2	1810	.70
1.00	3	610	.072	37.2	3620	.710	89.4	2570	2.22
2.49		613	.075	37.5	3740	.677	86.5	2540	4.60
0		608	.071	37.1	3580	.712	90.8	2550	.485
1.05	4	608	.073	37.1	3680	.730	93.1	2690	1.63
2.53		613	.075	37.5	3740	.684	90.0	2560	2.92
0		612	.073	37.3	3660	.687	89.5	2520	1.21
1.00	5	529	.075	32.7	4290	2.10	216	9010	1.66
2.58		532	.078	33.0	4420	2.03	201	8960	2.69
0		529	.074	32.7	4230	2.10	220	8900	1.19
1.10	6	528	.075	32.7	4290	2.14	217	9190	1.67
2.60		536	.079	33.1	4460	1.97	206	8800	2.64
0		531	.074	33.0	4200	1.98	215	8320	1.42
1.10	7	616	.045	37.6	2240	.657	52.6	1470	5.55
2.45		-	.045	-	-	-	52.8	-	-
0		614	.045	37.6	2240	.677	53.6	1520	2.20
1.00	8	499	.045	31.1	2700	3.44	193	9300	1.53
2.42		502	.045	31.3	2690	3.32	171	8940	3.16
0		500	.042	31.2	2520	3.38	185	8510	1.49
1.05	9	624	.107	38.0	5270	.584	111	3070	2.94
2.35		624	.110	38.0	5420	.584	109	3160	5.24
0		629	.109	38.3	5330	.540	113	2880	.223
1.50	10	566	.108	34.9	5800	1.27	208	7370	1.66
2.51		572	.110	35.1	5870	1.19	196	7450	1.97
0		569	.107	35.0	5720	1.23	204	7050	1.49

TABLE IV (Continued)

OFFBACE SERIES II FLIGHT TEST - FLIGHT "B" - (11-29-60)

Raw Data Primary Reductions

		Visicorder Deflections Channels							Temperatures				Pressures				Flow					Accelerations							
G	Loop	2	3	4	5	7	9	12	A-20	58	A-19	53	B-5	59	A-12	30	P ₃	P ₄	P ₅	P ₇	T ₃₀	$\sqrt{T_{30}}$	Nozzle .16 P ₇	Trans. Flow	Quality	m _o	Fore & Aft	Vert. 0-1G	Vert. 0-5G
		Loop Flow	P ₃	P ₄	P ₅	P ₇	Fore & Aft	Vert. 0-5G	T ₃		T ₄		T ₅		T ₃₀		psia	psia	psia	psia	°R		$\frac{.16 P_7}{\sqrt{T_{30}}}$	lb./min		lb./min			
		inches	inches	inches	inches	inches	inches	inches	°F		°F		°F		°F		psia	psia	psia	psia				lb./min		lb./min			
1.05	1	-	3.92	4.13	4.72	1.63	.05	1.05	137		140		60		1040		10.77	10.54	11.89	81.5	1500	38.7	.337	-		.329	.01	-	1.05
2.53		-	4.16	4.53	6.64	2.01	.32	2.53	137		140		60		1040		11.38	11.54	16.68	100.0	1500	38.7	.414	-		.400	.06	-	2.53
0		1.80	3.97	4.20	3.69	1.62	0	0	137		140		60		1040		10.90	10.70	9.29	81.5	1500	38.7	.337	.320		.329	0	0	0
1.03	2	1.90	3.87	4.15	4.70	1.60	0	1.03	140		140		60		1050		10.70	11.58	11.81	80.0	1510	38.85	.330	.333		.332	0	-	1.03
2.60		2.00	4.30	4.60	-	1.70	.25	2.60	140		140		60		1050		11.80	11.69	-	85.0	1510	38.85	.350	.343		.347	.06	-	2.60
0		1.80	4.10	4.40	3.80	1.60	0	0	140		140		60		1050		11.30	11.20	9.55	80.0	1510	38.85	.330	.322		.326	0	0	0
1.00	3	1.80	2.45	2.75	3.10	1.60	0	1.00	140		140		62		1060		7.17	7.75	7.83	80.0	1520	39.0	.328	.322		.325	0	-	1.00
2.60		2.05	2.80	3.10	5.30	1.65	.35	2.60	140		140		62		1060		8.05	8.00	13.30	82.5	1520	39.0	.339	.348		.344	.09	-	2.60
0		1.80	2.57	2.87	2.20	1.58	0	0	140		140		62		1060		7.45	7.41	5.58	79.0	1520	39.0	.324	.322		.323	0	0	0
1.00	4	1.80	2.50	2.80	3.20	1.60	.05	1.00	142		148		65		1070		7.34	7.30	8.07	80.0	1530	39.1	.328	.322		.325	.01	-	1.00
2.50		1.97	2.78	3.10	5.15	1.65	.40	2.50	142		148		65		1070		8.05	8.05	12.92	82.5	1530	39.1	.338	.341		.340	.08	-	2.50
0		1.80	2.56	2.88	2.20	1.60	0	0	142		148		65		1070		7.50	7.50	5.58	80.0	1530	39.1	.328	.322		.325	0	0	0
1.00	5	1.97	.90	1.28	1.56	1.65	.08	1.00	140		150		70		1080		3.26	3.55	4.02	82.5	1540	39.2	.337	.341	≈ 100%	.339	.02	-	1.00
2.50		2.11	1.10	1.47	3.46	1.70	.32	2.50	140		150		70		1080		3.76	4.03	8.78	85.0	1540	39.2	.347	.354		.351	.06	-	2.50
0		1.87	.91	1.28	.50	1.63	0	0	140		150		70		1080		3.29	3.55	1.40	81.5	1540	39.2	.333	.332		.333	0	0	0
1.00	6	1.85	.80	1.15	1.30	1.62	.08	1.00	135		140		70		1080		2.92	3.18	3.37	81.5	1540	39.2	.333	.330		.332	.02	-	1.00
2.50		2.00	1.00	1.35	3.10	1.65	.45	2.50	135		140		70		1080		3.44	3.67	7.87	82.5	1540	39.2	.337	.344		.341	.09	-	2.50
0		1.80	.83	1.18	.30	1.60	0	0	135		140		70		1080		3.00	3.23	.88	80.0	1540	39.2	.327	.322		.325	0	0	0
1.15	7	4.20	3.92	4.28	4.72	2.30	.10	1.15	138		148		70		1090		10.78	10.96	11.90	115.0	1550	39.4	.467	.511		.489	.02	-	1.15
2.40		4.20	4.25	4.60	6.45	2.33	.48	2.40	138		148		70		1090		11.61	11.70	16.41	116.0	1550	39.4	.472	.511		.492	.10	-	2.40
0		4.00	3.95	4.30	3.60	2.25	0	0	138		148		70		1090		10.87	10.97	9.10	112.0	1550	39.4	.455	.484		.470	0	0	0
1.05	8	3.96	4.03	4.40	4.75	2.30	0	1.05	140		147		70		1085		11.12	11.21	11.97	115.0	1545	39.3	.468	.497		.483	0	-	1.05
2.60		4.45	4.65	5.04	6.75	2.40	.15	2.26	140		147		70		1085		12.65	12.79	16.97	120.0	1545	39.3	.490	.525		.508	.03	-	2.26
0		4.20	4.25	4.60	3.90	2.30	0	0	140		147		70		1085		11.65	11.73	9.85	115.0	1545	39.3	.468	.511		.490	0	0	0
1.40	9	4.45	3.60	3.95	4.60	3.00	-.13	1.40	140		145		75		1070		10.05	10.12	11.62	150.0	1530	39.1	.614	.525		.570	-.03	-	1.40
2.32		4.45	3.57	3.92	5.52	2.57	.26	2.32	140		145		75		1070		9.95	10.05	13.89	128.5	1530	39.1	.526	.525		.526	.07	-	2.32
0		4.20	3.17	3.57	2.75	2.45	0	0	140		145		75		1070		8.95	9.18	7.02	122.0	1530	39.1	.500	.511		.506	0	0	0

p₃ - p₇ - Subscripts indicate visicorder channels on which pressure was recorded.T₃ - T₇ - Temperatures were recorded at identical points as indicated by subscripts.T₃₀ - Temperature taken at nozzle inlet.

TABLE IV (Continued)

OFFFACE SERIES II FLIGHT TEST - FLIGHT "B" - (11-29-60)

Intermediate Data Reduction

		Inlet Pressure Correction													Outlet Pressure Corrections							ΔP_{gf}			ΔP_{TPf}		
G	Loop	P_3 psia	v_{v3} ft ³ /lb	$\dot{m}_3$ lb/min	$\dot{m}_3$ lb/min-in ²	$\frac{v_{v3} \dot{m}_3^2}{2g}$ psi	P_o psia	v_{v0} ft ³ /lb	$\dot{m}_{A3c}$ lb/min-in ²	$\frac{v_{v0} \dot{m}_{A3c}^2}{2g}$ psi	$\frac{v_{v0} \dot{m}_{A3c}^2}{2g P_o}$	$\frac{P_o}{P_{3c}}$	P_{3c} psia	v_{v3c} ft ³ /lb	P_5 psia	Cond. Liq. Level inches	.491 gh psi	1.72(1-g) psi	Liquid Head Corr. psi	P_{5C} psia	L_B inches	$\frac{P_{3c} + P_{5C}}{2}$ psia	$\bar{v}_v$ ft ³ /lb	ΔP_{gf} psi	$P_{3c} - P_{5C}$ psi	M psi	ΔP_{TPf} psi
1.05 2.53 0	1	10.77 11.38 10.90	5.45 5.20 5.35	.082 .100 .082	5.70 6.95 5.70	.019 .027 .019	10.79 11.41 10.92	5.35 5.20 5.40	11.60 14.15 11.60	.078 .112 .079	.007 .010 .007	1.005 1.01 1.005	10.71 11.30 10.86	5.47 5.17 5.37	11.89 16.60 9.29	2.31 2.31 1.50	1.09 2.87 -	-.09 -2.63 1.72	-1.18 -5.50 1.72	10.71 11.18 11.01	18.69 18.69 19.50	10.71 11.24 10.94	5.42 5.20 5.35	.130 .185 .134	0 .12 -.15	.159 .224 .156	.159 .344 .01
1.03 2.60 0	2	10.70 11.80 11.30	5.50 5.00 5.25	.083 .087 .082	5.77 6.05 5.70	.020 .020 .018	10.72 11.82 11.32	5.50 5.00 5.20	11.70 12.30 11.60	.081 .082 .076	.008 .007 .007	1.005 1.005 1.005	10.68 11.75 11.27	5.50 5.00 5.22	11.81 - 9.55	2.31 2.50 1.50	1.17 3.20 -	-.05 -2.75 1.72	-1.22 -5.95 1.72	10.59 - 11.27	18.69 18.69 19.50	10.64 - 11.27	5.47 - 5.19	.133 - .130	.09 - 0	.163 .163 .152	.253 - .152
1.00 2.60 0	3	7.17 8.05 7.45	7.90 7.15 7.65	.081 .083 .081	5.63 5.77 5.63	.027 .026 .026	7.20 8.08 7.48	7.90 7.15 7.60	11.45 11.70 11.45	.112 .106 .108	.016 .013 .014	1.01 1.01 1.01	7.13 8.00 7.41	8.00 7.18 7.72	7.83 13.30 5.58	2.31 2.31 1.00	1.13 2.95 -	- -2.75 1.72	-1.13 -5.10 1.72	6.70 8.20 7.30	18.69 18.69 20.00	6.92 8.10 7.36	8.18 7.04 7.72	.191 .171 .193	.43 -.20 .11	.226 .212 .218	.656 .012 .328
1.00 2.50 0	4	7.34 8.05 7.50	7.70 7.15 7.60	.081 .085 .081	5.63 5.90 5.63	.026 .027 .026	7.37 8.08 7.53	7.70 7.10 7.30	11.45 12.00 11.45	.109 .110 .103	.015 .014 .014	1.01 1.01 1.01	7.30 8.00 7.45	7.80 7.18 7.42	6.07 12.92 5.58	2.19 2.19 1.00	1.08 2.69 -	- -2.58 1.72	-1.08 -5.27 1.72	6.99 7.65 7.30	18.81 18.81 20.00	7.15 7.83 7.38	7.93 7.29 7.71	.186 .188 .193	.31 .35 .15	.221 .224 .210	.531 .574 .360
1.00 2.50 0	5	3.26 3.76 3.29	16.3 14.2 16.1	.085 .088 .083	5.90 6.11 5.77	.061 .057 .058	3.32 3.83 3.35	15.8 14.0 15.8	12.00 12.45 11.70	.246 .234 .234	.074 .061 .070	1.09 1.07 1.08	3.04 3.58 3.10	18.3 15.6 18.1	4.02 8.78 1.40	2.44 2.56 1.38	1.20 3.14 -	- -2.58 1.72	-1.20 -5.72 1.72	2.82 3.06 3.12	18.56 18.44 19.62	2.93 3.32 3.11	17.90 15.90 16.90	.456 .434 .433	.22 .52 -.02	.570 .522 .535	.790 1.042 .515
1.00 2.50 0	6	2.92 3.44 3.00	17.9 15.3 17.5	.083 .085 .081	5.77 5.90 5.63	.064 .058 .060	2.98 3.50 3.06	17.5 15.1 17.2	11.70 12.00 11.45	.259 .235 .244	.087 .067 .080	1.11 1.08 1.10	2.68 3.24 2.78	20.8 18.6 20.0	3.37 7.87 .88	1.81 2.06 .75	.89 2.53 -	- -2.58 1.72	-.89 -5.11 1.72	2.48 2.76 2.60	19.19 18.94 20.05	2.58 3.00 2.69	20.10 17.50 19.40	.503 .455 .486	.20 .48 .18	.615 .579 .566	.815 1.059 .746
1.15 2.40 0	7	10.78 11.61 10.87	5.40 5.60 5.40	.122 .123 .118	8.49 8.55 8.20	.042 .044 .039	10.82 11.65 10.91	5.40 5.05 5.35	17.30 17.40 16.70	.175 .165 .161	.016 .014 .015	1.01 1.01 1.01	10.71 11.55 10.80	5.42 5.12 5.42	11.90 16.41 9.10	1.94 2.06 1.25	1.095 2.43 -	-.26 -2.41 1.72	-1.36 -5.84 1.72	10.54 10.57 10.82	19.06 18.94 19.75	10.63 10.56 10.81	5.43 5.50 5.38	.295 .300 .282	.17 -.02 -.02	.351 .335 .326	.521 .315 .306
1.05 2.26 0	8	11.12 12.65 11.65	5.30 4.70 5.10	.121 .127 .123	8.40 8.83 8.55	.040 .040 .040	11.16 12.69 11.69	5.25 4.70 5.05	17.10 18.00 17.40	.166 .165 .165	.015 .013 .014	1.01 1.01 1.01	11.00 12.56 11.57	5.35 4.75 5.10	11.97 16.97 9.85	1.81 2.06 1.25	.935 2.29 -	-.09 -2.17 1.72	-1.03 -4.46 1.72	10.94 12.51 11.57	19.19 18.94 19.75	10.97 12.54 11.57	5.30 4.69 5.07	.284 .274 .289	.06 .05 0	.338 .332 .334	.398 .382 .334
1.40 2.32 0	9	10.05 9.95 8.95	5.80 5.85 6.50	.143 .132 .127	9.95 9.18 8.83	.062 .053 .054	10.11 10.00 9.00	5.75 5.80 6.45	20.20 18.70 18.00	.254 .220 .226	.024 .022 .025	1.02 1.02 1.02	9.94 9.80 8.82	5.91 5.91 6.63	11.62 13.89 7.02	2.06 2.06 .38	1.42 2.35 -	-.69 -2.27 1.72	-2.11 -4.62 1.72	9.51 9.27 8.74	18.94 18.94 20.62	9.73 9.54 8.78	5.93 6.05 6.51	.437 .382 .415	.43 .53 .08	.521 .447 .464	.951 .977 .544

p_{5C} - p_5 reading corrected

TABLE IV (Continued)

OFFBACK SERIES II FLIGHT TEST - FLIGHT "B" - (11-29-60)

Plotted Data

G	Loop	T _{oF} _{3c}	m _{3c} lb/min	μ_{3c} ($\times 10^6$) lb/ft-sec	Re _{3c}	$\left(\frac{\bar{v}_v}{10}\right)^{1.25}$	u _{3c} ft/sec	$Re\left(\frac{\bar{v}_v}{10}\right)^{1.25}$	Φ
1.05 2.53 0	1	643 647 644	.070 .086 .070	39.1 39.3 39.1	3340 4100 3340	.465 .442 .457	63.5 73.2 62.3	1550 1810 1530	1.22 1.86 .075
1.03 2.60 0	2	643 - 647	.071 .076 .070	39.1 - 39.3	3400 - 3330	.470 - .440	64.4 61.5 60.6	1600 - 1465	1.90 - 1.17
1.00 2.60 0	3	604 616 608	.069 .071 .069	36.9 37.6 37.1	3500 3480 3480	.778 .644 .722	91.7 84.0 88.5	2720 2240 2520	3.43 .070 1.70
1.00 2.50 0	4	606 614 619	.069 .073 .069	37.0 37.5 37.7	3490 3640 3420	.748 .674 .722	89.5 86.2 85.0	2610 2450 2470	2.86 3.05 1.87
1.00 2.50 0	5	531 540 536	.073 .076 .071	33.0 33.4 33.2	4140 4250 4000	2.07 1.79 1.93	220.0 194 212	8570 7610 7720	1.73 2.40 1.19
1.00 2.50 0	6	521 530 524	.071 .073 .069	32.4 33.0 32.5	4100 4140 3970	2.39 2.01 2.29	243 224 229	9800 8320 9100	1.62 2.33 1.53
1.15 2.40 0	7	642 645 643	.105 .106 .101	39.1 39.3 39.1	5020 5050 4840	.466 .474 .460	93.9 89.1 90.5	2340 2390 2220	1.77 1.05 1.08
1.05 2.26 0	8	644 657 649	.104 .109 .106	39.2 40.0 39.5	4960 5100 5020	.452 .388 .428	91.5 85.5 88.8	2240 1980 2150	1.40 1.39 1.15
1.40 2.32 0	9	631 630 623	.123 .113 .109	38.5 38.4 38.0	5980 5500 5370	.520 .534 .584	119 111 119	3110 2930 3130	2.17 2.56 1.31

TABLE IV (Continued)

OFFFACE SERIES III FLIGHT TEST - FLIGHT "A" - (12-9-60)

Raw Data Primary Reductions

		Visicorder Deflections Channels						Temperatures				Pressures				Flow									
G *	Loop	Loop Flow	P ₃	P ₄	P ₅	P ₇	Vert. 0-5G	A-20	58	A-19	53	B-5	59	A-12	30	P ₃	P ₄	P ₅	P ₇	T ₃₀	√T ₃₀	Nozzle .16 P ₇ √T ₃₀	Trans. Flow	Quality	Select Flow
								T ₃ °F	T ₄ °F	T ₅ °F	T ₃₀ °F	psia	psia	psia	psia										
1.00	1						CHANNEL OFF	90		90		65		585											
0								90		90		65		585											
								90		90		65		585											
1.00	2							90		90		65		555											
0								90		90		65		555											
								90		90		65		555											
1.00	3	2.07	5.40	-	6.07	1.60		100		100		65		1061		13.86	-	15.24	80	1521	39.0	.328	.317		.323
		2.17	5.45	-	-	1.62		100		100		65		1061		14.00	-	-	81	1521	39.0	.332	.325		.329
0		1.90	5.37	-	4.78	1.60		100		100		65		1061		13.80	-	12.02	80	1521	39.0	.328	.304		.316
1.00	4	2.10	5.42	-	6.22	1.60		100		100		65		1063		13.93	-	15.62	80	1523	39.0	.328	.320		.324
		2.19	5.47	-	-	1.60		100		100		65		1063		14.05	-	-	80	1523	39.0	.328	.325		.327
0		2.01	5.37	-	4.80	1.60		100		100		65		1063		13.80	-	12.06	80	1523	39.0	.328	.312		.320
1.00	5	1.97	4.05	4.35	4.46	1.51		100		100		70		1065		10.55	10.91	11.25	75.5	1525	39.0	.310	.310		.310
		2.08	4.56	4.85	6.77	1.58		100		100		70		1065		11.81	12.18	17.00	79	1525	39.0	.324	.318		.321
0		1.90	4.10	4.33	3.40	1.52		100		100		70		1065		10.68	10.89	8.58	76.0	1525	39.0	.312	.305		.309
1.00	6	2.17	4.30	4.60	4.57	1.60		105		105		70		1074		11.25	11.55	11.50	80	1534	39.1	.328	.325		.327
		2.20	4.53	4.87	6.20	1.61		105		105		70		1074		11.83	12.20	15.55	81	1534	39.1	.332	.325		.329
0		2.05	4.20	4.47	3.40	1.60		105		105		70		1074		11.00	11.21	8.58	80	1534	39.1	.328	.315		.322
1.00	7	2.21	3.22	3.54	3.52	1.60		100		100		70		1080		8.48	8.94	8.90	80	1540	39.2	.326	.326		.326
		2.42	3.60	3.95	5.20	1.62		100		100		70		1080		9.42	9.95	13.05	81	1540	39.2	.331	.340		.336
0		2.15	3.26	3.55	2.47	1.60		100		100		70		1080		8.56	8.95	6.28	80	1540	39.2	.326	.322		.324
1.00	8	2.10	3.52	3.83	3.90	1.60		105		105		70		1080		9.30	9.65	9.81	80	1540	39.2	.326	.320		.323
		2.31	3.69	3.98	5.60	1.60		105		105		70		1080		9.75	10.05	14.05	80	1540	39.2	.326	.332		.329
0		2.10	3.43	3.77	2.70	1.60		105		105		70		1080		9.09	9.52	6.85	80	1540	39.2	.326	.320		.323
1.00	9	4.30	5.60	-	-	2.13		100		100		70		1080		14.38	-	-	106	1540	39.2	.433	.444		.439
		4.50	5.60	-	-	2.17		100		100		70		1080		14.38	-	-	108	1540	39.2	.441	.456		.449
0		4.10	5.60	-	6.20	2.08		100		100		70		1080		14.38	-	15.60	104	1540	39.2	.425	.435		.430
1.00	10	3.70	5.32	-	5.57	2.02		100		100		70		1080		13.67	-	16.53	101	1540	39.2	.412	.415		.414
		4.10	5.37	-	-	2.05		100		100		70		1080		13.80	-	-	102	1540	39.2	.417	.435		.426
0		3.52	5.30	-	4.60	2.00		100		100		70		1080		13.65	-	11.60	100	1540	39.2	.408	.403		.406
1.00	11																								
0																									
1.00	12						V																		
0																									

* G Meter Not Operating - Estimated Value From Air Force Meter Located In Condenser. Two glass condenser tubes (0.140, 0.137 in. ID)

P₃ - P₇ - Subscripts indicate visicorder channels on which pressure was recorded.

T₃ - T₇ - Temperatures were recorded at identical points as indicated by subscripts.

See Figure 5B for locations of subscripted variables.

T₃₀ - Temperature taken at nozzle inlet.

TABLE IV (Continued)

OFFBASE SERIES III FLIGHT TEST - FLIGHT "A" - (12-9-60)

Intermediate Data Reduction

G *	Loop	Inlet Pressure Correction											Outlet Pressure Corrections										ΔP_{gf}		ΔP_{TPf}		
		P_3 psia	v_{v3} ft ³ /lb	$\dot{m}_3$ lb/min	$\dot{m}_3$ lb/min	$\frac{v_{v3} \dot{m}_3^2}{2g}$ psi	P_o psia	v_{v0} ft ³ /lb	$\dot{m}_{A_{3c}}$ b/min-in ²	$\frac{v_{v0} \dot{m}_{A_{3c}}^2}{2g}$ psi	$\frac{\dot{m}_{A_{3c}}^2}{2g P_o}$	$\frac{P_o}{P_{3c}}$	P_{3c} psia	v_{v3c} ft ³ /lb	P_5 psia	Cond. Liq. Level inches	.491 gh psi	1.72(1-g) psi	Liquid Head Corr. psi	P_{5C} psia	L_B inches	$\frac{P_{3c} + P_{5C}}{2}$ psia	$\bar{v}_v$ ft ³ /lb	ΔP_{gf} psi	$P_{3c} - P_{5C}$ psi	M psi	ΔP_{TPf} psi
1.00	3	13.86	4.31	.162	11.30	.059	13.92	4.28	22.90	.242	.017	1.015	13.75	4.34	15.24	1.813	.89	-	-.89	14.35	19.19	14.05	4.23	.405	-.60	.492	-
2.60		14.00	4.27	.164	11.40	.060	14.06	4.22	23.20	.245	.017	1.015	13.85	4.30	-	1.750	2.24	-2.75	-4.99	-	19.25	-	-	-	-	.500	-
0		13.80	4.32	.137	9.52	.042	13.84	4.30	18.65	.162	.012	1.01	13.70	4.38	12.02	-	-	1.72	1.72	13.74	16.00	13.72	4.34	.230	-.04	.329	.289
1.00	4	13.93	4.29	.162	11.30	.059	13.99	4.27	22.90	.242	.017	1.015	13.80	4.31	15.62	1.688	.83	-	-.83	14.79	19.31	14.30	4.18	.403	-.99	.488	-
2.60		14.05	4.27	.164	11.40	.060	14.11	4.21	23.20	.245	.017	1.015	13.90	4.29	-	1.688	2.16	-2.75	-4.91	-	19.31	-	-	-	-	.499	-
0		13.80	4.32	.143	9.95	.046	13.85	4.30	19.30	.173	.013	1.01	13.70	4.36	12.06	-	-	1.72	1.72	13.78	16.50	13.74	4.33	.253	-.08	.351	.271
1.00	5	10.55	5.51	.155	10.80	.070	10.62	5.50	22.00	.287	.027	1.025	10.40	5.60	11.25	2.688	1.32	-	-1.32	9.93	18.31	10.17	5.71	.483	.47	.585	1.075
2.50		11.81	4.96	.160	11.10	.066	11.88	4.94	22.60	.272	.023	1.02	11.65	5.02	17.00	2.44	3.00	-2.58	-5.58	11.42	18.56	18.68	3.27	.295	.23	.585	.815
0		10.68	5.42	.133	9.25	.050	10.73	5.45	17.65	.184	.017	1.015	10.60	5.48	8.58	-	-	1.72	1.72	10.30	15.25	10.45	5.57	.252	.30	.368	.668
1.00	6	11.25	5.20	.164	11.40	.073	11.32	5.17	23.20	.300	.027	1.025	11.05	5.29	11.50	NR	NR	-	-	-	-	-	-	-	-	.615	-
2.60		11.83	4.96	.165	11.50	.071	11.90	4.92	23.30	.289	.024	1.02	11.65	5.02	15.55	1.63	2.08	-2.75	-4.83	10.72	19.37	11.19	5.21	.521	.93	.589	1.519
0		11.00	5.30	.150	10.42	.062	11.06	5.30	20.45	.240	.022	1.02	10.82	5.38	8.58	-	-	1.72	1.72	10.30	17.75	10.56	5.50	.389	.52	.486	1.006
1.00	7	8.48	6.77	.163	11.30	.094	8.57	6.68	23.10	.385	.045	1.05	8.16	7.00	8.90	2.188	1.08	-	-1.08	7.82	18.81	7.99	7.12	.682	.34	.807	1.147
2.60		9.42	6.10	.168	11.70	.090	9.51	6.08	23.80	.372	.039	1.04	9.15	6.28	13.05	1.938	2.48	-2.75	-5.23	7.82	19.06	7.99	7.12	.732	.33	.769	1.099
0		8.56	6.70	.144	10.00	.072	8.63	6.63	19.50	.272	.041	1.04	8.30	6.90	6.28	-	-	1.72	1.72	8.00	16.25	8.15	7.00	.412	.30	.566	.866
1.00	8	9.30	6.18	.162	11.30	.085	9.39	6.12	23.00	.350	.037	1.04	9.03	6.34	9.81	2.313	1.14	-	-1.14	8.67	18.69	8.85	6.50	.612	.36	.724	1.084
2.60		9.75	5.92	.165	11.50	.084	9.83	5.90	23.30	.346	.035	1.035	9.50	6.07	14.05	2.063	2.63	-2.75	-5.38	8.67	18.94	9.09	6.32	.620	.83	.711	1.541
0		9.09	6.32	.142	9.87	.067	9.16	6.29	19.00	.245	.027	1.025	8.94	6.41	6.85	-	-	1.72	1.72	8.57	15.87	8.76	6.55	.357	.37	.500	.870
1.00	9	14.38	4.16	.220	15.30	.107	14.49	4.12	31.20	.433	.030	1.03	14.09	4.22	-	1.688	.83	-	-.83	-	19.31	-	-	-	-	.888	-
2.60		14.38	4.16	.225	15.70	.110	14.49	4.12	31.80	.450	.031	1.03	14.05	4.23	-	1.438	1.84	-2.75	-4.59	-	19.56	-	-	-	-	.458	-
0		14.38	4.15	.202	14.03	.088	14.47	4.12	27.90	.346	.024	1.02	14.18	4.20	15.60	-	-	1.72	1.72	17.32	18.00	15.75	3.84	.512	-3.14	.706	-
1.00	10	13.67	4.35	.207	14.40	.098	13.77	4.32	29.30	.400	.029	1.03	13.35	4.46	16.53	1.063	.52	-	-.52	16.01	19.44	14.68	4.06	.662	-2.66	.827	-
2.50		13.80	4.32	.213	14.80	.102	13.90	4.30	30.10	.420	.030	1.03	13.50	4.41	-	1.125	1.38	-2.58	-3.96	-	19.87	-	-	-	-	.862	-
0		13.65	4.35	.195	13.57	.087	13.74	4.33	27.05	.342	.025	1.025	13.40	4.45	11.60	-	-	1.72	1.72	13.32	18.50	13.36	4.45	.574	-.08	.704	.624

* G Meter Not Operating - Estimated Value From Air Force Meter Located In Condenser.

$P_{5C} - P_5$ reading corrected

TABLE IV (Continued)

OFFBACE SERIES III FLIGHT TEST - FLIGHT "A" - (12-9-60)

Plotted Data

G *	Loop	T _{3c} °F	m _{3c} lb/min	μ _{3c} (× 10 ⁶)	Re _{3c}	$\left(\frac{v}{10}\right)^{1.25}$	u _{3c} ft/sec	$Re\left(\frac{v}{10}\right)^{1.25}$	Φ
1.00	3	666	.139	40.5	6420	.341	99.3	2190	-
2.60		666	.141	40.5	6510	-	100.0	-	-
0		666	.113	40.5	5210	.351	81.8	1830	1.26
1.00	4	666	.139	40.5	6420	.336	98.8	2250	-
2.60		666	.141	40.5	6510	-	99.5	-	-
0		666	.117	40.5	5400	.350	84.2	1890	1.07
1.00	5	642	.133	40.5	6150	.495	123.0	3050	2.23
2.50		650	.137	39.5	6490	.247	113.5	1600	2.76
0		642	.107	39.0	5130	.484	97.0	2480	2.65
1.00	6	647	.141	39.3	6710	-	123.0	-	-
2.50		650	.142	39.5	6720	.442	117.0	2970	2.92
0		644	.124	39.1	5930	.474	122.5	2810	2.59
1.00	7	617	.140	37.6	6960	.654	110.0	4550	1.68
2.60		626	.144	38.1	7080	.654	149.0	4630	1.50
0		618	.118	37.7	5850	.640	134.5	3740	2.10
1.00	8	626	.139	38.1	6820	.582	145.5	3970	1.77
2.60		630	.142	38.3	6940	.563	141.5	3900	2.49
0		625	.115	38.1	5650	.590	122.0	3340	2.44
1.00	9	670	.189	40.7	8700	-	132.0	-	-
2.60		670	.193	40.7	8880	-	132.0	-	-
0		669	.169	40.7	7790	.302	117.0	2350	-
1.00	10	664	.178	40.4	8250	.324	123.0	2670	-
2.50		665	.183	40.5	8450	-	133.0	-	-
0		665	.164	40.5	7580	.364	120.5	2760	1.09

* G Meter Not Operating - Estimated Value From Air Force Meter Located In Condenser.

EQUATIONS 55 AND 56 COMPARED WITH TEST RESULTS OBTAINED DURING ZERO-GRAVITY MANEUVER ABOARD THE KC-135 AIRCRAFT. SEE TABLE IV FOR OFFBASE TEST RESULTS.

FIGURE 28

when Δp - measured pressure drop

Δp_v - computed frictional vapor pressure drop due to vapor only

M - momentum

$$\text{and } d\Phi = \frac{d(\Delta p)}{\Delta p_v} \quad \text{Equation 58}$$

assuming no error in flow measurements or pressure levels which are needed to compute Δp_v and M . Dividing Equation 58 by 57 we have:

$$\frac{d\Phi}{\Phi} = \frac{d(\Delta p)}{\Delta p + M} \quad \text{Equation 59}$$

Since $d(\Delta p) = 0.2$ psi and $\Delta p + M$ ranges from about 0.1 to 1 psi, the percentage error in Φ can be from 20 to 200 percent and greater if the errors in flow measurements and pressure level are included. The data representing the large specific volumes, v_v equal to about 20 ft³/lb, gives the most accurate value of Φ since the pressure drops are large for a given flow rate at low vapor density. Figure 28 shows best agreement between data and Equation 55 for v_v greater than 10. The deviation between data and Equation 55 becomes greater for v_v less than 10. The complexity of the flow processes contrasted to the simply postulated flow mechanics is, of course, a contributing factor to the spread in the data correlation to an unknown degree.

Figure 1-II, Appendix II, compares the frictional two-phase pressure drop as computed by Equation 56 with the experimental frictional two-phase pressure drop as tabulated in Table IV for zero gravity conditions. Appendix II also contains a sample calculation.

Figure 28 contains the same quantities that were used in the empirical correlation of Φ in Reference 1, namely, Φ versus $(Re_o v_v)^{1.25}$. The increase in Φ for Reynolds number greater than 10^4 as indicated by Equation 55 in Figure 28 is at present unconfirmed except for the nitrogen-mercury tests which show an increase in Φ with Reynolds number. This trend can be observed in Figure 26 and in Figure 20 of Reference 1. The increase in Φ is caused by the increase in drag associated with the large number of small drops formed at the higher mass velocities. As the size of the droplets decreases, a limit is eventually reached where the flow becomes homogenized and behaves as a single-phase flow (fog flow) for which the Φ can be computed as 1.5. Further research is required to establish these trends and limits. However, this may be of only academic interest since the Reynolds number range of immediate concern in prototype condensers appears to be in the neighborhood of 10^4 .

The effect of a gravity field imposed on a flow field on the quantity Φ can be investigated by utilizing: (1) Equation 44 for computing Φ , (2) Equation 41 for computing the slip ratio S for substitution into Equation 44, (3) Equation 36 and Figures 23 and 22 for computing f_g for substitution into Equation 44. Equation 44 is plotted in Figure 29 together with data obtained from the OFFBACE condenser during downward condensing on the ground. The gravity data obtained during flight testing ($n = 1$ to $n = 2.5$) which is presented in Table IV has not been included in Figure 29 since it is suspected that gravity effects might be present

EQUATION 44 COMPARED WITH TEST RESULTS OBTAINED DURING GROUND TESTING
OF THE OFFFACE TEST RIG. SEE TABLE V.

FIGURE 29

in the instrumentation. The extreme accuracy needed to obtain valid data required a ground test (condensing downward) in which duplicate instrumentation was used for measuring pressures. One of these instruments, the manometer, is gravity actuated and thus is not applicable to flight testing.

Table V presents the ground test data plotted in Figure 29. The manometer and calibrated transducer data are tabulated separately so that one can observe the difference in instrument readings and the differences in the computed Φ values. The average values are plotted in Figure 29. The shaded area shown in Figure 29 represents the lower limit that Φ can go to if "full roughness" is not realized and f_g/f equals one. This can be readily understood if one examines Nikuradse data for artificially roughened pipes, Figure 22. These data show the emergence of the "roughness" curves with the smooth curves in certain regions of Reynolds numbers. In addition, E_σ equal to 0.25 has been selected as contributing to the lower limit of Φ in Figure 29. The data of Figure 17 show that $4E_\sigma$ equal to one represents an upper limit to these tests. Again the data representing the greatest accuracy in Figure 29 correspond to high specific volumes. Comparing the data of Figure 28 with the data of Figure 29 one would conclude that the gravity effects are somewhat greater than predicted by Equation 44. As should be expected, the data for the lower specific volume shows more sensitivity to gravity than the higher specific volumes. This is attributed to low vapor velocities and corresponding low droplet Froude numbers (see Figure 12, Reference 1) at the higher vapor density. As a result the two-phase flow is expected to be more sensitive to a gravity field. By comparing Figure 29 with Figure 28, the estimated change in Φ due to gravity is roughly 35 percent at $v_v = 5 \text{ ft}^3/\text{lb}$ and 20 percent at $v_v = 20 \text{ ft}^3/\text{lb}$ in the Reynolds number range of 5000.

In Figure 30 are plotted data obtained from an eight foot condenser condensing in the upward direction. As can be seen the Φ values are high compared to those of Figure 29 and Figure 28. Gravity should have a greater influence on the flow when acting in opposition to the flow direction than when acting in the same direction. This is due to the opposing entrainment forces acting on the wall droplet, thus allowing it to grow to a large size when the drag force is of the order of the gravity force. It appears that the gravity effect becomes small as the inlet Reynolds number exceeds 10,000 since the Φ values of Figure 30 approach values of 2.0 to 1.5 which are to be expected according to Figure 21 of Reference 1 and to Figure 28 of this report.

In Table VI are listed the three terms making up the Φ values of Equation 44, namely, droplet drag, wall friction due to droplets and the hydrostatic head term. The values are for those plotted in Figure 28 and Figure 29. It should be kept in mind that the lower limit of the wall friction is one because when $f_g = f$ the droplets are submerged in the laminar sublayer of the boundary layer and the wall appears smooth to the flow. Actual conditions will lie between "fully rough" which corresponds to the tabulated values and "smooth wall." Note that gravity influences the wall friction since it plays a part in drop entrainment (Table VI). The hydrostatic head term contributes less than 10 percent to the Φ values. In Table VI are also shown values as computed for the SNAP II prototype conditions. Note that the hydrostatic head term is greater than that of the OFFFACE condenser due to the longer condenser length.

TABLE V
RESULTS OF OFFBACK GROUND TESTING

Inlet Pressure Correction												Outlet Pressure Correction				$\Delta P_g - f$		$\Delta P_{te} - f$														
Run	P3	v_{v3}	$\dot{m}_3$	G_3	$\frac{v_{v3} G_3^2}{2g}$	P_o	v_v	G_{3c}	$\frac{v_{v3c} G_{3c}^2}{2g}$	$\frac{v_v G_{3c}^2}{2g P_o}$	$\frac{P_o}{P_2}$	P3c	v_{v3c}	P4	Liq. Level	.491(h)	$L_{EFF.}$	P4c	$\frac{P + P_{4c}}{2}$	$\bar{v}_v$	Δp_{gf}	$P_c - P_{4c}$	M	Δp_{gf}	T_{3c}	$\dot{m}_{3c}$	μ_{3c}	Re_{3c}	$\left(\frac{v_v}{10}\right)^{1.25}$	$Re_o \left(\frac{\bar{v}_v}{10}\right)^{1.25}$	ϕ	
	PSIA	ft ³ /#	#/min	#/in ² min	PSI	PSIA	ft ³ /#	#/in ² min	PSIA			PSIA	ft ³ /#	PSIA	in	PSIA	in	PSIA	PSIA	ft ³ /#	PSI	PSI	PSI	PSI	°F	#/min	#/ft sec (x 10 ⁶)					
Trans.	1	7.00	8.10	.122	8.48	.063	7.06	8.00	17.3	.259	.037	1.035	6.83	8.25	7.35	.87	.43	19.6	6.92	6.88	8.20	.458	-.09	.533	.443	603	.105	36.8	5350	.780	4170	.967
Trans.	2	7.14	7.92	.122	8.48	.058	7.20	7.85	17.3	.254	.035	1.035	6.96	8.15	7.25	.44	.22	20.1	7.03	7.00	8.08	.463	-.07	.527	.457	605	.105	37.0	5300	.766	4070	.988
Trans.	3	3.80	14.15	.101	7.02	.075	3.88	13.80	14.3	.305	.077	1.095	3.54	15.10	4.00	.44	.22	20.1	3.78	3.66	14.70	.576	-.24	.667	.427	549	.0865	33.9	4770	1.62	7730	.741
Trans.	4	2.82	18.60	.116	8.06	.130	2.95	17.80	16.4	.516	.175	1.37	2.16	23.70	2.77	.50	.25	20.0	2.52	2.34	22.0	1.13	-.36	1.38	1.02	510	.0995	31.8	5850	2.68	15,700	.903
Trans.	5	9.35	6.15	.127	8.83	.052	9.40	6.12	18.0	.214	.023	1.02	9.22	6.22	9.47	.50	.25	20.0	9.22	9.22	6.21	.384	0	.436	.436	627	.109	38.2	5340	.551	2940	1.135
Trans.	6	9.28	6.22	.122	8.48	.048	9.33	6.18	17.3	.200	.021	1.02	9.15	6.27	9.37	.38	.19	20.1	9.18	9.17	6.27	.354	-.03	.405	.375	626	.105	38.1	5150	.558	2880	1.06
Trans.	7	9.03	6.38	.111	7.71	.041	9.07	6.33	15.7	.168	.019	1.02	8.90	6.45	9.72	1.25	.61	19.25	9.11	9.02	6.37 (6.35)	.288	-.21	.343	.133	625	.0952	38.1	4670 (4670)	.569	2660	.462 (0.74)
Mano.	7	9.16	6.30	.111	7.71	.040	9.20	6.25	15.7	.166	.018	1.02	9.02	6.37	9.68	1.25	.61	19.25	9.07	9.05	6.33	.286	-.05	.339	.289	625	.0952	38.1	4670	.565	2640	1.01
Trans.	8	9.20	6.27	.120	8.35	.047	9.25	6.22	17.0	.194	.021	1.02	9.06	6.35	9.65	.88	.43	19.6	9.22	9.14	6.29 6.27	.339	-.16	.396	.236	626	.103	38.1	5050 5050	.560	2830	.696 0.87
Mano.	8	9.31	6.18	.120	8.35	.047	9.36	6.17	17.0	.193	.021	1.02	9.18	6.27	9.65	.88	.43	19.6	9.22	9.20	6.24	.337	-.04	.391	.351	627	.103	38.2	5050	.555	2800	1.04
Trans.	9	7.02	8.05	.118	8.20	.059	7.08	8.00	16.7	.241	.034	1.03	6.88	8.20	7.50	1.12	.55	19.4	6.95	6.92	8.15 8.08	.420	-.07	.494	.421	604	.101	36.9	5120 5110	.774	3970	1.00 .96
Mano.	9	7.27	7.80	.118	8.20	.057	7.33	7.71	16.7	.232	.032	1.03	7.11	7.95	7.56	1.12	.55	19.4	7.01	7.06	8.00	.412	.10	.479	.379	607	.101	37.1	5100	.756	3860	.920
Trans.	10	7.10	7.94	.115	8.00	.054	7.15	7.90	16.3	.227	.032	1.03	6.44	8.12	7.50	1.00	.49	19.5	7.01	6.97	8.10 7.98	.400	-.07	.466	.396	604	.099	36.9	5020 5010	.768	3860	.990 1.20
Mano.	10	7.31	7.77	.115	8.00	.053	7.36	7.71	16.3	.222	.030	1.03	7.15	7.90	7.55	1.00	.49	19.5	7.06	7.21	7.85	.388	.09	.453	.543	607	.099	37.1	5000	.739	3590	1.40
Trans.	11	3.77	14.20	.116	8.06	.100	3.87	13.90	16.4	.405	.105	1.145	3.38	15.70	3.60	.62	.30	19.9	3.30	3.34	15.8 15.9	.806	.08	.913	.993	544	.0995	33.6	5540 5545	1.77	9800	1.23 1.11
Mano.	11	3.65	14.70	.116	8.06	.103	3.75	14.30	16.4	.416	.111	1.16	3.23	16.30	3.67	.62	.30	19.9	3.37	3.30	16.0	.816	-.14	.947	.807	541	.0995	33.5	5550	1.80	10,000	.990
Trans.	12	3.60	14.80	.117	8.14	.106	3.71	14.40	16.6	.428	.115	1.17	3.17	16.70	3.35	.25	.12	20.25	3.23	3.20	16.5 16.1	.878	-.06	.995	.935	539	.101	33.4	5660 5645	1.87	10,600	1.065 1.13
Mano.	12	3.77	14.20	.117	8.14	.102	3.87	13.90	16.6	.414	.107	1.15	3.36	15.80	3.43	.25	.12	20.25	3.31	3.34	15.8	.840	.05	.940	.990	544	.101	33.6	5630	1.77	9980	1.18
Trans.	13	12.60	4.69	.212	14.70	.109	12.71	4.66	30.0	.454	.036	1.035	12.30	4.78	12.35	.25	.12	20.25	12.23	12.27	4.81	.835	.07	.930	1.00	656	.182	39.9	8540	.400	3420	1.20
Ground Test "F"																																

Ground Test "F"

TEST RESULTS OF A VERTICAL (CONDENSING UPWARD) TAPERED
CONDENSER (STEPPED TUBES). INLET DIAMETER 0.620 IN.,
OUTLET DIAMETER 0.0956 IN., TOTAL WEIGHT 8 FT

FIGURE 30

TABLE VI

Φ VALUES COMPUTED BY EQUATION 44

		Drag	Wall Friction	Hydrostatic Head	Φ
Re_o	ρ_v				
5×10^3	0.2	0.209	1.58	Zero Gravity	1.79
	0.1	0.209	1.28		1.49
8×10^3	0.05	0.209	1.04		1.25
	0.2	0.344	1.33		1.67
1×10^4	0.1	0.344	1.08		1.42
	0.05	0.344	1.00		1.34
5×10^4	0.2	0.434	1.23		1.66
	0.1	0.434	1.00		1.43
	0.05	0.434	1.00		1.43
	0.2	2.37	1.00		3.37
	0.1	2.37	1.00		3.37
	0.05	2.37	1.00		3.37
5×10^3	0.2	0.532	1.512	0.104	1.94
	0.1	0.257	1.250	0.016	1.49
8×10^3	0.05	0.225	1.017	0.004	1.24
	0.2	0.400	1.307	0.018	1.69
	0.1	0.362	1.061	0.004	1.42
	0.05	0.353	1.000	0.001	1.35
$E_\sigma = 0.0464$ $L = 1.67 \text{ ft}$ $D = 0.136 \text{ in.}$					
OFFBACE					
		Drag	Wall Friction	Hydrostatic Head	Φ
Re_o	ρ_v				
8×10^3	0.2	0.639	1.332	0.143	1.83
	0.1				
1×10^4	0.05	0.211	1.105	0.017	1.30
	0.2	0.333	1.253	0.044	1.54
	0.1				
	0.05	0.230	1.025	0.009	1.25
$E_\sigma = 0.0464$ $L = 7.85 \text{ ft}$					
$D = 0.319 \text{ in.}$ SNAP II Dimensions					

TABLE VI (Continued)

		Drag	Wall Friction	Hydrostatic Head	ϕ	
Re_o	ρ_v					
5×10^3	0.2	0.098	2.05	Zero Gravity	2.15	
	0.1	0.098	1.67		1.77	
	0.05	0.098	1.35		1.45	
8×10^3	0.2	0.161	1.73		1.89	
	0.1	0.161	1.40		1.56	
	0.05	0.161	1.14		1.30	
1×10^4	0.2	0.203	1.60		1.80	
	0.1	0.203	1.29		1.49	
	0.05	0.203	1.05		1.25	
$E_\sigma = 0.0464$ $L = 7.85 \text{ ft}$ $D = 0.319 \text{ in.}$						
SNAP II Dimensions						
		Drag	Wall Friction	Hydrostatic Head	ϕ	
Re_o	ρ_v					
5×10^3	0.2	0.350	2.031	0.078	2.30	
	0.1					
	0.05					
8×10^3	0.2	0.124	1.690	0.008	1.81	
	0.1	0.322	2.148	0.051	2.42	
	0.05	0.200	1.270	0.009	1.96	
	0.2	0.182	1.438	0.002	1.62	
$E_\sigma = 0.25$ $L = 1.67 \text{ ft}$ $D = 0.136 \text{ in.}$						
OFFBACE						
		Drag	Wall Friction	Hydrostatic Head	ϕ	
Re_o	ρ_v					
5×10^3	0.2	0.441	1.278	0.058	1.66	
	0.1	0.307	1.037	0.012	1.33	
	0.05	0.283	1.000	0.003	1.28	
8×10^3	0.2	0.477	1.084	0.014	1.55	
	0.1	0.446	1.00	0.004	1.44	
	0.05	0.439	1.00	0.001	1.44	
$E_\sigma = 0.025$ $L = 1.67 \text{ ft}$ $D = 0.136 \text{ in.}$						
OFFBACE

A comparison between the Φ values for zero gravity and downward condensing in 1 G for SNAP II dimensions shows a maximum change in Φ of 17 percent ($Re_o = 8 \times 10^3$ $\rho_v = 0.1$ or $v_v = 10$). At Reynolds numbers greater than 8×10^3 and specific volumes greater than 10 the gravity effects appear negligible. A tapered condenser tube would lower the limits in Reynolds number and specific volume at which changes in Φ due to gravity are first detected. Equations 28 and 29 indicate a reduction in the gravity term by a factor of 16 when going from a constant diameter tube to a constant velocity tube. In addition, the wall friction term is reduced by keeping drop sizes smaller by means of high vapor velocities all along the tube. The experimental data presented in Figures 28, 29, and 30 show more sensitivity to gravity at Reynolds number of 5000 than is indicated by theory (Table VI). As a result, it is estimated that the change in Φ for the SNAP II prototype condenser at $v_v = 5$ will be 40 percent and 23 percent at $v_v = 20$ ft³/lb for Reynolds number of 5000. At higher Reynolds number and for tapered tubes these percentages will be reduced.

4.3 Interfacial Stability in Zero Gravity

When one fills a tube with liquid, closes one end and inverts the tube, the liquid may or may not leave the tube. Small tubes tend to retain the liquid, while larger tubes allow the liquid to run out. The maximum size tube which will retain the liquid is customarily called a critical diameter tube. It is usually arrived at through a dynamic formulation although it can be arrived at from static stability considerations alone.

To make the discussion simple, let us first consider the two dimensional problem. Imagine a plane interface in a vessel with vapor below and liquid above. As long as the surfaces are precisely plane, the conditions of static equilibrium can be satisfied.

Now let us pose the question of what will happen if the interface is disturbed with some small wavelength. The result of the disturbance will be to reduce the potential energy of the displaced liquid. This will release energy. At the same time the length of the interface formed will be increased. This will absorb energy. For sufficiently small waves in a gravity field the amount of energy released by displacement will be less than that absorbed by formation of new surface and the interface will tend to oscillate about its neutral position if released. However, for a sufficiently long wave the distribution is clearly unstable as the amount of new surface created does not appreciably change while the mass of liquid moved to a position of lesser potential energy clearly increases. This critical wavelength for the two dimensional case is:

$$\lambda = 2\pi \sqrt{\frac{\sigma}{(\rho_f - \rho_g)g}}$$

Equation 60

where ρ_f = liquid density
 ρ_g = vapor density
 σ = surface tension
 g = local gravitational acceleration

An interface between two parallel vertical plates is stable if the spacing between the plates is less than $\lambda/2$. For a cylindrical, rather than plane, geometry the critical wavelength would be slightly different from this value. From a static and dynamic stability analysis the effect of contact angle can also be included (Reference 1). Figure 31 is a plot of critical diameter versus contact angle for a cylindrical container. Two regions are identified, stable and metastable. In the metastable region, a tube that begins to empty, due to a disturbance, will continue to empty as once the wall is covered by liquid the interface will have a contact angle of zero. If the tube diameter is reduced below the critical value for zero degrees or 180 degrees, a bubble should not rise, no matter what the disturbances are or what the contact angle is. Design in the metastable region may be too unreliable, thus the recommended diameter limit is:

$$D \leq 1.835 \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}} \quad \text{Equation 61}$$

The maximum diameter, D_{critical} , for a stable interface between liquid mercury and mercury vapor is 0.136 inch as computed from the above equation.

Experiments were conducted to test these critical diameter relations and to establish parameters needed to maintain a stable liquid column in the subcooler and inlet to the pump in the presence of various disturbances. These investigations were divided into two areas: static stability tests and stability tests with internal and external disturbances.

Reference 1 presents results of interfacial stability tests on mercury in a 1 G environment (ground test) with various disturbances imposed. During the zero-gravity flight, five test capsules of different diameters filled with water and five filled with mercury were observed in zero gravity. Figure 32 lists the diameters tested. Figures 33 and 34 show the nature of the body force fluctuations during the zero-gravity trajectory. It was deemed desirable to establish definitely the stability of the liquid interface contained in small diameter tubes in zero gravity with whatever extraneous disturbances might be present. Tests made at WADD and NASA using a zero-gravity flight trajectory showed a break-up of the liquid interface contained in transparent containers of large diameters filled with alcohol. For large diameter containers not only capillary waves but also gravity waves are present to contribute to surface instabilities. Other tests in smaller containers showed that a wetting liquid clings to the wall enclosing a gas bubble, whereas a non-wetting liquid such as mercury detaches from the walls of the container and forms a liquid sphere.

All liquid interfaces in the test capsules were observed to be stable except during one instant when the test platform struck an object during zero gravity at which time the water interface in the largest tube (0.625 inch diameter) was disrupted. Figure 32 shows the range of disturbance, as obtained from Figures 33 and 34, as a shaded area. The curves are the stability limits as computed from Figure 31 ($\beta' = 139$ degrees for mercury and $\beta' \approx 60$ degrees for water). The range of disturbances and the size of the capsules were such as to fall within the stable region in Figure 32. According to Figure 32 instability would have been noted in the larger tubes if $n = -0.22$ (mercury) and $n = -0.4$ (water). Since the maximum negative body

CURVE SHOWING REGIONS OF INSTABILITY, METASTABILITY, AND STABILITY FOR LIQUID CONTAINED IN A TUBE OF DIAMETER, D

FIGURE 31

PLOT SHOWING THE DISTURBANCES OBSERVED DURING ZERO GRAVITY MANEUVERS
AND THE DIAMETERS OF THE TEST CAPSULES FOR DEMONSTRATION OF INTERFACIAL STABILITY

FIGURE 32

GRAVITY FLUCTUATIONS DURING THE ZERO GRAVITY RUN

FIGURE 33

GRAVITY FLUCTUATIONS DURING THE ZERO-GRAVITY RUN

FIGURE 34

force disturbance encountered was $n = -0.02$, a diameter of 1.75 inches (mercury) and 3.25 inches (water) would have produced incipient interfacial instability. A photograph of the interfacial stability test rig obtained during zero gravity is shown in Figure 35. All interfaces are observed as stable since the diameters and disturbances were such as to fall within the stability limit shown in Figure 32.

4.4 Two-Phase Isothermal Flow Investigations

In a condenser of an orbiting vehicle, the propelling force moving the condensate to the subcooler is the drag force exerted on the liquid by the flowing vapor. Since under certain circumstances body forces may contribute to or retard the liquid flow, it is of importance to measure its effect on the flow. Condensers tested or operated in the vertical position on the ground and then projected into orbit will have a change in performance which in turn will affect connected components. The magnitude of the gravity effect is a quantity which the designer must know so that a high degree of confidence is established in the operation of his condenser under various conditions.

The quantity Φ is a direct measure of the effect of the flowing liquid on the pressure drop and pressure drop is the most important quantity influencing connected components. To obtain two-phase flow pressure drop data without the complication of boiling or condensing, flow tests were conducted using nitrogen gas and liquid mercury. Reference 1 reported the initial phase of these tests. These tests provide pressure drop data on a local basis, that is, the flowing quality remains constant across the test section. In Figures 36, 37 and 38 are plotted the results of tests made on bare 1/4, 3/8 and 1/2 inch glass and stainless steel tubes four feet long. The effect of gravity on Φ was determined by tilting the test section 15 degrees downward and then 15 degrees upward. The influence of gravity on the flow can be established by comparing the Φ values with gravity acting along the axis of flow with the Φ values for horizontal tubes. It should be kept in mind that gravity still plays a role in the establishment of the flow pattern in horizontal tubes, so to obtain a true picture of flow in a gravity-free field zero-gravity tests must be conducted. This, of course, is the purpose of the condenser tests in OFFBACE. When examining Figures 36, 37 and 38, the following should be kept in mind:

1. The effect of gravity on Φ when acting in the same direction as the flow is not expected to be as pronounced as when gravity acts opposite to the flow direction. This is borne out when the data of Figure 38 is contrasted to the data of Figure 37, and the data of Figure 36 is compared with the data of Figure 37.
2. The effect of gravity on Φ is more pronounced in the low quality regions where the amount of liquid hold-up is greatest.
3. The effect of gravity on Φ becomes negligible as the quality approaches one.
4. The integrated effect of gravity on Φ for a condenser can be approximated by contrasting Φ values at a quality of 0.5.

VIEW OF INTERFACIAL STABILITY TEST RIG DURING ZERO-GRAVITY MANEUVER. CAPSULES CONTAIN MERCURY. RIGHT CAPSULE IS ZERO-GRAVITY METER SHOWING SUSPENDED BALL. LEFT CAPSULE CONTAINS MERCURY LEG IN THE INVERTED POSITION.

Φ VALUES FOR 15° HORIZONTAL FLOW FOR VARIOUS QUALITIES, GAS VELOCITIES,
TUBE DIAMETER AND TUBE WALL MATERIAL

O VALUES FOR 15° UPFLOW FOR VARIOUS QUALITIES, GAS VELOCITIES, TUBE DIAMETER, AND TUBE WALL MATERIAL

FIGURE 38

5. Condensers with constant diameter tubes give vapor velocities which vary linearly with quality. Therefore, local condenser Φ values can be computed for each quality and gas velocity by successively reading the Φ values for each plot.
6. For a tapered condenser tube the vapor velocity can be held constant and a single plot can be utilized.

In general, there are no appreciable differences in Φ between the horizontal and down-flow data; however, for the velocity ranges of 80 to 110 ft/sec and 60 to 80 ft/sec, the Φ in the low quality regions for downflow appears somewhat greater than the Φ in the low quality region for horizontal flow. The possible reason for this can be only speculative. Differences in Φ ranging say below 50 percent ($d\Phi/\Phi \times 100$) would be difficult to observe due to the spread in data. In general, the upflow Φ values are greater than the Φ values for horizontal flow as is expected. At a quality of 0.5 the Φ values for upflow are greater than those for horizontal flow by roughly a factor of 1.5 in the low quality region (0 to 0.2 quality) and the values for upflow are greater than those for horizontal flow by factors ranging from roughly 6 to 1.5. The largest factor is associated with the lowest gas velocity.

4.5 Manifold Test

When more than one condenser tube is to be operated in parallel, it is desirable to produce equal loading and similar conditions in each tube. This can be done by making all tubes the same and by providing a source and sink plenum on each end of the tube. (A plenum is a large chamber which makes the flow conditions the same to each end of the tube.) To reduce weight and increase compactness, plenums of relatively small size are incorporated into parallel flow systems. These plenums, also referred to as manifolds, require careful design in order that they produce, as nearly as possible, uniform conditions to each attached tube.

A manifold or plenum of relatively small size will have frictional flow losses; thus it is impossible to have a constant total pressure along the axis of the manifold. However, if it is assumed that the manifold velocity head is lost as the flow turns normal to the manifold axis into the tube, then nearly uniform conditions will be obtained if the static pressure is maintained constant throughout the manifold. This design criterion is well known to designers of flow systems and can be found in appropriate engineering handbooks (Reference 16). The design procedure utilizing this criterion is referred to as the static regain method. This method of manifold design is commonly used in air duct design where a constant static pressure is desired at the duct outlets. The static regain design method attempts to control the static pressure regain caused by loss of fluid velocity when fluid is removed at the manifold outlets. It is desired that this static pressure regain be equal to the static friction pressure drop in each section, so that a constant static pressure manifold is obtained.

The following design procedure is recommended for manifold design for mercury condensers. (Refer to Figure 39, the schematic diagram)

CONDENSER SECTION (n)

FIGURE 39

1. Select desired manifold inlet velocity or Reynolds number. This will establish the size of the manifold.
2. Calculate inlet section diameter (D_{n-1}).
3. Assume that $(p_1)_{static} = (P_{t1})_{total}$ and $(p_2)_{static} = (P_{t2})_{total}$. This assumes the velocity head is lost in turning the stream tube into the condenser tube.
4. Calculate D_n by setting $(\Delta p)_{static\ regain} = (\Delta p)_{friction}$.
5. Assume the static regain efficiency (conversion of velocity head into head in the axial flow direction of the manifold) to be about 70 percent.
6. Assume that all liquid droplets which may be in the manifold are carried to the last condenser tube and calculate vapor quality in last manifold section.
7. Design last manifold section to give predetermined liquid level in last tube.

Condenser lengths should be within 3 percent of the design values for each condenser tube.

To substantiate the static regain design method as applied to mercury condensers, a test rig was designed as shown in Figure 40. The tubes were horizontal so that gravity would be eliminated as an agent in establishing liquid levels and liquid level stability. Thus zero-gravity conditions were simulated. The tubes were supplied by mercury vapor generated in a pot boiler. A superheater was added to the inlet line to minimize moisture carryover and condensation. Two different types of tests were run. One test was made with the drain valves closed which produces a condition where the liquid level is independent of pressure. In this test it was possible to study the effect of condensing length on flow rate and compare the four tubes operating at approximately the same temperature. Another test was run with the drain valves open, so the liquid level was established by pressure drop considerations. This test simulated actual condenser operation with the exception that flow was allowed to build up in the tubes for metering purposes. Two manifolds were tested. One was stepped as shown in Figure 41, and the other was constant diameter as shown in Figure 42.

The liquid build-up pattern for a typical run with a stepped manifold is shown in Figure 41. The drain valves were closed. The liquid level build-ups in the first three tubes was about equal, but in the fourth tube it was slightly higher. This is believed to be caused by moisture carryover in the inlet lines. The liquid build-up pattern for a typical run with a constant diameter manifold and with drain valves closed is shown in Figure 42. Again, the first three tubes received about equal flow, and the last tube received some moisture carryover. These tests demonstrated that flow rate is not determined by manifold configuration, but rather by the condenser tube lengths. If equal condenser lengths produce equal flow rates, then flow rate must be proportional to condenser length. This agrees with the usual analytical heat transfer model based on uniform heat transfer and equal tube diameters.

TEST SETUP FOR MANIFOLD TEST.
TUBES ARE IN HORIZONTAL POSITION TO SIMULATE ZERO GRAVITY

FIGURE 40

TAPERED MANIFOLD - VALVES CLOSED
TYPICAL RUN

FIGURE 41

STRAIGHT MAN FOLD - VALVES CLOSED
TYPICAL RUN

FIGURE 42

TAPERED MANIFOLD - VALVES OPEN

FIGURE 43

With the drain valves open, another degree of freedom for the liquid inventory is introduced, and actual condenser performance was simulated. The interface pressures were all equal since the liquid manifold pressure losses were negligible. Figure 43 shows the liquid level positions and the build-up when a stepped manifold was used. The liquid levels were different because the manifold was not fabricated exactly to the dimensions specified by the constant static pressure design and as a result there was a static pressure change in the manifold.

A calculation of pressure drops along the four fluid paths was made to determine whether the liquid level relationships which were observed would agree with the liquid level relationship which was predicted according to the design procedure. It was found that it is possible to predict interface positions very accurately by the static regain method, namely, within 3 percent. It may be concluded that it is possible to design a manifold with the desired liquid levels by the static regain method. The design of the liquid manifold plays a small role as long as the liquid velocity and pressure drop is kept negligibly small. This is the case for the prototype system and for the test apparatus; as a result a stepped liquid manifold has not been incorporated in the test setup. The test of the constant diameter vapor manifold with the drain valves open proved that this manifold is undesirable because the liquid levels were grossly unbalanced and their locations were unpredictable. By removing liquid inventory from the test apparatus, it was possible to operate the parallel tube condenser with a single liquid interface in the drain tube, thus demonstrating the feasibility of this mode of operation.

In the oscillations of the liquid legs in a vertical U-tube manometer, gravity is the restoring force. In the manifold tests large unbalances were set up frequently by allowing one or two condenser tubes to fill with liquid. The drain valves were opened quickly, allowing the liquid freedom to move among the tubes. In every case, the liquid interfaces returned to an equilibrium condition and no oscillation or liquid level instability was observed. Pressure forces appear to be the restoring force. Section 4.6 further discusses this problem.

4.6 Parallel Tube Operational Problems in Zero Gravity

The location and stability of the liquid legs during multiple tube - multiple liquid interface operation of a condenser depends on several factors, namely: (1) manifold design, (2) heat transfer unbalances, (3) differences in tube geometry. The manifold problem and experimentation is described in Section 4.5. The effect of heat transfer unbalances and of differences in tube geometry on liquid level can be investigated analytically and the results compared with observation made during zero-gravity maneuvers of the OFFBACE test rig. The basis for the analysis is schematically shown in Figure 44. The vapor and liquid manifolds are at constant pressure, making the pressure drop in each tube the same.

Liquid Leg Stability:

The pressure drop across the tube is,

$$\Delta P_{TP} = \Phi f' \frac{L}{D} \frac{\rho_v u_o^2}{2g_s} - \frac{\rho_v u_o^2}{g_s} \quad \text{Equation 62}$$

f' includes the effect of a vapor flow reduced to zero at the liquid interface. (See Appendix of Reference 1).

SCHEMATIC FOR ANALYZING PARALLEL TUBE STABILITY

FIGURE 44

The limit of stability is defined as:

$$\frac{d(\Delta p_{TP})}{d(\rho_v u_o)} = 0$$

Equation 63

As a result Equation 62 becomes:

$$\frac{\Phi f' L}{D} > 2 \text{ for stability } (\Phi \text{ and } f' \text{ are considered constant}) \quad \text{Equation 64}$$

Since both Φ and f' are also functions of $(\rho_v u_o)$ or Re_o , the differentiation of Equation 62 should include these as variables. Equation 62 would then become,

$$\Phi f' \frac{L}{D} > 2.5 \text{ for stability } (\Phi \text{ and } f' \text{ are variables}) \quad \text{Equation 64A}$$

which applies in the range of SNAP II design conditions. Appendix III shows the analysis and Figure III-1 and Figure III-2 show the relationship of Φ and f' with Re_o .

Substituting the following OFFBACE test conditions into Equation 64 we have,

$$\begin{aligned} Re_o &= 5,000 \text{ and } f' = 0.0122 \text{ (Figure A-1, Reference 1).} \\ \Phi &= 1.5 \text{ (approx.)} \\ L &= 1.67 \text{ ft.} \\ D &= 0.136 \text{ in.} \\ \text{and, } \Phi f' \frac{L}{D} &= \frac{1.5 \times 0.0122 \times 1.67 \times 12}{0.136} = 2.7 \end{aligned} \quad \text{Equation 65}$$

$$\text{if } \Phi \text{ were near } 1.0 \text{ then } \Phi f' \frac{L}{D} = 1.8$$

Thus, OFFBACE condenser conditions are such that symptoms of near instability might be detectable, such as sluggish oscillations of the liquid interfaces. However, no definite oscillations attributed to instability were detected.

SNAP II condenser requirements are such that the L/D ratio is about twice that of the OFFBACE condenser. This creates confidence in the liquid leg stability of the SNAP II condenser in zero gravity.

Liquid Leg Steady-State Positions:

The pressure drop in a condenser tube in turbulent flow can be expressed as:

$$\Delta p = \frac{K \dot{m}^{1.75} L}{D^{4.75}} \quad \text{Equation 66}$$

where K is a constant containing $\Phi f'$, μ_v , and g_s .

The radiation heat transfer from the condenser surface can be expressed as:

$$\dot{m} h_{fv} = K' \epsilon L (T_R^4 - T_o^4) \quad \text{Equation 67}$$

where K' is a constant containing the fin dimensions and the Stephen - Boltzmann constant.

Combining Equation 66 and 67, we have:

$$\Delta p = \frac{K'' \epsilon^{1.75} L^{2.75}}{D^{4.75}} \left[(T_c - \Delta T)^4 - T_o^4 \right]^{1.75} \quad \text{Equation 68}$$

where $T_R = T_c - \Delta T$ and K'' is a constant.

Since the pressure drop can be altered by means of various effects we have,

$$d(\Delta p) = \frac{\partial \Delta p}{\partial \epsilon} d\epsilon + \frac{\partial \Delta p}{\partial L} dL + \frac{\partial \Delta p}{\partial D} dD + \frac{\partial \Delta p}{\partial \Delta T} d(\Delta T) + \frac{\partial (\Delta p)}{\partial T_o} dT_o \quad \text{Equation 69}$$

Thus, changes in fin emissivity, condenser length (liquid leg change), tube diameter, fin temperature drop, and the sink temperature are included as factors effecting the pressure drop. Differentiating Equation 68 we have:

$$\frac{\partial (\Delta p)}{\partial \epsilon} = 1.75 \epsilon^{0.75} \left(\frac{\Delta p}{\epsilon^{1.75}} \right)$$

$$\frac{\partial (\Delta p)}{\partial L} = 2.75 L^{1.75} \left(\frac{\Delta p}{L^{2.75}} \right)$$

$$\frac{\partial (\Delta p)}{\partial D} = -4.75 D^{-3.75} \left(\frac{\Delta p}{D^{4.75}} \right)$$

$$\frac{\partial (\Delta p)}{\partial (\Delta T)} = -1.75 \left[(T_c - \Delta T)^4 - T_o^4 \right]^{0.75} 4(T_c - \Delta T)^3 \frac{\Delta p}{\left[(T_c - \Delta T)^4 - T_o^4 \right]^{1.75}}$$

$$\frac{\partial (\Delta p)}{\partial T_o} = -1.75 \left[(T_c - \Delta T)^4 - T_o^4 \right]^{0.75} 4 T_o^3 \frac{\Delta p}{\left[(T_c - \Delta T)^4 - T_o^4 \right]^{1.75}}$$

For parallel tubes with constant pressure plenums we have,

$$\frac{d(\Delta p)}{\Delta p} = 0$$

and approximately:

$$(T_c - \Delta T)^4 - T_o^4 \cong T_c^4 ; (T_c - \Delta T)^3 \cong T_c^3$$

We have by Equation 69:

$$\frac{d(\Delta p)}{\Delta p} = 1.75 \frac{d\epsilon}{\epsilon} + 2.75 \frac{dL}{L} - 4.75 \frac{dD}{D} - 7 \frac{d(\Delta T)}{T_c} - \frac{7 T_o^3 d T_o}{T_c^4} \quad \text{Equation 70}$$

and

$$\frac{dL}{L} = -0.63 \frac{d\epsilon}{\epsilon} + 1.73 \frac{dD}{D} + 2.55 \frac{d(\Delta T)}{T_c} + 2.55 T_o^3 \frac{d T_o}{T_c^4} \quad \text{Equation 71}$$

The OFFBACE test condenser contained four tubes, three of which were glass (0.137, 0.140, 0.135 in. ID) and one of stainless steel (0.129 in. ID). The greatest difference in diameter of the transparent tubes was 0.005 in. Therefore, according to Equation 71, the greatest difference in liquid leg length should be:

$$dL = 1.67 \times 12 \times 1.73 \frac{0.005}{0.135} = 1.28 \text{ inches}$$

The difference in liquid leg length as observed during the zero-gravity trajectory was between 1 and 1.5 inches when the system was free from non-condensables. When the system was not well degassed, expansion of entrapped gas bubbles in the liquid legs during zero gravity produced changes in the liquid lengths, the amount depending on how much gas was contained in each leg. The effect of non-condensables in the liquid mercury is the same as adding mercury to the system in zero gravity, that is, the gross movement of the liquid decreases the condenser area.

Liquid length differences in zero gravity for tapered tubes can be analyzed by modifying Equation 66, namely:

$$\Delta p \propto \frac{L^{2.75}}{D_o^{2.75} \left[D_o - \left(\frac{D_o - D_e}{L_T} \right) L \right]} \left[\frac{1}{D_o} + \frac{1}{2.75 \left[D_o - \left(\frac{D_o - D_e}{L_T} \right) L \right]} \right] \quad \text{Equation 72}$$

The mass flow will be held constant for this case. Let $D_o = A$ and $D_o - D_e = B$ thus,

$$\Delta p \propto \frac{L^{2.75}}{A^{2.75} (A-BL)} \left[\frac{1}{A} + \frac{1}{2.75 (A-BL)} \right]$$

and by proper manipulation:

$$\frac{d(\Delta p)}{\Delta p} = - \frac{L^{2.75} 2.75 B + L^{1.75} (A-BL) (2.75)^2 + A L^{1.75} 2.75 dL}{L^{2.75} (A-BL) 2.75 + L^{2.75} A}$$

$$= - \frac{2.75 A^{3.75} 2 (A-BL) (-B)}{2.75 A^{3.75} (A-BL)^2}$$

and

$$\frac{d(\Delta p)}{\Delta p} = \left[\frac{-2.75 BL}{2.75 (A-BL) + A} + 2.75 \frac{+ 2 BL}{A-BL} \right] \frac{dL}{L} \quad \text{Equation 73}$$

A tapered tube to meet SNAP II requirements may have

$$D_o = 0.67 \text{ inches} \quad D_e = 0.16 \text{ inches} \quad L = 104 \text{ inches}$$

and Equation 73 gives,

$$\frac{d(\Delta p)}{\Delta p} = 7.85 \frac{dL}{L} \quad (\text{tapered})$$

and by Equation 70:

$$\frac{d(\Delta p)}{\Delta p} = 2.75 \frac{dL}{L} \quad (D = \text{constant})$$

and for equal changes in ϵ , D , ΔT , T_o ,

$$dL_{D=\text{constant}} = 2.86 dL_{\text{Tapered}} \quad \text{Equation 74}$$

Equation 74 shows that the liquid leg movement in a tapered tube is less than for a tube of constant diameter for the same unbalances in ϵ , D , ΔT , and T_o .

Equation 71 for a tapered tube now becomes

$$\frac{dL}{L} = -0.22 \frac{d\epsilon}{\epsilon} + 0.60 \frac{dD}{D} + 0.89 \frac{d(\Delta T)}{T_c} + 0.89 \frac{T_o^3 dT_o}{T_c^4} \quad \text{Equation 75}$$

since the terms in Equation 70 remain the same except the second term on the right side of the equation.

Sample calculations will illustrate the utility of the derived equations. Assume incident solar radiation on several tubes in the SNAP II prototype condenser. Compute the differences in liquid lengths between the irradiated tubes and the shaded tubes. Compare the tapered tube with the straight tube.

$$T_o^4 = \frac{\alpha P_{inc}}{\sigma \epsilon} = \frac{0.80 \times 430}{0.171 \times 10^{-8} \times 0.90}$$

$$T_o = 687 \quad T_o^4 = 2230 \times 10^8 \quad T_o^3 = 0.324 \times 10^9$$

$$T_c^4 = (1.060)^4 \times 10^{12}$$

$$dL/L = 0.89 \frac{T_o^3 dT_o}{T_c^4} \quad (\text{Equation 75}) = \frac{0.89 \times 0.324 \times 10^9 \times 687}{1.202 \times 10^{12}}$$

$$dL/L = 0.16$$

$$dL = 104 \times 0.16 = 16.6 \text{ inches (tapered)}$$

By Equation 74,

$$dL = 16.6 \times 2.86 = 47.5 \text{ inches (D = constant)}.$$

If the absorptivity were 0.2 instead of 0.8:

$$dL/L = 0.039$$

$$dL = 104 \times 0.039 = 4.1 \text{ inches (tapered)}$$

$$dL = 4.1 \times 2.86 = 11.7 \text{ inches (D = constant)}$$

This illustrates the desirability of tapered tubes over straight tubes during conditions of unbalance.

5.0 GRAVITY EFFECTS IN OFFBACE TEST RIG PERFORMANCE

The OFFBACE test program has been carried out to evaluate overall system performance as well as to examine individual component operation during the zero-gravity run. As shown in Figure 1, the body forces ranged from zero to 2.5 g's during this maneuver. Thus it is possible to analyze the data obtained over a range of gravity conditions from zero to 2.5 g.

5.1 Overall System Operation

The OFFBACE system was found to operate satisfactorily during these tests. It was indicated that a properly designed mercury Rankine turboelectric power system will operate in the zero gravity environment experienced in space. In addition, an appreciable amount of valuable information, which will assist in ensuring this proper design, was obtained. Each component was found to operate in a manner similar to that assumed in the original system design.

Considerable discussion of condenser phenomena is given in earlier sections of this report. Two graphical descriptions of OFFBACE condenser operation for typical runs are given in Figures 48 and 52. It is now of interest to note the operation of the pump, boiler, and nozzle-desuperheater combination in the variable gravity environment.

5.2 Pump Operation

The pump used in these tests was a SNAP II centrifugal unit run by a variable-transformer-controlled electric motor. Figures 46 and 50 show that there was some change in pump pressure levels during these runs. These changes in pressures are explained by considering the effect of inlet pressure variations on pump performance. Figure 53 shows the performance curve for the pump used in these tests.

In the OFFBACE system there was a liquid head between the condenser interface and the pump impeller. Thus any body force changes due to gravity were reflected in hydrostatic head changes at the pump inlet. This caused some variation in pump pressure rise according to Figure 53. The pump outlet pressure variations were then directly responsible for changes in boiler outlet pressure as shown in Figures 47 and 51.

It is then possible to calculate the effect of pump variations on overall system performance by considering the vapor nozzle effects shown in Figures 45 and 49. The nozzle inlet pressure given here is exactly the boiler outlet pressure which has been established as affected by the pump. It is also the pressure which would be provided at the turbine inlet in an actual system and therefore affects system performance by changing turbine pressures and flow rates.

If we consider all changes in pump power negligible and notice that the turbine pressure drop change is negligible, it is possible to base system power output on turbine flow rate alone. In this case, turbine flow rate is directly proportional to the nozzle inlet pressure. The following gives the changes in system output from 0 to 2.5 g's based on the nozzle inlet pressures from Figures 45 and 49.

OFFFACE VAPOR NOZZLE PERFORMANCE DURING KEPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 45

OFFBACK PUMP PERFORMANCE DURING KEPPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 46

BOILER PERFORMANCE DURING KEPPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 47

OFFBACK CONDENSER PERFORMANCE DURING KEPPLER AN ZERO-GRAVITY TRAJECTORY

FIGURE 48

OFFBACE VAPOR NOZZLE PERFORMANCE DURING KEPPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 49

OFFFACE PUMP PERFORMANCE DURING KEPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 50

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BOILER PERFORMANCE DURING KEPPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 51

OFFFACE CONDENSER PERFORMANCE DURING KEPPLERIAN ZERO GRAVITY TRAJECTORY

FIGURE 52

OFFFACE PUMP PERFORMANCE AT 30,000 RPM
FLOW 25 LB/MIN

FIGURE 53

$$\text{Run 5} = \frac{110}{105} = 1.05$$

$$\text{Run 8} = \frac{86}{81} = 1.06$$

This shows a change of 5% in system power output in going from 0 to 2.5 g.

NOTE: The actual SNAP II system is designed to have no hydrostatic head between the condenser interface and the pump. Therefore no change in pump inlet pressure should be expected, and no change in overall system output is indicated for the SNAP II system.

5.3 Boiler Operation

The OFFBACE boiler was a radiant heated, once-through, forced convection, stepped tube coiled in a four-inch diameter. Design was based on SNAP II boiler design data. It is seen in Figures 47 and 51 that the boiler outlet pressure closely follows the boiler inlet (pump outlet) pressure. Thus the boiler pressure drop remains relatively constant.

The wall temperatures measured in several ground and flight test runs are given in Figures 54 to 56. The mercury saturation temperature is drawn as a dotted line. The tube coverage by the three radiant heaters is indicated at the tops of the figures. The large temperature differences between wall temperatures and saturation temperatures immediately suggest film boiling and, as a result, the heat transfer coefficient can be correlated and compared with the integrated film boiling equation for forced convection developed in Reference 3. This equation formed the basis for ground test correlations for the SNAP II development boiler.

The heat transfer coefficients were calculated from the test data and were plotted in Figure 57. At the preheater-boiler interface globules of mercury are formed during the inception of boiling. The evaporation of these globules is sensitive to the strength of the gravity field until small drops are formed and vortex flow is established. A stepped tube boiler minimizes gravity sensitivity. Since the zero-gravity data point (see Figure 57) appears to fall on a line having the same slope as the theoretical curve for film boiling - which is based on vortex boiling and which does not include gravity in its derivation - it can be concluded that gravity played a negligible role in boiler heat transfer.

OFFFACE BOILER TUBE WALL TEMPERATURES MEASURED DURING KEPLERIAN ZERO-GRAVITY TRAJECTORY

FIGURE 54

OFFFACE BOILER ΔT GROUND TEST

FIGURE 55

OFFFACE ΔT GROUND TEST

FIGURE 56

COMPARISON OF OFFFACE BOILER PERFORMANCE WITH THEORETICAL
FILM BOILING CURVE (REFERENCE 3)

FIGURE 57

6.0 OFFBACE SYSTEM STARTUP

It is presently proposed that nuclear turboelectric power systems such as SNAP II be capable of commencing operation after being launched into space. This requires knowledge of the problems associated with system startup under zero-gravity conditions to insure that these systems possess this capability. An OFFBACE test was conducted to provide data of a semi-quantitative nature on the transient effects associated with system startup in zero-gravity for comparison with ground test data obtained using a similar startup procedure.

One method for system startup in space that is planned for the SNAP II system is to inject liquid mercury into the preheated boiler. Vaporization begins as the liquid mercury reaches the hot boiler tubes. The pressure of the interior of the boiler tubes then rises and the vapor leaves the boiler. The vapor enters the rotating package and starts rotation of the mercury turbine which drives the combined shaft unit.

The orbital startup tests were accomplished without major modifications to the Mark II test package using this method. The reservoir in the Mark II package was pressurized as a startup tank to supply pressure to the pump inlet. Initial flow was supplied from this pressurized reservoir by opening a series of valves. This provided the pump inlet pressure required for zero-gravity operation. The condenser discharge valve to the pump was closed for zero-gravity operation to prevent liquid from backing up into the condenser-subcooler area. Only a general picture of zero-gravity startup was sought. The test rig was not instrumented for a thorough startup transient analysis and conditions could not be controlled accurately enough to permit a rigorous analysis of the results.

Figures 58 and 59 show several system parameters plotted with respect to time for a zero-gravity startup and a ground startup. Time required to reach a specific boiler inlet pressure was the major difference in operation. As shown, the boiler inlet pressure rose more rapidly in the zero-gravity test than in the ground test. Examination of the procedure for admitting flow to the boiler at the beginning of the test can account for this difference.

Two effects could not be accurately controlled during admission of flow to the boiler in zero-gravity. One uncontrollable effect was the magnitude of the variable hydrostatic head at the pump inlet during the zero-gravity run. The other was the time required for flight personnel to manually open the valve in the reservoir inlet line to the pump. The relative importance of these effects cannot be determined. The overall effect of these uncontrolled variables was to allow initial flow to the boiler to be more rapid in the zero-gravity run, as can be seen by comparing the plots of flow rates versus time in Figures 58 and 59.

The other quantities plotted continued to rise throughout the data run, indicating that startup was not completed in this time interval. Comparison of boiler output pressure traces shows that they differ only by a factor of time. Condenser pressure curves presented are probably not comparable. The system apparently was not completely evacuated in the flight test, so the initial condenser manifold pressure was higher in the flight test.

OFFFACE SERIES III FLIGHT TEST #B-9 (12-15-60)
ZERO-GRAVITY SYSTEM STARTUP DATA

FIGURE 58

OFFFACE SERIES III GROUND SYSTEM STARTUP TEST (12-8-60) STARTUP DATA

FIGURE 59

This test showed that the zero-gravity startup techniques proposed for SNAP II appear satisfactory. Although transient unbalances were experienced during the initiation of flow, the liquid perturbations were quickly damped out.

7.0 CONCLUSIONS

1. Pressure drop changes in mercury condensers can be expected when going from 1 to 0 G if the Reynolds number is less than 10^4 and if the vapor specific volume is less than $10 \text{ ft}^3/\text{lb}$. This applies to condensing downward.
2. At a Reynolds number of 5000 and specific volumes of $5 \text{ ft}^3/\text{lb}$ a pressure drop change amounting to 40 percent can be expected in going from 1 to 0 G. This applies to condensing downward.
3. The mechanics of mercury condensing has been sufficiently well established so that confident predictions can be made as to zero-gravity condenser design and performance.
4. Surface tension, vapor drag, and gravity are the primary factors in establishing the two-phase flow patterns and resulting Φ values. The object is to minimize the influence of the gravity term on the design and performance of the prototype condenser.
5. Stable water and mercury interfaces can be maintained in a zero-gravity environment against disturbance amounting to $+0.055$ and -0.02 G in glass tubes having diameters less than about 0.5 in. I.D.
6. As demonstrated by an upward condensing experiment and by an upward flowing (15 degree tilt) nitrogen-mercury test rig, the gravity effects will be much greater flowing upward than when flowing downward.
7. Flow unbalance caused by improper vapor manifolding, unequal tube dimensions, and heat transfer will affect the position of the liquid interfaces in zero gravity. This applies when multiple liquid interfaces in parallel tubes are used.
8. Tapered tubes will be less sensitive to gravity from a pressure drop standpoint than tubes of constant diameter.
9. Tapered tubes show less sensitivity to liquid level differences produced by unbalances in heat transfer caused by solar or other sources of radiation.
10. A design procedure for a lightweight vapor manifold has been established by test and theory.
11. Dynamic stability in zero gravity of multiple liquid interfaces during multiple tube condensing can be maintained if $\Phi f' L/D \cong 2.5$.

8.0 RECOMMENDATIONS

To reduce the number of unknowns which still remain and to improve the accuracy of correlations which will permit the minimization of design tolerances and prototype component weights, further research should be undertaken. The following experiments are still required:

1. To Extend Condenser Data:
 - A. Obtain condensing pressure drop data for a greater range of tube geometries.
 - B. Obtain condenser pressure drop data for Reynolds numbers greater than 15×10^3 to close the gap between the nitrogen-mercury data and available condenser data and to establish the trend in ϕ for these higher Reynolds numbers.
 - C. Run further pressure drop tests on condensers to determine whether or not ϕ increases beyond a Reynolds number of 10^4 as indicated by theory and by nitrogen-mercury flow tests.
 - D. Measure local ϕ values during condensing by using multiple pressure taps along the condenser tube.
 - E. Determine effect of spring insert on condenser performance. A spring insert in conjunction with a lower flow rate may be comparable to a bare tube condenser with a higher flow rate insofar as gravity effects and pressure drop are concerned.
 - F. Determine the effect on condenser operation if "wetting" of the condenser tube walls occurs.
2. To Develop Mathematical Analysis and Physical Understanding of the Condensing Process:
 - A. Study experimentally the trajectory of mercury drops in various gravity-flow fields to provide the data necessary for a more accurate computation of the slip ratio, a very important parameter in computing ϕ for forced convection condensing with and without body forces. This can be done using high speed photographic methods.
 - B. Extend data on effects of inserts (twisted ribbon or spring) on the trajectory and dynamics of liquid drops.
 - C. Determine entrainment drop sizes in a mercury vapor environment using a stainless steel heat transfer surface. The majority of available data was

obtained in glass tubes with nitrogen gas under adiabatic conditions.

- D. Refine mathematical treatment to include the integrated effects of drops of various sizes moving through different paths toward the interface. Evaluate E_{σ} for mercury drops for forced convection condensation in the presence of body forces by the mathematical techniques of Bashforth and Adams (Reference 6). Measure drop deformation optically in the above-mentioned conditions to determine E_{σ} .
- E. Define Liquid-Vapor Interfacial Stability Limits for Mercury in a Steel tube at Condensing Temperature (600°F) with Controlled Disturbances (Known Frequency and Amplitude). Determine stability limits of mercury interface during controlled internal disturbances in which mercury droplets are sprayed onto the interface. Identify magnitude of the internal interface disturbance by controlling drop sizes, number and velocity.

3. To Study Other Problem Areas:

- A. Test OFFBACE condenser with larger pressure drops to improve accuracy of measurement of the gravity effects. Tapered tubes, as well as constant diameter tubes, should be tested in zero gravity to establish flow regime and pressure drop sensitivity to changes in external body forces.
- B. Experimentally determine startup performance of condensers, studying flow pattern, interface position, and thermal transients.
- C. Analytically and experimentally determine a more complete stability criterion for parallel tube operation where flow is opposite body forces which have a powerful destabilizing effect.
- D. Develop optimum degassing techniques for degassing procedure during initial fillup, intermittent degassing, and continuous degassing.

9.0 REFERENCES

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NOMENCLATURE

A	area
$C_{d\delta}$	drag coefficient for drop
D	diameter
D_o	inlet diameter
D_e	exit diameter
D_n	see Figure 39
E_σ	surface tension quantity (see Equation 7)
F	force
f	gas friction factor
f'	mean gas only friction factor for condensing (see Ref. 1)
f_δ	gas friction factor with drops on wall
G	gravity
G_o	$\rho_v u_{v_o}$
g	local gravitational acceleration
gh	local gravitational acceleration times liquid height in inches
g_s	$32.174 \frac{\text{lbm-ft}}{\text{lbf-sec}^2}$ conversion factor
h	heat transfer coefficient
h_c	condensing heat transfer coefficient
h_{fv}	latent heat
h_δ	drop heat transfer coefficient based on drop projected area
K, K', K''	constants defined by Equations 66, 67 and 68 respectively
K_v	vapor thermal conductivity

K_f	liquid thermal conductivity
L	length
L_B	effective condensing length of right front tube in Mark II Test Rig
M	momentum, $\rho/v_o u_{vo}^2 / g_s$
$\dot{m}$	mass flow rate
$\dot{m}_A$	mass flow rate per unit area. Subscript indicates point of reading.
$\dot{m}_v$	vapor mass flow rate
$\dot{m}_f$	liquid mass flow rate
$\dot{m}_o$	total flow at inlet
n	g/g_s
$N_{A\delta}$	acceleration group $\frac{\delta}{(\epsilon u_v)^2} \frac{d(\epsilon u_v)}{dt}$
N_F	droplet Froude number, $\frac{3}{2} \frac{\rho_v u_v^2}{\delta_c \rho_f n g_s}$
$N_{R\delta}$	droplet Reynolds number, $\frac{\delta_c \rho_v u_v (1 - \epsilon)}{\mu_v}$
Nu_δ	drop Nusselt number = $h_\delta \delta / K_f$
N_v	number of drops per unit volume
N_W	droplet Weber number, $\frac{\rho_v u_v^2 \delta_c}{2 g_s \sigma}$
$N_{wt\delta}$	gravity group $\delta_c \left[\frac{4}{3} \frac{g \rho_v (\rho_f - \rho_v)}{\mu_v^2} \right]^{1/3}$
N_s	number of drops per unit area
$N_{\sigma\delta}$	$\frac{g_s \sigma \rho_v \delta_c}{\mu_v^2}$
p	pressure

P_{inc}	incident radiation per unit area
p_o	inlet pressure
P_{v_o}	inlet vapor density
Re_o	inlet Reynolds number based on tube diameter
Re_v	vapor Reynolds number ($Du_v\rho_v/\mu_v$)
R_L	volume fraction occupied by liquid
r_o	pipe radius
$r_o/\delta_{(sand)}$	Nikuradse's relative sand roughness ratio
S	perimeter length
t	time
T_c	condensing temperature
T_o	ambient temperature
u	velocity
u_e	critical entrainment velocity
u_f	liquid velocity
u_o	inlet velocity
u_r	$u_v - u_f$ = relative velocity of liquid droplets
u_v	vapor velocity
v_v	vapor specific volume
X	quality

Greek Symbols

α	absorptivity
β	contact angle
ΔP_{δ}	vapor pressure drop due to drops on wall
ΔP_{TP}	two phase pressure drop
Δp_v	vapor pressure drop due to smooth wall friction
ΔT	temperature difference
ΔT_m	mean temperature difference
δ	drop diameter
δ_c	critical drop diameter at entrainment
ϵ	emissivity or slip ratio u_f/u_v
θ	angle of inclination
θ'	time
θ_c	drop growth period
λ	wavelength of liquid interface disturbance
μ_v	vapor viscosity
μ_f	liquid viscosity
π	3.141
ρ_v	vapor density
ρ_{v_o}	inlet vapor density
ρ_f	liquid density
σ	Stephan-Boltzmann constant or surface tension
τ_w	wall shear stress
Φ	$\frac{dp_{TP}(\text{friction})}{dp_v}$ (see Equations 3 and 5)

APPENDIX I

COMPUTATION FOR DROPLET DRAG COEFFICIENT USING FIGURE 10

$$N_{R\delta} = \frac{(1 - \epsilon) \rho_v u_v \delta_c}{\mu_v} \approx \frac{\rho_v u_v \delta_c}{\mu_v} \text{ for } \epsilon \ll 1$$

$$N_{R\delta} (\text{average}) = \frac{Re_o}{2} \frac{\delta_c}{D}$$

For zero gravity the critical drop size can be computed from

$$\frac{\rho_v u_v^2 \delta_c}{\sigma} = 4 E_\sigma \quad (\text{Eq. 10})$$

$$\therefore N_{R\delta} = \frac{\rho_v u_{v_o} D}{\mu_v^2} \frac{8 E_\sigma}{\rho_v \left(\frac{u_{v_o}}{2}\right)^2 \frac{D}{g_s}} = \frac{16 E_\sigma g_s \sigma}{\mu_v u_{v_o}}$$

$$N_{R\delta} = \frac{16 \times 0.0464 \times 32.2 \times 0.0324}{0.367 \times 10^{-4} u_{v_o}} = \frac{2.11 \times 10^4}{u_{v_o}}$$

test data range $u_{v_o} = 100 \text{ ft/sec.}$

$$\therefore N_{R\delta} = \underline{211}$$

$$N_{\sigma\delta} = \frac{D \rho_f \sigma g_s}{\mu_v^2} \frac{\delta_c}{D} \frac{\rho_v}{\rho_f} = \frac{\rho_v \delta_c \sigma g_s}{\mu_v^2}$$

also

$$N_{\sigma\delta} = \frac{\rho_v \sigma g_s}{\mu_v^2} \frac{8 E_\sigma \sigma g_s}{\rho_v u_v^2} = \left(\frac{\sigma g_s}{\mu_v u_v} \right)^2 8 E_\sigma$$

$$N_{\sigma\delta} = \left(\frac{0.0324 \times 32.2}{0.367 \times 10^{-4} u_v} \right)^2 8 \times 0.0464$$

let

$$u_v = u_{v_o}/2$$

$$N_{\sigma_\delta} = \left(\frac{5.7 \times 10^4}{u_{v_o}} \right)^2 0.371$$

test data range $u_{v_o} = 100 \text{ ft/sec.}$

$$\therefore N_{\sigma_\delta} = 1.21 \times 10^5$$

From Figure 10,

$$\therefore C_{d_\delta} \approx \underline{0.7} \quad @ \quad N_{R_\delta} = \underline{211} \quad \text{and} \quad N_{\sigma_\delta} = 1.21 \times 10^5$$

APPENDIX II

SAMPLE CALCULATION FOR CALCULATED ΔP_{TP} (frictional) (See Figure II-1)

$$\Delta P_{TP} \text{ (frictional)} = \Phi \Delta P_v$$

$$\Delta P_v = f' \frac{L}{D} \frac{\rho_v u_{vo}^2}{2g_s} = \frac{\Phi f' \bar{V}_v}{2g_s} Re_o^2 \left(\frac{\mu_v}{D} \right)^2 \frac{L}{D} \left(\begin{array}{l} \text{applies to complete} \\ \text{condensing, } X = 1 \text{ to } X = 0 \end{array} \right)$$

where f' is determined from Figure 1-I, Reference 1, Equation 56 ($n = 0$).

$$\Phi = 2.75 \times 10^{-5} Re_o^{1.05} + \frac{57.6}{Re_o^{0.364} V_v^{0.307}}$$

$$D = 0.136 \text{ inches}$$

$$L = 1.67 \text{ ft}$$

Series II, Flight A, Loop 10 (Table IV)

$$Re_o = 5720, \bar{V}_v = 11.8 \text{ ft}^3/\text{lb}, f' = 0.0123 \text{ (Figure 1-III)},$$

$$\mu_v = 0.367 \times 10^{-4} \text{ lb/ft-sec}$$

$$\Delta P_{TP} \text{ (frictional)} = \left(2.75 \times 10^{-5} Re_o^{1.05} + \frac{57.6}{Re_o^{0.364} V_v^{0.307}} \right) \left(\frac{f' \bar{V}_v}{2g_s} \left[Re_o \frac{\mu_v}{D} \right]^2 \frac{L}{D} \right)$$

$$\Delta P_{TP} \text{ (frictional)} = 158 \text{ lb/ft}^2 ; 1.095 \text{ lb/in}^2$$

COMPARISON OF ZERO GRAVITY EXPERIMENTAL FRICTION PRESSURE DROP DATA
FOR CONDENSING MERCURY IN A CONSTANT DIAMETER TUBE
WITH CALCULATED VALUES (EXCLUSIVE OF MOMENTUM TERM)

FIGURE II-1

APPENDIX III

MULTIPLE LIQUID INTERFACE STABILITY

$$\Delta P_{TP} = \Phi f' \frac{L}{D} \frac{\rho_v u_{v_o}^2}{2g_s} - \frac{\rho_v u_{v_o}^2}{g_s} \quad \text{Equation 62}$$

$$\frac{d(\Delta P_{TP})}{d(G_o)} = \Phi f' \frac{L}{D} \frac{G_o}{\rho_v g_s} + \frac{L G_o^2}{D \rho_v 2g_s} \left[f' \frac{d\Phi}{dG_o} + \Phi \frac{df'}{dG_o} \right] - \frac{2G_o}{\rho_v g_s}$$

where $G_o = \rho_v u_{v_o}$

limit of stability $d(\Delta P_{TP}) / dG_o = 0$

$$\therefore 0 = \Phi f' \frac{L}{D} + \frac{L}{D} \frac{G_o}{2} \left[f' \frac{d\Phi}{dG_o} + \Phi \frac{df'}{dG_o} \right] - 2$$

$$0 = \Phi f' \frac{L}{D} \left[1 + \frac{G_o}{2\Phi f'} \left(f' \frac{d\Phi}{dG_o} + \Phi \frac{df'}{dG_o} \right) \right] - 2$$

$$0 = \Phi f' \frac{L}{D} \left[1 + \frac{G_o}{2\Phi} \frac{d\Phi}{dG_o} + \frac{G_o}{2f'} \frac{df'}{dG_o} \right] - 2$$

$$0 = \Phi f' \frac{L}{D} \left[1 + \frac{Re_o}{2\Phi} \frac{d\Phi}{dRe_o} + \frac{Re_o}{2f'} \frac{df'}{dRe_o} \right] - 2$$

for stability,

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 + \frac{Re_o}{2\Phi} \frac{d\Phi}{dRe_o} + \frac{Re_o}{2f'} \frac{df'}{dRe_o} \right]}$$

For SNAP II zero gravity conditions,

$$Re_o = 8500$$

$$V_v = 10 \text{ ft}^3/\text{lb}$$

$$\Phi = 1.55 \text{ (Figure III-2)}$$

$$f' = 0.117 \text{ (Figure III-1)}$$

From Figure III-2

$$\Phi = \text{const. } Re_o^{-0.2}$$

$$\frac{d\Phi}{dRe_o} = (Re_o^{0.2} \Phi)_1 \frac{(-0.2)}{Re_o^{1.2}}$$

or

$$\frac{d\Phi}{dRe_o} = \frac{-1.89}{Re_o^{1.2}}$$

∴

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 + \frac{Re_o (-1.89)}{2 \Phi Re_o^{1.2}} + \frac{Re_o (-0.01423)}{2 f' Re_o^{1.2}} \right]}$$

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 - \frac{0.945}{\Phi Re_o^{0.2}} - \frac{0.00712}{f' Re_o^{0.2}} \right]}$$

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 - \frac{0.945}{1.55 (8500)^{0.2}} - \frac{0.00712}{0.117 (8500)^{0.2}} \right]}$$

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 - 0.1 \quad -0.1 \right]} \geq \underline{2.5}$$

also

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 + \frac{Re_o}{2\Phi} \frac{d\Phi}{dRe_o} + \frac{Re_o}{2f'} \frac{df'}{dRe_o} \right]}$$

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 + \frac{Re_o}{2\Phi} (Re_o^{0.2}\Phi)_1 \frac{(-0.2)}{Re_o^{1.2}} + \frac{Re_o}{2f'} (f' Re_o^{0.2})_1 \frac{(-0.2)}{Re_o^{1.2}} \right]}$$

$$\Phi f' \frac{L}{D} \geq \frac{2}{\left[1 - 0.1 - 0.1 \right]} \geq \underline{2.5}$$

GAS ONLY CONDENSING INTEGRATED FRICTION FACTOR
FOR CONSTANT DIAMETER CONDENSER TUBES
(REFERENCE 1)

FIGURE III-1

Φ VERSUS INLET REYNOLDS NUMBER AS COMPUTED FROM EQUATION 55
(FOR ZERO GRAVITY, SAME PROPERTY VALUES AS IN EQUATION 56)
FOR SNAP II DIMENSIONS

SNAP II Dimensions:
D = 0.319 in.
L = 7.85 ft

FIGURE III-2

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